

From: [REDACTED]
To: [Manston Airport](#)
Subject: TR020002 : Revised deadline and invitation to resubmit, Manston DCO
Date: 31 January 2020 10:12:25
Attachments: [Manston Climate Change.pdf](#)
[Archive.zip](#)

Dear Sirs

I am an interested party in respect of the Manston Airport DCO (TR020002).

Please find attached my submission relating specifically to the Climate Change section in the letter of 17th January 2020 from the Secretary of State.

I have also attached supporting documentation bundled as a zip file.

Yours faithfully

Dr Philip Shotton

TR020002 : Revised deadline and invitation to resubmit, Manston DCO

In response to the invitation from the Secretary of State in his letter published 17th January 2020 in relation to the above matter, in particular section 22, Climate Change, I would ask that the following submission be included in the examination.

The reasons for rejecting the Manston DCO are many and various. However the one pressing issue, the most important issue faced by all of us on this planet, is climate change. Without doubt the Manston DCO should be rejected for this one reason.

Since the close of the DCO examination there has been a number of significant changes in local, national and international responses to the climate change emergency facing us all that render this application completely inappropriate given the challenges facing us to address carbon emissions.

As recently as last week (24th January) Uttlesford District Council's Planning Committee reversed an earlier decision (made in November 2018) to allow the increase of the passenger cap at Stansted Airport¹. The reasons for the refusal "were made in relation to noise, air quality and climate change, matters that the committee agreed **were material planning changes since the approval was granted.**" (my emphasis). The council planning committee were undoubtedly taking into account recent information on the increasing danger to human life by the continuing increase in carbon dioxide emissions despite the clear scientific consensus that emissions **must** be reduced starting immediately.

In May last year Parliament declared a Climate Emergency², recognising the clear and present danger of climate change caused by man-made emissions primarily from burning fossil fuels. An emergency requires an immediate response. In such circumstances **no** airport expansion should be permitted, let alone the creation of a **new** airport focused on freight located in a completely inappropriate part of the country more than 4 hours drive away from the 'golden triangle'.

An analysis by the International Council on Clean Transportation³ found that worldwide CO2 emissions from commercial flights are rising up to 70% faster than predicted by the UN. The UK is the world's third largest emitter of CO2 from aviation, responsible for 4% of global aviation CO2 emissions, behind only the US (24%) and China (13%).

¹ Uttlesford District Council - Stansted Airport planning application.pdf

² <https://www.bbc.co.uk/news/uk-politics-48126677>

³ CCC CCC-Meeting-the-UK-Aviation-target-2009.pdf

The current Secretary of State for Transport, Grant Shapps, said at a speech at Cranfield University on 19th September 2019⁴: “We need to get to grips with commercial aviation greenhouse gas emissions for the sake of our children and our fragile environment.”

Despite the need to constrain flights to have any chance of meeting UK carbon emission targets, passenger air travel is expected to continue to rise.

Forecast increase in passenger numbers increases the potential bellyhold capacity and makes pure freight look even less commercially and environmentally attractive.

The Committee on Climate Change in their letter to the SoS for Transport, Grant Shapps, stated: “Carbon intensity can be improved through [the] use of more fuel efficient planes (new aircraft and engine designs), improving air space management, and use of biofuels.”⁵

The proposed new Manston Airport is primarily to be a dedicated freight hub. Freight planes tend to be older stock, less fuel efficient than their passenger counterparts. The only airline to express any interest in Manston, Magma Airlines, own 4 planes, two of which are unable to use Manston due to the length of the runway. The average age of their fleet is over 25 years, designed and built in an era when the technology to limit noise and increase fuel efficiency, thereby reducing pollution, was considerably less developed than today. Given the expected increase in belly-hold capacity in modern, fuel efficient planes it is beyond belief that anyone can consider the creation of a **new** airport for dedicated freight.

A dedicated freight operation is both unneeded (due to spare bellyhold capacity) and more polluting and climate damaging due to the fleet mix.

The Tyndall Centre for Climate Change Research states that: “the aviation industry is more simply structured [than shipping], but there are few opportunities to reduce emissions because the aircraft are already highly efficient. As a result, the aviation sector relies heavily on emissions trading to deliver cuts in emissions, rather than delivering its own plan. Reducing the demand for aviation by reducing the number of flights or reducing the distance travelled would make a substantial contribution to reducing aviation emissions, and to addressing climate change.”⁶

The Tyndall Centre for Climate Change Research says we need to cut emissions by 90% by 2050⁷ – they believe this can be done, provided that a programme of work is started in the next four years. Others, including the Environmental Transport Association (ETA), believe the descent needs to be steeper, to achieve 90% in developed countries by 2030.⁸

4

<https://www.cranfield.ac.uk/press/news-2019/secretary-of-state-for-transport-grant-shapps-calls-for-an-d-electric-revolution-in-the-skies>

⁵ Letter-from-Lord-Deben-to-Grant-Shapps-IAS.pdf

⁶ <https://www.tyndall.ac.uk/ideas-and-insights/aviation-shipping>

⁷ Tyndall Centre for Climate Change Research - twp126.pdf

⁸ ETA <https://www.eta.co.uk/environmental-info/air-travels-impact-on-climate-change/>

The IPCC stated at Monaco, Sept 25 – “The latest Intergovernmental Panel on Climate Change (IPCC) Special Report highlights the urgency of prioritizing timely, ambitious and coordinated action to address unprecedented and enduring changes in the ocean and cryosphere. [...] Choices made now are critical for the future of our ocean and cryosphere”⁹.

To keep the climate safe we need drastic cuts in air travel. Efficiency savings such as more direct flights shave off small fractions but are dwarfed by planned growth.

The IPCC estimates that the warming effect of aircraft emissions is about 1.9 times that of carbon dioxide alone, due to the other gases produced by planes¹⁰.

Emissions from the aviation industry are forecast to grow both in real terms and as a proportion of the national total. In the UK, the share of emissions taken up by aviation is predicted to grow from around 6% today to 25% by 2050, even if the sector is successfully capped at level of 37.5 MtCO₂ (equivalent to UK aviation emissions in 2005) which has been recommended by the Committee on Climate Change (CCC).¹¹

In the UK, where the aviation market is relatively mature, demand for aviation is still expected to grow by around 1-3% annually to 2050, while global growth rates are 4-5% per annum, easily outstripping ICAO’s ‘aspirational’ target of annual 2% efficiency gains until 2050.

The key recommendations of the CCC in a letter to Grant Shapps, 24/9/2019 : “The planning assumption for international aviation and shipping should be to achieve net-zero emissions by 2050. This should be reflected in the Government’s forthcoming Aviation Strategy and as their Clean Maritime Plan is taken forward. It means reducing actual emissions in these sectors and is likely to require some use of greenhouse gas removals (GGRs) to offset remaining emissions”¹².

Extra levies on those who fly frequently, reformed taxes or a price on carbon and management of the amount of airport capacity in the UK are among the potential measures suggested by the CCC.¹³

Current planned additional capacity in London, including a third runway at Heathrow, “is likely to leave at most very limited room for growth at non-London airports” the committee said. The recommendations come in a letter from Lord Deben, the committee’s chairman to transport secretary Grant Shapps on including international aviation and shipping emissions in the UK’s targets to cut greenhouse gas emissions to zero overall by 2050.

⁹ IPCC <https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/>

¹⁰ IPCC av-en.pdf

¹¹ CCC limits <https://www.aef.org.uk/issues/climate/>

¹² CCC Letter-from-Lord-Deben-to-Grant-Shapps-IAS.pdf

¹³ <https://www.independent.co.uk/environment/climate-change-crisis-net-zero-aviation-emissions-heathrow-airport-shipping-ccc-a9117976.html>

Councils are starting to respond to the immediacy of the climate emergency. As noted above, Uttlesford council recently rejected an application to increase the passenger cap at Stansted Airport¹⁴

Councillors heard that the proposed expansion would result in an extra million tonnes of CO2 emissions a year and that Stansted is already the biggest single source of CO2 emissions in the East of England. With the world facing a climate emergency, many councillors emphasised that the priority was to reduce carbon emissions, **not to sanction a planning application that would make matters worse**. The proposed expansion would also have meant increased noise, air pollution and health risks for residents not only in the vicinity of the airport and under flightpaths, but also over a wider area. (my emphasis). The increased noise, air pollution and health risks are particularly acute for Ramsgate, lying as it does immediately under the flight path and less than 1.4 miles from the end of the runway.

To put it bluntly, **any** increase in air transport movements is incompatible with the urgent need to curtail our CO2 emissions. An unnecessary freight airport in the wrong part of the country, supported by dubious documentation and funding, with the likelihood of causing immense harm both environmentally and medically to the local (and wider) area, should not be open to consideration. There is **no** good reason for allowing this DCO, and I urge the Secretary of State for Transport wisely to use his powers to reject the application.

Whatever the outcome of this examination, the world is moving on. At all levels in society climate change is **the** key issue. Climate change activism is now mainstream, particularly among the young who stand to inherit the planet in whatever state the politicians leave it. Despite the continuing belief among the more myopic politicians, that Extinction Rebellion is a terrorist organisation, the campaigning group is held in high regard by very many people, not least those whose task it is to sit in judgment.

May I finish by quoting the wonderful remarks of a District Judge, following an Extinction Rebellion trial on 29th January 2020:

"This is going to be my last Extinction Rebellion trial for a little while. I think they only allow us to do so many of these before our sympathies start to overwhelm us.

When I started, I was fully expecting to see the usual crowd of anarchists and communists, and all the dreadful things the Daily Mail say you are.

I have to say I have been totally overwhelmed by all the defendants. It is such a pleasure to deal with people so different from those I deal with in my regular life. Thank you for your courtesy, thank you for your integrity, thank you for your honesty.

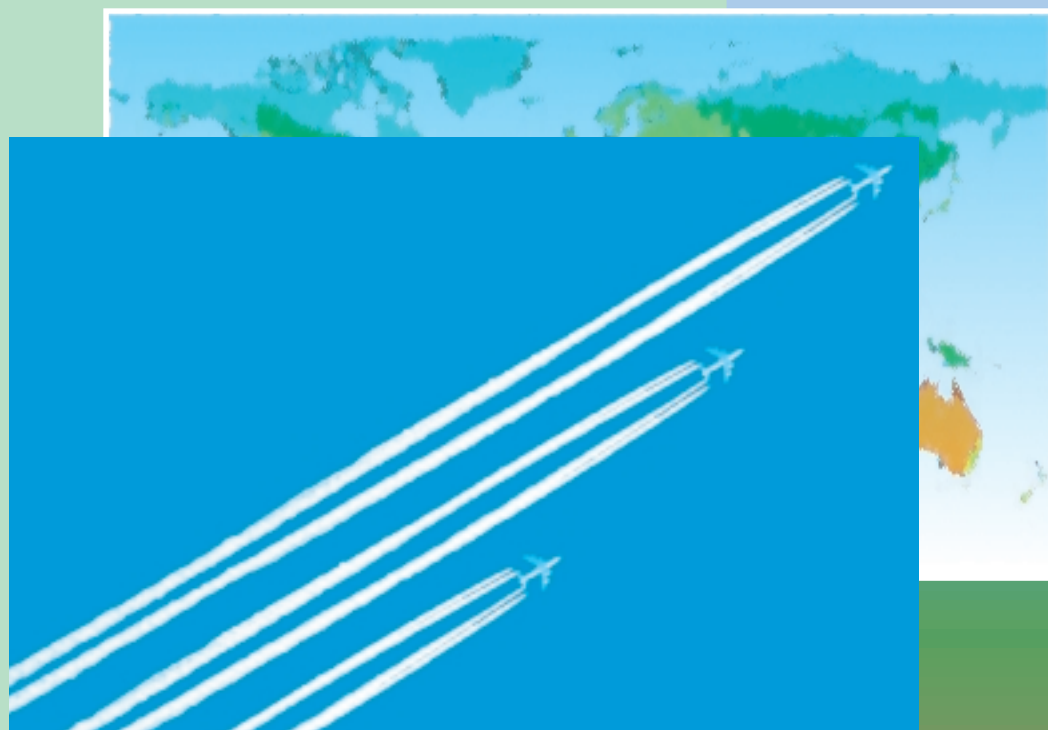
You have to succeed."

They will succeed. We number among them and WE will succeed.

¹⁴ <http://uttlesford.gov.uk/article/4869/Stansted-Airport-planning-application>



INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE



IPCC SPECIAL REPORT AVIATION AND THE GLOBAL ATMOSPHERE

Summary for Policymakers



INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE



Summary for Policymakers

Aviation and the Global Atmosphere

Edited by

Joyce E. Penner
University of Michigan

David H. Lister
*Defence Research
and Evaluation Agency*

David J. Griggs
UK Meteorological Office

David J. Dokken
*University Corporation
for Atmospheric Research*

Mack McFarland
DuPont Fluoroproducts

A Special Report of IPCC Working Groups I and III

in collaboration with the

Scientific Assessment Panel to the Montreal Protocol
on Substances that Deplete the Ozone Layer

Published for the Intergovernmental Panel on Climate Change

© 1999, Intergovernmental Panel on Climate Change

ISBN: 92-9169-

Contents

Foreword	v
Preface	vii
1. Introduction	3
2. How Do Aircraft Affect Climate and Ozone?	3
3. How are Aviation Emissions Projected to Grow in the Future?	4
4. What are the Current and Future Impacts of Subsonic Aviation on Radiative Forcing and UV Radiation?	6
4.1 Carbon Dioxide	6
4.2 Ozone	6
4.3 Methane	6
4.4 Water Vapour	7
4.5 Contrails	7
4.6 Cirrus Clouds	8
4.7 Sulfate and Soot Aerosols	8
4.8 What are the Overall Climate Effects of Subsonic Aircraft?	8
4.9 What are the Overall Effects of Subsonic Aircraft on UV-B?	9
5. What are the Current and Future Impacts of Supersonic Aviation on Radiative Forcing and UV Radiation? ...	9
6. What are the Options to Reduce Emissions and Impacts?	10
6.1 Aircraft and Engine Technology Options	10
6.2 Fuel Options	10
6.3 Operational Options	11
6.4 Regulatory, Economic, and Other Options	11
7. Issues for the Future	12
List of IPCC Outputs	13

Foreword

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to: (i) assess available information on the science, the impacts, and the economics of, and the options for mitigating and/or adapting to, climate change and (ii) provide, on request, scientific/technical/socio-economic advice to the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). Since then the IPCC has produced a series of Assessment Reports, Special Reports, Technical Papers, methodologies, and other products that have become standard works of reference, widely used by policymakers, scientists, and other experts.

This Special Report was prepared following a request from the International Civil Aviation Organization (ICAO) and the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. The state of understanding of the relevant science of the atmosphere, aviation technology, and socio-economic issues associated with mitigation options is assessed and reported for both subsonic and supersonic fleets. The potential effects that aviation has had in the past and may have in the future on both stratospheric ozone depletion and global climate change are covered; environmental impacts of aviation at the local scale, however, are not addressed. The report synthesizes the findings to identify and characterize options for mitigating future impacts.

As is usual in the IPCC, success in producing this report has depended first and foremost on the enthusiasm and cooperation of experts worldwide in many related but different disciplines.

G.O.P. Obasi

Secretary-General
World Meteorological Organization

We would like to express our gratitude to all the Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, and Expert Reviewers. These individuals have devoted enormous time and effort to produce this report and we are extremely grateful for their commitment to the IPCC process.

We would also like to express our sincere thanks to:

- Robert Watson, the Chairman of the IPCC and Co-Chair of the Scientific Assessment Panel to the Montreal Protocol
- John Houghton, Ding Yihui, Bert Metz, and Ogunlade Davidson—the Co-Chairs of IPCC Working Groups I and III
- Daniel Albritton, Co-Chair of the Scientific Assessment Panel to the Montreal Protocol
- David Lister and Joyce Penner, the Coordinators of this Special Report
- Daniel Albritton, John Crayston, Ogunlade Davidson, David Griggs, Neil Harris, John Houghton, Mack McFarland, Bert Metz, Nelson Sabogal, N. Sundararaman, Robert Watson, and Howard Wesoky—the Science Steering Committee for this Special Report
- David Griggs, David Dokken, and all the staff of the Working Group I and II Technical Support Units, including Mack McFarland, Richard Moss, Anne Murrill, Sandy MacCracken, Maria Noguer, Laura Van Wie McGrory, Neil Leary, Paul van der Linden, and Flo Ormond, and Neil Harris who provided additional help
- N. Sundararaman, the Secretary of the IPCC, and his staff, Rudie Bourgeois, Cecilia Tanikie, and Chantal Ettori.

K. Töpfer

Executive Director
United Nations Environment Programme
and
Director-General
United Nations Office in Nairobi

Preface

Following a request from the International Civil Aviation Organization (ICAO) to assess the consequences of greenhouse gas emissions from aircraft engines, the IPCC at its Twelfth Session (Mexico City, 11–13 September 1996) decided to produce this Special Report, *Aviation and the Global Atmosphere*, in collaboration with the Scientific Assessment Panel to the Montreal Protocol. The task was initially a joint responsibility between IPCC Working Groups I and II but, following a change in the terms of reference of the Working Groups (Thirteenth Session of the IPCC, Maldives, 22 and 25–28 September 1997), the responsibility was transferred to IPCC Working Groups I and III, with administrative support remaining with the Technical Support Units of Working Groups I and II.

Although it is less than 100 years since the first powered flight, the aviation industry has undergone rapid growth and has become an integral and vital part of modern society. In the absence of policy intervention, the growth is likely to continue. It is therefore highly relevant to consider the current and possible future effects of aircraft engine emissions on the atmosphere. A unique aspect of this report is the integral involvement of technical experts from the aviation industry, including airlines, and airframe and engine manufacturers, alongside atmospheric scientists. This involvement has been critical in producing what we believe is the most comprehensive assessment available to date of the effects of aviation on the global atmosphere. Although this Special Report is the first IPCC report to consider a particular industrial subsector, other sectors equally deserve study.

The report considers all the gases and particles emitted by aircraft into the upper atmosphere and the role that they play in modifying the chemical properties of the atmosphere and initiating the formation of condensation trails (contrails) and cirrus clouds. The report then considers (a) how the radiative properties of the atmosphere can be modified as a result, possibly leading to climate change, and (b) how the ozone layer could be modified, leading to changes in ultraviolet radiation reaching the Earth's surface. The report also considers how potential changes in aircraft technology, air transport operations, and the institutional, regulatory, and economic framework might affect emissions in the future. The report does not deal with the effects of engine emissions on local air quality near the surface.

The objective of this Special Report is to provide accurate, unbiased, policy-relevant information to serve the aviation industry and the expert and policymaking communities. The report, in describing the current state of knowledge, also identifies areas where our understanding is inadequate and where further work is urgently required. It does not make policy recommendations or suggest policy preferences, thus is consistent with IPCC practice.

This report was compiled by 107 Lead Authors from 18 countries. Successive drafts of the report were circulated for review by experts, followed by review of governments and experts. Over 100 Contributing Authors submitted draft text and information to the Lead Authors and over 150 reviewers submitted valuable suggestions for improvement during the review process. All the comments received were carefully analysed and assimilated into a revised document for consideration at the joint session of IPCC Working Groups I and III held in San José, Costa Rica, 12–14 April 1999. There, the Summary for Policymakers was approved in detail and the underlying report accepted.

We wish to express our sincere appreciation to the Report Coordinators, David Lister and Joyce Penner; to all the Coordinating Lead Authors, Lead Authors, and Review Editors whose expertise, diligence, and patience have underpinned the successful completion of this report; and to the many contributors and reviewers for their valuable and painstaking dedication and work. We thank the Steering Committee for their wise counsel and guidance throughout the preparation of the report. We are grateful to:

- ICAO for hosting the initial scoping meeting for the report and the final drafting meeting, and for translating the Summary for Policymakers into Arabic, Chinese, French, Russian, and Spanish (ICAO also provided technical inputs requested)
- The government of Trinidad and Tobago for hosting the first drafting meeting
- The International Air Transport Association (IATA) for hosting the second drafting meeting
- The government of Costa Rica for hosting the Joint Session of IPCC Working Groups I and III (San José, 12–14 April 1999), where the Summary for Policymakers was approved line by line and the underlying assessment accepted.

In particular, we are grateful to John Crayston (ICAO), Steve Pollonais (Government of Trinidad and Tobago), Leonie Dobbie (IATA), and Max Campos (government of Costa Rica) for their taking on the demanding burden of arranging for these meetings.

We also thank Anne Murrill of the Working Group I Technical Support Unit and Sandy MacCracken of the Working Group II Technical Support Unit for their tireless and good humored support throughout the preparation of the report. Other members of the Technical Support Units of Working Groups I and II also provided much assistance, including Richard Moss, Mack McFarland, Maria Noguer, Laura Van Wie McGrory, Neil Leary, Paul van der Linden, and Flo Ormond. The staff of the IPCC Secretariat, Rudie Bourgeois, Cecilia Tanikie, and

Chantal Ettori, provided logistical support for all government liaison and travel of experts from the developing and transitional economy countries.

Robert Watson, IPCC Chairman

John Houghton, Co-Chair of IPCC Working Group I

Ding Yihui, Co-Chair of IPCC Working Group I

Bert Metz, Co-Chair of IPCC Working Group III

Ogunlade Davidson, Co-Chair of IPCC Working Group III

N. Sundararaman, IPCC Secretary

David Griggs, IPCC Working Group I TSU

David Dokken, IPCC Working Group II TSU

SUMMARY FOR POLICYMAKERS

AVIATION AND THE GLOBAL ATMOSPHERE

A Special Report of Working Groups I and III of the Intergovernmental Panel on Climate Change

This summary, approved in detail at a joint session of IPCC Working Groups I and III (San José, Costa Rica, 12–14 April 1999), represents the formally agreed statement of the IPCC concerning current understanding of aviation and the global atmosphere.

Based on a draft prepared by:

David H. Lister, Joyce E. Penner, David J. Griggs, John T. Houghton, Daniel L. Albritton, John Begin, Gerard Bekebrede, John Crayston, Ogunlade Davidson, Richard G. Derwent, David J. Dokken, Julie Ellis, David W. Fahey, John E. Frederick, Randall Friedl, Neil Harris, Stephen C. Henderson, John F. Hennigan, Ivar Isaksen, Charles H. Jackman, Jerry Lewis, Mack McFarland, Bert Metz, John Montgomery, Richard W. Niedzwiecki, Michael Prather, Keith R. Ryan, Nelson Sabogal, Robert Sausen, Ulrich Schumann, Hugh J. Somerville, N. Sundararaman, Ding Yihui, Upali K. Wickrama, Howard L. Wesoky

1. Introduction

This report assesses the effects of aircraft on climate and atmospheric ozone and is the first IPCC report for a specific industrial subsector. It was prepared by IPCC in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, in response to a request by the International Civil Aviation Organization (ICAO)¹ because of the potential impact of aviation emissions. These are the predominant anthropogenic emissions deposited directly into the upper troposphere and lower stratosphere.

Aviation has experienced rapid expansion as the world economy has grown. Passenger traffic (expressed as revenue passenger-kilometres²) has grown since 1960 at nearly 9% per year, 2.4 times the average Gross Domestic Product (GDP) growth rate. Freight traffic, approximately 80% of which is carried by passenger airplanes, has also grown over the same time period. The rate of growth of passenger traffic has slowed to about 5% in 1997 as the industry is maturing. Total aviation emissions have increased, because increased demand for air transport has outpaced the reductions in specific emissions³ from the continuing improvements in technology and operational procedures. Passenger traffic, assuming unconstrained demand, is projected to grow at rates in excess of GDP for the period assessed in this report.

The effects of current aviation and of a range of unconstrained growth projections for aviation (which include passenger, freight, and military) are examined in this report, including the possible effects of a fleet of second generation, commercial supersonic aircraft. The report also describes current aircraft technology, operating procedures, and options for mitigating aviation's future impact on the global atmosphere. The report does not consider the local environmental effects of aircraft engine emissions or any of the indirect environmental effects of aviation operations such as energy usage by ground transportation at airports.

2. How Do Aircraft Affect Climate and Ozone?

Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases, including carbon dioxide (CO₂), ozone (O₃), and methane (CH₄); trigger formation of condensation trails (contrails); and may increase cirrus cloudiness—all of which contribute to climate change (see Box on page 4).

The principal emissions of aircraft include the greenhouse gases carbon dioxide and water vapour (H₂O). Other major emissions are nitric oxide (NO) and nitrogen dioxide (NO₂) (which together are termed NO_x), sulfur oxides (SO_x), and soot. The total amount of aviation fuel burned, as well as the total emissions of carbon dioxide, NO_x, and water vapour by aircraft, are well known relative to other parameters important to this assessment.

The climate impacts of the gases and particles emitted and formed as a result of aviation are more difficult to quantify than the emissions; however, they can be compared to each other and to climate effects from other sectors by using the concept of radiative forcing.⁴ Because carbon dioxide has a long atmospheric residence time (≈100 years) and so becomes well mixed throughout the atmosphere, the effects of its emissions from aircraft are indistinguishable from the same quantity of carbon dioxide emitted by any other source. The other gases (e.g., NO_x, SO_x, water vapour) and particles have shorter atmospheric residence times and remain concentrated near flight routes, mainly in the northern mid-latitudes. These emissions can lead to radiative forcing that is regionally located near the flight routes for some components (e.g., ozone and contrails) in contrast to emissions that are globally mixed (e.g., carbon dioxide and methane).

The global mean climate change is reasonably well represented by the global average radiative forcing, for example, when evaluating the contributions of aviation to the rise in globally averaged temperature or sea level. However, because some of aviation's key contributions to radiative forcing are located mainly in the northern mid-latitudes, the regional climate response may differ from that derived from a global mean radiative forcing. The impact of aircraft on regional climate could be important, but has not been assessed in this report.

Ozone is a greenhouse gas. It also shields the surface of the Earth from harmful ultraviolet (UV) radiation, and is a common air pollutant. Aircraft-emitted NO_x participates in ozone chemistry. Subsonic aircraft fly in the upper troposphere and lower stratosphere (at altitudes of about 9 to 13 km), whereas supersonic aircraft cruise several kilometres higher (at about 17 to 20 km) in the stratosphere. Ozone in the upper troposphere and lower stratosphere is expected to increase in response to NO_x increases and methane is expected to decrease. At higher altitudes, increases in NO_x lead to decreases in the stratospheric ozone layer. Ozone precursor (NO_x) residence times in these regions increase with altitude, and hence perturbations to ozone by aircraft depend on the altitude of NO_x injection and vary from regional in scale in the troposphere to global in scale in the stratosphere.

¹ ICAO is the United Nations specialized agency that has global responsibility for the establishment of standards, recommended practices, and guidance on various aspects of international civil aviation, including environmental protection.

² The revenue passenger-km is a measure of the traffic carried by commercial aviation: one revenue-paying passenger carried 1 km.

³ Specific emissions are emissions per unit of traffic carried, for instance, per revenue passenger-km.

⁴ Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square metre (Wm⁻²). Positive values of radiative forcing imply a net warming, while negative values imply cooling.

The Science of Climate Change

Some of the main conclusions of the Summary for Policymakers of Working Group I of the IPCC Second Assessment Report, published in 1995, which concerns the effects of all anthropogenic emissions on climate change, follow:

- Increases in greenhouse gas concentrations since pre-industrial times (i.e., since about 1750) have led to a positive radiative forcing of climate, tending to warm the surface of the Earth and produce other changes of climate.
- The atmospheric concentrations of the greenhouse gases carbon dioxide, methane, and nitrous oxide (N₂O), among others, have grown significantly: by about 30, 145, and 15%, respectively (values for 1992). These trends can be attributed largely to human activities, mostly fossil fuel use, land-use change, and agriculture.
- Many greenhouse gases remain in the atmosphere for a long time (for carbon dioxide and nitrous oxide, many decades to centuries). As a result of this, if carbon dioxide emissions were maintained at near current (1994) levels, they would lead to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppmv (approximately twice the pre-industrial concentration of 280 ppmv) by the end of the 21st century.
- Tropospheric aerosols resulting from combustion of fossil fuels, biomass burning, and other sources have led to a negative radiative forcing, which, while focused in particular regions and subcontinental areas, can have continental to hemispheric effects on climate patterns. In contrast to the long-lived greenhouse gases, anthropogenic aerosols are very short-lived in the atmosphere; hence, their radiative forcing adjusts rapidly to increases or decreases in emissions.
- Our ability from the observed climate record to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long-term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land-surface changes. Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate.
- The IPCC has developed a range of scenarios, IS92a-f, for future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land use, technological changes, energy availability, and fuel mix during the period 1990 to 2100. Through understanding of the global carbon cycle and of atmospheric chemistry, these emissions can be used to project atmospheric concentrations of greenhouse gases and aerosols and the perturbation of natural radiative forcing. Climate models can then be used to develop projections of future climate.
- Estimates of the rise in global average surface air temperature by 2100 relative to 1990 for the IS92 scenarios range from 1 to 3.5°C. In all cases the average rate of warming would probably be greater than any seen in the last 10 000 years. Regional temperature changes could differ substantially from the global mean and the actual annual to decadal changes would include considerable natural variability. A general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days.
- Average sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets. Estimates of the sea level rise by 2100 relative to 1990 for the IS92 scenarios range from 15 to 95 cm.
- Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events.

Water vapour, SO_x (which forms sulfate particles), and soot⁵ play both direct and indirect roles in climate change and ozone chemistry.

3. How are Aviation Emissions Projected to Grow in the Future?

Global passenger air travel, as measured in revenue passenger-km, is projected to grow by about 5% per year between 1990 and 2015, whereas total aviation fuel use—including passenger, freight, and military⁶—is projected to increase by 3% per year, over the same period, the difference being due largely to improved aircraft efficiency. Projections beyond this time are more

uncertain so a range of future unconstrained emission scenarios is examined in this report (see Table 1 and Figure 1). All of these scenarios assume that technological improvements leading to reduced emissions per revenue passenger-km will continue in the future and that optimal use of airspace availability (i.e.,

⁵ Airborne sulfate particles and soot particles are both examples of aerosols. Aerosols are microscopic particles suspended in air.

⁶ The historical breakdown of aviation fuel burn for civil (passenger plus cargo) and military aviation was 64 and 36%, respectively, in 1976, and 82 and 18%, respectively, in 1992. These are projected to change to 93 and 7%, respectively, in 2015, and to 97 and 3%, respectively, in 2050.

Table 1: Summary of future global aircraft scenarios used in this report.

Scenario name	Avg. traffic growth per year (1990–2050) ¹	Avg. annual growth rate of fuel burn (1990–2050) ²	Avg. annual economic growth rate	Avg. annual population growth rate	Ratio of traffic (2050/1990)	Ratio of fuel burn (2050/1990)	Notes
Fa1	3.1%	1.7%	2.9% 1990–2025 2.3% 1990–2100	1.4% 1990–2025 0.7% 1990–2100	6.4	2.7	Reference scenario developed by ICAO Forecasting and Economic Support Group (FESG); mid-range economic growth from IPCC (1992); technology for both improved fuel efficiency and NO _x reduction
Fa1H	3.1%	2.0%	2.9% 1990–2025 2.3% 1990–2100	1.4% 1990–2025 0.7% 1990–2100	6.4	3.3	Fa1 traffic and technology scenario with a fleet of supersonic aircraft replacing some of the subsonic fleet
Fa2	3.1%	1.7%	2.9% 1990–2025 2.3% 1990–2100	1.4% 1990–2025 0.7% 1990–2100	6.4	2.7	Fa1 traffic scenario; technology with greater emphasis on NO _x reduction, but slightly smaller fuel efficiency improvement
Fc1	2.2%	0.8%	2.0% 1990–2025 1.2% 1990–2100	1.1% 1990–2025 0.2% 1990–2100	3.6	1.6	FESG low-growth scenario; technology as for Fa1 scenario
Fe1	3.9%	2.5%	3.5% 1990–2025 3.0% 1990–2100	1.4% 1990–2025 0.7% 1990–2100	10.1	4.4	FESG high-growth scenario; technology as for Fa1 scenario
Eab	4.0%	3.2%			10.7	6.6	Traffic-growth scenario based on IS92a developed by Environmental Defense Fund (EDF); technology for very low NO _x assumed
Edh	4.7%	3.8%			15.5	9.4	High traffic-growth EDF scenario; technology for very low NO _x assumed

¹Traffic measured in terms of revenue passenger-km.
²All aviation (passenger, freight, and military).

ideal air traffic management) is achieved by 2050. If these improvements do not materialize then fuel use and emissions will be higher. It is further assumed that the number of aircraft as well as the number of airports and associated infrastructure will continue to grow and not limit the growth in demand for air travel. If the infrastructure was not available, the growth of traffic reflected in these scenarios would not materialize.

IPCC (1992)⁷ developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth,

land use, technological changes, energy availability, and fuel mix during the period 1990 to 2100. Scenario IS92a is a mid-range emissions scenario. Scenarios of future emissions are not predictions of the future. They are inherently uncertain because they are based on different assumptions about the future, and

⁷ IPCC, 1992: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K.Varney (eds.)]. Cambridge University Press, Cambridge, UK, 200 pp.

the longer the time horizon the more uncertain these scenarios become. The aircraft emissions scenarios developed here used the economic growth and population assumptions found in the IS92 scenario range (see Table 1 and Figure 1). In the following sections, scenario Fa1 is utilized to illustrate the possible effects of aircraft and is called the reference scenario. Its assumptions are linked to those of IS92a. The other aircraft emissions scenarios were built from a range of economic and population projections from IS92a-e. These scenarios represent a range of plausible growth for aviation and provide a basis for sensitivity analysis for climate modeling. However, the high growth scenario Edh is believed to be less plausible and the low growth scenario Fc1 is likely to be exceeded given the present state of the industry and planned developments.

4. What are the Current and Future Impacts of Subsonic Aviation on Radiative Forcing and UV Radiation?

The summary of radiative effects resulting from aircraft engine emissions is given in Figures 2 and 3. As shown in Figure 2, the uncertainty associated with several of these effects is large.

4.1 Carbon Dioxide

Emissions of carbon dioxide by aircraft were 0.14 Gt C/year in 1992. This is about 2% of total anthropogenic carbon dioxide emissions in 1992 or about 13% of carbon dioxide emissions from all transportation sources. The range of scenarios considered here projects that aircraft emissions of carbon dioxide will continue to grow and by 2050 will be 0.23 to 1.45 Gt C/year. For the reference scenario (Fa1) this emission increases 3-fold

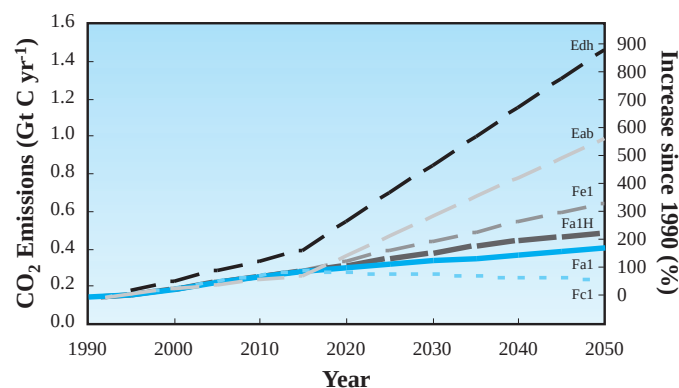


Figure 1: Total aviation carbon dioxide emissions resulting from six different scenarios for aircraft fuel use. Emissions are given in Gt C [or billion (10^9) tonnes of carbon] per year. To convert Gt C to Gt CO₂ multiply by 3.67. The scale on the righthand axis represents the percentage growth from 1990 to 2050. Aircraft emissions of carbon dioxide represent 2.4% of total fossil fuel emissions of carbon dioxide in 1992 or 2% of total anthropogenic carbon dioxide emissions. (Note: Fa2 has not been drawn because the difference from scenario Fa1 would not be discernible on the figure.)

by 2050 to 0.40 Gt C/year, or 3% of the projected total anthropogenic carbon dioxide emissions relative to the mid-range IPCC emission scenario (IS92a). For the range of scenarios, the range of increase in carbon dioxide emissions to 2050 would be 1.6 to 10 times the value in 1992.

Concentrations of and radiative forcing from carbon dioxide today are those resulting from emissions during the last 100 years or so. The carbon dioxide concentration attributable to aviation in the 1992 atmosphere is 1 ppmv, a little more than 1% of the total anthropogenic increase. This percentage is lower than the percentage for emissions (2%) because the emissions occurred only in the last 50 years. For the range of scenarios in Figure 1, the accumulation of atmospheric carbon dioxide due to aircraft over the next 50 years is projected to increase to 5 to 13 ppmv. For the reference scenario (Fa1) this is 4% of that from all human activities assuming the mid-range IPCC scenario (IS92a).

4.2 Ozone

The NO_x emissions from subsonic aircraft in 1992 are estimated to have increased ozone concentrations at cruise altitudes in northern mid-latitudes by up to 6%, compared to an atmosphere without aircraft emissions. This ozone increase is projected to rise to about 13% by 2050 in the reference scenario (Fa1). The impact on ozone concentrations in other regions of the world is substantially less. These increases will, on average, tend to warm the surface of the Earth.

Aircraft emissions of NO_x are more effective at producing ozone in the upper troposphere than an equivalent amount of emission at the surface. Also increases in ozone in the upper troposphere are more effective at increasing radiative forcing than increases at lower altitudes. Due to these increases the calculated total ozone column in northern mid-latitudes is projected to grow by approximately 0.4 and 1.2% in 1992 and 2050, respectively. However, aircraft sulfur and water emissions in the stratosphere tend to deplete ozone, partially offsetting the NO_x-induced ozone increases. The degree to which this occurs is, as yet, not quantified. Therefore, the impact of subsonic aircraft emissions on stratospheric ozone requires further evaluation. The largest increases in ozone concentration due to aircraft emissions are calculated to occur near the tropopause where natural variability is high. Such changes are not apparent from observations at this time.

4.3 Methane

In addition to increasing tropospheric ozone concentrations, aircraft NO_x emissions are expected to decrease the concentration of methane, which is also a greenhouse gas. These reductions in methane tend to cool the surface of the Earth. The methane concentration in 1992 is estimated here to be about 2% less than that in an atmosphere without aircraft. This aircraft-induced reduction of methane concentration is much smaller than the observed overall 2.5-fold increase since pre-industrial

times. Uncertainties in the sources and sinks of methane preclude testing the impact of aviation on methane concentrations with atmospheric observations. In the reference scenario (Fa1) methane would be about 5% less than that calculated for a 2050 atmosphere without aircraft.

Changes in tropospheric ozone are mainly in the Northern Hemisphere, while those of methane are global in extent so that, even though the global average radiative forcings are of similar magnitude and opposite in sign, the latitudinal structure of the forcing is different so that the net regional radiative effects do not cancel.

4.4 Water Vapour

Most subsonic aircraft water vapour emissions are released in the troposphere where they are rapidly removed by precipitation

within 1 to 2 weeks. A smaller fraction of water vapour emissions is released in the lower stratosphere where it can build up to larger concentrations. Because water vapor is a greenhouse gas, these increases tend to warm the Earth's surface, though for subsonic aircraft this effect is smaller than those of other aircraft emissions such as carbon dioxide and NO_x .

4.5 Contrails

In 1992, aircraft line-shaped contrails are estimated to cover about 0.1% of the Earth's surface on an annually averaged basis with larger regional values. Contrails tend to warm the Earth's surface, similar to thin high clouds. The contrail cover is projected to grow to 0.5% by 2050 in the reference scenario (Fa1), at a rate which is faster than the rate of growth in aviation fuel consumption. This faster growth in contrail cover is expected because air traffic will increase mainly in the upper troposphere where contrails form preferentially, and may also occur as a result of improvements in aircraft fuel efficiency. Contrails are triggered from the water vapour emitted by aircraft and their optical properties depend on the particles emitted or formed in the aircraft plume and on the ambient atmospheric conditions. The radiative effect of contrails depends on their optical properties and global cover, both of which are uncertain. Contrails have been observed as line-shaped clouds

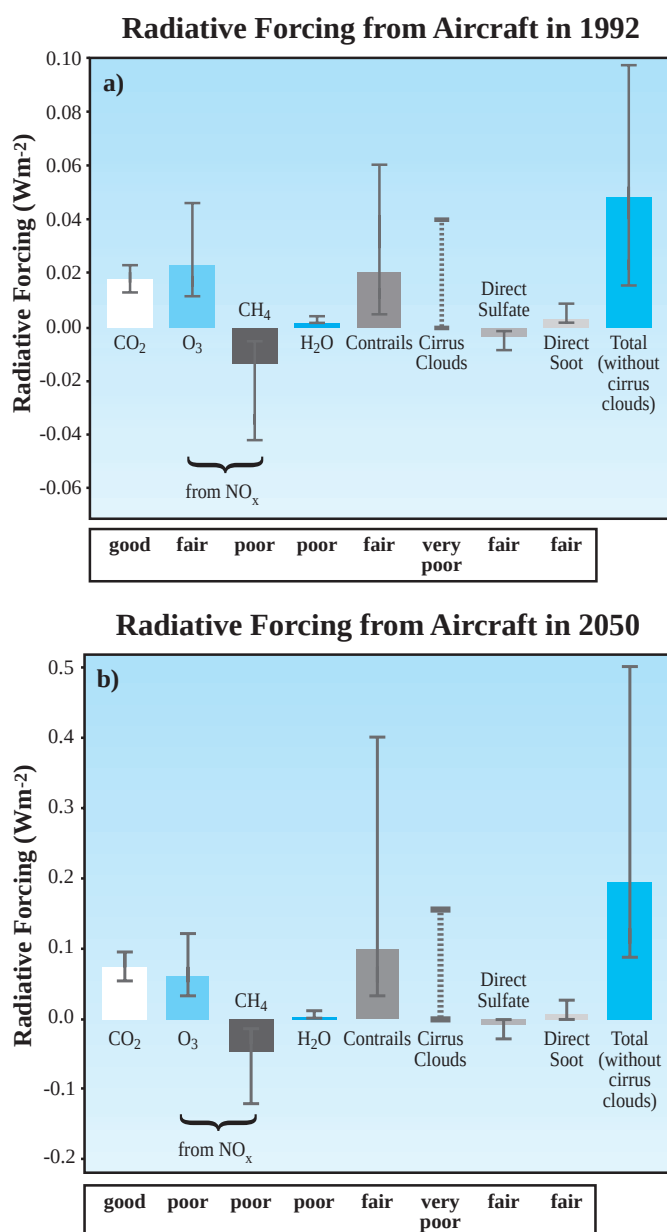


Figure 2: Estimates of the globally and annually averaged radiative forcing (Wm^{-2}) (see Footnote 4) from subsonic aircraft emissions in 1992 (2a) and in 2050 for scenario Fa1 (2b). The scale in Figure 2b is greater than the scale in 2a by about a factor of 4. The bars indicate the best estimate of forcing while the line associated with each bar is a two-thirds uncertainty range developed using the best knowledge and tools available at the present time. (The two-thirds uncertainty range means that there is a 67% probability that the true value falls within this range.) The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The uncertainty estimate for the total radiative forcing (without additional cirrus) is calculated as the square root of the sums of the squares of the upper and lower ranges for the individual components. The evaluations below the graph (“good,” “fair,” “poor,” “very poor”) are a relative appraisal associated with each component and indicate the level of scientific understanding. It is based on the amount of evidence available to support the best estimate and its uncertainty, the degree of consensus in the scientific literature, and the scope of the analysis. This evaluation is separate from the evaluation of uncertainty range represented by the lines associated with each bar. This method of presentation is different and more meaningful than the confidence level presented in similar graphs from *Climate Change 1995: The Science of Climate Change*.

by satellites over heavy air traffic areas and covered on average about 0.5% of the area over Central Europe in 1996 and 1997.

4.6 Cirrus Clouds

Extensive cirrus clouds have been observed to develop after the formation of persistent contrails. Increases in cirrus cloud cover (beyond those identified as line-shaped contrails) are found to be positively correlated with aircraft emissions in a limited number of studies. About 30% of the Earth is covered with cirrus cloud. On average an increase in cirrus cloud cover tends to warm the surface of the Earth. An estimate for aircraft-induced cirrus cover for the late 1990s ranges from 0 to 0.2% of the surface of the Earth. For the Fa1 scenario, this may possibly increase by a factor of 4 (0 to 0.8%) by 2050; however, the mechanisms associated with increases in cirrus cover are not well understood and need further investigation.

4.7 Sulfate and Soot Aerosols

The aerosol mass concentrations in 1992 resulting from aircraft are small relative to those caused by surface sources. Although aerosol accumulation will grow with aviation fuel use, aerosol mass concentrations from aircraft in 2050 are projected to remain small compared to surface sources. Increases in soot tend to warm while increases in sulfate tend to cool the Earth's surface. The direct radiative forcing of sulfate and soot aerosols from aircraft is small compared to those of other aircraft emissions. Because aerosols influence the formation of clouds, the accumulation of aerosols from aircraft may play a role in enhanced cloud formation and change the radiative properties of clouds.

4.8 What are the Overall Climate Effects of Subsonic Aircraft?

The climate impacts of different anthropogenic emissions can be compared using the concept of radiative forcing. The best estimate of the radiative forcing in 1992 by aircraft is 0.05 Wm^{-2} or about 3.5% of the total radiative forcing by all anthropogenic activities. For the reference scenario (Fa1), the radiative forcing by aircraft in 2050 is 0.19 Wm^{-2} or 5% of the radiative forcing in the mid-range IS92a scenario (3.8 times the value in 1992). According to the range of scenarios considered here, the forcing is projected to grow to 0.13 to 0.56 Wm^{-2} in 2050, which is a factor of 1.5 less to a factor of 3 greater than that for Fa1 and from 2.6 to 11 times the value in 1992. These estimates of forcing combine the effects from changes in concentrations of carbon dioxide, ozone, methane, water vapour, line-shaped contrails, and aerosols, but do not include possible changes in cirrus clouds.

Globally averaged values of the radiative forcing from different components in 1992 and in 2050 under the reference scenario (Fa1) are shown in Figure 2. Figure 2 indicates the best

estimates of the forcing for each component and the two-thirds uncertainty range.⁸ The derivation of these uncertainty ranges involves expert scientific judgment and may also include objective statistical models. The uncertainty range in the radiative forcing stated here combines the uncertainty in calculating the atmospheric change to greenhouse gases and aerosols with that of calculating radiative forcing. For additional cirrus clouds, only a range for the best estimate is given; this is not included in the total radiative forcing.

The state of scientific understanding is evaluated for each component. This is not the same as the confidence level expressed in previous IPCC documents. This evaluation is separate from the uncertainty range and is a relative appraisal of the scientific understanding for each component. The evaluation is based on the amount of evidence available to support the best estimate and its uncertainty, the degree of consensus in the scientific literature, and the scope of the analysis. The total radiative forcing under each of the six scenarios for the growth of aviation is shown in Figure 3 for the period 1990 to 2050.

The total radiative forcing due to aviation (without forcing from additional cirrus) is likely to lie within the range from 0.01 to 0.1 Wm^{-2} in 1992, with the largest uncertainties coming from contrails and methane. Hence the total radiative forcing may be about two times larger or five times smaller than the best estimate. For any scenario at 2050, the uncertainty range of radiative forcing is slightly larger than for 1992, but the largest variations of projected radiative forcing come from the range of scenarios.

Over the period from 1992 to 2050, the overall radiative forcing by aircraft (excluding that from changes in cirrus

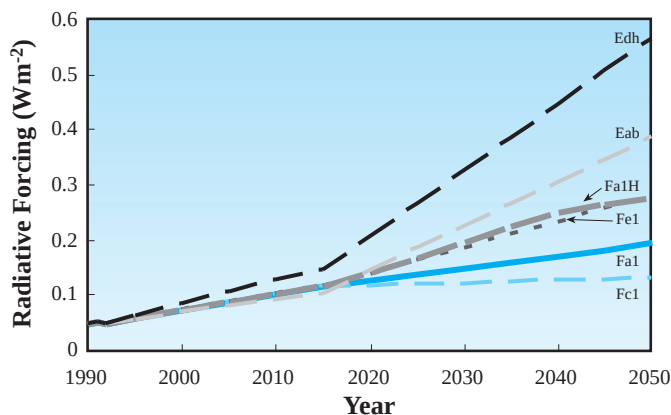


Figure 3: Estimates of the globally and annually averaged total radiative forcing (without cirrus clouds) associated with aviation emissions under each of six scenarios for the growth of aviation over the time period 1990 to 2050. (Fa2 has not been drawn because the difference from scenario Fa1 would not be discernible on the figure.)

⁸ The two-thirds uncertainty range means there is a 67% probability that the true value falls within this range.

clouds) for all scenarios in this report is a factor of 2 to 4 larger than the forcing by aircraft carbon dioxide alone. The overall radiative forcing for the sum of all human activities is estimated to be at most a factor of 1.5 larger than that of carbon dioxide alone.

The emissions of NO_x cause changes in methane and ozone, with influence on radiative forcing estimated to be of similar magnitude but of opposite sign. However, as noted above, the geographical distribution of the aircraft ozone forcing is far more regional than that of the aircraft methane forcing.

The effect of aircraft on climate is superimposed on that caused by other anthropogenic emissions of greenhouse gases and particles, and on the background natural variability. The radiative forcing from aviation is about 3.5% of the total radiative forcing in 1992. It has not been possible to separate the influence on global climate change of aviation (or any other sector with similar radiative forcing) from all other anthropogenic activities. Aircraft contribute to global change approximately in proportion to their contribution to radiative forcing.

4.9 What are the Overall Effects of Subsonic Aircraft on UV-B?

Ozone, most of which resides in the stratosphere, provides a shield against solar ultraviolet radiation. The erythemal dose rate, defined as UV irradiance weighted according to how effectively it causes sunburn, is estimated to be decreased by aircraft in 1992 by about 0.5% at 45°N in July. For comparison, the calculated increase in the erythemal dose rate due to observed ozone depletion is about 4% over the period 1970 to 1992 at 45°N in July.⁹ The net effect of subsonic aircraft appears to be an increase in column ozone and a decrease in UV radiation, which is mainly due to aircraft NO_x emissions. Much smaller changes in UV radiation are associated with aircraft contrails, aerosols, and induced cloudiness. In the Southern Hemisphere, the calculated effects of aircraft emission on the erythemal dose rate are about a factor of 4 lower than for the Northern Hemisphere.

For the reference scenario (Fa1), the change in erythemal dose rate at 45°N in July in 2050 compared to a simulation with no aircraft is -1.3% (with a two-thirds uncertainty range from -0.7 to -2.6%). For comparison, the calculated change in the erythemal dose rate due to changes in the concentrations of trace species, other than those from aircraft, between 1970 to 2050 at 45°N is about -3%, a decrease that is the net result of two opposing effects: (1) the incomplete recovery of stratospheric ozone to 1970 levels because of the persistence of long-lived halogen-containing compounds, and (2) increases in projected surface emissions of shorter lived pollutants that produce ozone in the troposphere.

5. What are the Current and Future Impacts of Supersonic Aviation on Radiative Forcing and UV Radiation?

One possibility for the future is the development of a fleet of second generation supersonic, high speed civil transport (HSCT) aircraft, although there is considerable uncertainty whether any such fleet will be developed. These supersonic aircraft are projected to cruise at an altitude of about 19 km, about 8 km higher than subsonic aircraft, and to emit carbon dioxide, water vapour, NO_x , SO_x , and soot into the stratosphere. NO_x , water vapour, and SO_x from supersonic aircraft emissions all contribute to changes in stratospheric ozone. The radiative forcing of civil supersonic aircraft is estimated to be about a factor of 5 larger than that of the displaced subsonic aircraft in the Fa1H scenario. The calculated radiative forcing of supersonic aircraft depends on the treatment of water vapour and ozone in models. This effect is difficult to simulate in current models and so is highly uncertain.

Scenario Fa1H considers the addition of a fleet of civil supersonic aircraft that was assumed to begin operation in the year 2015 and grow to a maximum of 1 000 aircraft by the year 2040. For reference, the civil subsonic fleet at the end of the year 1997 contained approximately 12 000 aircraft. In this scenario, the aircraft are designed to cruise at Mach 2.4, and new technologies are assumed that maintain emissions of 5 g NO_2 per kg fuel (lower than today's civil supersonic aircraft which have emissions of about 22 g NO_2 per kg fuel). These supersonic aircraft are assumed to replace part of the subsonic fleet (11%, in terms of emissions in scenario Fa1). Supersonic aircraft consume more than twice the fuel per passenger-km compared to subsonic aircraft. *By the year 2050, the combined fleet (scenario Fa1H) is projected to add a further 0.08 Wm^{-2} (42%) to the 0.19 Wm^{-2} radiative forcing from scenario Fa1 (see Figure 4). Most of this additional forcing is due to accumulation of stratospheric water vapour.*

The effect of introducing a civil supersonic fleet to form the combined fleet (Fa1H) is also to reduce stratospheric ozone and increase erythemal dose rate. The maximum calculated effect is at 45°N where, in July, the ozone column change in 2050 from the combined subsonic and supersonic fleet relative to no aircraft is -0.4%. The effect on the ozone column of the supersonic component by itself is -1.3% while the subsonic component is +0.9%.

The combined fleet would change the erythemal dose rate at 45°N in July by +0.3% compared to the 2050 atmosphere without aircraft. The two-thirds uncertainty range for the combined fleet is -1.7% to +3.3%. This may be compared to the projected change of -1.3% for Fa1. Flying higher leads to larger ozone column decreases, while flying lower leads to smaller ozone column decreases and may even result in an ozone column increase for flight in the lowermost stratosphere. In addition, emissions from supersonic aircraft in the Northern Hemisphere stratosphere may be transported to the Southern Hemisphere where they cause ozone depletion.

⁹ This value is based on satellite observations and model calculations. See **WMO**, 1999: *Scientific Assessment of Ozone Depletion: 1998*. Report No. 44, Global Ozone Research and Monitoring Project, World Meteorological Organization, Geneva, Switzerland, 732 pp.

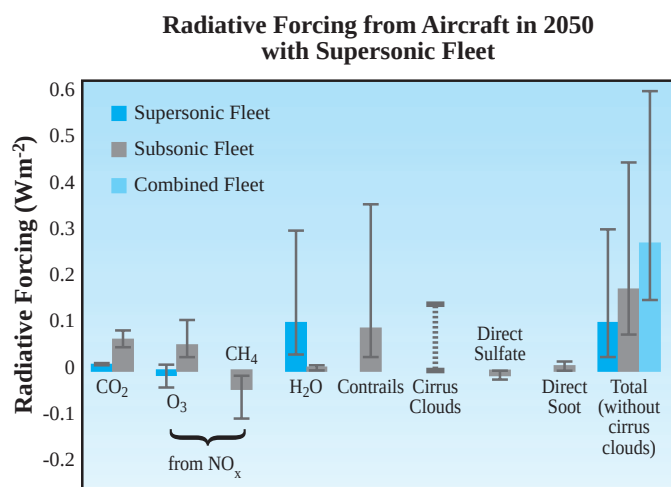


Figure 4: Estimates of the globally and annually averaged radiative forcing from a combined fleet of subsonic and supersonic aircraft (in Wm^{-2}) due to changes in greenhouse gases, aerosols, and contrails in 2050 under the scenario Fa1H. In this scenario, the supersonic aircraft are assumed to replace part of the subsonic fleet (11%, in terms of emissions in scenario Fa1). The bars indicate the best estimate of forcing while the line associated with each bar is a two-thirds uncertainty range developed using the best knowledge and tools available at the present time. (The two-thirds uncertainty range means that there is a 67% probability that the true value falls within this range.) The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The uncertainty estimate for the total radiative forcing (without additional cirrus) is calculated as the square root of the sums of the squares of the upper and lower ranges. The level of scientific understanding for the supersonic components are carbon dioxide, “good;” ozone, “poor;” and water vapour, “poor.”

6. What are the Options to Reduce Emissions and Impacts?

There is a range of options to reduce the impact of aviation emissions, including changes in aircraft and engine technology, fuel, operational practices, and regulatory and economic measures. These could be implemented either singly or in combination by the public and/or private sector. Substantial aircraft and engine technology advances and the air traffic management improvements described in this report are already incorporated in the aircraft emissions scenarios used for climate change calculations. Other operational measures, which have the potential to reduce emissions, and alternative fuels were not assumed in the scenarios. Further technology advances have the potential to provide additional fuel and emissions reductions. In practice, some of the improvements are expected to take place for commercial reasons. The timing and scope of regulatory, economic, and other options may affect the introduction of improvements and may affect demand

for air transport. Mitigation options for water vapour and cloudiness have not been fully addressed.

Safety of operation, operational and environmental performance, and costs are dominant considerations for the aviation industry when assessing any new aircraft purchase or potential engineering or operational changes. The typical life expectancy of an aircraft is 25 to 35 years. These factors have to be taken into account when assessing the rate at which technology advances and policy options related to technology can reduce aviation emissions.

6.1 Aircraft and Engine Technology Options

Technology advances have substantially reduced most emissions per passenger-km. However, there is potential for further improvements. Any technological change may involve a balance among a range of environmental impacts.

Subsonic aircraft being produced today are about 70% more fuel efficient per passenger-km than 40 years ago. The majority of this gain has been achieved through engine improvements and the remainder from airframe design improvement. A 20% improvement in fuel efficiency is projected by 2015 and a 40 to 50% improvement by 2050 relative to aircraft produced today. The 2050 scenarios developed for this report already incorporate these fuel efficiency gains when estimating fuel use and emissions. Engine efficiency improvements reduce the specific fuel consumption and most types of emissions; however, contrails may increase and, without advances in combustor technology, NO_x emissions may also increase.

Future engine and airframe design involves a complex decision-making process and a balance of considerations among many factors (e.g., carbon dioxide emissions, NO_x emissions at ground level, NO_x emissions at altitude, water vapour emissions, contrail/cirrus production, and noise). These aspects have not been adequately characterized or quantified in this report.

Internationally, substantial engine research programmes are in progress, with goals to reduce Landing and Take-off cycle (LTO) emissions of NO_x by up to 70% from today's regulatory standards, while also improving engine fuel consumption by 8 to 10%, over the most recently produced engines, by about 2010. Reduction of NO_x emissions would also be achieved at cruise altitude, though not necessarily by the same proportion as for LTO. Assuming that the goals can be achieved, the transfer of this technology to significant numbers of newly produced aircraft will take longer—typically a decade. Research programmes addressing NO_x emissions from supersonic aircraft are also in progress.

6.2 Fuel Options

There would not appear to be any practical alternatives to kerosene-based fuels for commercial jet aircraft for the next

several decades. Reducing sulfur content of kerosene will reduce SO_x emissions and sulfate particle formation.

Jet aircraft require fuel with a high energy density, especially for long-haul flights. Other fuel options, such as hydrogen, may be viable in the long term, but would require new aircraft designs and new infrastructure for supply. Hydrogen fuel would eliminate emissions of carbon dioxide from aircraft, but would increase those of water vapour. The overall environmental impacts and the environmental sustainability of the production and use of hydrogen or any other alternative fuels have not been determined.

The formation of sulfate particles from aircraft emissions, which depends on engine and plume characteristics, is reduced as fuel sulfur content decreases. While technology exists to remove virtually all sulfur from fuel, its removal results in a reduction in lubricity.

6.3 Operational Options

Improvements in air traffic management (ATM) and other operational procedures could reduce aviation fuel burn by between 8 and 18%. The large majority (6 to 12%) of these reductions comes from ATM improvements which it is anticipated will be fully implemented in the next 20 years. All engine emissions will be reduced as a consequence. In all aviation emission scenarios considered in this report the reductions from ATM improvements have already been taken into account. The rate of introduction of improved ATM will depend on the implementation of the essential institutional arrangements at an international level.

Air traffic management systems are used for the guidance, separation, coordination, and control of aircraft movements. Existing national and international air traffic management systems have limitations which result, for example, in holding (aircraft flying in a fixed pattern waiting for permission to land), inefficient routings, and sub-optimal flight profiles. These limitations result in excess fuel burn and consequently excess emissions.

For the current aircraft fleet and operations, addressing the above-mentioned limitations in air traffic management systems could reduce fuel burned in the range of 6 to 12%. It is anticipated that the improvement needed for these fuel burn reductions will be fully implemented in the next 20 years, provided that the necessary institutional and regulatory arrangements have been put in place in time. The scenarios developed in this report assume the timely implementation of these ATM improvements, when estimating fuel use.

Other operational measures to reduce the amount of fuel burned per passenger-km include increasing load factors (carrying more passengers or freight on a given aircraft), eliminating non-essential weight, optimizing aircraft speed, limiting the use of auxiliary power (e.g., for heating, ventilation),

and reducing taxiing. The potential improvements in these operational measures could reduce fuel burned, and emissions, in the range 2 to 6%.

Improved operational efficiency may result in attracting additional air traffic, although no studies providing evidence on the existence of this effect have been identified.

6.4 Regulatory, Economic, and Other Options

Although improvements in aircraft and engine technology and in the efficiency of the air traffic system will bring environmental benefits, these will not fully offset the effects of the increased emissions resulting from the projected growth in aviation. Policy options to reduce emissions further include more stringent aircraft engine emissions regulations, removal of subsidies and incentives that have negative environmental consequences, market-based options such as environmental levies (charges and taxes) and emissions trading, voluntary agreements, research programmes, and substitution of aviation by rail and coach. Most of these options would lead to increased airline costs and fares. Some of these approaches have not been fully investigated or tested in aviation and their outcomes are uncertain.

Engine emissions certification is a means for reducing specific emissions. The aviation authorities currently use this approach to regulate emissions for carbon monoxide, hydrocarbons, NO_x , and smoke. The International Civil Aviation Organization has begun work to assess the need for standards for aircraft emissions at cruise altitude to complement existing LTO standards for NO_x and other emissions.

Market-based options, such as environmental levies (charges and taxes) and emissions trading, have the potential to encourage technological innovation and to improve efficiency, and may reduce demand for air travel. Many of these approaches have not been fully investigated or tested in aviation and their outcomes are uncertain.

Environmental levies (charges and taxes) could be a means for reducing growth of aircraft emissions by further stimulating the development and use of more efficient aircraft and by reducing growth in demand for aviation transportation. Studies show that to be environmentally effective, levies would need to be addressed in an international framework.

Another approach that could be considered for mitigating aviation emissions is emissions trading, a market-based approach which enables participants to cooperatively minimize the costs of reducing emissions. Emissions trading has not been tested in aviation though it has been used for sulfur dioxide (SO_2) in the United States of America and is possible for ozone-depleting substances in the Montreal Protocol. This approach is one of the provisions of the Kyoto Protocol where it applies to Annex B Parties.

Voluntary agreements are also currently being explored as a means of achieving reductions in emissions from the aviation

sector. Such agreements have been used in other sectors to reduce greenhouse gas emissions or to enhance sinks.

Measures that can also be considered are removal of subsidies or incentives which would have negative environmental consequences, and research programmes.

Substitution by rail and coach could result in the reduction of carbon dioxide emissions per passenger-km. The scope for this reduction is limited to high density, short-haul routes, which could have coach or rail links. Estimates show that up to 10% of the travelers in Europe could be transferred from aircraft to high-speed trains. Further analysis, including trade-offs between a wide range of environmental effects (e.g., noise exposure, local air quality, and global atmospheric effects) is needed to explore the potential of substitution.

7. Issues for the Future

This report has assessed the potential climate and ozone changes due to aircraft to the year 2050 under different scenarios. It recognizes that the effects of some types of aircraft emissions are well understood. It also reveals that the effects of others are not, because of the many scientific uncertainties. There has been a steady improvement in characterizing the potential impacts of human activities, including the effects of aviation on the global atmosphere. The report has also examined technological advances, infrastructure improvements, and regulatory or market-based measures to reduce aviation emissions. Further work is required to reduce scientific and other uncertainties, to understand better the options for reducing emissions, to better inform decisionmakers, and to improve the understanding of the social and economic issues associated with the demand for air transport.

There are a number of key areas of scientific uncertainty that limit our ability to project aviation impacts on climate and ozone:

- The influence of contrails and aerosols on cirrus clouds
- The role of NO_x in changing ozone and methane concentrations
- The ability of aerosols to alter chemical processes
- The transport of atmospheric gases and particles in the upper troposphere/lower stratosphere
- The climate response to regional forcings and stratospheric perturbations.

There are a number of key socio-economic and technological issues that need greater definition, including *inter alia* the following:

- Characterization of demand for commercial aviation services, including airport and airway infrastructure constraints and associated technological change
- Methods to assess external costs and the environmental benefits of regulatory and market-based options
- Assessment of the macroeconomic effects of emission reductions in the aviation industry that might result from mitigation measures
- Technological capabilities and operational practices to reduce emissions leading to the formation of contrails and increased cloudiness
- The understanding of the economic and environmental effects of meeting potential stabilization scenarios (for atmospheric concentrations of greenhouse gases), including measures to reduce emissions from aviation and also including such issues as the relative environmental impacts of different transportation modes.

LIST OF IPCC OUTPUTS

I. IPCC FIRST ASSESSMENT REPORT, 1990

- a) **CLIMATE CHANGE — The IPCC Scientific Assessment.** The 1990 report of the IPCC Scientific Assessment Working Group (*also in Chinese, French, Russian and Spanish*).
- b) **CLIMATE CHANGE — The IPCC Impacts Assessment.** The 1990 report of the IPCC Impacts Assessment Working Group (*also in Chinese, French, Russian and Spanish*).
- c) **CLIMATE CHANGE — The IPCC Response Strategies.** The 1990 report of the IPCC Response Strategies Working Group (*also in Chinese, French, Russian and Spanish*).
- d) **Overview and Policymaker Summaries, 1990.**

Emissions Scenarios (prepared by the IPCC Response Strategies Working Group), 1990.

Assessment of the Vulnerability of Coastal Areas to Sea Level Rise — A Common Methodology, 1991.

II. IPCC SUPPLEMENT, 1992

- a) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Scientific Assessment.** The 1992 report of the IPCC Scientific Assessment Working Group.
- b) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Impacts Assessment.** The 1992 report of the IPCC Impacts Assessment Working Group.

CLIMATE CHANGE: The IPCC 1990 and 1992 Assessments — IPCC First Assessment Report Overview and Policymaker Summaries, and 1992 IPCC Supplement (*also in Chinese, French, Russian and Spanish*).

Global Climate Change and the Rising Challenge of the Sea. Coastal Zone Management Subgroup of the IPCC Response Strategies Working Group, 1992.

Report of the IPCC Country Study Workshop, 1992.

Preliminary Guidelines for Assessing Impacts of Climate Change, 1992.

III. IPCC SPECIAL REPORT, 1994

CLIMATE CHANGE 1994 — Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios.

IV. IPCC SECOND ASSESSMENT REPORT, 1995

- a) **CLIMATE CHANGE 1995 — The Science of Climate Change** (including Summary for Policymakers). Report of IPCC Working Group I, 1995.
- b) **CLIMATE CHANGE 1995 — Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change** (including Summary for Policymakers). Report of IPCC Working Group II, 1995.

- c) **CLIMATE CHANGE 1995 — The Economic and Social Dimensions of Climate Change** (including Summary for Policymakers). Report of IPCC Working Group III, 1995.
- d) **The IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change**, 1995.

(Please note: the IPCC Synthesis and the three Summaries for Policymakers have been published in a single volume and are also available in Arabic, Chinese, French, Russian and Spanish.)

V. IPCC METHODOLOGIES

- a) **IPCC Guidelines for National Greenhouse Gas Inventories** (3 volumes), 1994 (*also in French, Russian and Spanish*).
- b) **IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations**, 1995 (*also in Arabic, Chinese, French, Russian and Spanish*).
- c) **Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories** (3 volumes), 1996.

VI. IPCC TECHNICAL PAPERS

TECHNOLOGIES, POLICIES AND MEASURES FOR MITIGATING CLIMATE CHANGE — IPCC Technical Paper 1, 1996 (*also in French and Spanish*).

AN INTRODUCTION TO SIMPLE CLIMATE MODELS USED IN THE IPCC SECOND ASSESSMENT REPORT — IPCC Technical Paper 2, 1997 (*also in French and Spanish*).

STABILIZATION OF ATMOSPHERIC GREENHOUSE GASES: PHYSICAL, BIOLOGICAL AND SOCIO-ECONOMIC IMPLICATIONS — IPCC Technical Paper 3, 1997 (*also in French and Spanish*).

IMPLICATIONS OF PROPOSED CO₂ EMISSIONS LIMITATIONS — IPCC Technical Paper 4, 1997 (*also in French and Spanish*).

VII. IPCC SPECIAL REPORT, 1997

THE REGIONAL IMPACTS OF CLIMATE CHANGE: AN ASSESSMENT OF VULNERABILITY (including Summary for Policymakers, which is available in Arabic, Chinese, English, French, Russian and Spanish).
A Special Report of IPCC Working Group II, 1997.

VIII. IPCC SPECIAL REPORT, 1999

AVIATION AND THE GLOBAL ATMOSPHERE (including Summary for Policymakers, which is available in Arabic, Chinese, English, French, Russian and Spanish).
A Special Report of IPCC Working Groups I and II, 1999.

Meeting the UK aviation target – options for reducing emissions to 2050

Committee on Climate Change
December 2009





natur**ally**responsible[®]

Printed by **Seacourt** to the most stringent environmental systems using **Waterless** Offset (0% water and 0% Isopropyl alcohol or harmful substitutes), 100% renewable energy and vegetable oil based inks on paper with 100% recycled content. **Seacourt** is registered to EMAS and ISO 14001, prints to ISO12647 Colour Standard, is a CarbonNeutral[®] company and FSC certified TT-COC-2132.

Contents

Foreword	2
The Committee on Climate Change	4
Acknowledgements	6
Executive summary	7
Chapter 1: Background and methodology for the review of UK aviation emissions	30
Chapter 2: Reference demand and emissions projections	48
Chapter 3: Alternatives to air travel: high-speed rail and videoconferencing	66
Chapter 4: Improvement in fleet fuel efficiency through technology innovation	82
Chapter 5: Use of biofuels and hydrogen in aviation	96
Chapter 6: Non-CO ₂ climate effects of aviation	120
Chapter 7: Meeting the 2050 aviation target	134
Glossary	152



Chairman's Foreword

In our December 2008 report we presented an initial analysis of aviation emissions. We concluded that these will become an increasingly significant share of total emissions, both because aviation emissions will increase over time and because total allowed emissions will fall. We showed a scenario where the UK's 80% emissions reduction target could be achieved by keeping aviation emissions in 2050 around current levels together with deep cuts in other sectors. In this scenario, aviation emissions would account for around 25% of all allowed UK emissions of Greenhouse Gases in 2050.

In January 2009, the Government decided both to expand Heathrow airport, and to set a target that UK aviation emissions of CO₂ in 2050 should not exceed 2005 levels. The Committee was asked to advise on options for reducing emissions below business as usual to meet the target and on the implications for aviation expansion in the 2020s.

This Report sets out our advice on the implications of the aviation target. It analyses the potential to reduce the carbon intensity of air travel through technological improvements in airframe and engine design, through operational efficiency improvements and through the use of sustainable biofuels. The more rapidly carbon intensity can be reduced, the greater is the extent to which aviation demand can increase while still meeting the emissions target. The report also explores the likely impact of a carbon price on demand and the potential reduction from modal shift to high-speed rail and the use of videoconferencing.

The Report finds that there is potential for aviation demand to increase while still meeting the Government's target – in the most likely scenario, a 60% increase in demand is allowed. Higher increases might be possible if technological progress and the development of sustainable biofuels were more rapid than currently envisaged, but it is not prudent to base current policy on the assumption that speculative future technological breakthroughs are achieved.

It is important to note, moreover, that the allowable demand increase is far below that which would result if demand were unconstrained by carbon prices or limits on airport capacity. Deliberate policies to limit demand below its unconstrained level are therefore essential if the target is to be met.

The allowable overall level of demand increase could be compatible with a range of different approaches to capacity expansion at specific airports, and it is not the role of the Committee to address the other factors which should determine the balance of demand between different airports. The policies pursued, should however be consistent with a total demand increase limited to at most 60% by 2050.

We will publish further analysis of the role of aviation in carbon budgets, and an assessment of any global aviation deal coming out of Copenhagen in our progress report to Parliament in June next year and in our advice on the UK's fourth budget in December.

The Committee and the Secretariat have delivered this report in the context of what has been a very busy year and a challenging work programme for the year ahead. On behalf of the Committee I would like to thank the Secretariat for their excellent support and dedication.



The Committee on Climate Change



Lord Adair Turner, Chair

Lord Turner of Ecchinswell is the Chair of the Committee on Climate Change and Chair of the Financial Services Authority. He has previously been Chair at the Low Pay Commission, Chair at the Pension Commission, and Director-General of the Confederation of British Industry (CBI).



David Kennedy, Chief Executive

David Kennedy is the Chief Executive of the Committee on Climate Change. Previously he worked on energy strategy at the World Bank, and design of infrastructure investment projects at the European Bank for Reconstruction and Development. He has a PhD in economics from the London School of Economics.



Dr Samuel Fankhauser

Dr Samuel Fankhauser is a Principal Research Fellow at the Grantham Research Institute on Climate Change at the London School of Economics. He is a former Deputy Chief Economist of the European Bank for Reconstruction and Development and former Managing Director (Strategic Advice) at IDEACarbon.



Professor Michael Grubb

Professor Michael Grubb is Chairman of the international research network Climate Strategies. He is also senior research associate at Cambridge University and holds a visiting professorship at Imperial College.



Sir Brian Hoskins

Professor Sir Brian Hoskins, CBE, FRS is the Director of the Grantham Institute for Climate Change at Imperial College, London and Professor of Meteorology at the University of Reading. He is a Royal Society Research Professor and is also a member of the National Science Academies of the USA and China.

**Professor Julia King**

Professor Julia King became Vice-Chancellor of Aston University in 2006, having previously been Principal of the Engineering Faculty at Imperial College, London, before that she held various senior positions at Rolls-Royce plc in the aerospace, marine and power business groups. In March 2008 she delivered the 'King Review' that examined vehicle and fuel technologies that, over the next 25 years, could help to reduce carbon emissions from road transport.

**Lord John Krebs**

Lord Krebs is an internationally renowned scientist and Principal of Jesus College, Oxford University and also chair of the Adaptation Sub-Committee. He sits in the House of Lords as an independent cross-bencher and is currently chairing an enquiry by the Science and Technology Select Committee into Nanotechnology and Food.

**Lord Robert May**

Professor Lord May of Oxford, OM AC FRS holds a Professorship jointly at Oxford University and Imperial College. He is a Fellow of Merton College, Oxford. He was until recently President of The Royal Society, and before that Chief Scientific Adviser to the UK Government and Head of its Office of Science & Technology.

**Professor Jim Skea**

Professor Jim Skea is Research Director at UK Energy Research Centre (UKERC) having previously been the Director at the Policy Studies Institute (PSI). He has also acted as Launch Director for the Low Carbon Vehicle Partnership and was Director of the Economic and Social Research Council's Global Environmental Change Programme.



Acknowledgements

The Committee would like to thank:

The core team that prepared the analysis for the report. This was led by David Kennedy and included: Owen Bellamy, Ben Combes, Elgon Corner, Michele Pittini, Stephen Smith and Jonathan Stern. It also included Professor David Lee as an expert adviser.

Other members of the CCC secretariat that contributed to the report: Mark Bainbridge, Swati Khare-Zodgekar, David Joffe, Eric Ling, Nina Meddings, Claire Thornhill and Emily Towers.

A number of individuals that provided significant support: Richard Clarkson, Judith Corbyn, Kat Deyes, Lynnette Dray, Colin Dunn, Graham French, David Hart, Chris Hewett, Chris Holland, Jo Howes, Tim Johnson, Naresh Kumar, Peter Lockley, Ricky Moroni, Chris Nicholls, Brian Pearce, Alberto Pompermaier, Andreas Schäfer, Neil Shorten, Amy Vanstone and Roger Worth.

A number of organisations for their support, including the Aviation Environment Federation, the Civil Aviation Authority, the Department for Transport, the Department for Business Innovation and Skills, the Department for Energy and Climate Change, the International Air Transport Association, the International Energy Agency, National Air Traffic Services, Rolls-Royce, Shell, Sustainable Aviation and the World Wildlife Fund.

A wide range of stakeholders who engaged with us, attended our expert workshops, or met with the CCC bilaterally.

Executive summary

In January 2009 the Government decided to support a third runway at Heathrow Airport, committing to an expansion of allowable Aircraft Traffic Movements (ATMs) at Heathrow from 480,000 to 605,000 per annum. Alongside this decision, the Government set a target that CO₂ emissions from UK aviation in 2050 should be at or below 2005 levels. It therefore asked the Committee 'to assess scope for [emissions] reductions, including from improvements in technology and the effects of appropriate policy levers; and the implications of further aviation expansion beyond 2020'. In addition it signalled that in 2020, the Government would ask the Committee to advise on whether a further expansion of Heathrow allowable ATMs (from 605,000 to 702,000) was or was not compatible with achieving the 2050 target.

UK aviation CO₂ emissions in 2005 were estimated to be 37.5 MtCO₂ on a bunker fuels basis. This report therefore sets out the Committee's assessment of the actions required to ensure that UK aviation CO₂ emissions in 2050 do not exceed 37.5 MtCO₂, and in particular assesses the maximum increase in demand from current levels which is likely to be consistent with this target given current best estimates of future technological progress. If the target were to be achieved, aviation emissions would account for around 25% of the UK's total allowed emissions under the economy wide 80% cut in 2050 relative to 1990 included in the Climate Change Act.

In making our assessment, we start by projecting the possible growth of demand and emissions if there were no carbon price constraining demand and if no limits were placed on airport capacity expansion. We then consider scope for reducing emissions relative to reference projections through carbon prices, modal shift from aviation to rail/high-speed rail, substitution of communications technologies such as videoconferencing for business travel, improvements in fleet fuel efficiency, and use of biofuels in aviation. We conclude by setting out scenarios for aviation emissions to 2050 encompassing the range of options for reducing emissions, comparing emissions in 2050 with the target and considering how any gap might be closed.

The report also notes the potential implications of non-CO₂ aviation effects on global warming. The scale of such effects is still scientifically uncertain, and the effects are not covered by the Kyoto Protocol, the UK Climate Change Act or the Government's aviation target. The Committee notes the likely need to account for these effects in future global and UK policy frameworks, but we do not propose a specific approach in this report. Our assessment of required policies is therefore focused on the target as currently defined – keeping 2050 UK aviation CO₂ emissions to no more than 37.5 MtCO₂.



The key messages in the report are:

Projected demand growth

- **In the absence of a carbon price and with unconstrained airport expansion, UK aviation demand could grow over 200% between 2005 and 2050:**

- Demand for aviation has grown by 130% over the past 20 years in a context where GDP has increased by 54% and air fares have fallen significantly.
- Given forecast real income growth of around 150% in the period to 2050, and absent a carbon price or capacity constraint, we project that demand could grow by over 200% from the 2005 level of 230 million passengers annually to 695 million passengers in 2050.

- **A rising carbon price and capacity constraints could reduce demand growth by 2050 to 115%:**

- Specifically, this would result from a carbon price rising gradually to £200/tCO₂ in 2050, together with limits to airport capacity expansion envisaged in the 2003 Air Transport White Paper (i.e. with expansion at Edinburgh, Heathrow, Stansted, and then no further expansion).

Modal shift and videoconferencing

- **There is scope for a useful contribution to achieving the 2050 target through modal shift from air to rail and increased use of videoconferencing:**

- There is scope for significant modal shift to rail/high-speed rail on domestic and short-haul international routes to Europe, which could reduce aviation demand by up to 8% in 2050.
- There is uncertainty over scope for substitution of videoconferencing for business travel. We reflect this in a conservative range from very limited substitution to a reduction of 30% in business demand in 2050.
- Together modal shift and videoconferencing could result in a reduction in emissions of up to 7 MtCO₂ in 2050.

Improvements in fleet fuel efficiency

- **Fleet fuel efficiency improvement of 0.8% annually in the period to 2050 is likely given current technological trends and investment intentions**

- The Committee's current expectation is that improvement in fleet fuel efficiency of 0.8% per annum in the period to 2050 is achievable through evolutionary airframe and engine technology innovation, and improved efficiency of Air Traffic Management and operations.
- This pace of improvement would reduce the carbon intensity of air travel (e.g. grams of CO₂ per seat-km) by about 30%.

- There would be scope for further improvement (i.e. up to 1.5% per annum) if funding were to be increased and technology innovation accelerated.

Use of biofuels in aviation

- **Concerns about land availability and sustainability mean that it is not prudent to assume that biofuels in 2050 could account for more than 10% of global aviation fuel:**

- It is likely that use of aviation biofuels will be both technically feasible and economically viable.
- However, there will be other sectors which will compete with aviation for scarce biomass feedstock (e.g. road transport sector for use in HGVs, household sector biomass for cooking and heating, power generation for co-firing with CCS technology).
- And it is very unclear whether sufficient land and water will be available for growth of biofuels feedstocks given the need to grow food for a global population projected to increase from the current 6.7 billion to around 9.1 billion in 2050.
- Biofuel technologies that would not require agricultural land for growth of feedstocks (e.g. biofuels from algae, or biofuels grown with water from low-carbon desalination) may develop to change this picture but must be considered speculative today.
- Given these concerns, it is not prudent today to plan for high levels of biofuels penetration. We have assumed 10% penetration in our Likely scenario.

Aviation non-CO₂ effects

- **Aviation non-CO₂ effects are likely to result in global warming and will therefore need to be accounted for in future international and UK frameworks. This may have implications for the appropriate long-term UK aviation target:**

- The UK Government's aviation target excludes these additional non-CO₂ effects, consistent with international convention and the UK Climate Change Act, as they do not derive directly from emissions of Kyoto gases.
- Aviation non-CO₂ effects are however almost certain to result in some additional warming, but with considerable scientific uncertainty over their precise magnitude.
- It will therefore be important, as scientific understanding improves, to account for aviation non-CO₂ effects in the future international policy framework and in the overall UK framework for emissions reduction.
- The implications for appropriate emissions reduction across different sectors of the economy are unclear, but some further reduction in aviation emissions may be required. This will be relevant when considering expansion of aviation capacity in the 2020s.



Achieving the aviation emissions target

- **Given prudent assumptions on likely improvements in fleet fuel efficiency and biofuels penetration, demand growth of around 60% would be compatible with keeping CO₂ emissions in 2050 no higher than in 2005:**

- In our Likely scenario, assumptions on improvement in fleet fuel efficiency and biofuels penetration result in annual carbon intensity reduction of around 0.9%.
- The cumulative reduction of around 35% in 2050 provides scope for achieving the target with around 55% more Air Traffic Movements (ATMs). With increasing load factors over time this could allow for around 60% more passengers than in 2005.
- Given currently planned capacity expansion and with a demand response to the projected carbon price and to some of the opportunities for modal shift, demand could grow around 115% between now and 2050.
- Constraints on demand growth in addition to the projected carbon price would therefore be required to meet the 2050 target.

- **Future technological progress may make more rapid demand growth than 60% compatible with the target, but it is not prudent to plan on the assumption that such progress will be achieved:**

- It is possible that improvements in fleet fuel efficiency will progress more rapidly than currently anticipated, and/or that the prospects for sustainable biofuels will become more favourable over time.
- Unless and until emerging evidence clearly illustrates that this is the case, however, it is prudent to design current policy around a maximum demand increase of 60%.

- **A 60% increase in total UK demand could be consistent with a range of policies as regards capacity expansion at specific airports:**

- The maximum increase in ATMs compatible with the emissions target is around 3.4 million per year in 2050 compared to around 2.2 million per year in 2005.
- Total current theoretical capacity at all airports in the UK is around 5.6 million ATMs but demand cannot be easily switched between different geographical locations and capacity utilisation differs hugely between for instance 97% at Heathrow and well below 50% at some smaller airports outside the top ten.
- Optimal capacity plans at specific airports therefore need to reflect factors other than total national demand levels, and it is not the Committee's role to assess such factors.

- The combination of different policies (e.g. tax and capacity plans) should however be designed to limit total demand increase to a maximum of around 60%, until and unless technological developments suggest that any higher figure would be compatible with the emissions target.

We summarise the analysis that underpins these messages in 6 sections:

1. Aviation demand trends and projections
2. Reducing emissions through modal shift and videoconferencing
3. Reducing emissions through improvements in fleet fuel efficiency
4. Scope for use of biofuels in aviation
5. Non-CO₂ climate effects of aviation
6. Meeting the UK's 2050 aviation target

Throughout the report, we assume that UK action is in the context of an international agreement which limits aviation emissions in all countries:

- Action at the European level is required in order to avoid leakage from UK airports to hubs in other Member States.
- Action at a global level is required in order to constrain aviation emissions in a way that is consistent with achieving broader climate change objectives.

The Committee's September 2009 recommendations to Government on an international deal are summarised in Box ES.1.

Box ES.1 The Committee on Climate Change's advice on a framework for reducing global aviation emissions

Capping global aviation emissions

- Aviation CO₂ emissions should be capped, either through a global sectoral deal or through including domestic and international aviation emissions in national or regional (e.g. EU) emissions reduction targets.
- Ideally all aviation CO₂ emissions would be capped. However, an interim phase where the cap applies to all departing and arriving flights in developed countries with exemptions for intra-developing country flights may be necessary.
- The level of emissions reduction ambition under any international agreement should be no less than that already agreed by the EU (i.e. developed country net emissions in 2020 should be no more than 95% of average annual emissions from 2004-2006).



Box ES.1 continued

Auctioning allowances in cap and trade schemes

- Emissions allowances under a cap and trade scheme should be fully auctioned so as to avoid windfall profits for airlines that would ensue under free allowance allocation.
- Aviation auction revenues are one of a number of possible sources for funding of adaptation in developing countries that should be agreed as part of a global deal in Copenhagen.
- Significant R&D that is urgently required to support innovation in the aviation industry should be considered in the context of a global deal for aviation, and funded from aviation auction revenues or other sources.

Emission reductions within the aviation sector

- Emissions trading will be useful for an interim period in providing flexibility to achieve cost-effective emissions reductions, subject to the caveat that the carbon price in any trading scheme should provide strong signals for appropriate demand management and supply side innovation.
- The aviation industry should also plan however, for deep cuts in gross CO₂ emissions relative to baseline projections (e.g. for developed country aviation emissions to return to no more than 2005 levels in 2050), which will be required as a contribution to meeting the G8's agreed objective to reduce total global emissions in 2050 by 50%.

Non-CO₂ effects of aviation

- Non-CO₂ effects of aviation must be addressed as part of any international framework through commitment to a schedule for introduction of appropriate policy instruments (e.g. covering NO_x, cirrus and contrails). Given current scientific understanding, early introduction of measures to reduce NO_x emissions may be feasible and should be seriously considered.

1. Aviation demand trends and projections

Aviation demand has increased in the UK by around 130% since 1990, from 104 million passengers flying in 1990 to 238 million passengers in 2008, in a context where income has increased by 54% and average fares have fallen by around 50% between 1997 and 2006.

Within this aggregate growth, there have been significant increases in demand for both short-haul and long-haul flying (Figure ES.1):

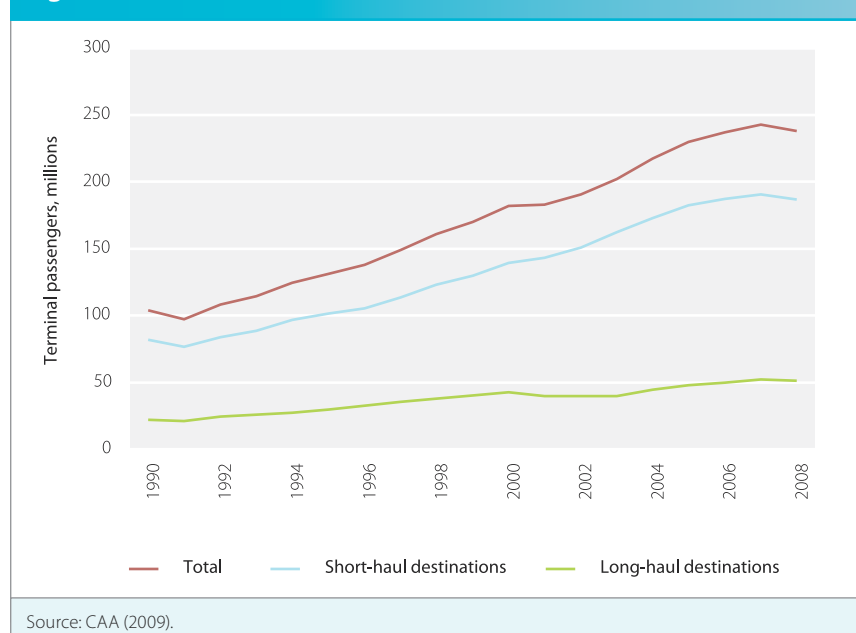
- Short-haul demand has increased by 128% from 82 million to 187 million passengers per year.
- Long-haul demand has increased by 133% from 22 million to 51 million passengers per year.

Both leisure and business travel have grown but the growth of leisure has been particularly dynamic:

- Leisure demand has increased by 185% from around 63 million to 180 million passengers per year.
- Business demand has increased by 70% from around 35 million to 60 million passengers per year.

Survey data suggests that around 50% of the UK adult population travels by plane annually and that likelihood of flying is closely related to income. Amongst people who fly the average number of flights per year also varies significantly by income, with those on incomes of more than £60,000 per annum flying on average just under four times per year, and those on less than £20,000 flying two times per year. Income elasticity of demand is thus high, both as between income groups and over time.

Figure ES.1 UK aviation demand since 1990





Emissions growth has been slightly less than demand growth (e.g. 120% compared to 130%) over the period 1990 to 2007. Three main factors account for this difference:

- Increasing load factors over time have reduced emissions growth relative to demand growth.
- Improvements in fleet fuel efficiency have also reduced emissions growth relative to demand growth.
- These effects have however been somewhat offset by relatively high demand growth in the long-haul segment, for which emissions per flight are relatively high, and which now accounts for around 70% of total UK aviation emissions (Figure ES.2).

Future demand is likely to grow rapidly as high income elasticity outweighs moderate price elasticity (Table ES.1).

Given an assumption of around 150% real UK GDP growth in the period to 2050, alternative projections for future demand suggest that (Figure ES.3):

Figure ES.2 Distribution of UK aviation emissions by distance in 2005

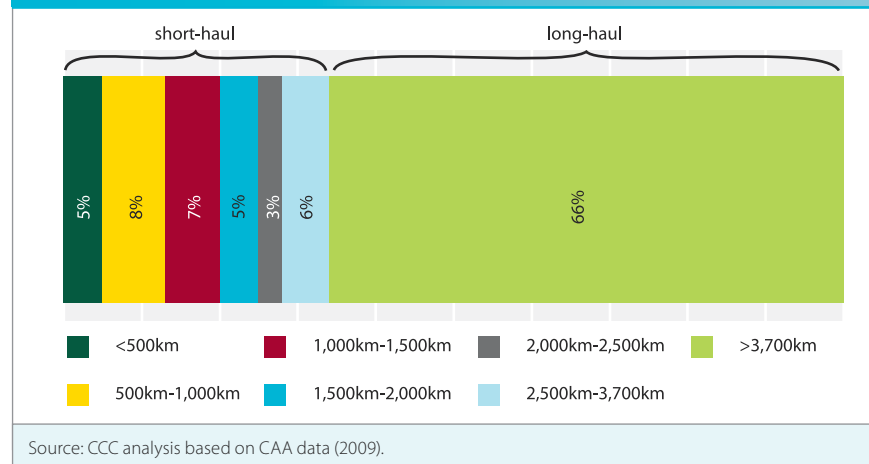
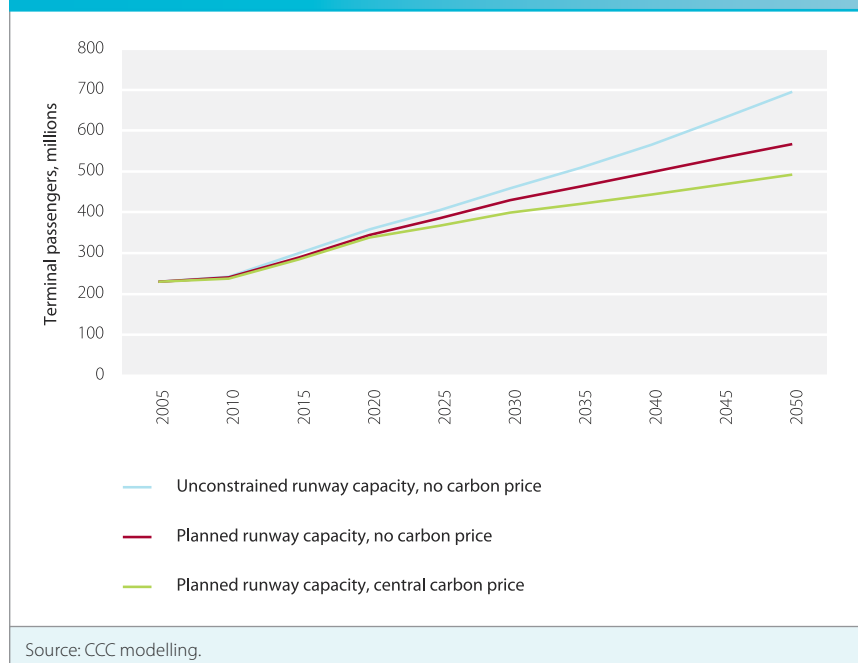


Table ES.1 DfT Elasticity estimates¹

	Price elasticities	Income elasticities
UK Business	-	1.4
UK Leisure	-1.0	1.5
Foreign Business	-	0.6
Foreign Leisure	-0.2	0.7

Source: DfT (2009).

¹ DfT could not identify a statistically significant relationship between business demand and air fares in their modelling. Nevertheless, estimates from the literature reviewed for the CCC by MVA Consultancy pointed to a small but non-zero price elasticity of -0.2. We have run sensitivities on our three core scenarios with this elasticity and the impact in 2050 is less than 1 MtCO₂ in all scenarios and therefore would not materially alter our conclusions.

Figure ES.3 Reference demand projections

- With no runway capacity constraints and no carbon price, demand would grow by over 200% by 2050 relative to 2005 levels (i.e. from 230 million passengers to 695 million passengers annually)
- With runway capacity at levels envisaged in the 2003 Air Transport White Paper (i.e. with new capacity at Edinburgh, Heathrow and Stansted) and no carbon price demand would grow by around 150% by 2050 relative to 2005 levels (i.e. from 230 million passengers to 570 million passengers annually)
- With runway capacity at levels envisaged in the Air Transport White Paper and under a central case carbon price (i.e. rising to £200/tCO₂ in 2050) demand would grow by 115% by 2050 relative to 2005 levels (i.e. from around 230 million passengers to around 490 million passengers annually).

In projecting emissions going forward, we translate our demand projections to estimates of Air Traffic Movements (ATMs) and then convert ATMs to emissions; we subsequently adjust emissions projections to reflect scope for improvement in the fuel efficiency of the fleet (see section 3 below).

With no runway capacity constraints and no carbon price, and if the carbon intensity of air travel remained unchanged (i.e. no technological progress) emissions would rise to just under 100 MtCO₂ in 2050. With planned capacity constraints and a central case carbon price, and with no technological progress, emissions would rise to around 74 MtCO₂ in 2050.



2. Reducing emissions through modal shift and videoconferencing

The scope for modal shift between aviation and rail/high-speed rail depends critically on route distance. Our analysis suggests that journeys up to 800km offer significant potential for substitution from aviation to high-speed rail. In particular, market shares of up to 90% on Anglo-Scottish routes, and 60% on short-haul routes (e.g. Amsterdam, Dusseldorf and Frankfurt) may be achievable in the context of a UK high-speed rail line and a fully integrated European high-speed network (Figure ES.4 a and b).

There is scope for considerable uptake of videoconferencing. However it is uncertain how far this will substitute for air travel, rather than resulting in a higher level of business interaction with travel patterns unchanged. Current best business practice suggests that videoconferencing can substitute for up to 30% of travel, but the largest reductions relate to within company communications and similar reductions may not be possible when travel is for meetings between firms. Further analysis of scope for videoconferencing to substitute for business travel would require comprehensive data on trip patterns including frequency with which business travellers fly, the purpose of their meetings (internal versus external), the number of meetings per trip, etc. Given current uncertainties, we assume a conservative range from very limited business travel substitution to a 30% reduction in business demand for air travel in 2050.

Overall our scenarios for modal shift and videoconferencing suggest a potential to reduce emissions by up to 7 MtCO₂ in 2050. Under a policy regime which involved constraints on capacity but which allowed demand to increase to fill the allowed capacity, some of this reduction would be offset by increases in other categories of demand (e.g. long-haul leisure). For this reason modal shift and videoconferencing effects show up as small on our charts illustrating emission scenarios assuming planned capacity constraints (see Section 6 below). Modal shift and videoconferencing will however have a significant role to play in delivering economic benefits and increased business efficiency, and as optimal responses to likely required policies (e.g. constraints on slot capacities focussed on routes where high-speed rail is an alternative, or carbon taxes which will fall heavily on more carbon intensive business class seats).

Figure ES.4a Projected rail mode share on selected domestic routes in 2050 (with new UK high-speed line)

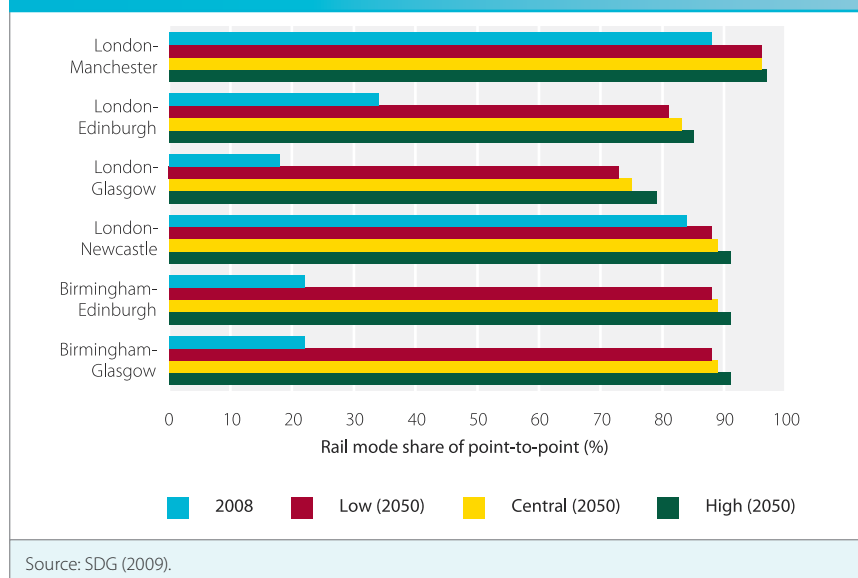
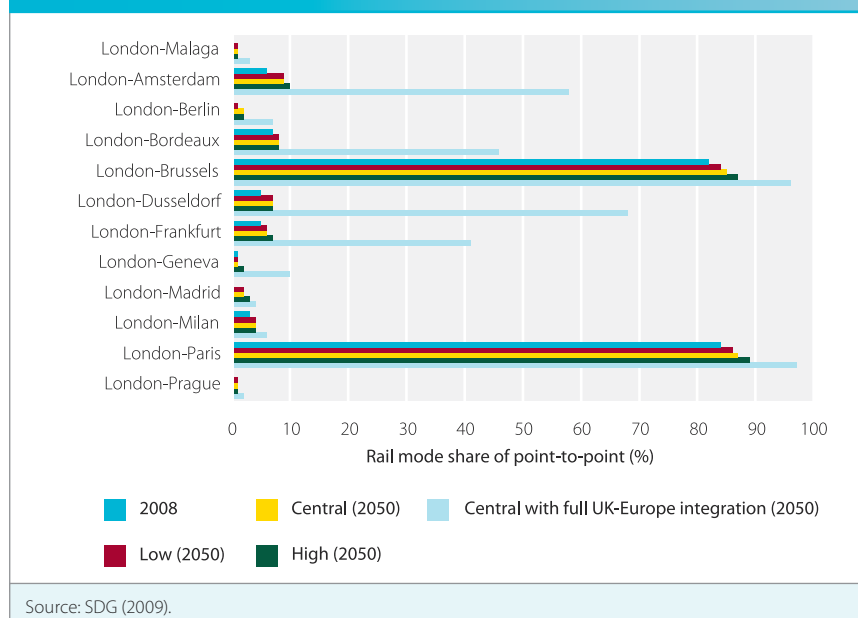


Figure ES4.b Projected rail mode share on selected routes from London to mainland Europe in 2050





3. Reducing emissions through improvements in fleet fuel efficiency

Engine and airframe improvements could increase the fuel efficiency of new aircraft by up to 40% in the 2020s relative to new aircraft in 2005. Major manufacturers currently plan to introduce these improvements in new narrow-body aircraft families in the 2020s, with no firm plans to introduce new families for other market segments beyond the 2010s. Once introduced, these families will make up a small but increasing proportion of new aircraft entering the fleet, where the latter reflects turnover of the existing stock (e.g. around 4% annually) and increased demand. More radical technology innovation (e.g. blended wing aircraft) could offer significant potential for emissions reduction, although this would require as yet unplanned high levels of investment.

In addition to airframe improvement there is scope for efficiency improvement in Air Traffic Management (e.g. through flying direct routes at optimal heights and avoiding holding at airports) and operations (e.g. through maximising payload, reducing cabin deadweight and improving airport operations) which together could reduce emissions by up to around 13%.

We set out scenarios for improvement in annual fleet fuel efficiency the period to 2050 from 0.8% to 1.5% on a seat-km basis, with variation largely driven by assumptions on timing of new technology deployment. The low end of the range corresponds to deployment of evolutionary technology starting in the period 2025-2030 – the Committee's current expectation – with the high end reflecting earlier deployment and the introduction of more radical technologies.

4. Scope for use of biofuels in aviation

It is likely that use of aviation biofuels will be both technically feasible and economically viable, particularly in a world of increasing carbon prices. However, there is considerable uncertainty over sustainability of biofuels use in aviation.

Since sustainability constraints apply at a global level, we cannot assess sustainability by reference to the biofuels use of one country alone. The UK can only consider a major role for biofuels as sustainable if that role would be sustainable when applied globally. The Committee therefore believes that, for instance, the UK should only assess a 10% biofuels use in aviation as sustainable if we are confident that sustainable biofuels could account for 10% of total global aviation fuel use.

Key considerations relating to use of sustainable biofuels in aviation include demand for biofuels from other sectors, the need to feed an increasing global population, limited confidence about biofuels routes which do not require use of potential agricultural land, and the lifecycle emissions reductions from biofuels:

- International Energy Agency (IEA) scenarios for 2050 include use of biofuels in aviation, shipping, and road transport, with use of biomass for cooking and heating in developing countries, and in CHP generation or co-firing power generation in conjunction with CCS technology; 100% biofuels penetration in aviation together with use of biomass in other sectors as envisaged in the IEA scenarios could require 9.3 million km² of land for growth of feedstocks.
- Land and water availability should be considered in the context of global population which is projected to rise from 6.7 billion to 9.1 billion by 2050, with demand for food possibly increasing by more than 70% as people become richer². Whilst there are some optimistic estimates suggesting this food demand can be met with land to spare, these would require significant agricultural productivity improvement at a time of constrained use of carbon intense fertilisers, declining water resources and climate change impacts; given these uncertainties we cannot therefore be confident that there will be adequate land available for growth of biofuels feedstocks.
- Technological progress may make possible biofuels which would not require potential agricultural land or scarce water for growth of feedstock (e.g. biofuels from waste, forest residues, algae, or using desert land and water from low-carbon desalination processes). But there are significant uncertainties around the viability and/or the pace of development of these routes for biofuels production. It would not therefore be prudent to base current policy on the assumption these routes will make possible high levels of sustainable biofuels penetration in aviation.
- The emissions reductions actually achieved by using biofuels will depend on the emissions generated in their production and their direct and indirect impacts on land use. Biofuel feedstock production could for instance cause food production to shift to currently forested land, land with carbon rich soils, or less productive land where more intensive use of fertiliser is required. We have assumed an average emissions savings relative to fossil fuels of 50%.

Reflecting these considerations, our scenarios for biofuels penetration in aviation in 2050 range from 10% (Likely) to 30% (Speculative). Given uncertainty about whether the higher figures are compatible with sustainability, it is not prudent to base current policy on the assumption of a penetration rate above 10%. It is possible that over time more optimistic assumptions may become justified but these should only be used as a base for policy if and when there is clear evidence that all sustainability concerns have been addressed.

² The increase in demand for food will reflect not only increased population but also changes in diet, with a wide range of assumptions possible as to how far developing world diets will converge towards developed world resource intensive patterns (e.g. with higher proportion of meat and dairy). Estimates of total additional agricultural production required range from 50 to 100%.



5. Non-CO₂ climate effects of aviation

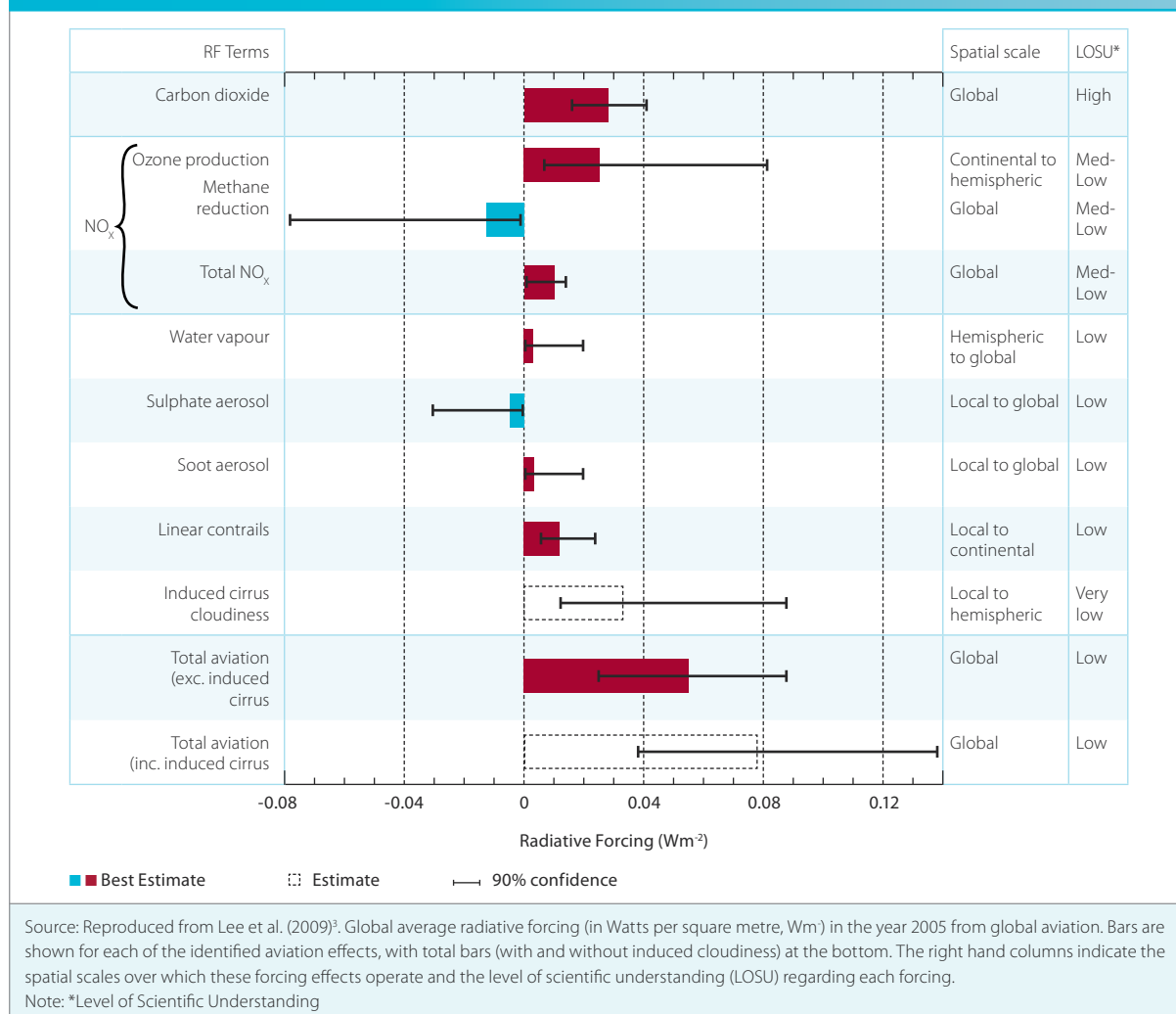
The Kyoto framework, the UK's Climate Change Act and the UK's 2050 aviation target all exclude aviation non-CO₂ effects since these do not derive from emissions of any of the six greenhouse gases covered by the Kyoto Protocol. It is highly likely however that the net impact of non-CO₂ effects – particularly contrails and other induced cloud formation – is to increase the global warming impact of aviation beyond that suggested by CO₂ emission alone (Figure ES.5).

The precise scale of the additional impact is unclear and there are considerable scientific uncertainties still to be resolved, but it is highly likely that these non-CO₂ effects are significant. It will therefore be important that they are accounted for in future international policy frameworks and in the overall UK policy framework for emissions reduction.

While this report concentrates on the UK Government aviation target as currently expressed in terms of CO₂ alone, we therefore comment also on the possible implications of considering non-CO₂ effects. The inclusion of non-CO₂ aviation effects into the UK policy framework could be reflected in three different ways (or a mix of these ways):

- The total level of CO₂ equivalent emissions allowed in 2050 across all sectors of the economy could be increased to reflect the fact that the starting level of relevant emissions today is higher than previously assessed. This approach however may not be consistent with the overall climate change objectives which the Committee considered when it recommended the 2050 target which has now been adopted by Parliament.
- The aviation target could be restated to be that total aviation effects (CO₂ and non-CO₂ combined) should be no higher in 2050 than in 2005. This would be consistent with the Government's principle of returning aviation emissions to 2005 levels by 2050, but would require that other sectors of the economy to achieve even bigger reductions than those envisaged by the Committee in its first (December 2008) report.
- The aviation target could be adapted to include non-CO₂ effects with total CO₂ equivalent emissions (combining CO₂ and non-CO₂ effects) required to fall between 2005 and 2050 rather than simply not increase.

The most appropriate response is unclear and would need to reflect consideration of the different costs of achieving emissions reductions in different sectors of the economy, as well analysis of the latest scientific understanding of the global warming effects and the evolution of the international and European policy framework. Future work by the Committee, for instance our review in 2020 of further slot release at Heathrow, will need to take account of these considerations alongside latest information on the pace of the technology advances discussed in sections 3 and 4.

Figure ES.5 Aviation radiative forcing components in 2005



6. Meeting the UK's 2050 aviation target

We have developed three scenarios which combine different assumptions about rates of change in respect to modal shift, videoconferencing, improvement in fleet fuel efficiency, and biofuels⁴:

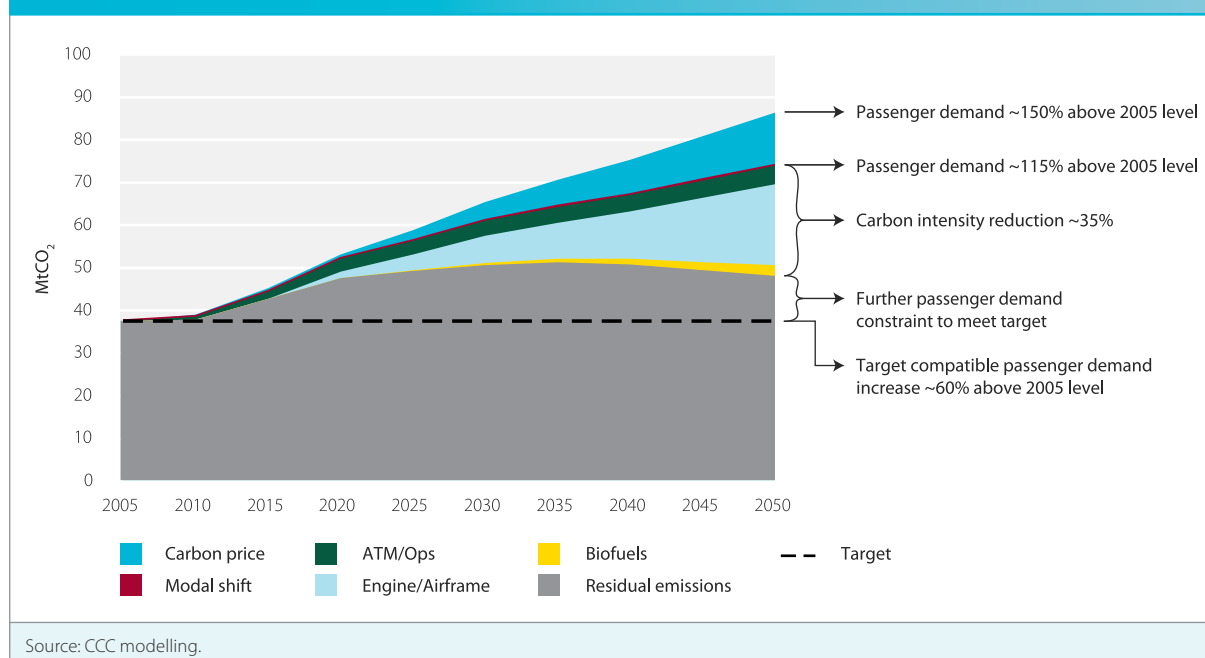
- **Likely scenario:** This reflects demand reductions and carbon intensity reductions likely to be achieved given current policies, investment levels and the pace of technological advance.
- **Optimistic scenario:** This would require both:
 - A significant shift from current policy (e.g. in respect to high-speed rail), and an increase in the level of investment in new aircraft technologies and/or in the pace of fleet renewal as well as improvements in ATM and operations so as to make a 1.0% per annum improvement in carbon efficiency attainable.
 - Progress of biofuel technologies which would make it reasonable to assume that a 20% penetration was compatible with sustainability.
- **Speculative scenario:** This would require both technological breakthroughs and a significant increase in the pace of aircraft fuel efficiency improvements. In addition, it would require the development of sustainable biofuels which are currently speculative (e.g. biofuels from algae), or an evolution of global population, food demand and agricultural productivity which would make possible the sustainable and large scale use of current agricultural land and water to grow biofuel feedstocks. These developments are assessed today as very unlikely.

Meeting the target in the Likely scenario

In our Likely scenario we assume annual improvements in fleet fuel efficiency of 0.8% together with 10% biofuels penetration in 2050. This combination of improvement in fleet fuel efficiency and biofuels penetration implies a carbon intensity reduction of around 35% in 2050 relative to the reference projection (Figure ES.6). As a result an increase in ATMs of around 55% relative to 2005 levels would be compatible with the target of ensuring that 2050 CO₂ emissions did not exceed the 2005 level of 37.5 MtCO₂. Given increasing load factors over time, an increase in passengers of around 60% on 2005 levels by 2050 would be possible, taking total annual passenger numbers from 230 million to around 370 million. This would be equivalent to taking total passenger trips (one departure plus one arrival) from 115 million in 2005 to around 185 million in 2050.

This target-compatible demand growth of around 60% compares with the growth of over 200% which might result in a world where there were no capacity constraints and no carbon price.

⁴ These should not be compared with the Committee's Current, Extended and Stretch scenarios defined in the context of UK emissions excluding aviation, where there is less uncertainty about abatement potential and more policy levers are available at the UK level.

Figure ES.6 Likely scenario (planned capacity)

On the demand side, however, the Likely scenario incorporates the future capacity limits assumed by the 2003 Air Transport White Paper. It also allows for the impact of carbon price in line with our central projections (rising gradually to around £200/tCO₂ by 2050), and for some modal shift to conventional rail. These assumptions generate a demand growth of 115% relative to current levels by 2050.

Meeting the 2050 target that CO₂ emissions are no higher than 37.5 MtCO₂ is therefore likely to require policy measures to restrain demand which go beyond our central projected carbon price. The policy instruments which could achieve this restraint include a carbon tax on top of the forecast carbon price, limits to further airport expansion, and restrictions on the allocation of take-off and landing slots even where airports have the theoretical capacity available.

Meeting the target in other scenarios

In the *Optimistic* scenario, we assume 1.0% annual improvement in fleet fuel efficiency and 20% biofuels penetration in 2050. This combination of improvement in fleet fuel efficiency and biofuels penetration implies a carbon intensity reduction of around 45% in 2050. As a result it would be possible to increase ATMs by around 80% and passenger numbers by around 85% and still meet the target that CO₂ emissions should not exceed 37.5 MtCO₂ in 2050 (Figure ES.7). Passenger trips (one departure plus one arrival) could increase from 115 million in 2005 to around 215 million in 2050.



Given demand growth under this scenario of 115%, meeting the target would still require additional policy measures to constrain demand beyond those implied by the 2003 Air Transport White Paper and the central carbon price projection. But these additional measures would not need to be as restrictive as in the Likely scenario.

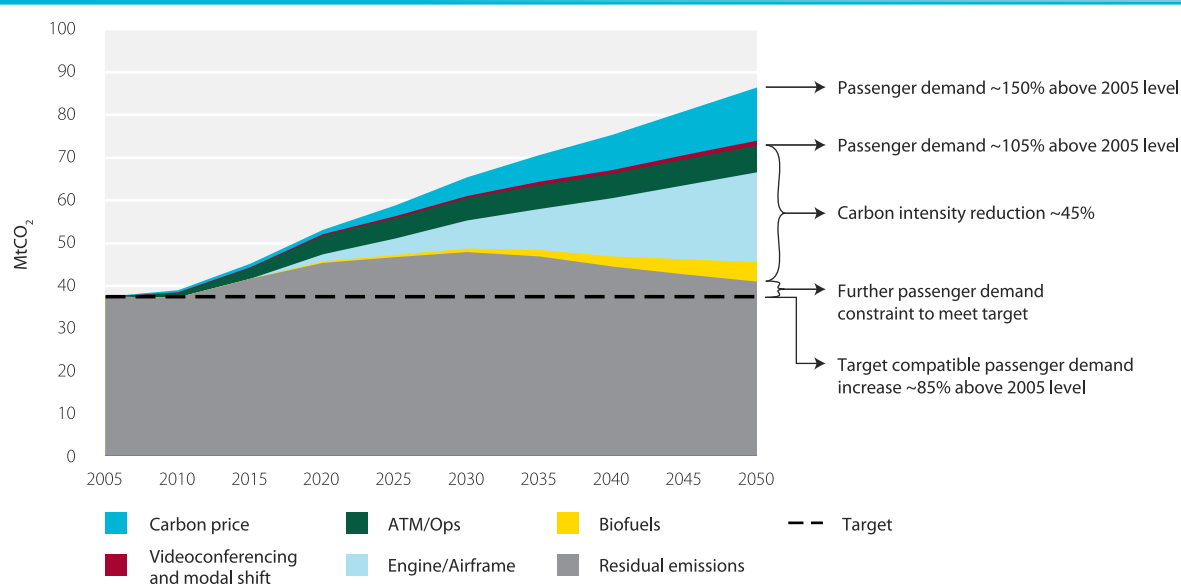
In the *Speculative* scenario, we assume annual improvement in fleet fuel efficiency 1.5% and biofuels penetration of 30% in 2050. The implied carbon intensity reduction is around 55% by 2050. This would make an increase in ATMs of around 125% and of passengers of around 135% compatible with meeting the target. The combination of already planned capacity limits, the demand response to the projected carbon price and opportunities for modal shift and videoconferencing, would produce a demand increase below this 135%. No additional policy measures would therefore be required to meet the target (Figure ES.8).

It should be noted however that even in this scenario the maximum demand increase compatible with the target (135% increase in passengers) is much lower than the increase which our projections suggest would occur in a world of no constraints (i.e. with no carbon price and unlimited airport expansion).

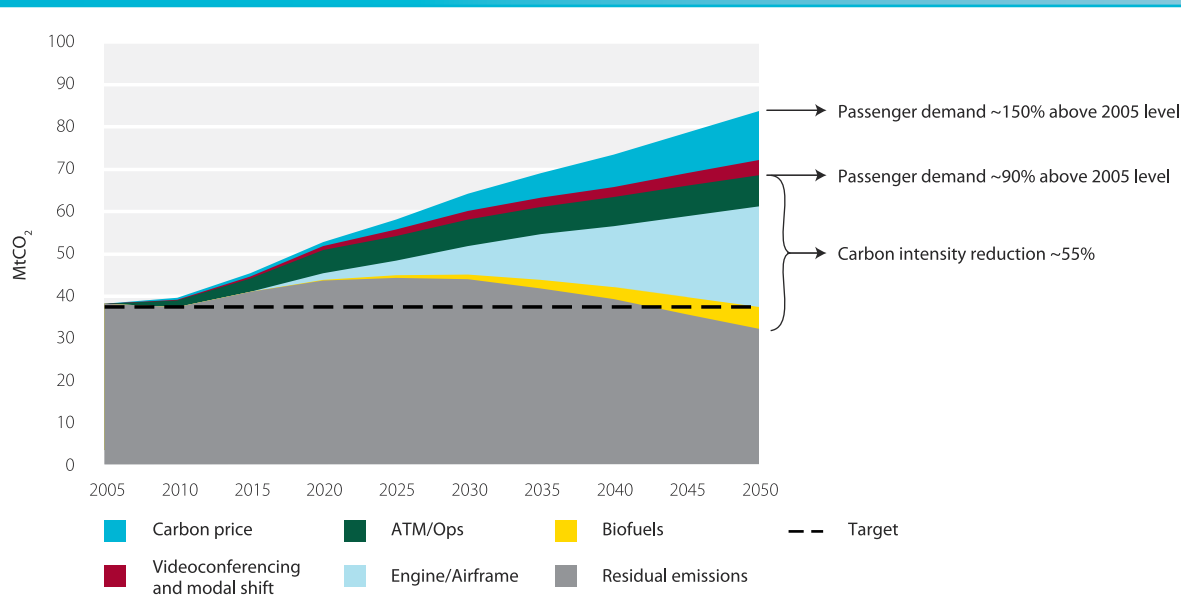
The high growth in aviation demand which would occur in an unconstrained environment illustrates the high value which people place on the opportunity to fly, in particular for leisure purposes. If the Optimistic or Speculative scenarios can be achieved, the number of flights compatible with meeting the 37.5 MtCO₂ target increases.

In considering the difference between scenarios, three aspects should be distinguished:

- Achieving greater modal shift to rail and greater use of videoconferencing does not increase the total target-compatible level of demand, but it makes it possible for more of that total to be devoted to other uses (e.g. long-haul leisure) where there are no alternatives to air travel. Investing in a new high-speed rail line and promoting full integration of UK and European high-speed networks can increase the potential for modal shift. Promotion of videoconferencing technologies could ensure higher levels of business travel substitution.
- Achieving more rapid fuel efficiency improvements directly increases target-compatible demand growth. It could be fostered through increasing investment in R&D, introducing regulatory limits on new aircraft CO₂ performance, exploring possible benefits from early scrappage of older aircrafts, and full implementation of SESAR and NATS initiatives on ATM efficiency improvement.

Figure ES.7 Optimistic scenario (planned capacity)

Source: CCC modelling.

Figure ES.8 Speculative scenario (planned capacity)

Source: CCC modelling.



- The higher the percentage of biofuels use which can be considered sustainable the greater the target-compatible demand increase. Here however it is not clear that higher investment will necessarily drive more rapid improvement, since there is inherent uncertainty about what progress can be achieved, and about the implications of population growth and food demand for land use. We therefore need to observe through time the development of speculative technologies, and trends in agricultural productivity and land availability. Governments could however encourage investment in those technologies most likely to be sustainable. And expanded use of biofuels will need to be underpinned by a global policy framework to mitigate the risks of harmful land-use changes resulting from the growth of biofuel feedstocks.

Several of these developments which might make possible more rapid demand increases than in the Likely scenario are ones over which the UK acting alone has only small influence. EU or broader international action would be required to accelerate the pace of improvement of fleet fuel efficiency and international action would be required to develop a framework to mitigate against risks of indirect land use impacts from biofuels.

The prudent assumption on which to base policy today is therefore that reductions in the carbon intensity of air travel will be limited to the reduction of around 35% achieved in the Likely scenario, implying a maximum allowable increase in ATMs of around 55% and a maximum demand increase of around 60%. If faster technology progress is in fact achieved this can be reflected in adjustments in policy over time.

Implications for airport expansion and slot allocation

The 2003 Air Transport White Paper proposed that there could be airport runway capacity expansions at Edinburgh, Heathrow and Stansted, but at no other airports. In January 2009, the Government decided in favour of a third runway at Heathrow and in favour of increasing slot capacity there from 480,000 to 605,000. It decided however, that any decisions on the allocation of further slot capacity (to the maximum theoretical potential of 702,000 with a third runway in place) should be subject to recommendations from the Committee on Climate Change in 2020 on whether further expansion then appears compatible with the target of restricting CO₂ emissions to a maximum 37.5 MtCO₂ in 2050. The Terms of Reference for this report in addition asked the Committee to consider 'the implications [for meeting the 2050 target] of further aviation expansion in the 2020s'.

The key implication from our analysis is that future airport policy should be designed to be in line with the assumption that total ATMs should not increase by more than about 55% between 2005 and 2050, i.e. from today's level of 2.2 million to no more than around 3.4 million in 2050. This constraint could be consistent with a range of policies as regards capacity expansion at specific airports.

Total current theoretical capacity at all airports in the UK is about 5.6 million ATMs which is already in excess both of today's actual ATMs and of maximum ATMs compatible with the 2050 target (Table ES.2a and b). But demand cannot be easily switched between different geographical locations, and there is a tendency for demand to concentrate at major hubs, given the advantages of inter-connection between different routes. As a result, capacity utilisation differs hugely between for instance, 97% at Heathrow and well below 50% at some smaller airports outside the top ten.

If demand was allowed to grow in line with the demand assumptions of the Likely scenario, with passenger numbers growing 115% there would be around 4 million ATMs by 2050. Our modelling suggests that an allocation of demand at this level would entail Heathrow operating at its maximum 702,000 capacity (with a third runway) with several other airports highly utilised (Table ES.2b). Our analysis suggests however total ATMs need to be restricted to a maximum of about 3.4 million in 2050, about 0.6 million below the level modelled in the Likely scenario.

Table ES.2a: Actual runway capacity and utilisation in 2005

Airport	Maximum runway capacity (ATMs, '000s)	Actual use (ATMs, '000s)	Capacity utilisation	Spare capacity (ATMs, '000s)
Heathrow	480	466	97%	14
Gatwick	260	248	95%	12
Stansted	241	166	69%	75
London City	73	60	82%	13
Luton	100	72	72%	28
Bristol	188	58	31%	130
Birmingham	186	111	60%	75
Manchester	276	213	77%	63
Glasgow	188	93	50%	95
Edinburgh	186	106	57%	79
Other UK Airports	3,400	568	17%	2,832
Total	5,577	2,160	39%	3,417

Source: CCC modelling.

**Table ES.2b:** Projected runway capacity, utilisation and target compatible ATMs in 2050
(Likely scenario assumptions)^{5,6}

Airport	Maximum runway capacity (ATMs, '000s)	Planned capacity, ATM distribution ('000s)	Capacity utilisation	Spare capacity (ATMs, '000s)
Heathrow	702	702	100%	0
Gatwick	260	260	100%	0
Stansted	480	317	66%	163
London City	120	120	100%	0
Luton	135	135	100%	0
Bristol	226	127	56%	98
Birmingham	206	206	100%	0
Manchester	500	449	90%	51
Glasgow	226	198	88%	27
Edinburgh	450	224	50%	226
<i>Other UK Airports</i>	<i>4,000</i>	<i>1,227</i>	<i>31%</i>	<i>2,773</i>
Total	7,304	3,965	54%	3,339
Target compatible ATMs		3,418		
Difference between the Likely scenario and target compatible ATMs		547		

Source: CCC modelling.

This restriction could be achieved through a range of different policies relating to taxes, capacity expansion or slot allocation at specific airports. Optimal decisions on specific airport capacity do not therefore mechanically follow from national aggregate demand, but need to reflect a wide range of other factors such as customer preference, alternatives to air travel, local environmental impact, competition between UK airports and continental hubs, and economic impacts both local and national. It is not the Committee's role to assess these factors.

The Committee's clear conclusion is however that the combination of future aviation policies (combining tax, capacity expansion and slot allocation decisions) should be designed to be compatible with a maximum increase in ATMs of about 55% between now and 2050, and that this should continue to be the policy approach until and unless technological developments suggest that any higher figure would be compatible with the emission target.

⁵ The ATM distribution is an indicative model output rather than a definitive view on the distribution in the Likely scenario.

⁶ Stansted utilisation and total demand may be higher in practice when suppressed demand is reallocated from other London airports.

Future work of the Committee on aviation

Further work on aviation emissions by the Committee over the next year will include:

- Assessing whether international aviation emissions should be included in carbon budgets given the final mechanisms agreed by the EU for allocating EU ETS allowances across Member States.
- Assessing the relative costs of emission reductions in different sectors of the economy (including aviation) within the context of the Committee's development of recommendations for the fourth budget period (2023-2027) which will be delivered in December 2010. This will entail consideration of the feasibility of reductions in other sectors sufficient to offset the fact that aviation emissions are likely to grow before falling back to the 37.5 MtCO₂ level.

Over the longer term the Committee will:

- Review any new evidence on improvement in fleet fuel efficiency, sustainable biofuels and aviation non-CO₂ effects and their implications for the maximum demand increase compatible with meeting the emissions target.
- In 2020 advise Government on whether release of the second tranche of slots from Heathrow capacity expansion (from 605,000 to 702,000) is then compatible with meeting the 2050 target.

The Committee's next annual report to Parliament in June 2010 will include an assessment of latest data on UK aviation emissions and will reflect any developments on international aviation policy resulting from the Copenhagen climate change summit.

Chapter 1

Background and methodology for the review of UK aviation emissions

30

In our December 2008 report¹, we set out a preliminary analysis of aviation emissions including emissions projections and scope for emissions reduction through innovation in engine, airframe and fuel technology. We concluded that global aviation emissions could account for a significant proportion of total allowed global emissions in 2050, and we argued that they should therefore be included in climate change strategies and policy frameworks. This would provide incentives for supply and demand side aviation emissions reductions, and ensure that total UK emissions are reduced in line with appropriate targets informed by climate science.

In January 2009, the Government set a target to reduce UK aviation emissions in 2050 back to 2005 levels or below. Together with a 90% cut in CO₂ emissions from other sectors, this would broadly achieve the economy-wide target in the Climate Change Act to reduce emissions by 80% in 2050 relative to 1990. The Government asked the Committee to undertake a review of the long-term path for UK aviation emissions, and to consider how the 2050 target could be met through technology improvement and the use of appropriate policy levers, accounting for implications of planned aviation expansion in the 2020s.

This chapter sets out the Committee's approach to the review, which comprises:

- Developing reference case demand and emissions projections
- Considering alternatives to air travel, namely modal shift from aviation to rail and increased use of communication technologies such as videoconferencing
- Assessing scope for emissions reductions through fuel efficiency improvements
- Assessing scope for emissions reductions through the use of sustainable biofuels
- Considering non-CO₂ effects of aviation
- Identifying potential gaps between emissions projections and the 2050 target, and setting out options for closing any gaps, including through explicit constraints on demand growth.

¹ Committee on Climate Change (2008). Building a low-carbon economy – the UK's contribution to tackling climate change. See: <http://www.theccc.org.uk/reports/building-a-low-carbon-economy>



The chapter is set out in three sections:

1. Key aviation messages in our December 2008 report
2. The Government's 2050 UK aviation emissions target
3. The Committee's approach to the review.

1. Key aviation messages in our December 2008 report

The analysis in our December 2008 report focused on three areas:

- (i) Projections of global aviation emissions
- (ii) Projections of UK aviation emissions
- (iii) Accounting for international aviation emissions under the Climate Change Act.

(i) Projections of global aviation emissions

Aviation emissions growth

We showed in our 2008 report that following ten years of 5% annual demand growth, global aviation emissions currently account for up to 2.4% of global total CO₂ emissions². We argued that there will be significant demand growth in the period to 2050 based on income growth in developed and developing countries.

The Committee considered, *inter alia*, the CONSAVE scenarios for aviation emissions under alternative assumptions about policies to constrain demand growth (Box 1.1). These showed that in a world with largely unconstrained demand growth, aviation emissions could account for 15-20% of total allowed CO₂ emissions in 2050 under global emissions reduction scenarios required to limit the risk of dangerous climate change (i.e. to cut global emissions by at least 50% in 2050 and reduce emissions to an average of just over 2 tCO₂e per capita)³.

The Committee argued, therefore, that it is essential that aviation should be covered by a policy framework which:

- (i) Ensures aviation faces an appropriate cost of carbon so as to provide an incentive both for supply side abatement and for demand constraint
- (ii) Ensures that the total level of emissions (i.e. from aviation and other sectors) is reduced in line with appropriate scientific targets.

² The percentage relates to aviation CO₂ emissions as a percentage of overall global CO₂ emissions (excluding emissions relating to land-use).

³ The preferred global emission scenarios in our 2008 report pointed to a range of 20-24 GtCO₂e by 2050. For a population of 9.2 billion, this translates to 2.1-2.6 tCO₂e per capita.

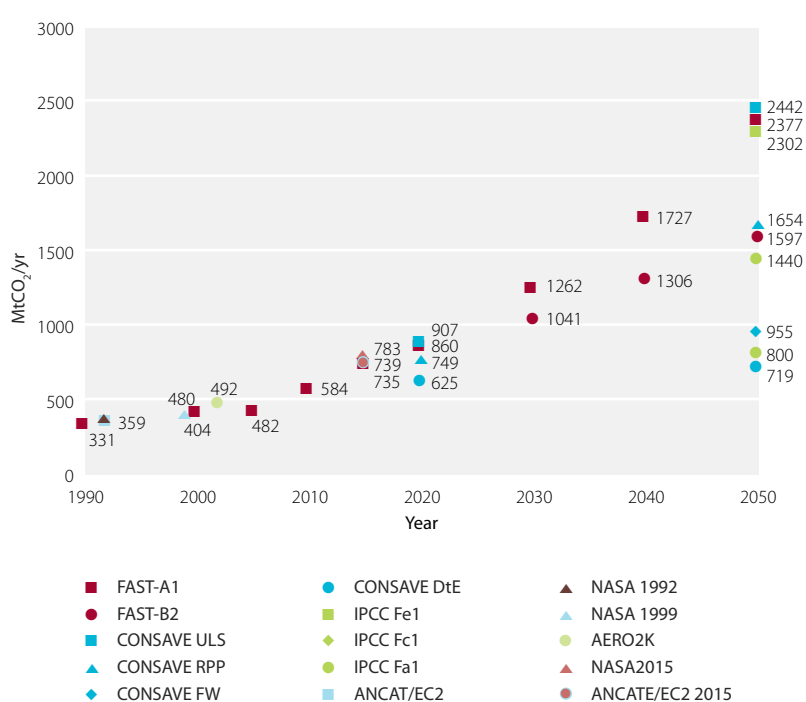
Box 1.1 Projections of global aviation emissions to 2050

There are many projections for global aviation emissions and this makes it hard to establish one 'business as usual' case. Projections vary widely, depending on the precise assumptions made about income convergence, traffic growth, fuel efficiency trend, the regulatory environment, consumer behaviour and on the scope of the study.

The CONSAVE scenarios (Figure B1.1) show four possible scenarios for the growth of global (domestic and international) aviation emissions. The scenarios range from 'Unlimited Skies' (ULS), which is comparable with an unconstrained demand scenario, but pressure on capacity at airports, to 'Down to Earth' (DtE), which would require strong policy action and regulation.

In a world without significant policy action at the global level, we are more likely to be on a path resembling the CONSAVE ULS scenario, which would result in 2.4 GtCO₂ from global aviation in 2050 under an assumption that fleet efficiency improves by 1.5% annually. Global CO₂ emissions from aviation at around these levels would, in 2050, account for 15-20% of all CO₂ emissions permitted under the CCC preferred global emissions reduction scenarios set out in the CCC's December 2008 report.

Figure B1.1 Global Aviation Emissions Scenarios (Including Consave)



Source: IPCC WG3 AR4, Fig. 5.6, (2007).

Emissions reduction through technology innovation

The CONSAVE 'Unlimited Skies' scenario highlighted in our 2008 report includes assumptions that the fuel efficiency of the global aircraft fleet will improve at an annual average rate around 1.5% in the period to 2050. This is contingent on new, efficient aircraft being introduced in the fleet and on efficiency improvements in Air Traffic Management (ATM) (e.g. by flying more direct routes, adopting different altitude profiles and reducing holding at airports) and operations (e.g. increasing load factors and the efficiency of airport operations).

The Committee commissioned work from QinetiQ to identify the scope for efficiency improvement. This study suggested that upper-bound evolutionary changes to airframe and engine technologies, together with changes in efficiency of ATM and operations could result in a new production aircraft in 2025 being 40-50% more fuel efficient than one produced in 2006 (on a passenger-km basis). This is broadly consistent with both the assumptions in the CONSAVE scenario and with industry targets. For example, efficiency targets for new aircraft set by the Advisory Council for Aeronautics Research in Europe (ACARE) aim for CO₂ emissions per passenger-km from a new aircraft to be 50% lower in 2020 than 2000.

It should be noted that these percentages refer to new aircraft that could be available for service at a certain date in the future; it would then take a relatively long time (given the long lifetime of aircraft) for these aircraft to be taken up in significant numbers and contribute to improving the average efficiency of the global fleet.

(ii) Projections of UK aviation emissions

Historic and projected aviation emissions

UK aviation CO₂ emissions have grown by over 50% in the past ten years due to increasing demand in both passenger and freight traffic (Figure 1.1); aviation CO₂ emissions now account for around 5% of total UK GHG emissions (Figure 1.2).

Figure 1.1 UK aviation demand and emissions 1996-2007

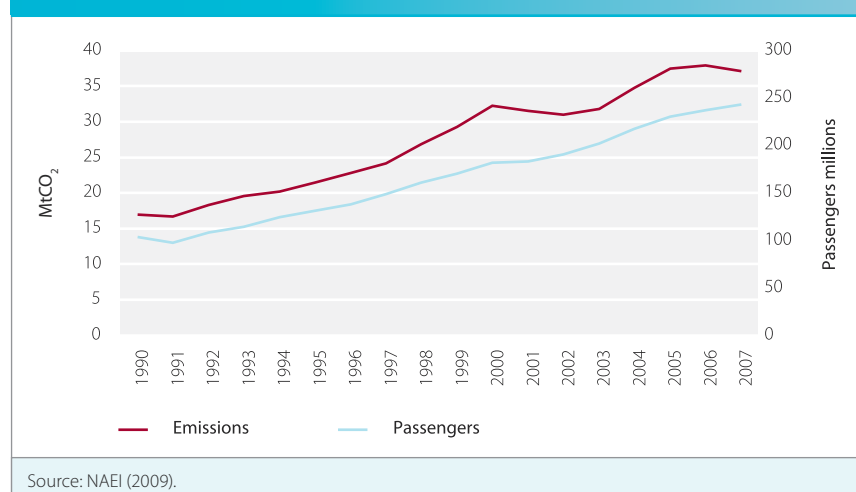
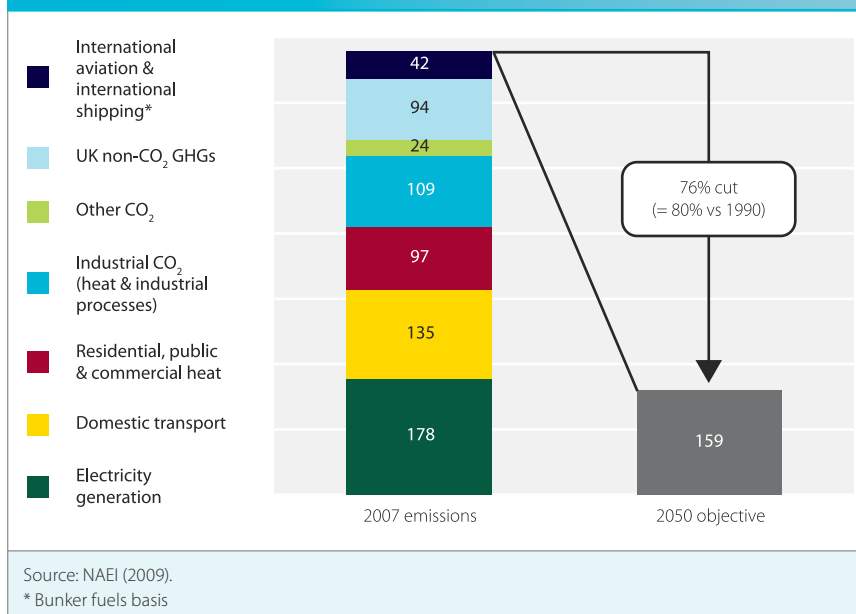
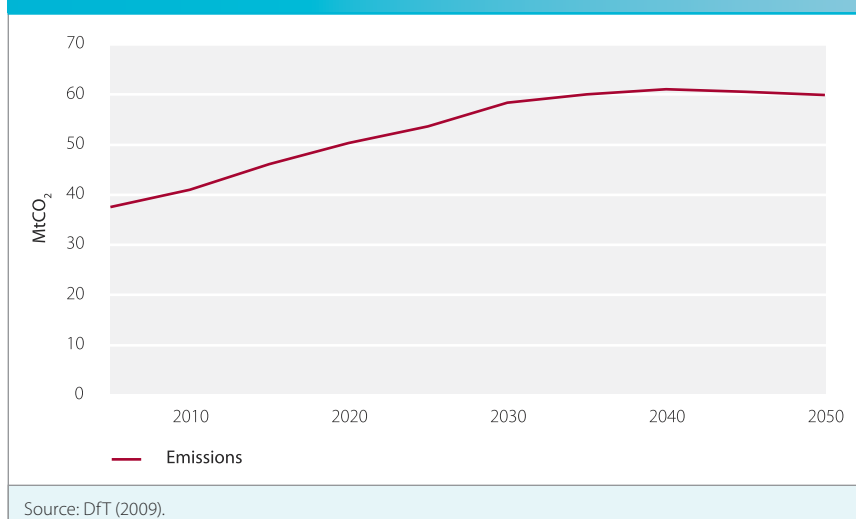


Figure 1.2 Breakdown of UK Kyoto GHG emissions by sector (MtCO₂)

Going forward, the Department for Transport's (DfT) central projections for UK aviation emissions published in January 2009 show emissions increasing from 37.5 MtCO₂ in 2005 to around 60 MtCO₂ by 2030, then remaining flat to 2050 (Figure 1.3). The projections are driven by demand growth which is accommodated with additional airport capacity before 2030, and improvements in the fuel efficiency of the fleet of the order 1% annually; the projections flatten out beyond 2030 due to a combination of continuing efficiency improvements, infrastructure constraints and market saturation. Under the projections, UK aviation emissions would account for around 35% of total allowed UK greenhouse gas (GHG) emissions in 2050 to meet an 80% emissions reduction target (i.e. 60 MtCO₂ from a total of around 160 MtCO₂e).

Figure 1.3 DfT central projections of aviation emissions growth to 2050

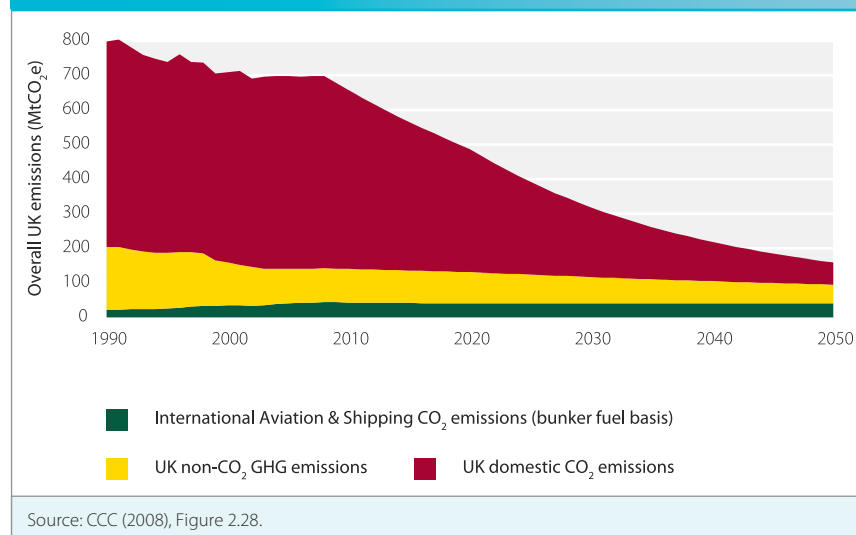
Economy-wide emissions reduction scenarios

Our 2008 report included a range of scenarios for achieving an 80% cut in economy-wide emissions. These typically included early energy efficiency improvement and decarbonisation of the power sector, with extension of low-carbon electricity to transport and heating from the 2020s.

Our analysis suggested that there should be limited reliance on purchase of offset credits to meet long-term targets given that these will become increasingly scarce/ expensive as all countries aim to achieve very challenging emissions reduction targets; it is therefore not prudent to plan that aviation will be a net purchaser of credits in the global market in 2050 and beyond.

We designed a scenario to show how the 80% target could be achieved across all sectors including aviation with very limited offset credit purchase. Specifically, we showed that if aviation emissions in 2050 were broadly equal to 2005 levels, if shipping followed the same pattern and if non-CO₂ emissions were reduced by 70% relative to 1990, then a 90% cut in CO₂ emissions from other sectors would achieve an 80% economy-wide cut (Figure 1.4).

Figure 1.4 Indicative path to the UK target of an 80% reduction in GHG emissions in 2050



The difference between allowed emissions on the path to 2050 and feasible emissions reductions for non-aviation sectors represents an indicative ceiling on aviation emissions over the next decades. This ceiling initially grows but begins to fall from around 2030 on the path to returning to 2005 levels in 2050 (Box 1.2).

However, the fact that there is a challenging emissions constraint in 2050 suggests that scope for growth in emissions on the path to 2050 may actually be limited given the long-lived nature of aviation assets (e.g. airports, planes, etc.); our focus in this report is therefore meeting the 2050 target rather than any possible increase on the path to 2050.

Box 1.2 Indicative ceiling for UK aviation emissions to 2050

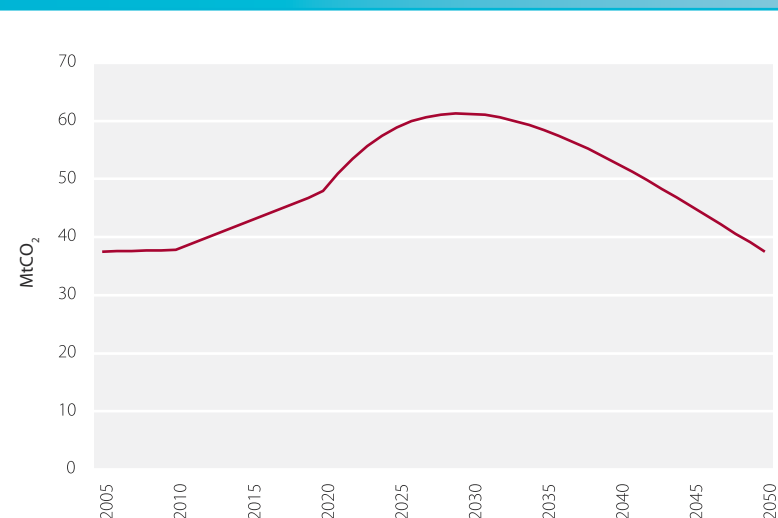
Figure B1.2 shows an illustrative emissions pathway for the UK aviation sector consistent with the 2050 aviation target, the overall, economy-wide target of reducing GHG emissions by 80%, and a set of assumptions about emissions reduction in other sectors of the economy.

The pathway was derived as follows:

- To 2020, aviation emissions are assumed to follow our Likely scenario (Box 1.5).
- In 2020, total emissions are defined by an economy-wide emissions reduction of 42% (the Committee's Intended budget) together with business as usual emissions in aviation and shipping.
- From 2020, economy-wide emissions are assumed to fall on an equal annual percentage reduction trajectory to an 80% reduction in 2050.
- The pathway for aviation is the residual of the economy-wide trajectory less emissions in other sectors; consistent with our December 2008 report, we have assumed that CO₂ emissions outside aviation fall on an equal annual percentage reduction trajectory to a 90% reduction in 2050, and non-CO₂ gases fall on an annual equal percentage emissions reduction to a 70% reduction in 2050.

The pathway shows some scope for emissions growth (e.g. peaking in 2029 with emissions 63% above 2005 levels) before returning to 2005 levels by 2050.

Figure B1.2 Indicative ceiling for UK aviation emissions



Source: NAEI (2009) and CCC calculations.

(iii) Accounting for UK aviation emissions under the Climate Change Act

In the context of providing advice on the level and scope of the first three carbon budgets, the Committee was required to consider whether international aviation should be formally included. The Committee's position was that international aviation should be part of climate strategy and would ideally be included in carbon budgets⁴.

In practice, however, the Committee identified a complexity arising from differences in appropriate emissions allocation methodologies and the proposed methodology for allocating EU ETS allowances:

- The United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body for Scientific and Technological Advice (SBTA) has recommended that four methodologies for allocating aviation emissions be considered further: bunker fuels, nationality of airline, international departures/arrivals on an aircraft basis, international departures/arrivals on a passenger basis. Each of these methodologies allocates a similar percentage (7-8%) of total global international aviation emissions to the UK (Box 1.3).
- Within the EU ETS, however, the proposal at the time was that EU airlines would be administered by the Member State in which they were issued their operating licence, with non-EU airlines administered by the Member State which accounts for the largest proportion of their emissions. This could result in the UK administering allowances covering up to 60 MtCO₂ (i.e. significantly more than the 35 MtCO₂ under a bunker fuel methodology).

The Committee considered inclusion of international aviation in carbon budgets under two alternative allocation methodologies: administration under the EU ETS, and bunker fuel estimates. The Committee argued:

- Inclusion on the basis of EU ETS administration would not reflect the UK's actual aviation emissions and therefore would not be an appropriate basis for inclusion.
- Inclusion on a bunker fuels basis would be appropriate but potentially confusing given the existence of the EU ETS methodology.

The Committee therefore concluded that international aviation emissions should not for the time being be included in carbon budgets. They were reflected, however, in the Committee's advice, which proposed carbon budgets that, together with the EU ETS cap on aviation emissions, would be an appropriate contribution to required global emissions reductions over the first three budgets.

⁴ Domestic aviation is already explicitly included in carbon budgets as per the Kyoto Protocol reporting requirements.

Box 1.3 Alternative approaches to measure UK aviation emissions

Total UK aviation emissions comprise of domestic aviation emissions plus a UK share of international aviation emissions.

Domestic aviation emissions relate to internal UK flights and are reported in the National Atmospheric Emissions Inventory (NAEI) for the purposes of the UK emission reduction commitments. These emissions accounted for around 2.4 MtCO₂ in 2005, and are therefore a relatively small proportion (around 0.3%) of total UK GHG emissions.

There is a variety of possible ways of determining the UK share of international aviation emissions. Alternative methodologies recommended for further consideration by the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) include the following:

- **Bunker fuels:** Emissions from fuel used for international flights and sold in the UK would be attributed to the UK.
- **Airline nationality:** Emissions from British airlines would be attributed to the UK.
- **International departures and arrivals on an aircraft basis:** Emissions of out-bound flights from the UK would be attributed to the UK while emissions of the return flight would be attributed to the destination country.
- **International departures and arrivals on a passenger basis:** Emissions of out-bound flights from the UK, adjusted by a passenger-km index to reflect seat bandings of different flights, would be attributed to the UK.

On a 'bunker fuel basis' (which is reported as a memorandum item in the UNFCCC National Register), UK international aviation emissions were around 35 MtCO₂ in 2005.

In our December 2008 report, we illustrated that the alternative SBSTA methodologies for allocating international aviation emissions all lead to the UK being allocated a share of 7-8% of the global total.

Since the 2008 report was published, it has become clear to the Committee that the EU ETS methodology in the Directive (published in January 2009) actually suggests an approach to attribute emissions to individual Member States that may be consistent with methodologies recommended by the UNFCCC. Specifically, while the 85% of emission allowances to be freely allocated to airlines will follow the EU ETS administration rules, the revenues from auctioning the remaining 15% will be attributed to member countries on the basis of an all-departing/ third country arriving flights principle.

Given that the approach for allocating auction revenues from aviation inclusion in the EU ETS to Member States may be consistent with suitable methodologies for allocating aviation emissions (thereby reducing the potential for confusion), it is appropriate to reconsider inclusion of international aviation emissions in the UK carbon budgets.

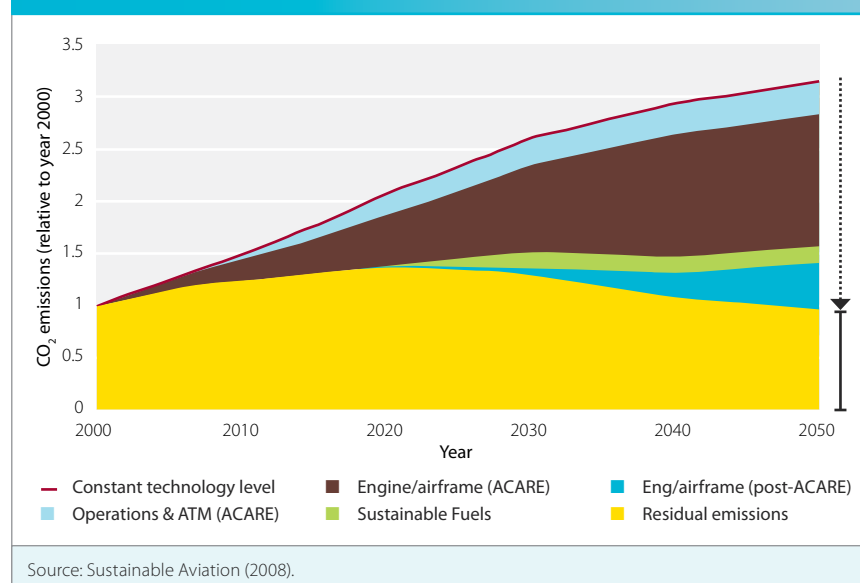
The Committee will reconsider the case for inclusion of international aviation emissions in carbon budgets as part of a wider legislative package covering the fourth budget and possible amendments to the first three budgets following the Copenhagen climate summit; the Committee's advice on the fourth budget will be published at the end of 2010, as required under the Climate Change Act.

2. The Government's 2050 aviation emissions target

In January 2009 the Government set a new target to reduce UK aviation emissions to 2005 levels or below in 2050 as part of its decision to support expansion of Heathrow. Two factors were important in determining this target:

- The Committee's 2008 report and the scenarios showing that reducing aviation emissions to around 2005 levels and cutting CO₂ emissions in other sectors by 90% would achieve the economy-wide 80% Kyoto GHG emissions reduction target.
- Analysis by Sustainable Aviation – a UK aviation industry group – showing how UK aviation emissions could be reduced back to 2000 levels in 2050 through a combination of ATM, engine and airframe innovation and use of biofuels (Figure 1.5)⁵.

Figure 1.5 The Sustainable Aviation CO₂ Roadmap



⁵ See: <http://www.sustainableaviation.co.uk/images/stories/key%20documents/sa%20road%20map%20final%20dec%2008.pdf>

The target is consistent with assumptions that it is prudent not to plan for net credit purchase by the aviation industry further out to 2050, and that other countries will be operating under similar constraints on aviation emissions:

- The fact that the target is set in terms of gross rather than net emissions (i.e. it relates to actual emissions rather than emissions net of purchase of credits from other sectors or from the international carbon markets) reflects an assumption that the supply of cheap credits will be exhausted over time and that it is therefore important for the aviation sector to focus on reducing its own emissions.
- The target would result in positive environmental impact if other countries were operating under similar constraints on aviation emissions; if this were not to be the case, demand and emissions would be displaced, at least to an extent, to other countries. It is reasonable to assume that other countries will be operating under similar constraints given the very challenging targets to reduce global emissions and achieve climate objectives in the period to 2050 and beyond.

The Committee was requested to carry out a review of aviation emissions⁶ focusing on:

- UK trends in aviation emissions
- The basis for measurement for the UK target for aviation emissions in 2050
- The scope for reductions, including from improvements in technology and the effect of appropriate policy levers; and the implications of further aviation expansion beyond 2020
- An appropriate structure and/or international target regime to support a global deal to reduce aviation emissions.

This report covers the first three areas. The Committee reported separately to the Secretaries of State for Transport and Energy and Climate Change on international aviation in September 2009 and made a set of recommendations for a global deal that would both constrain aviation emissions in a way consistent with meeting climate objectives, and avoiding leakage through a multilateral rather than unilateral approach (Box 1.4).

⁶ See: <http://hmccc.s3.amazonaws.com/2009-01-14%20Letter%20from%20Geoff%20Hoon.pdf>

Box 1.4 The Committee on Climate Change's advice on a framework for reducing global aviation emissions

Capping global aviation emissions

- Aviation CO₂ emissions should be capped, either through a global sectoral deal or through including domestic and international aviation emissions in national or regional (e.g. EU) emissions reduction targets.
- Ideally all aviation CO₂ emissions would be capped. However, an interim phase where the cap applies to all departing and arriving flights in developed countries with exemptions for intra-developing country flights may be necessary.
- The level of emissions reduction ambition under any international agreement should be no less than that already agreed by the EU (i.e. developed country net emissions in 2020 should be no more than 95% of average annual emissions from 2004-2006).

Auctioning allowances in cap and trade schemes

- Emissions allowances under a cap and trade scheme should be fully auctioned so as to avoid windfall profits for airlines that would ensue under free allowance allocation.
- Aviation auction revenues are one of a number of possible sources for funding of adaptation in developing countries that should be agreed as part of a global deal in Copenhagen.
- Significant R&D that is urgently required to support innovation in the aviation industry should be considered in the context of a global deal for aviation, and funded from aviation auction revenues or other sources.

Emission reductions within the aviation sector

- Emissions trading will be useful for an interim period in providing flexibility to achieve cost-effective emissions reductions, subject to the caveat that the carbon price in any trading scheme should provide strong signals for appropriate demand management and supply side innovation.
- The aviation industry should also plan, however, for deep cuts in gross CO₂ emissions relative to baseline projections (e.g. for developed country aviation emissions to return to no more than 2005 levels in 2050), which will be required as a contribution to meeting the G8's agreed objective to reduce total global emissions in 2050 by 50%.

Non-CO₂ effects of aviation

- Non-CO₂ effects of aviation must be addressed as part of any international framework through commitment to a schedule for introduction of appropriate policy instruments (e.g. covering NO_x, cirrus and contrails). Given current scientific understanding, early introduction of measures to reduce NO_x emissions may be feasible and should be seriously considered.

3. The Committee's approach to the review

The basis for measuring the UK aviation target

As already noted, the methodologies proposed by the UNFCCC for allocation of global aviation emissions to national levels – bunker fuels, nationality of airlines, departing flights – gives a broadly similar level of UK international aviation emissions. In our December 2008 report, we considered inclusion of international aviation emissions in carbon budgets on the basis of a bunker fuels methodology, given that this is the convention for measuring domestic aviation emissions in the UK's national emissions inventory, and international aviation emissions as a memo item in the UNFCCC National Register.

Going forward, it is likely that there may be scope for more precise measurement based on flight specific fuel consumption data. The Committee will consider further the appropriate methodology for measuring compliance with the UK's aviation emissions target, and whether there is evidence to suggest an alternative to bunker fuels may be appropriate, in the context of its advice about whether aviation should be included in carbon budgets.

Projecting emissions for comparison with the target

In order to understand how the 2050 target might be achieved, we have developed reference demand and emissions projections, and then explored scope for emissions reductions through modal shift from aviation to rail, increased use of videoconferencing as a possible substitute for business travel, improvement in the fuel efficiency of the fleet through evolutionary and more radical technology innovation, and the use of sustainable biofuels.

Based on these options, we have defined three core scenarios reflecting increasingly optimistic assumptions about technological developments and policy intensity (Box 1.5). We have considered the implications of these scenarios in relation to both CO₂ emissions and non-CO₂ effects of aviation. We have also assessed the extent of possible constraints to demand growth that may be required to close any gap to the 2050 target. We have done this drawing on in-house analysis, modelling commissioned from expert consultants, DfT analysis, and extensive discussions with aviation industry stakeholders. Specifically, we adopted the following steps:

- **Reference demand and emissions projections.** The Committee commissioned MVA to develop a model of UK aviation demand and emissions. We have used this to develop two types of reference scenarios:
 - A reference scenario with unconstrained demand growth, and an assumption of no improvement in fuel efficiency relative to the current situation. These represent a hypothetical worst case from a carbon perspective (e.g. because of scope for technology innovation that would reduce emissions) and show the scale of the challenge in terms of required emissions reductions to meet the 2050 target.

– A reference scenario which retains the assumption of no improvement in fuel efficiency but introduces a demand constraint in response to carbon prices reflected in the cost of air travel. In addition, we follow the DfT convention and model a capacity constrained system (e.g. expansion as envisaged in the 2003 Air Transport White Paper and recent announcements⁷, currently existing capacity only, etc.).

- **Modal shift to rail and increased videoconferencing:** The Committee commissioned SDG to assess scope for switch from short-haul (domestic and international) aviation to rail and high-speed rail. The analysis carried out by SDG does not attempt to quantify the costs and benefits (e.g. travel time savings) of investment in high-speed rail. It does however provide an estimate of the order of magnitude of the reduction in demand for flights that would ensue under plausible scenarios for modal shift, which we reflect in our emissions projections. Our analysis also includes scope for reduced air travel as a result of videoconferencing, which may become more attractive with technology innovation and increasing cost of air travel.

- **Fleet efficiency improvement through technology innovation:** We build on our work last year – which identified scope for a new production aircraft in 2025 to be 40-50% more fuel efficient than one produced in 2006 – using a hybrid top-down (fleet average) /bottom-up (new aircraft) approach to model improvements of fleet efficiency under a plausible range of scenarios. These range from what is achievable under the current framework to what is achievable but very unlikely and would require a significant shift in policy and investment. We then adjust the emissions factor reference projections to account for efficiency improvement scenarios, both as regards technology innovation and improved efficiency in Air Traffic Movements and operations.

- **Use of sustainable biofuels:** It is likely that large scale use of biofuels in aviation will be technically feasible. There are outstanding questions, however, about the sustainable production of biofuels and the quantity of sustainable biofuels that may be available for use in aviation. The Committee has developed a number of scenarios for sustainable biofuels use in global and UK aviation, given constraints on availability of land and other resources; our scenarios allow for emissions reductions from biofuels under alternative assumptions about the level of sustainable biofuels, their lifecycle savings, and the use of sustainable biofuels in aviation rather than other sectors.

- **Aviation non-CO₂ effects:** The UK aviation target relates to Kyoto GHGs, and therefore to CO₂ only; the core of this report focuses on aviation CO₂ emissions. The Committee has also reviewed the current scientific evidence based on non-Kyoto/ non-CO₂ effects (e.g. NO_x, contrails, etc.) and the

⁷ Specifically, in modelling capacity in line with current plans, we assume that additional runways will be built by 2030 at Heathrow, Stansted and Edinburgh and that more efficient use of existing runways at other airports will result in increased capacity.

implications of including these in the UK's emissions targets (e.g. the need for further CO₂ emissions reductions in aviation and/or further cuts in other sectors to achieve the UK's climate objective). The Committee is not proposing that aviation non-CO₂ effects should currently be included in the UK's aviation target. These effects are likely, however, to be significant, and should therefore be considered as part of any strategy for emissions reduction in aviation and more generally, with inclusion contingent upon better scientific understanding in the context of an internationally agreed approach. Aviation non-CO₂ effects are included in this report as an additional source of uncertainty when assessing how emissions targets for UK aviation may be achieved.

- **Options for addressing a potential gap:** Where a gap remains between emissions projections and the 2050 aviation target, this could be closed through a number of complementary options, including maximising the potential for demand reductions through modal shift to rail and videoconferencing, accelerating efficiency improvements and investing in the development of low-carbon fuels.
- **Explicit constraints on demand growth:** In the absence of a compelling case for any of the above routes the Government may need to consider explicitly constraining demand growth. We consider at a high level the order of magnitude of *target compatible* demand growth, and any implications for aviation expansion.

The remainder of the report sets out in detail the blocks of analysis above.

Box 1.5 Approach for dealing with uncertainty and developing scenarios in assessing options for meeting the UK's 2050 aviation target

A constant theme running through the analysis is that of the considerable uncertainty over UK aviation emissions projections due to:

- **Policy uncertainty:** For example, airport capacity expansion, development of a high-speed rail network in the UK and Europe, the framework for support of aviation R&D
- **Demand uncertainty:** For example, uncertainty about responses to changing incomes and prices, opportunities for modal shift to rail, opportunities for reducing the need to fly through technologies such as videoconferencing
- **Technology uncertainty:** For example, uncertainty relating to the pace of engine and airframe technology innovation, availability of land for growing biofuel feedstock, availability of biofuels which do not require significant amounts of land
- **Scientific uncertainty:** For example, on the magnitude of non-CO₂ effects.

Box 1.5 continued

We have allowed for uncertainty by developing three scenarios for each of the options to reduce emissions, each of which is a more aggressive/less likely departure from the current situation in terms of policy and technology:

- **Likely scenario:** This reflects demand reductions and carbon intensity reductions likely to be achieved given current policies, investment levels and the pace of technological advance.
- **Optimistic scenario:** This would require both a significant shift from current policy (e.g. in respect to high-speed rail), an increase in the level of investment in new aircraft technologies and/or in the pace of fleet renewal as well as improvements in ATM and operations and progress on sustainable biofuels technologies.
- **Speculative scenario:** This would require both technological breakthroughs and a significant increase in the pace of aircraft fuel efficiency improvements. In addition, it would require the development of sustainable biofuels which are currently speculative (e.g. biofuels from algae), or an evolution of global population, food demand and agricultural productivity which would make possible the sustainable and large scale use of current agricultural land and water to grow biofuel feedstocks. These developments are assessed today as very unlikely.

We note that these definitions are applied to options which are not always directly comparable. For example, it is currently more likely that the possible scenario for modal shift ensues following a decision to invest in a high-speed rail line in the UK, as opposed to the possible scenario for fleet efficiency improvement, which could require a new policy approach at the European level, together with significantly increased investment in technology innovation. The scenario names should therefore be interpreted pragmatically.

Also, these should not be compared with the Committee's Current, Extended and Stretch scenarios defined in the context of UK emissions excluding aviation, where there is less uncertainty about abatement potential and more policy levers are available at the UK level.

In projecting emissions net of abatement opportunities we start with a reference emissions projection from which we net off emissions reductions under different scenarios. We adopt a prudent approach which attaches most weight to the Likely scenario, and does not currently plan for the Optimistic or Speculative scenarios in the absence of new evidence to suggest an increased likelihood that these will ensue.

Box 1.5 continued

We allow for further uncertainty over exogenous demand drivers by overlaying sensitivities across these scenarios. For example, in the Likely scenario for modal shift, videoconferencing, fleet efficiency improvement and biofuels, we consider emissions under assumptions of central, low and high fossil fuel and carbon prices. We also consider demand sensitivities for different assumptions about capacity to understand any implications of achieving the 2050 target for demand expansion in the 2020s.

Chapter 2

Reference demand and emissions projections

48

This chapter sets out reference demand and emissions projections across which scenarios reflecting different assumptions on modal shift, fleet fuel efficiency improvement and biofuels penetration can be overlaid (see Chapter 7).

Our reference demand projections reflect alternative assumptions about fossil fuel prices, carbon prices and capacity constraints. They are constructed using a detailed model which disaggregates demand into various categories (e.g. short-haul, long-haul), combines assumptions on demand drivers with estimates of income and price elasticities, and then converts demand projections to emissions projections under assumptions about emissions factors. The model, which was independently developed, benchmarks closely to DfT's January 2009 CO₂ emissions forecasts (e.g. within 0-8% for passengers, Air Traffic Movements (ATMs) and CO₂ emissions to 2050).

Our reference emissions projections reflect, for indicative purposes, an assumption that there is no improvement in fleet fuel efficiency relative to the current situation¹; we set out our assessment of scope for improvement in fleet fuel efficiency in Chapter 4, and the impact that this would have on emissions in Chapter 7.

The key messages in the chapter are:

- In a world with unconstrained demand growth, UK aviation demand could increase by over 200% in 2050 relative to 2005 levels, from 230m passengers in 2005 to 695m annual passengers in 2050.
- In a world with currently planned infrastructure expansion (i.e. extra runway capacity at Heathrow, Stansted and Edinburgh as envisaged in the 2003 Air Transport White Paper) and a carbon constraint reflected in a 2050 carbon price of £200/tCO₂, UK aviation demand would be around 115% higher in 2050 than in 2005, increasing from 230m passengers in 2005 to 490m annual passengers in 2050.
- Emissions in 2050 would be around 100% higher than in 2005, allowing for a carbon constraint as above and planned infrastructure expansion but without any increase in fleet fuel efficiency or biofuels penetration; slightly lower emissions growth than demand growth reflects increasing load factors and changes in the destination mix over time.

¹ Specifically, the seat-km per tonne of fuel for the fleet as a whole remains constant.



We set out the analysis that underpins these messages in five sections:

1. UK aviation demand since 1990
2. Demand drivers
3. Reference demand projections
4. Reference emissions projections
5. How we will use reference projections

1. UK aviation demand since 1990

Total demand, short-haul and long-haul demand

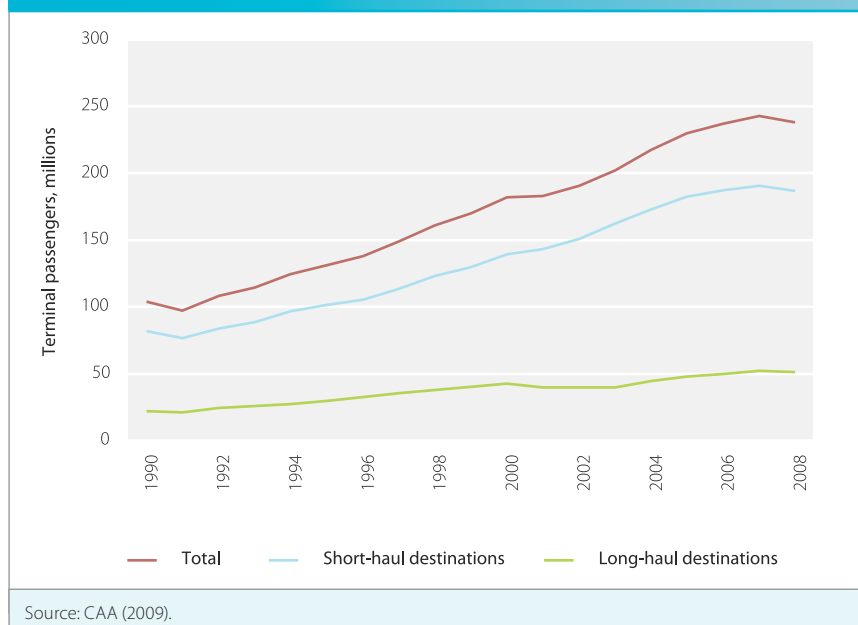
Total aviation demand in the UK² increased by around 130% (i.e. from 104m passengers to 238m passengers) between 1990 and 2008 and around 4.9% on an annualised basis, and 18% (i.e. from 202m passengers to 238m passengers) in the period 2003 to 2008 and around 3.4% on an annualised basis (i.e. the pace of increase fell in the five years to 2008). This was in a context of rising incomes and falling fares resulting in significant demand increase for both short and long-haul flying³:

- UK GDP increased by 54% between 1990 and 2008, and by 12% from 2003 to 2008.
- Air fares fell by around 50% between 1997 and 2006.
- Short-haul demand increased by 128% (i.e. from 82m passengers to 187m passengers) between 1990 and 2008, and 15% (i.e. from 162m passengers to 187m passengers) over the period 2003 to 2008 (Figure 2.1).
- Long-haul demand increased by 133% (i.e. from 22m passengers to 51m passengers) between 1990 and 2009, and 30% (i.e. from 40m passengers to 51m passengers) over the period 2003 to 2008 (Figure 2.1).

Short-haul demand currently accounts for the majority of passengers (78%) but less than 40% of passenger-kms given relative distances of short and long-haul flights; this distinction is important in understanding the relative impact of changes in demand by flight category on total aviation emissions, see Section 4 below.

² Data provided by the UK Civil Aviation Authority (CAA), and refers to all departing and arriving passengers.

³ Where underlying data is disaggregated by region we have assumed that travel to destinations in Europe is short-haul and beyond Europe is long-haul. Where actual distance is indicated, we are consistent with Defra/DECC conversion factors and assume that flights up to 3,700km are short-haul and flights greater than 3,700km are long-haul, which is broadly consistent with the Europe/Non-Europe split.

Figure 2.1 UK aviation demand since 1990

Purpose, destination and class of flying

Travel for purposes of leisure and business has changed significantly over the last twenty years (Table 2.1). Specifically:

- Survey data suggests that the number of passengers travelling for leisure purposes has increased from around 63 million in 1991 to around 180 million in 2008; leisure flights now account for around 75% of the total.
- The proportion of passengers travelling for business purposes has increased more slowly, from around 35 million in 1991 to around 60 million in 2008.

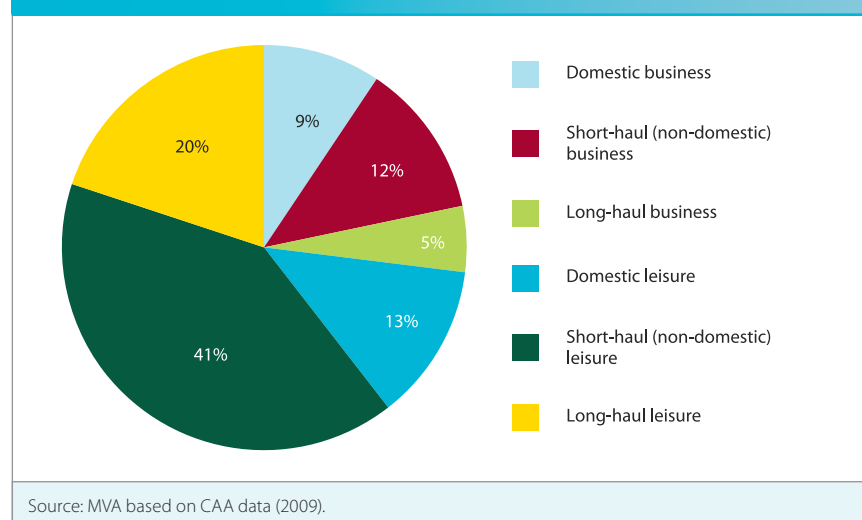
Table 2.1 Trends in UK aviation by purpose

Sector	1991		2008	
	Passengers	Proportion	Passengers	Proportion
Leisure	63m	(65%)	180m	(75%)
Business	35m	(35%)	60m	(25%)

Source: CCC calculations and CAA survey data (1991, 2008).

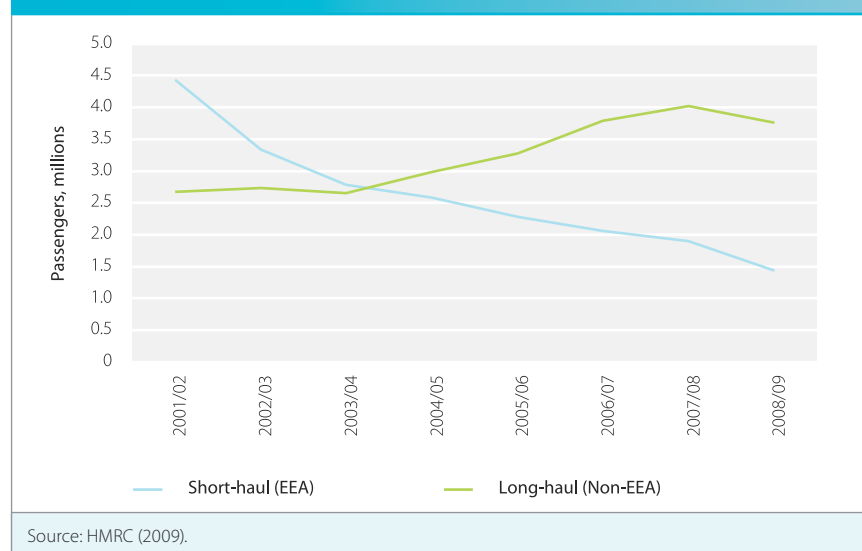
Figure 2.2 shows the distribution of UK aviation passengers by distance and purpose in 2005, based on CAA data.

Figure 2.2 Distribution of UK aviation passengers by distance and purpose in 2005



Demand for premium (non-economy) class travel (whether for purposes of business or leisure) has also changed significantly over time. Since 2001/02 demand for long-haul premium class travel (outside the European Economic Area [EEA]) has increased by 41% (i.e. from 2.7m departing passengers to 3.8m departing passengers) whereas demand for short-haul premium flying (within the EEA) has fallen by 68% (i.e. from 4.4m departing passengers to 1.4m departing passengers)⁴. The growth in premium class long-haul is therefore broadly in step with growth in long-haul generally, and we have assumed that this continues to be the case in projecting demand forward (Figure 2.3).

Figure 2.3 UK trends in premium class travel



⁴ HMRC (2009), *Air Passenger Duty Bulletin*.

Number of people flying by income group

Survey evidence suggests that around 50% of the UK adult population travels by plane in any given year⁵ (a consistent proportion since 2003) and that likelihood of flying is closely related to income (Figure 2.4a).

Amongst those who fly, the average number of flights per year also varies significantly by income, with those on incomes of more than £60,000 per annum flying on average just under four times per year, and those on less than £20,000 flying two times per year (Figure 2.4b). Income elasticity of demand is thus high, both between income groups and over time. Income growth is therefore an important driver of demand growth.

Figure 2.4a UK air travel by annual income group

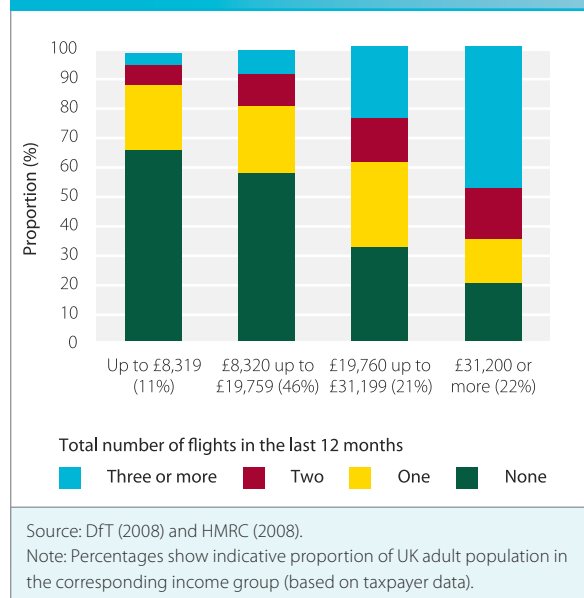
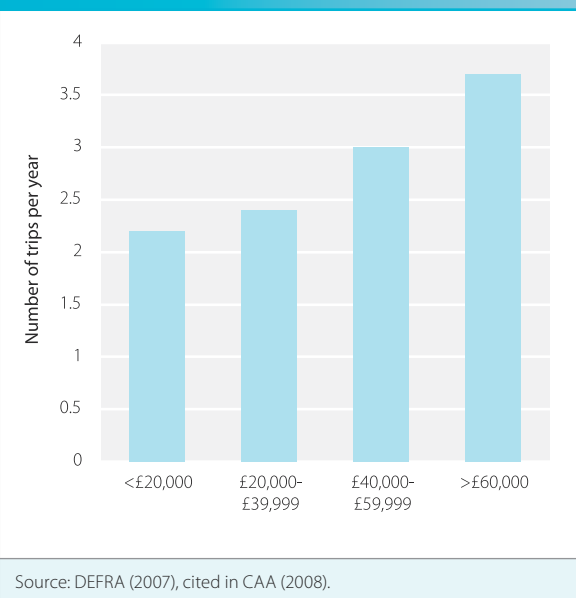


Figure 2.4b Mean number of trips per air passenger by income group



Freight demand

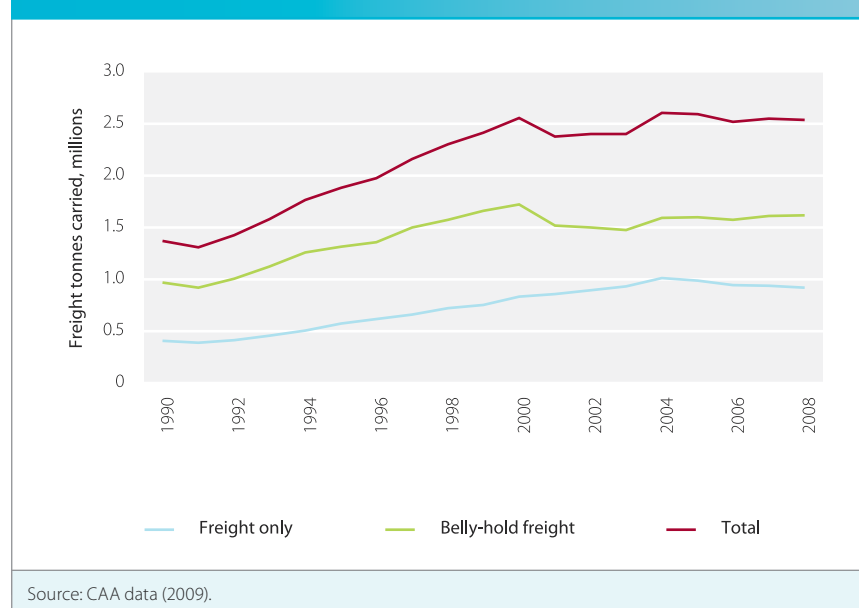
Total UK freight aviation, measured in tonnes carried, has increased by 85% over the period 1990 to 2008 (from 1.4m tonnes to 2.5m tonnes) but only 6% over the period 2003 to 2008 (from 2.4m tonnes to 2.5m tonnes).

Two-thirds of total UK freight by volume is carried in passenger aircraft ('belly-hold' freight). The volume of belly-hold freight has increased by 167% over the period 1990 to 2008 (from 1m tonnes to 2.5m tonnes), although growth has flattened out in this decade growing by 10% over the period 2003 to 2008 (Figure 2.5).

⁵ DfT (2008), *Public experiences of and attitudes to air travel*.

Freight-only flights account for only a small proportion of total UK aviation (e.g. around 3% of ATMs and 2% of emissions⁶). Volumes carried by freight-only flights increased by 127% over the period 1990 to 2008 (from 0.4m tonnes to 0.9m tonnes), although as with belly-hold freight growth has been subdued in the past decade and volumes carried fell slightly by 1% over the period 2003 to 2008 (Figure 2.5). Notwithstanding these trends, given the magnitude of freight-only aviation relative to the total, it is unlikely to have a major impact on total UK aviation emissions going forward.

Figure 2.5 Demand for UK aviation freight



The impact of the recession on demand

At the global level, the economic downturn has had a significant impact on global demand for aviation. Analysis by IATA suggests that international passenger air demand fell by up to 10% in the first half of 2009, with freight demand showing sharper falls approaching 25%.

At the UK level, aviation demand fell by 2% in 2008 and 10% in the first half of 2009 as a result of the recession.

Going forward, we would expect aviation demand growth (globally and in the UK) to resume as GDP returns to growth. Consistent with HM Treasury, we have assumed that the rate of GDP growth will ultimately return to pre-recession trends, but with a once-and-for-all reduction in the level of output; we reflect this once-and-for-all adjustment in our demand projections, to which we now turn.

⁶ DfT (2009), *UK Air Passenger Demand and CO₂ Forecasts*.

2. Demand drivers

Income and price demand elasticities

We have shown that increasing demand for aviation in the UK has occurred in a context of increasing GDP and falling fares. There is a comprehensive body of evidence which formally bears out these relationships in the UK, with income elasticities estimated to be around 1.5 (i.e. a 10% increase in income will result in a 15% increase in demand), and price elasticities of around -1 in the leisure market and close to zero in the business market; we have used DfT estimates (Table 2.2), which are consistent with the literature, as the basis for our demand projections.

Table 2.2 DfT Elasticity estimates⁷

	Price elasticities	Income elasticities
UK Business	-	1.4
UK Leisure	-1.0	1.5
Foreign Business	-	0.6
Foreign Leisure	-0.2	0.7

Source: DfT (2009).

Assumptions on growth, fossil fuel prices and carbon prices

Given our assumptions on demand elasticities, we apply these to assumptions on key demand drivers:

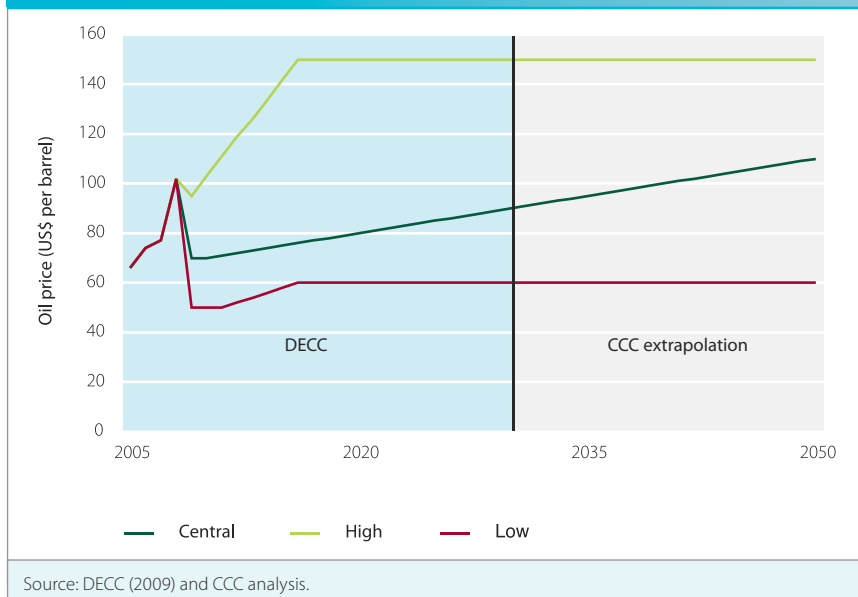
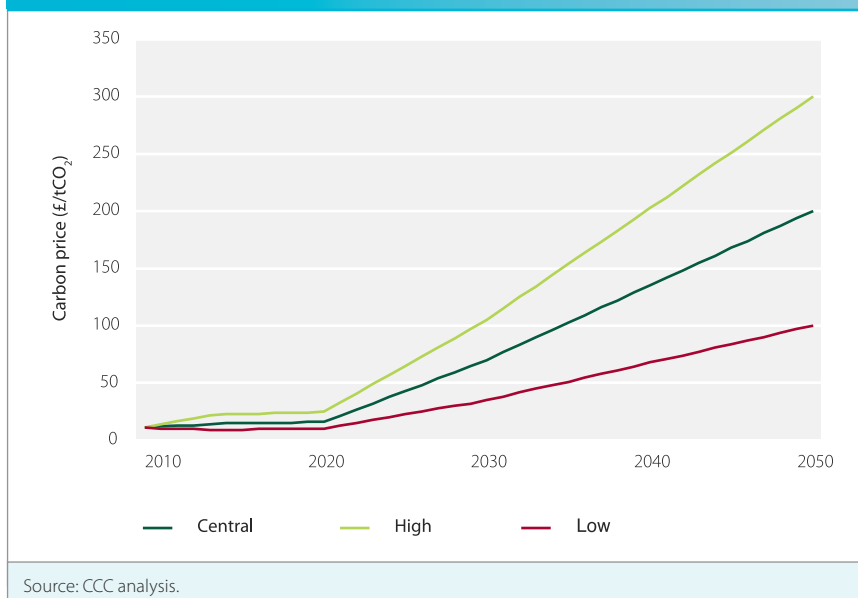
GDP growth: We use GDP growth forecasts that incorporate the effects of the economic downturn, and are based on HM Treasury forecasts for the UK and IMF forecasts for the rest of the world. For example, we have assumed average annual UK GDP growth of 2.1% over the period to 2050. The GDP growth forecasts incorporate demographic changes among other drivers.

Fossil fuel prices: We use DECC's fossil fuel price assumptions, extrapolating beyond 2030 based on the pre-2030 trend. The range of oil prices is US\$60 to US\$150/barrel in 2050 (Figure 2.6). To the extent that the oil price is above US\$150 in 2050 this would reduce the contribution required from other emissions reduction levers in meeting the 2050 target.

Carbon prices: We use our own carbon price assumptions, based on modelling using DECC's marginal abatement cost and GLOCAF models. Carbon prices range between £100 and £300/t CO₂ in 2050⁸. Our central carbon price projection rises to £200/tCO₂ in 2050 (Figure 2.7). The 2050 carbon prices are based on the assumption of a comprehensive global trading regime from 2030 onwards, and emissions reductions consistent with a long-term stabilisation goal of 475-500ppm.

⁷ DfT could not identify a statistically significant relationship between business demand and air fares in their modelling. Nevertheless, estimates from the literature reviewed for the CCC by MVA Consultancy pointed to a small but non-zero price elasticity of -0.2. We have run sensitivities on our three core scenarios with this elasticity and the impact in 2050 is less than 1 MtCO₂ in all scenarios and therefore would not materially alter our conclusions.

⁸ The impact on fares of our carbon prices is fully additional to that of Air Passenger Duty (APD). In all of our scenarios, APD is assumed to be charged according to the APD rates outlined in last year's Pre-Budget Report (HM Treasury (2008) Chapter 7, pp 138-139 available at: www.hm-treasury.gov.uk/d/pbr08_chapter7_159.pdf)

Figure 2.6 Fossil fuel price assumptions**Figure 2.7** Carbon price assumptions

These assumptions together project incomes that will be around 150% higher than today, and fares around 75% higher in a central fossil fuel price and central carbon price case. Assuming income elastic demand and less price elastic demand, suggests that we would expect to see significant demand growth to 2050.

Assumptions on infrastructure capacity

Demand growth may be constrained depending on the level of infrastructure capacity. In projecting demand, we model various scenarios reflecting different assumptions on the level of infrastructure capacity (e.g. assuming current capacity, addition of runway capacity as envisaged in the 2003 Air Transport White Paper [i.e. Heathrow, Stansted and Edinburgh], see Box 2.1).

Box 2.1 Air Transport White Paper 2003 and runway capacity assumptions

In 2003, the Government published a White Paper on the future of air transport in the UK¹. This set out a strategic framework for the development of airport capacity in the UK up to 2030.

The White Paper did not in itself authorise any new developments, but set out a framework to guide future planning applications and allow the relevant organisations to plan ahead – it was permissive not prescriptive. It recommended making best use of existing capacity where available, for example by expanding terminal capacities. It also set out where additional runway capacity may be required.

In this report we have made assumptions about airport runway capacity in line with current plans, including the 2003 White Paper and updated for recent announcements. Specifically, we assume that additional runways will be built by 2030 at Heathrow, Stansted and Edinburgh. We also assume increases in capacity resulting from more efficient use of existing runways, or changes in planning permission at: Manchester, Luton, Bristol, Birmingham, Glasgow and London City airports.

¹ DfT (2003), *The Future of Air Transport*.

Assumptions on demand saturation

Growth in demand for aviation in the UK may slow over time as the market becomes increasingly mature. This reflects, for example, decreasing opportunities for spending additional time travelling at the margin. To reflect increasing market maturity our modelling mirrors DfT's approach and adjusts income elasticities downwards over time to capture an overall slowing of growth in aviation demand.

3. Reference demand projections

We have made our demand and emission projections⁹ using a model that we commissioned from MVA Consultancy (Box 2.2).

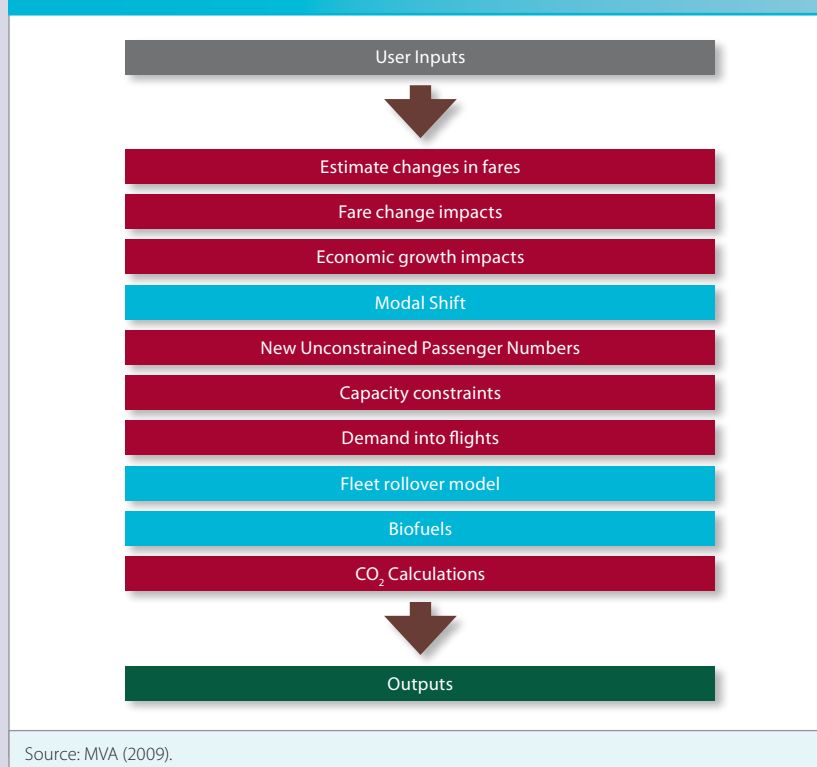
⁹ In our projections (and subsequent scenarios) the passenger demand estimates refer to all departing and arriving passengers. Emissions estimates are on an all departing basis to enable reconciliation with bunker fuel estimates.

Box 2.2 The MVA Consultancy model of UK aviation

Overview

The Committee commissioned MVA Consultancy to develop a reduced form model for projecting UK aviation demand and emissions out to 2050. The scope of the model was to forecast: aviation passenger demand within, from and to the UK; the associated air traffic movements (ATMs), both passenger and freight; and the resulting departing CO₂ emissions.

Figure B2.2 MVA model schematic



The forecasts are based on data provided by the Civil Aviation Authority (CAA) for 2005 which includes detailed information on the routes flown to/from UK airports and their characteristics such as number of flights, passengers and aircraft types used.

Input assumptions are combined with the 2005 base data to estimate the effects on demand due to economic growth (covering 15 world regions) and changes in air fares (e.g. due to changes in fossil fuel and carbon prices).

Available airport capacity is a choice variable and can act as a constraint to demand growth.

The forecasts of demand can be modified to reflect the impact of modal shift to rail and videoconferencing.

Box 2.2 continued

Demand is projected first in terms of passenger numbers. These are then converted into ATMs for each of the traffic lines represented in the model, reflecting for example airlines optimising behaviour, route profitability and load factors.

The overall CO₂ emissions are calculated by combining all the above steps, and accounting for any improvements in aircraft fuel efficiency and use of biofuels.

Projecting demand and emissions

The responsiveness of aviation demand to changes in income and price are represented in the model through income and price elasticities. We have used assumptions in line with DfT forecasts which are consistent with the literature. These elasticities show that income is a strong driver of demand and that business passengers are less price sensitive than leisure passengers.

To reflect increasing market maturity, our modelling mirrors DfT's approach and adjusts income elasticities downwards over time to capture an overall slowing of growth in aviation demand.

Reconciling modelled emissions and bunker fuel estimates

In common with other detailed 'bottom-up' modelling of UK aviation emissions, there is a gap between modelled emissions and the 'top-down' estimates of CO₂ resulting from bunker fuel sales (the method used to report aviation emissions as a memo item to the UNFCCC). This discrepancy may be due to a range of factors including: deviations between actual routes and great circle distance, tankering, and the effects of aircraft ageing. Therefore, we follow the approach used by DfT and introduce a residual adjustment to reconcile the two items.

Scope

Due to the reduced form nature of the model a number of possible features are outside its scope:

- Airport capacity constraints are reflected only in terms of aircraft movements (i.e. runway capacity) and not terminal passengers.
- Thirty one airports are represented in the model. However, explicit capacity constraints are only considered for the ten largest UK airports.
- Passenger re-allocation between UK airports is not explicitly considered.
- The model is limited to improvements in the fuel efficiency of new aircraft, and therefore does not incorporate retrofitting measures.

Further detail on the modelling approach is available in a methodology technical note prepared by MVA Consultancy and available on our website at www.theccc.org.uk

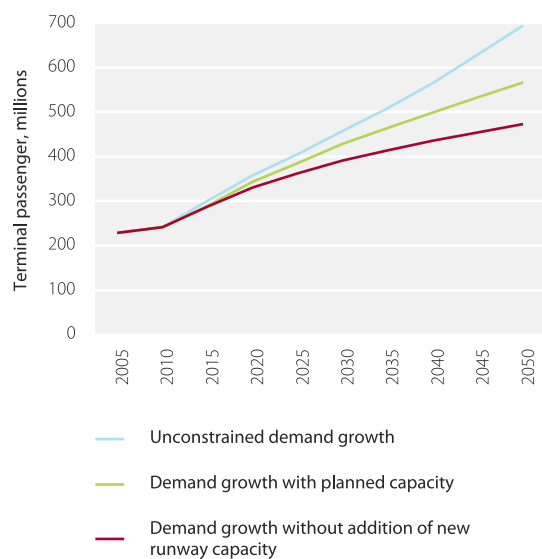
Our range of reference demand projections comprises three projections under alternative capacity assumptions and three projections with planned capacity (i.e. as in the 2003 Air Transport White Paper and recent announcements) under alternative assumptions about carbon prices and fossil fuel prices:

- **Unconstrained demand growth:** This projection assumes that airport capacity will always be available to meet any growth in demand. In 2050, demand grows by over 200% over 2005 levels (i.e. 695m annual passengers compared to 230m annual passengers in 2005).
- **Demand growth with planned capacity:** This projection constrains airport runway capacity in line with planned capacity. This scenario reflects the DfT approach to demand/emissions modelling (i.e. they assume capacity addition as envisaged in the 2003 Air Transport White Paper but no further addition). In 2050, demand grows by around 150% over 2005 levels (i.e. growing to 570m annual passengers).
- **Demand growth without addition of new runway capacity:** This projection assumes that there is no additional airport runway capacity in the UK in the period to 2050, and demand growth therefore occurs based on increased use of currently spare capacity. Demand in 2050 is around 105% above 2005 levels¹⁰ (i.e. growing to 475m annual passengers). Unless similar demand constraints were to apply across the EU, some of the demand suppressed due to capacity constraints would be displaced to hub airports in other Member States.
- **Demand growth with planned capacity and central carbon and fossil fuel price projections:** This projection assumes planned infrastructure expansion as above, and introduces a central carbon price as described in Figure 2.7. Together, this leads to demand in 2050 being around 115% higher than 2005 levels (i.e. growing to 490m annual passengers).
- **Demand growth with planned capacity and high carbon and fossil fuel prices:** Assuming high carbon and fossil fuel prices leads to demand in 2050 being around 100% higher than 2005 levels (i.e. growing to 455m annual passengers).
- **Demand growth with planned capacity and low carbon and fossil fuel prices:** Assuming low carbon and fossil fuel prices leads to demand in 2050 being around 140% higher than 2005 levels (i.e. growing to 555m annual passengers).

Our projections therefore range from demand growth of around 115% in the period 2005 to 2050 with a central carbon price and an infrastructure constraint, to over 200% without carbon prices or infrastructure constraints.

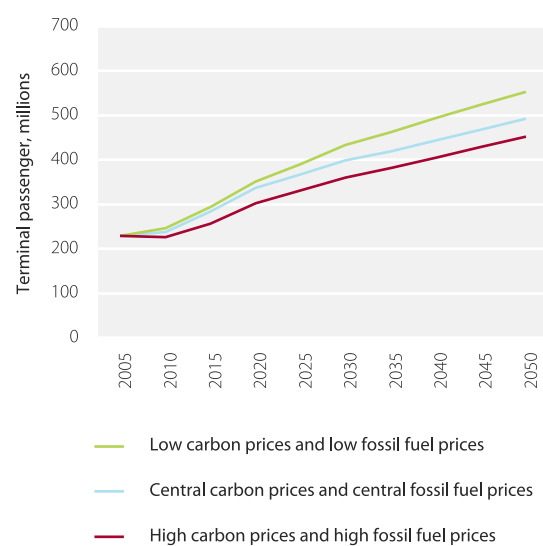
¹⁰ We have focused on runway capacity and not terminal capacity. To the extent that terminal capacity constraints exist and are not addressed demand projections could be lower.

Figure 2.8a Reference demand projections: effect of changes in runway capacity



Source: CCC modelling.

Figure 2.8b Reference demand projections: planned capacity, effect of changes in carbon and fossil fuel prices



Source: CCC modelling.

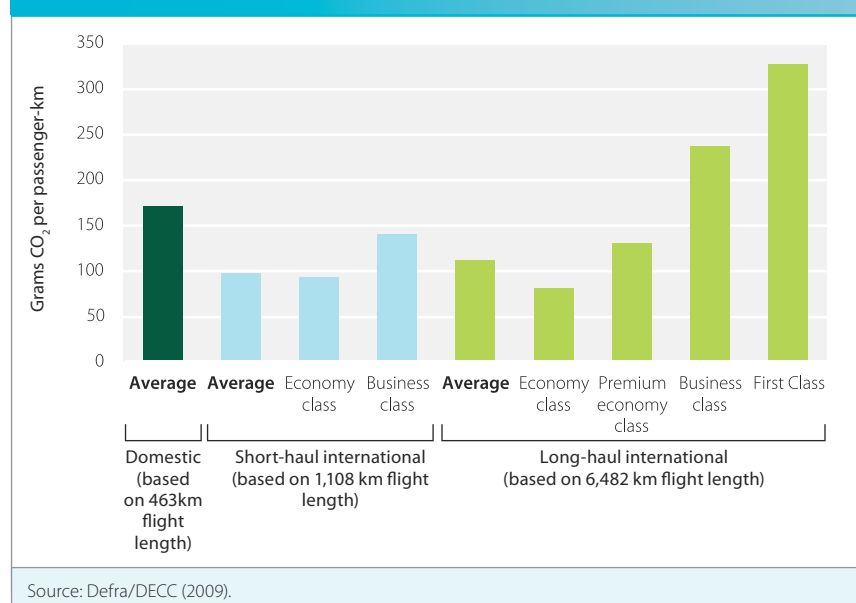
4. Reference emissions projections

We would broadly expect emissions growth to reflect: growth in overall demand; change in the composition of demand between short/long-haul; and technology improvement.

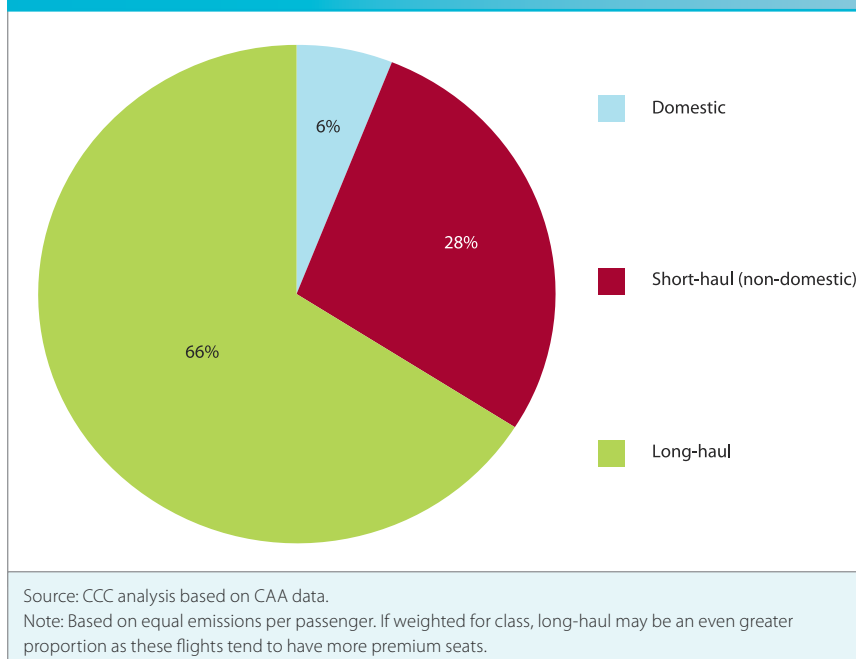
This is borne out in UK data, which shows that emissions increased by 120% over the period 1990-2007 compared to a demand increase of 130%.

That emissions have grown more slowly than demand reflects in part increasing load factors over time, but this is somewhat offset by relatively high growth in long-haul flights. These are relatively efficient in terms of emissions per passenger-km for an equivalent seat size (e.g. economy), but account for a disproportionate share of emissions given much higher mileage on long-haul compared to short-haul (Figure 2.9). Long-haul flights therefore account for the majority of UK aviation emissions, notwithstanding that short-haul flights account for higher passenger numbers (Figure 2.10).

Figure 2.9 Defra/DECC air passenger conversion factors¹¹



¹¹ We do not use per passenger conversion factors in our analysis, but use per flight conversion factors that are based on the same underlying data, i.e. the CORINAIR Emissions Inventory Guidebook.

Figure 2.10 UK aviation CO₂ emissions: indicative split by distance

Going forward, we translate our demand projections to emissions projections in two steps:

- The first step converts passenger demand¹² estimates to ATMs. This depends on airport capacity constraints, and airlines' decisions on frequency of flights and size of aircraft deployed.
- The second step converts ATMs to emissions, based on the fuel efficiency of aircraft type used and the distance flown on the route.

In our reference projections we assume that there is no improvement in fleet fuel efficiency relative to the current position. Our range of emissions projections mirrors our demand projections and therefore comprises three projections under alternative capacity assumptions and three projections with planned capacity under alternative assumptions about carbon prices and fossil fuel prices:

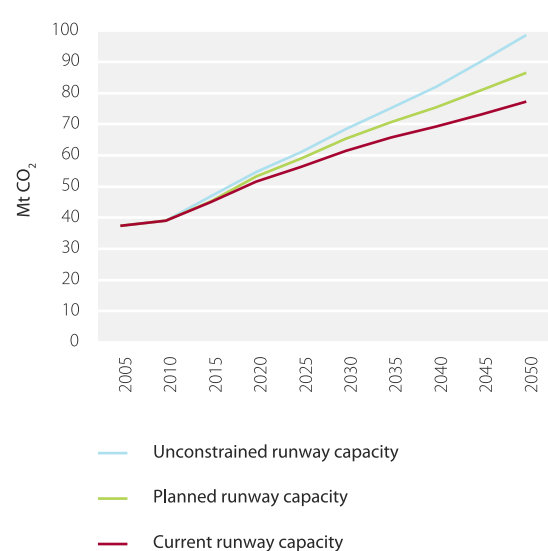
- **Emissions based on unconstrained demand growth:** In this projection emissions grow by around 160% in 2050 over 2005 levels (i.e. from 37.5 MtCO₂ in 2005 to just under 100 MtCO₂ in 2050).
- **Emissions based on demand growth with planned runway capacity:** In this projection emissions grow by around 130% in 2050 over 2005 levels (i.e. to around 87 MtCO₂ in 2050).
- **Emissions based on demand growth without addition of new runway capacity:** In this projection emissions grow by around 105% in 2050 over 2005 levels (i.e. to around 77 MtCO₂ in 2050).

¹² In our analysis the business/leisure split is by purpose i.e. not by class.

- **Emissions based on demand growth with planned capacity and central carbon and fossil fuel price projections:** In this projection emissions grow by around 95% in 2050 over 2005 levels (i.e. to around 74 MtCO₂ in 2050).
- **Emissions based on demand growth with planned capacity and high carbon and fossil fuel prices:** In this projection emissions grow by around 80% in 2050 over 2005 levels (i.e. to around 68 MtCO₂ in 2050).
- **Emissions based on demand growth with planned capacity and low carbon and fossil fuel prices:** In this projection emissions grow by around 130% in 2050 over 2005 levels (i.e. to around 85 MtCO₂ in 2050).

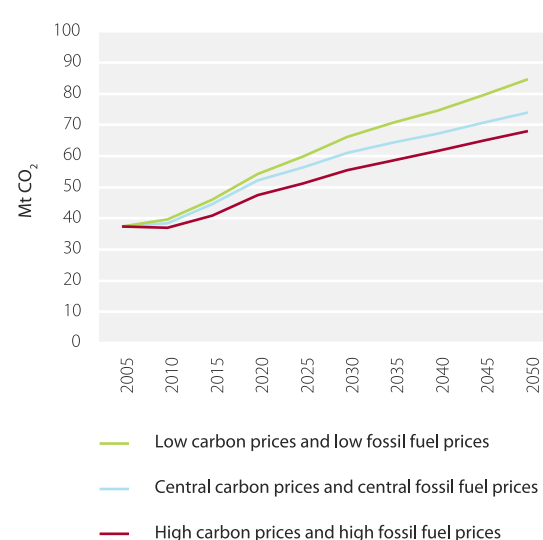
There is a broad trend evident across scenarios that emissions growth is slightly lower than demand growth, which in part reflects increasing average plane load factors in the period to 2050 from around 75% in 2005 to around 85% in 2050, and changes in the route mix. To the extent that load factors do not increase as assumed, then emissions projections would be higher and require more emissions reductions to meet the 2050 target.

Figure 2.11a Reference emissions projections: effect of changes in runway capacity



Source: CCC modelling.

Figure 2.11b Reference emissions projections: planned capacity, effect of changes in carbon and fossil fuel prices



Source: CCC modelling.

5. How we will use the reference projections

The reference projections provide an illustrative starting point for our analysis. In meeting the 2050 target there are a number of options for reducing emissions below the levels in the reference projections (e.g. alternatives to air travel, fuel efficiency improvement, use of biofuels).

We now consider each of these options in turn, and then bring together the different strands of analysis, overlaying emissions reductions from these options on the reference projections.

Specifically, we develop scenarios for emissions reductions from the range of options which we overlay across the central case demand/emissions projections. We also consider the impact of departure from the central case through sensitivity analysis around alternative carbon price/fossil fuel price assumptions. We illustrate alternative strategies towards aviation expansion for meeting the 2050 target.

Chapter 3

Alternatives to air travel: high-speed rail and videoconferencing

In Chapter 2 we considered various demand projections reflecting different assumptions on fossil fuel prices, carbon prices, and infrastructure investment. In this chapter, we broaden our demand analysis by considering scope for modal shift between aviation and conventional rail/high-speed rail, and for substituting air travel with videoconferencing¹.

Our approach is to develop estimates of feasible emissions reduction potential from modal shift and videoconferencing. We do not consider wider socio-economic costs and benefits (for example, travel time savings from high-speed rail for existing rail customers), impact on the local environment or scope for modal shift from cars to high-speed rail. We do not therefore attempt an economic analysis of whether investment in high-speed rail is desirable; such an analysis is beyond the remit of this report.

The main messages in the chapter are:

- Modal shift can offer a useful contribution to meeting the 2050 target, particularly if a new UK high-speed line is built and the European network becomes more fully integrated. However, the potential emissions reduction is relatively small in the context of the overall aviation target, reflecting the relatively small share of domestic and short-haul aviation emissions in total UK aviation emissions.
- It is unclear how videoconferencing will impact the demand for business travel. Based on current evidence, however, we cannot be confident that this effect will be significant. We reflect uncertainty over the potential impact of videoconferencing in a range of penetration from no net impact on business air travel demand (which models a world where there are rebound effects, and where videoconferencing is additional rather than a substitute for business travel) to a 30% reduction in business air travel demand in 2050, which is consistent with the high end estimated in the academic literature and current best practice (e.g. as achieved by BT and Vodafone).
- Taken together there is scope for demand reduction of up to 16% (i.e. 91m passengers) and emissions reduction up to 7 MtCO₂ in 2050 from modal shift and videoconferencing.

¹ Videoconferencing here encompasses a broad suite of communications technologies including the latest visual technology developments.



We now consider:

1. The potential for shifting from air to rail
2. Scope for substituting videoconferencing for air travel
3. Total emissions reductions from modal shift and videoconferencing.

1. The potential for shifting from air to rail

The choice of travel mode between air and rail is a function of relative cost, including travel time and convenience. Other things being equal (i.e. prices, service quality), passengers will choose the mode which minimises travel time.

We have reviewed the evidence on point-to-point travel times by aviation and rail. This suggests that the range beyond which rail cannot compete on travel time is around 800 km:

- On journeys of less than 400 km conventional rail will usually be faster than air for point-to-point journeys (e.g. London to Manchester is 296 km by rail, London to Brussels 373 km).
- On journeys below 800 km high-speed rail has the potential to enable significant modal shift (e.g. London to Edinburgh 632 km by rail, London to Amsterdam 605 km).
- However, above 800 km the air option is likely to be faster in terms of overall door-to-door journey time and as a result the rail option would need to have other advantages (e.g. significantly lower prices) to be competitive. For example, cities such as Berlin (1,204 km from London by rail), Milan (1,406 km) and Madrid (1,942 km) are beyond the 800 km range.

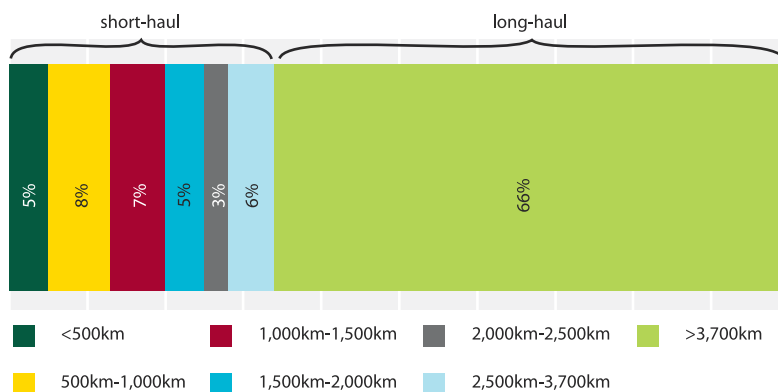
An indication of the order of magnitude for emissions reduction potential from modal shift is the share of total UK aviation emissions accounted for by journeys within the range at which rail could potentially compete. In 2005, domestic and short-haul aviation covering distances up to 1,000 km accounted for around 13% of total UK aviation emissions (i.e. up to 5 MtCO₂ – Figure 3.1).

This represents an upper bound on feasible emissions reductions from aviation given that:

- Not all flights are substitutable by rail (e.g. across the Irish Sea).
- Not all destinations will be connected by high-speed rail.
- Even for connected destinations, these will not achieve 100% market share – particularly for longer routes and where there is only partial integration of the European high-speed network.
- There are emissions associated with rail/ high-speed rail (i.e. in building new infrastructure, and in running trains to the extent that the electricity grid is not fully decarbonised).

In order to move from this high level assessment to a more detailed understanding, we commissioned analysis from consultants Steer Davies Gleave (Box 3.1).

Figure 3.1 Distribution of UK aviation emissions by distance in 2005



Source: CCC analysis based on CAA data (2009).

Box 3.1 Summary of SDG modal shift model

Overview

The SDG model estimates the potential for modal shift between UK aviation and rail. In particular, the model estimates the effect on modal share between air and rail as a result of:

- Changes in journey time and other journey time related factors: these could be either small changes such as those that are expected to result from the deployment of the Intercity Express Programme (IEP), or step changes as a result of the construction of new high-speed lines covering certain city pairs.
- Changes in the price of either mode: these could be due to possible carbon pricing or other revision to fares.

Model structure

The model covers five key elements, each of which is a separate component of the demand model:

- 1. Market share:** This estimates the extent to which air and rail market share on the routes modelled may change as a result of changes to journey time, price or other factors. It is the most important – and most complex – element of the model.
- 2. Price module:** The price module calculates the operating costs for air and rail operators and translates them into the fare charged by the rail and air operator for each modelled route.

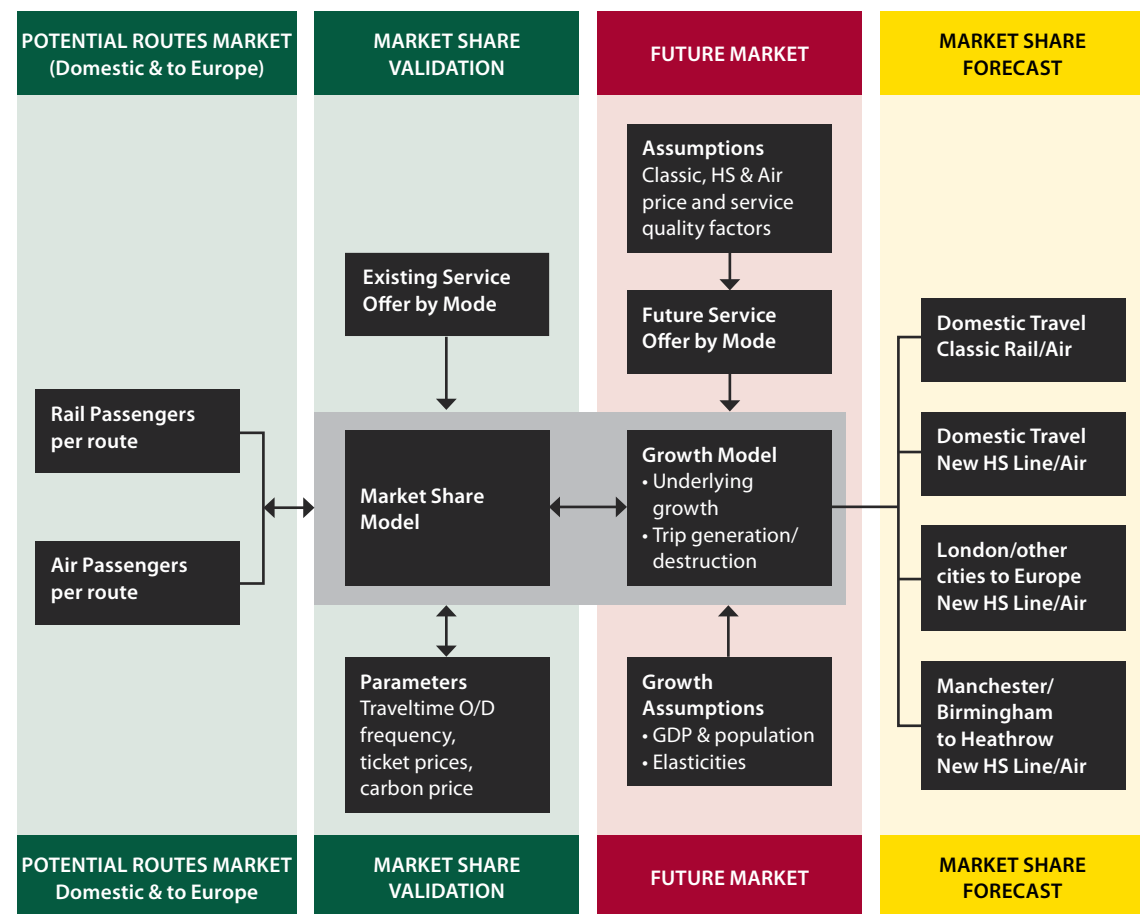
Box 3.1 continued

3. Underlying growth: Economic and population growth is reflected in projected demand growth.

4. Trip generation/reduction: Trip generation or reduction will also be a significant consequence of (for example) construction of a high-speed line or introduction of carbon pricing for air transport.

5. Route substitution: Market analysis suggests that an important effect of journey time and cost changes could be leisure passengers choosing short distance rail trips rather than longer distance air trips. The route substitution module estimates this effect.

Figure B3.1 Overview of the SDG model structure



Source: SDG (2009).

Box 3.1 continued

The model provides an assessment of the total air travel demand that may switch from air to rail. Within the scope of the study it was not possible to model every single route within the UK and between the UK and Europe. Therefore, 23 representative city pairs were modelled explicitly – 12 routes from London to mainland Europe, five routes from other UK cities to mainland Europe, six domestic routes, and three routes to Heathrow. SDG then match non-modelled routes, where there could be some modal shift, to one of the modelled routes. The model then assumes that the modal shift on the non-modelled routes will be the same as the modelled routes. The route substitution calculation was conducted on the full list of UK routes.

Market share model

The main component of the demand model is the market share module. The output from this module is the forecast modal shift between air and rail on each route as a result of changes to journey time and cost. The market share module is based around a logit model, which calculates market share on each route on the basis of the generalised cost of each mode. This cost reflects two elements, the generalised journey time and the price.

Generalised journey time is a weighted sum of all the journey time related factors (the main journey time factors are: in-vehicle time, frequency, interchanges, access and egress times and check in time). The journey time actually spent in the main mode of transport is given a weight of one and all other journey time factors are weighted in respect to this. The SDG logit model was calibrated against observed market data for the 23 selected routes.

Scenarios

SDG developed four scenarios for the CCC: low, central, high and central with full UK-Europe integration.

- The first three of these scenarios relate to different combinations of oil and carbon prices (e.g. central relates to central forecasts of oil and carbon prices – we use these assumptions, without a new UK high-speed line, in our **Likely** scenario and with a new UK high-speed line in our **Optimistic** scenario).
- The central scenario with full UK-Europe integration uses the same oil and carbon price assumptions as the central scenario, but the rail service between the UK and Europe is assumed to become fully integrated – we use these assumptions (with a new UK high-speed line) in our **Speculative** scenario. More specifically:

Box 3.1 continued

- Competing rail operators are allowed to enter the market, reducing any producer surplus over operating costs.
- Direct rail services are introduced on all modelled flows.
- The current international rail check-in time is reduced from 30 minutes to 15 minutes.
- Rail access charges are reduced on the majority of routes.

For more information on the model, scenarios and results please see the SDG report¹, which is available on our website at www.theccc.org.uk

¹ Steer Davies Gleave (2009), *Potential for modal shift from air to rail*.

We now set out our conclusions based on this analysis in three sections:

- (i) Scope for modal shift from domestic aviation to rail
- (ii) Scope for modal shift from short-haul international aviation to rail
- (iii) Emissions reduction scenarios.

(i) Scope for modal shift from domestic aviation to rail

SDG analysis suggests that incremental enhancements (e.g. Intercity Express Programme) will have limited scope to significantly change market share on routes between destinations where there is currently a high degree of air travel (e.g. Scotland to London). This is for two main reasons:

- Incremental changes are unlikely to have a large impact on travel times.
- The system is capacity constrained.

The SDG analysis also considered the impact of more radical change in the form of a new high-speed rail line (delivered by the early 2020s) connecting London to Scotland via Birmingham and Manchester, both with and without a Heathrow spur. Their analysis suggested that there may be scope for high-speed rail to gain a market share up to 90% on Anglo-Scottish routes, and 40% between Manchester and Heathrow (Box 3.2). The percentage of rail share between Manchester and Heathrow could be greater than 40% but to achieve this there would need to be integrated air and rail services (including ticketing and baggage transfer).

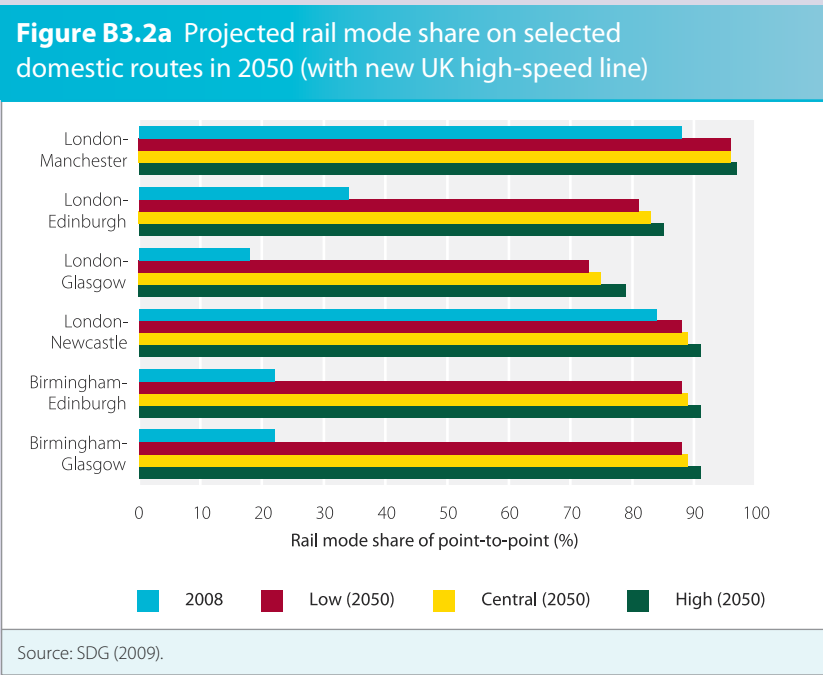
Box 3.2 Summary of analysis on modal shift to rail

Domestic routes

Rail market share is expected to increase slightly in 2025 without a high-speed line on Anglo-Scottish routes due to committed upgrades (e.g. up to a 15 percentage point increase in rail mode share on these routes) such as completion of the West Coast Route Modernisation and the introduction of Intercity Express Programme (IEP) trains.

If a new high-speed line is introduced a much greater shift from air to rail is expected on these routes with rail mode share increasing by up to 50 percentage points in 2025.

In 2050 with a new high-speed line, rail market share is projected to increase from current levels of 20-35% to 75-90% on Anglo-Scottish routes and small increases on other key routes e.g. from 88% to 97% on London to Manchester (Figure B3.2a). The greater improvement on Anglo-Scottish routes is due to the potential for more significant reductions in travel time over these longer distances.



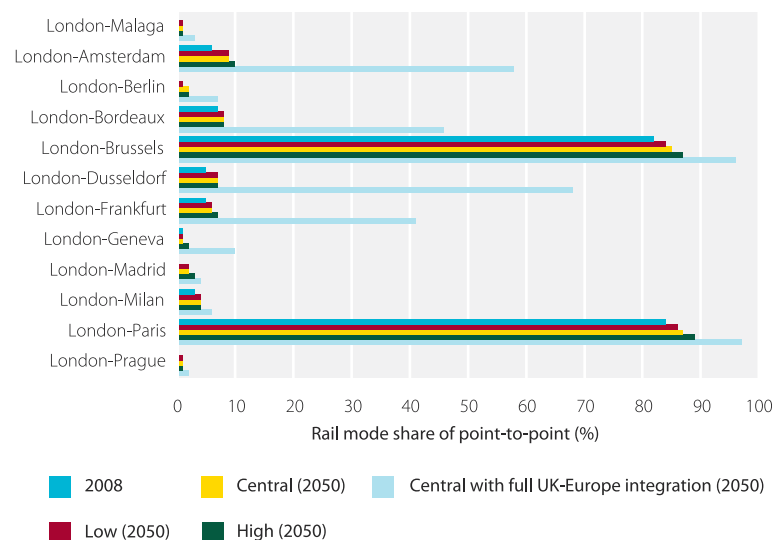
Box 3.2 continued

UK to Europe

The projected rail market share on routes from London to mainland Europe is largely dependent on integration of the European network (Box 3.1). Without integration, in the three main scenarios (low, central and high) limited modal shift is achieved in both 2025 and 2050 – up to a five percentage point increase in rail modal share.

In the central scenario with full UK-Europe integration and a significantly improved (and lower priced) rail service offer, more significant modal shift is achieved on key routes such as London-Frankfurt, London-Dusseldorf, London-Bordeaux, and London-Amsterdam, particularly in 2050 where on some of these routes rail gains a majority market share. In contrast, on much longer routes even with an integrated network very limited modal shift is expected to occur. For example, London-Malaga and London-Madrid are projected to have less than a five percent rail share in 2050 (Figure B3.2b).

Figure B3.2b Projected rail mode share on selected routes from London to mainland Europe in 2050

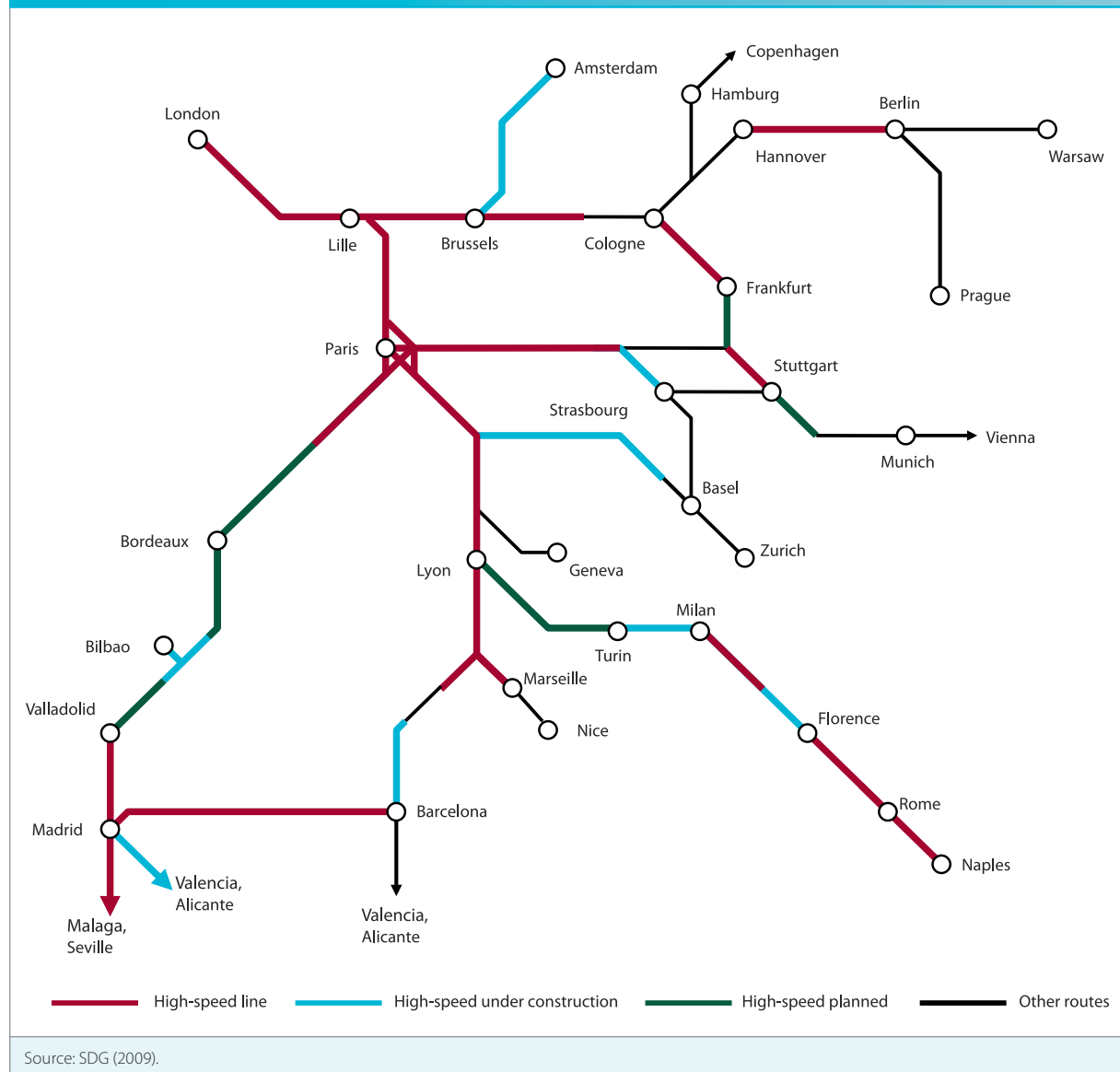


Source: SDG (2009).

(ii) Scope for modal shift from short-haul international aviation to rail

A number of European countries have or plan to have high-speed rail networks. This presents an opportunity for the UK to target modal shift from short-haul international aviation to rail using currently spare capacity through the Channel Tunnel Rail Link. UK passengers would have access to a European high-speed rail network stretching from Seville to Berlin and from Amsterdam to Naples (Figure 3.2).

Figure 3.2 Map of planned European high-speed rail network



The SDG analysis suggests that given this opportunity, high-speed rail could gain a market share of 30-60% on routes from London to Amsterdam, Dusseldorf and Frankfurt (Box 3.2), with some increase possible on routes already well served by high-speed rail (e.g. London to Paris and Brussels), particularly if the European network becomes fully integrated.

The analysis suggests, however, that there would be limited scope for significantly increased market share on longer distance routes where the vast majority of passengers currently travel by plane (e.g. London to Berlin, Milan, or Madrid).

In total, the SDG analysis suggests a range for emissions reductions from modal shift (accounting for increases in rail emissions) of 0.4 MtCO₂ to 2.2 MtCO₂ in 2050, compared to SDG projected emissions from air and rail travel domestically and to Europe of 23 MtCO₂ to 27 MtCO₂ in 2050 (Box 3.3).

Box 3.3 Total air and rail emissions reduction from modal shift

SDG's main model output was projected modal shift from air to rail. The SDG demand outputs were then input into the MVA demand and emissions model to calculate the impact on aviation demand and emissions to be consistent with the inputs and modelling of the CCC's scenarios.

Nevertheless, SDG did provide an estimate of the total CO₂ emissions from air and rail travel within the UK and between the UK and other parts of Europe. In the most optimistic scenario, air-rail mode shift reduces CO₂ emissions in 2050 by around 2.2 MtCO₂, with full integration of the European network and a new UK high-speed line. On the other hand, if the European network is not fully integrated and there are low oil and carbon prices, this emissions reduction would be closer to 0.4 MtCO₂ in 2050 (Figure B3.3).

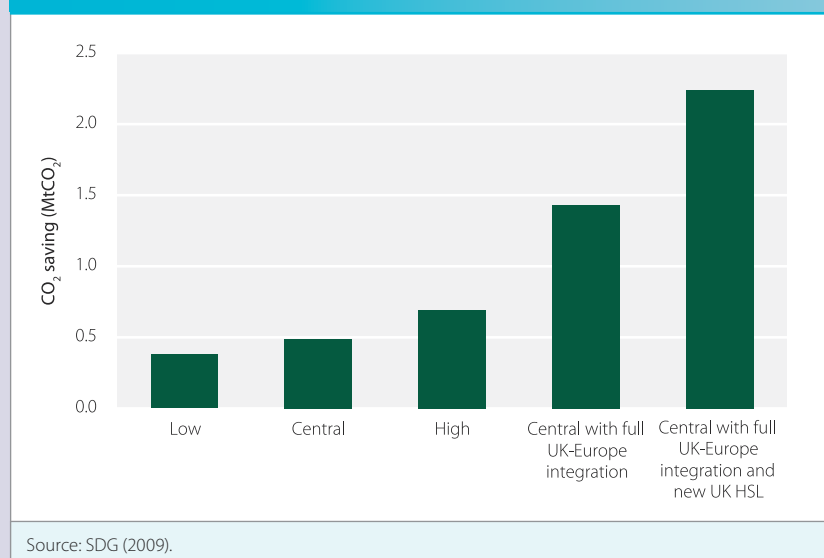
These estimates include increased emissions from rail:

- By 2050 gross savings from reduced air travel alone could be up to 10% greater than these combined air and rail emission savings estimates. In 2050 the rail emissions are small due to the assumption that the European power sector will be significantly decarbonised by this time.
- In 2025, when the power sector is likely to be less decarbonised, the total savings (gross savings from reduced air travel offset by increased emissions from rail) would be around 50% lower than gross savings from reduced air travel alone due to rail being more carbon intensive.

Therefore, power sector decarbonisation is crucial to unlock real savings from modal shift from air to rail.

Box 3.3 continued

Figure B3.3 SDG estimates of CO₂ savings from modal shift from air to rail in 2050



(iii) Emissions reduction scenarios

We have constructed three scenarios for emissions reduction² due to modal shift from domestic and short-haul international aviation to rail and high-speed rail:

- Under our **Likely** scenario we reflect current firm policy commitments. Specifically, we assume that UK investment in rail improvements to conventional rail (e.g. introduction of new Intercity Express Programme (IEP) trains) proceed as planned and so do the expected investments in the European high-speed rail network. However we assume that no new UK high-speed rail line is built and that the European network remains only partially integrated (Box 3.1). These result in a 1% demand reduction (i.e. 8m passengers) and 0.3 MtCO₂ emissions reduction in 2050.
- Under our **Optimistic** scenario we assume a policy shift in the UK, with firm commitment to investing in a new UK high-speed rail line connecting London with Scotland via Manchester and Birmingham and including a Heathrow spur. Nonetheless we assume that this augmented UK high-speed rail line still operates within a European network that remains only partially integrated. These result in a 4% demand reduction (i.e. 23m passengers) and 0.6 MtCO₂ emissions reduction in 2050.

² These estimates are based on the MVA demand and emissions model used for our scenarios and will therefore differ slightly from SDG's estimates due to slightly different modelling approaches. Nevertheless, the estimates are all within the estimated range for emissions reduction potential.

- Under our **Speculative** scenario we assume a policy shift in the UK and Europe such that there is a new high-speed rail line in the UK and a fully integrated European high-speed rail network. These result in an 8% demand reduction (i.e. 44m passengers) and 1.7 MtCO₂ emissions reduction in 2050.

The maximum emissions reduction potential from modal shift to rail in 2050 of around 2 MtCO₂ offers a useful contribution to meeting the 2050 target, notwithstanding that this is relatively small compared to our central reference projection in which total UK aviation emissions in 2050 are around 81 MtCO₂ in the unconstrained case with a carbon price, reflecting the relatively small share of domestic and short-haul aviation emissions in total UK aviation emissions.

2. Scope for substituting videoconferencing for air travel

Videoconferencing is becoming an increasingly attractive alternative to flying in the business sector. This could translate to a useful emissions reduction as videoconferencing technology improves and the cost of flying increases over time, given that business travel accounts for around a quarter of all UK aviation demand by purpose.

There is some evidence that videoconferencing could substitute for air travel:

- Academic research suggests that videoconferencing could reduce business flights by up to 35%, with low estimates centred on 10% (Box 3.4).
- A recent survey by the Institute of Travel and Meetings (ITM) indicated that travel and meeting managers of leading UK companies and Government departments expect communication technology such as videoconferencing to drive an 18% reduction in demand for business travel and travel to meetings³.
- The World Wildlife Fund (WWF) has launched the 'One in Five Challenge,' under which participating organisations aim to reduce their business flights by 20% within five years. Of the eight participants, BT and Vodafone have already achieved 20-30% reductions over recent years.

Scope for videoconferencing should not, however, be overstated:

- There is some evidence suggesting that meetings based on videoconferencing may be additional, rather than substituting for meetings which require air travel, with the possibility of rebound effects (Box 3.4).

³ ITM (Sep 2009), *Demand, Supply and Convergence*.

Box 3.4 Does videoconferencing substitute for business flights?

Academic studies

Academic studies carried out in the 1990s on the potential effects of videoconferencing on business flying predicted ambitious reductions of up to 40% in the next two decades (Arvai (1991)², Burger (1995)³).

However, recent research has shown that the relationship can actually function in the opposite direction, with greater telecommunications use accompanying increases in total travel (Wang and Law (2007)⁴, Choo and Mokhtarian (2007)⁵). This raises a question over the extent to which videoconferencing actually substitutes for business travel⁶.

A recent paper by Cairns (2009)⁷ suggests that there is significant potential for uptake of videoconferencing to substitute for business travel as:

- Technical and cost barriers have largely been addressed.
- Videoconferencing is widely perceived to reduce stress and unnecessary travelling time, particularly for routine internal meetings.

In order to assess the potential substitution effect from videoconferencing more precisely, additional information is needed relating to:

- The types of organisation and individuals that could most readily use videoconferencing. For example, are a small minority of individuals flying very frequently and would these individuals benefit from a reduction in flying? Or by contrast, is the majority of business travel constituted by individuals taking one to two trips per year, which are high value trips?
- Data on currently occurring meetings: whether they are internal or external, their frequency and whether or not they are clustered together i.e. individuals arranging several meetings for one trip.
- The types of interaction where videoconferencing could genuinely substitute for a physical event.

Box 3.4 continued

Preliminary market review

A brief market review carried out by the CCC found the following:

- Many companies are installing videoconferencing facilities.
- In the absence of strong targets for flight reductions videoconferencing uptake was generally accompanied by rising total travel volumes and in one case rising air travel per employee.
- However, those companies that had installed the facilities but had also set ambitious targets (such as those now participating in WWF's *One in Five Challenge*) were able to achieve significant reductions in air travel.

Further evidence on trip patterns and purposes is required in order to better understand the scope for substitution of videoconferencing for business travel.

2 Arvai (1991), *Telecommunications and business travel: the revolution has begun.*

3 Burger (1995), *Videoconferencing impacts on air travel demand.*

4 Wang and Law (2007), *Impacts of information and communication technologies on time use and travel behaviour: a structural equations analysis.*

5 Choo and Mokhtarian (2007), *Telecommunications and travel demand and supply: Aggregate structural equation models for the US.*

6 Bender and Stephenson (1998), *Contemporary issues affecting the demand for business air travel in the United States.*

7 Cairns (2009), *Can teleconferencing reduce business travel?*

Our view is that the impact which videoconferencing could have on air travel is very uncertain and depends on a detailed understanding of trip purpose. We therefore cover a broad range in our scenarios, from no net impact due to videoconferencing to a 30% net reduction in business travel:

- Under our **Likely** scenario we assume that videoconferencing has no net impact on aviation demand, under the assumption that it results in rebound effects and additional meetings rather than substituting for existing meetings.
- Under our **Optimistic** scenario we assume that videoconferencing results in a net demand reduction. Specifically, we assume a 10% reduction in business aviation demand in 2050 (rising on a linear trend from 2005) consistent with the low end of the range from the academic literature.
- Under our **Speculative** scenario we assume an impact consistent with the high end of the range from the academic literature and current best practice, which would probably require a combination of policies to promote videoconferencing and targets to reduce flights in companies. Specifically, we assume a reduction in business demand of 30% in 2050 (rising on a linear trend from 2005).

In order to better understand which of these scenarios may be more plausible, further analysis is required. This would focus on trip patterns, for example, the frequency with which business travellers fly, the purpose of their meeting (e.g. internal versus external), the number of meetings per trip (Box 3.4); these data are currently commercially but not publicly available.

3. Total emissions reductions from modal shift and videoconferencing

In order to allow for possible overlap between modal shift and videoconferencing (e.g. a journey which is made on high-speed rail cannot also be substituted by videoconferencing), we combine our two sets of scenarios to give overall estimates for aviation demand and emissions reduction⁴:

- Our **Likely** scenario assumptions result in modal shift equivalent to reducing air travel demand by 1% of passengers (i.e. 8m) and 2% ATMs in 2050. We assume that videoconferencing has no net impact on aviation demand. The impact on emissions is, therefore, a 0.3 MtCO₂ emissions reduction in 2050.
- Our **Optimistic** scenario modal shift and videoconferencing⁵ assumptions result in a reduction equivalent to reducing air travel demand by 7% of passengers (i.e. 40m) and 10% of ATMs in 2050, and an emissions reduction of 2.4 MtCO₂ in 2050.
- Our **Speculative** scenario modal shift and videoconferencing assumptions result in a reduction equivalent to reducing air travel demand by 16% of passengers (i.e. 91m) and 19% of ATMs in 2050, and an emissions reduction of 7 MtCO₂ in 2050.

⁴ These estimates correspond to a scenario with unconstrained demand growth; see Chapter 7 for a discussion of potential in a capacity constrained system where some of modal shift and videoconferencing translates to easing of suppressed demand rather than demand reduction.

⁵ In both the Optimistic and Speculative scenarios, emissions savings from videoconferencing could in practice be higher if passengers displaced reflect a disproportionate share of premium class travel, which have higher associated per passenger emissions.

Chapter 4

Improvement in fleet fuel efficiency through technology innovation

This chapter sets out our assessment of the degree to which improvements in aircraft fuel efficiency combined with improved efficiency in Air Traffic Management (ATM) and operations could contribute to reducing emissions from UK aviation. It builds on the analysis in our December 2008 report, which suggested that a new production aircraft in 2025, flying in an improved operational environment, could be up to 50% more efficient than a 2006 aircraft on a passenger-km basis, and that improvements in annual fleet fuel efficiency using upper-bound evolutionary technology of the order 1.5% may be achievable.

In developing our assessment, we have considered:

- Analysis on abatement potential from technology innovation prepared by QinetiQ for our December 2008 report;
- Analysis of the current and future aviation fleet that we have commissioned from MVA;
- A wide range of additional studies and analyses including the IATA technology roadmap report, the Sustainable Aviation roadmap, and consultancy reports commissioned by UK and foreign government agencies;
- Findings of our workshops and discussions with industry experts.

The key messages in this chapter are:

- Evolutionary technology innovation could lead to fuel efficiency improvements in new aircraft of the order 35-45% by 2025, and introduction of more speculative radical technologies could make new aircraft up to 60% more efficient by 2050, compared to 2006 levels.
- More efficient ATM and operations could contribute between an additional 6-13% per flight by 2020.
- The combination of aircraft, ATM and operational efficiency improvements could result in a range for annual improvement in fleet fuel efficiency from 0.8-1.5% per seat-km between 2005 and 2050.



We set out the analysis that underpins these messages in three sections:

1. Scope for improvement in aircraft fuel efficiency
2. Scope for improved efficiency in ATM and operations
3. Scenarios for improvement in annual fleet fuel efficiency.

1. Scope for improvement in aircraft fuel efficiency

Fuel burn is a key determinant of aviation economics given that fuel costs account for up to 35% of total aviation costs. The aviation industry has therefore focused on fuel efficiency improvement through engine and aircraft innovation, which has resulted in a reduction in total energy intensity of more than 60% since 1970. This section focuses on scope for further engine and airframe innovation going forward.

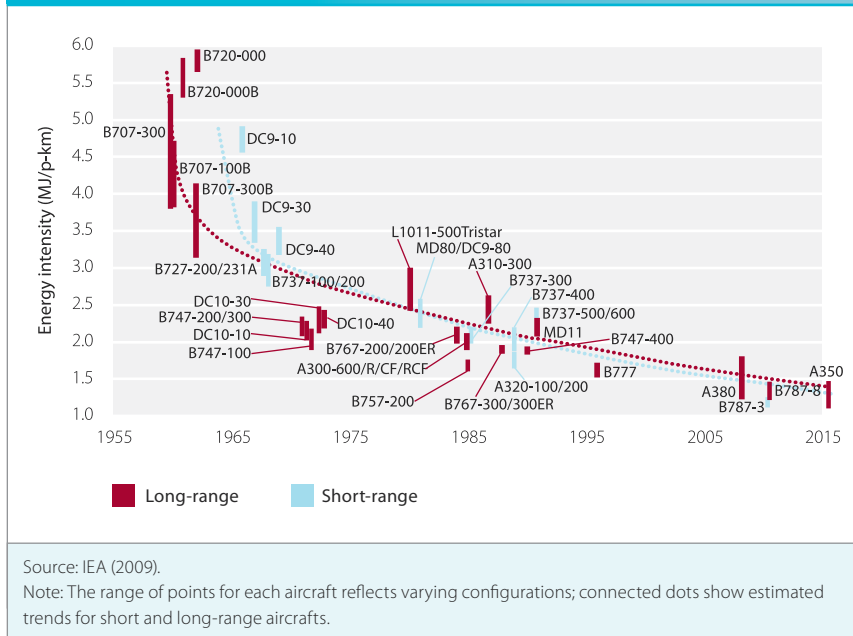
We now consider:

- (i) Historical fuel efficiency improvements
- (ii) Future improvements from evolutionary technology innovation
- (iii) Future improvements from radical technology innovation
- (iv) Scenarios for fuel efficiency improvement from engine and airframes.

(i) Historical fuel efficiency improvements

Aircraft fuel efficiency has improved substantially since the beginning of the jet era in the 1960s, and from 1970 to 2000 total energy intensity was reduced by more than 60% (Figure 4.1). This reduction was due to a combination of factors including:

- Improvement in engine efficiencies, driven for example by the introduction of high bypass ratio turbo-fan engines in the early 1970s and subsequent evolutionary improvements in engine performance;
- Airframe improvements such as reduced drag and weight (as a result of improved aerodynamics and advanced materials) and increasing size of aircraft;
- ATM and operational improvements such as more efficient routing and increasing load factors.

Figure 4.1 Historical improvements in aircraft fuel efficiency

(ii) Future improvements from evolutionary technology innovation

Technical potential for fuel efficiency improvement

There are a number of evolutionary technologies that could help achieve further fuel efficiency improvements in new aircraft over the next 20 years or so and beyond:

Evolutionary engine improvements

- **Improvements in thermodynamic efficiency of engines**, for example increasing the turbine entry temperature (TET) although this will tend to increase NO_x emissions;
- **Improvement in propulsive efficiency of engines**, including by optimisation of aerodynamic design of fan and turbine components;
- **Development of geared turbo-fan engines**, to address inefficiencies in the architecture of conventional turbo-fan engines.

Evolutionary airframe improvements

- **Airframe weight reduction**, including further replacement of metals by lighter composite materials in aircraft structures;
- **Improvements in aircraft lift/drag ratio**, for instance by improving aerodynamic design and shape of aircraft and increasing laminar flow control.

Table 4.1 Potential fuel savings from evolutionary measures by 2025

Technology/ abatement opportunity	Impact	Total Saving in 2025
Airframe	20-30%	35-45%
Engine	15-20%	

Source: QinetiQ (2008).

Analysis that we commissioned from QinetiQ in the context of our December 2008 report suggested that together these potential innovations provide scope for a 35% to 45% efficiency improvement by 2025 relative to a 2006 model (Table 4.1).

In addition, there are a number of opportunities for retrofitting of existing aircraft, including:

- **Addition of winglets and riblets**, which can improve wing aerodynamics and therefore fuel burn although this needs to be balanced against extra weight;
- **Aircraft polishing**, instead of painting can help reduce fuel burn by saving weight;
- **Airframe component replacement**, such as upgrading engines can provide improvements in fuel consumption;
- **Improved maintenance**, for example to achieve better performance retention in engines.

ACARE targets for new aircraft

The Advisory Council for Aeronautics Research in Europe (ACARE) has set targets for efficiency of a new aircraft (Box 4.1). These incorporate a reduction in CO₂ of 50% per passenger-km by 2020 measured against 2000 levels, of which it is envisaged that around 40% will ensue from engine and airframe innovation, with the remainder due to improved ATM contributions.

Meeting the ACARE target for a new aircraft by 2020 will however be very challenging given current plans for introduction of new aircraft families:

- Our expectation is that major aircraft manufacturers will start to develop new aircraft families for narrow-body aircraft to enter the market in the 2020s (e.g. B737/A320 replacements), but have no firm plans to develop new aircraft families for other market segments that would reach ACARE equivalent efficiency standards.
- The development and certification of a new aircraft family typically takes around 10 years. Where aircraft incorporate high levels of new technology introduction, the timescale is likely to be significantly longer. The earliest possible date at which a new ACARE type aircraft could be introduced is therefore around 2020. Technology innovation, integration and certification can all lead to the entry date being later than originally planned (e.g. as has been the case for the Airbus 380 and Boeing 787).

Box 4.1 ACARE process and targets

The Advisory Council for Aeronautics Research in Europe (ACARE)¹ was formed in 2001 and comprises 39 members from European Member States, the Commission and stakeholders from industry, airlines, airports and academia.

In 2002 ACARE launched a 'Vision for 2020' that set goals in five key areas: Quality and Affordability, Environment, Safety, Security, and Air Transport System Efficiency.

On the Environment, five goals were identified for 2020:

1. To reduce fuel consumption and CO₂ emissions by 50% per passenger-km:
 - Airframe contribution of 20-25%
 - Engine contribution of 15-20%
 - ATM contribution of 5-10%
2. To reduce perceived external noise by 50%
3. To reduce NO_x emissions by 80%
4. To reduce other emissions (e.g. soot, CO, UHC, SO_x, particulates etc)
5. To minimise the industry impact on the global environment, including the impact of manufacturing, maintenance and disposal.

There are likely to be trade-offs between these environmental objectives at the margin. For example, there are trade-offs in engine design and operation between CO₂, NO_x and noise. Improvements in NO_x and noise are likely to be at the expense of improvements in fuel efficiency and therefore CO₂ emissions.

To implement their Vision for 2020, ACARE developed a Strategic Research Agenda which has been reviewed and updated periodically. A full review is expected in 2010 with a new Strategic Agenda in 2012.

¹ www.acare4europe.com

At best, therefore, the ACARE target is most likely to be achieved with a narrow-body aircraft. More generally, it is very unlikely that an ACARE equivalent aircraft will be produced for turboprop, regional jet and wide-body/long-haul aircraft by 2020. At current levels of investment, and given the lead times for development of new technologies and new aircraft families, it is more likely that improvements in the ACARE range will be achieved in the late 2020s, or possibly beyond, for new aircraft introduced across a range of types.

Fleet rollover and implications for technology uptake

The pace at which engine and airframe innovation have the potential to reduce fleet emissions reflects aircraft life:

- Typical aircraft life is around twenty-five years.
- Given this, new aircraft entering the fleet annually to replace existing aircraft are unlikely to comprise a significant proportion of the overall fleet.
- New aircraft will also be required to meet incremental demand growth.

If new aircraft families were to be introduced no later than 2030, these would account for the majority of the fleet in 2050.

(iii) Future improvements from radical technology innovation

There is potential for additional fuel efficiency improvement above and beyond what is available from evolutionary innovation, although this would require technological breakthroughs and significant research, development and demonstration. Possible radical technology innovations include:

- **Open rotor engines**, where the fan blades are not surrounded by a casing. This removes some of the trade-offs between diameter, weight and drag allowing better fuel burn. There is some debate over the extent to which open rotor is an evolutionary or radical technology. The consensus among experts is that this approach will require a very high level of engine/aircraft integration and is only being considered for narrow-body aircraft. Moreover, open rotor engines may be needed for a narrow-body aircraft to be able to achieve overall ACARE type efficiency improvements in the 2020s.
- **Blended wing bodies**, offering improved airframe aerodynamics through a flattened profile and wing structures that are smoothly blended to the body.

Analysis from QinetiQ suggests that these radical measures taken together could improve efficiency by a further 15% in addition to the 35-45% increase from evolutionary innovation.

Economics of radical technologies

High levels of expenditure, in the order of tens of billions of pounds, are likely to be required to develop and demonstrate new technologies.

The result may be cost-effective technology options (i.e. resulting in net cost savings given a carbon price), although this is inherently very uncertain given the current early stage of technology development.

In order for radical technology innovation to have a significant impact in the period to 2050, this would have to be available in tandem with the introduction of new aircraft families. Given the long lead time for radical technology innovation (i.e. decades), funding would have to be made available in the short term in order to allow deployment in new aircraft families in the coming decades.

(iv) Scenarios for fuel efficiency improvement from engines and airframes

We have designed three scenarios for fuel efficiency improvement of engines and airframes. We have used a hybrid approach, combining estimates of annual improvement in the fuel efficiency of the average fleet from recent studies (i.e. top-down) with modelling of the uptake of new engine/airframe designs under different assumptions about the timing of new aircraft deployment (i.e. bottom-up).

The scenarios range from what is achievable under the current framework (Likely scenario) and likely to ensue; to what is achievable but very unlikely and would require a significant shift in policy and investment (Speculative scenario). The most ambitious scenario (Speculative), which includes technologies that are still at the concept stage, should be viewed with considerable caution unless there is new evidence to suggest a significant increase in the pace of technology innovation.

Specific assumptions in the three scenarios are:

- Under our **Likely** scenario we assume a 0.7% annual improvement in fleet fuel efficiency from engines and airframes on a seat-km basis. This is broadly consistent with: known entry into service of aircraft in the 2010s; narrow-body ACARE type aircraft starting to penetrate the fleet in the mid-late 2020s; ACARE equivalent other aircraft types starting to penetrate the fleet in the early-mid 2030s.
- Under our **Optimistic** ambition scenario we assume a 0.9% annual improvement in fleet fuel efficiency from engines and airframes on a seat-km basis. This broadly reflects a world where known entry of aircraft in the 2010s ensues; narrow-body ACARE type aircraft start to penetrate the fleet in mid-2020s; ACARE equivalent other aircraft types start to penetrate the fleet in the late 2020s to early 2030s.
- Under our **Speculative** scenario we assume a 1.2% annual improvement in fleet fuel efficiency on a seat-km basis. This is broadly consistent with a world where known entry of aircraft in the 2010s ensues; narrow-body ACARE type aircraft start to penetrate the fleet in the early 2020s; ACARE equivalent other aircraft types start to penetrate the fleet in the mid-2020s. Beyond the ACARE equivalent generation there could be a further generation that captures up to an additional 15% beyond ACARE equivalent improvements, with these aircraft starting to penetrate the fleet in the 2040s.

2. Scope for improved efficiency in ATM and operations

The fuel efficiency of flights depends not only on the aircraft but also on the efficiency of the flight plan (which in turn is affected by ATM), operational decisions including ground operations (e.g. taxiing at airport), and the optimisation of aircraft payloads.

We now consider:

- (i) Scope for ATM efficiency improvement
- (ii) Scope for operational efficiency improvement
- (iii) Scenarios for ATM and operational efficiency improvement.

(i) Scope for ATM efficiency improvement

Current inefficiencies in ATM

The Civil Air Navigation Services Organisation (CANSO) estimates that global ATM is currently 92-94% fuel efficient. Europe however (with its fragmented and congested airspace) is only between 89% and 93% fuel efficient.

Reasons for inefficiency include:

- Aircraft not flying the most direct route between airports (horizontal inefficiencies);
- Aircraft not flying at optimal height, and changing height in stages (vertical inefficiencies);
- Aircraft holding in the air at busy airports.

These inefficiencies may be explained by:

- Institutional factors:
 - Taking longer routes to fly around military airspace;
 - Handover protocols between Functional Airspace Blocks (FABs) requiring aircraft to transition between blocks at specified locations.
- Safety constraints:
 - The need to leave adequate horizontal and vertical space between flights, with implications for admissible routes and flight levels;
 - The need to avoid bad weather systems by changing route or altitude.
- Capacity constraints resulting in holding at busy airports. In the UK for example, according to NATS, aircraft circling in arrival account for roughly 2% of CO₂ emissions in their controlled airspace (around 0.5 MtCO₂). Three-quarters of these emissions are generated at Heathrow (which currently operates at 99% capacity). More generally, there is a correlation between capacity utilisation and holding (Table 4.2).

Table 4.2 Capacity utilisation and holding

Airport	Average Holding Time	Capacity utilisation
Heathrow	10 minutes	99%
Frankfurt	5 minutes	74%
Amsterdam	2 minutes	73%

Source: CCC collated data for latest available year.

- Trade-offs between fuel efficiency and noise pollution resulting in route design to avoid urban areas, and available capacity not being used early in the morning and late at night which could otherwise reduce holding.
- Cost of over-flying airspace differs between different areas and can affect whether the shortest route is chosen (e.g. London trans-atlantic flying over Ireland rather than Scotland).
- Split incentives, between Governments/Air Traffic Control agencies, who would have to drive efficiency improvement, and airlines, who would enjoy the benefit of improvement in the form of lower fuel consumption. Additionally, FABs cross national boundaries and therefore require international collaboration.

Opportunities for improving efficiency of ATM

In the UK, National Air Traffic Services (NATS) has a target to reduce emissions, in their controlled airspace, from ATM by 10% by 2020. Their plan to meet the target is described in Box 4.2.

This is a UK-based target but there are a range of other initiatives that could help, and may to some extent be necessary, for this target to be achieved. More specifically:

- In Europe, the Single European Sky ATM Research programme (SESAR) is aiming to achieve a reduction in fuel burn for each flight within the Single European Sky airspace by 10% by 2020 relative to 2006.
- The Atlantic Interoperability Initiative to Reduce Emissions (AIRE) coordinates SESAR and NEXTGEN to increase the efficiency of flights between Europe and the US.

Box 4.2 NATS target reduction from ATM by 2020

NATS are responsible for air traffic management of UK and North Atlantic airspace, and air traffic control at 15 UK airports.

In 2009, NATS published its environmental strategy¹, which included a target to reduce CO₂ emissions by an average of 10% per flight by 2020 in their controlled airspace. They expect contributions to this target to come from all phases of flight:

- **Improving the vertical profile of flights:** Adopting smooth 'continuous climb' and 'continuous descent' approaches to the take-off and landing stage of flights could contribute to improved flight efficiency by reducing the amount of thrust and associated fuel burn. NATS estimates that fuel savings from the descent and climb phases of flight (including holding) could contribute savings per flight of 4.75% and 3.25% respectively.
- **Improving the horizontal profile of flights:** There is scope for improved flight fuel efficiency through optimisation of cruising height, speed and route. This would require better integration of air traffic control between different countries, and exploring opportunities for increased, safe access to military airspace. NATS estimates that improvements to the cruise phase could deliver potential fuel savings of 1.5% per flight in their controlled airspace in and around the UK.
- **Improving airport operations:** There is potential for fuel savings from more efficient operational procedures while aircraft are on the ground, for example from taxiing. NATS estimate fuel savings from airport operations could provide savings of 0.5% per flight (see section ii).

¹ NATS (2009), *Acting Responsibly: NATS and the Environment 2009*, [www.nats.co.uk/uploads/NATSEnvironmentPlan\(1\).pdf](http://www.nats.co.uk/uploads/NATSEnvironmentPlan(1).pdf)

(ii) Scope for operational efficiency improvement

There are a number of opportunities to improve operational efficiency beyond improving passenger load factors (i.e. seat occupancy):

- **Maximising payload:** Maximising belly-hold freight carriage in addition to seat occupancy would reduce the need for separate freight-only flights. However, this is a commercial decision for airlines, and may not be compatible with all business models such as those based on quick turnaround.
- **Reducing cabin deadweight:** QinetiQ analysis suggests that at a global level this could offer a small potential of reducing fuel burn by up to 1%.
- **Improving airport operations:** QinetiQ analysis suggests that up to a 2% reduction in global fuel consumption could be achieved by ground towing.

(iii) Scenarios for ATM and operational efficiency improvement

In designing our scenarios for increased efficiency in ATM and operations, we have taken account of the key ongoing ATM initiatives affecting the UK and potential improvement from operations identified by QinetiQ:

We have constructed three scenarios:

- Under our **Likely** scenario we assume a compounded 6% improvement from ATM and operations between 2005 to 2020, with ATM expected to contribute the majority of the improvement (i.e. 5%). This is a relatively prudent estimate which reflects the challenge of meeting and maintaining ATM improvements against a backdrop of increasing demand.
- Under our **Optimistic** scenario we assume a compounded 9% improvement from ATM and operations between 2005 to 2020, with ATM expected to contribute 7% to 8% of the improvement.
- Under our **Speculative** scenario we assume a compounded 13% improvement from ATM and operations between 2005 to 2020, with ATM expected to contribute 9% to 10% of the improvement – i.e. achieving current ambitious ATM targets by 2020 and maintaining those efficiencies against a backdrop of increasing demand to 2050. This may be near an upper bound of what is achievable through ATM and operations and could require both aircraft reconfiguration and payload maximisation.

3. Scenarios for annual improvement in fleet fuel efficiency

We have combined our scenarios for engine and airframe innovation, ATM and operations into three scenarios for overall improvement in fleet fuel efficiency:

- Our **Likely** scenario reflects improvement in average fleet fuel efficiency between 2005 and 2050 of 0.8% per year on a seat-km basis.
- Our **Optimistic** scenario reflects improvement in average fleet fuel efficiency between 2005 and 2050 of 1.0% per year on a seat-km basis.
- Our **Speculative** scenario reflects improvement in average fleet fuel efficiency of 1.5% per year on a seat-km basis.

These scenarios, which are within the envelope from recent studies (Table 4.3), are used in our analysis of options for meeting the 2050 target in Chapter 7.

Table 4.3 Comparison between CCC average annual improvements in fleet fuel efficiency and other analyses

Source	Year	Scope	Annual average improvement in efficiency to 2050 (%)
CCC	2009	UK	0.8% (Likely), 1.0% (Optimistic), 1.5% (Speculative)
DfT central	2009	UK	1.1% (to 2030), 0.75% (to 2050)
Sustainable Aviation	2008	UK	2.1%
US FAA	2009	Global	1.0% (low trend), 1.5% (optimistic trend)
IEA	2009	Global	0.9% (High Baseline), 1.1% (Baseline), 1.5% (BLUE Map scenario)
QinetiQ (for CCC)	2008	Global	up to 1.5%
IPCC	1999	Global	1.3% (to 2010), 1.0% (to 2020), 0.5% (to 2050)

Source: CCC collated data and calculations.

In addition to the percentages used in recent analysis, industry groups such as IATA and ICAO's GIACC have set aspirational fuel efficiency goals of 1.5% to 2020 and 2.0% to 2050 respectively.

Chapter 5

Use of biofuels and hydrogen in aviation

The use of biofuels in aviation has been confirmed in recent trials as being technically feasible and specifications for some types of aviation biofuels have already been included in US standards. The extent to which biofuels can be used to meet aviation emissions targets, however, will depend crucially on sustainability, and the extent to which sustainable biofuels are best used in aviation.

This chapter considers lifecycle emissions from biofuels, when emissions from growth of feedstock, fuel production and land-use change are accounted for. It sets out alternative uses for available bioenergy, including use of biofuels in road transport and shipping, renewable heat, power generation and household uses (e.g. cooking and heating). It considers broader sustainability questions relating to the use of land for biofuels in the context of a significantly increasing global population, constrained water resources, climate change impacts on agriculture and concerns about biodiversity. Based on a high-level assessment of these factors, the chapter sets out scenarios for the use of sustainable biofuels in global and UK aviation. Finally, the chapter considers possible use of hydrogen in aviation.

The key messages in the chapter are:

- There are at least three areas of uncertainty over the potential for use of biofuels in aviation:
 - It is not clear whether scarce biofuels should be used in aviation or other sectors (e.g. road transport, shipping, etc.).
 - It is also not clear that sufficient land required to grow substantial volumes of biofuels feedstock will actually be available given the need to feed a significantly increasing global population in the period to 2050, nor is it clear that risks of indirect land-use change through growth of biofuels crops can be adequately addressed.
 - Technological breakthroughs are required in order that second and third generation biofuels which do not require potential agricultural land (e.g. algae) become commercially available.



- Given this uncertainty, we set out a range of scenarios for penetration of biofuels in global aviation from 10% to 30% in 2050, with a lifecycle emissions reduction of 50% compared to oil-derived kerosene. It is prudent to plan for 10% penetration given current sustainability concerns, without ruling out the possibility of significantly higher levels of penetration.
- Evidence suggests that there are significant challenges to use of hydrogen power in aviation, and that a cautious approach is therefore justified.

We set out the analysis that underpins these messages in 2 sections:

1. Use of sustainable biofuels in aviation
2. Use of hydrogen in aviation.

1. Use of sustainable biofuels in aviation

In understanding the role for use of biofuels in aviation, we have assessed technical barriers, and high-level sustainability constraints including lifecycle emissions impacts, alternative uses for biofuels and limits on the level of sustainable biofuels given competing demands for land to produce food to feed a growing global population.

We now consider:

- (i) Technical potential for use of biofuels in aviation
- (ii) Sustainability constraints on the use of biofuels
- (iii) Scenarios for use of sustainable biofuels in aviation.

(i) Technical potential for use of biofuels in aviation

Industry focus on biofuels

There has recently been increasing interest in the use of biofuels¹ in aviation given concerns over the jet fuel prices, and carbon constraints due to the introduction of cap and trade schemes:

- Jet fuel prices: historically fuel costs have accounted for up to 35% of airlines operating costs and oil prices have been high and volatile over the past five years, reaching a maximum of almost US \$150/bbl relative to the current level of around US \$80/bbl.
- Carbon constraints: IATA estimates that inclusion of aviation in the EU ETS will result in a cost increase equivalent to a 19% increase in fuel expenses by 2020.

¹ There is a wider range of 'alternative fuels' that could in principle be used in aviation, including not only biomass derived fuels but also synthetic fuels derive from coal and natural gas. However these routes have not been included in our analysis as they are unlikely to help significantly reduce CO₂ emissions from aviation (see the recent report by RAND and MIT *Infrastructure, Safety and Environment*, 2009).

Recent trials (Box 5.1) suggest that the use of biofuels in aviation is technically feasible; additionally, some biofuels blends are already included in US jet fuel specifications with new blends expected to be included in the coming years.

Box 5.1 Aviation trials of alternative fuels

In recent years the aviation industry has been conducting a series of laboratory, ground and (since 2008) flight tests with a range of different alternative fuels in order to collect the data required by the certification process.

The main players in these tests have been the large airframe manufacturers (Boeing, Airbus), aircraft engine manufacturers (GE Aviation, Rolls-Royce, Pratt & Whitney and their respective joint ventures CFM and IAE) and the petroleum, petrochemical and gas process technology supplier, UOP.

The five flight tests conducted to date have all been of blends of fossil fuel with up to 50% of an alternative fuel. Four of the tests have used fuel derived from a range of biomass feedstocks, while one has used a Fischer-Tropsch (FT) fuel derived from natural gas. The flight tests ranged from 1.5 to 3 hours duration and included a range of 'normal' and 'non-normal' flight manoeuvres (the latter including, for example, in-flight engine shutdown and relight).

Table B5.1 Summary of civil aviation biofuels test flights

Date	Airline	Fuel supplier	Blend	Airframe manufacturer	Engine manufacturer	No. of engines	Flight duration
February 2008	Virgin Atlantic	UOP, Imperium Renewables	20% coconut and babassu methyl ester	Boeing 747-400	GE CF6-80C2	1 of 4	3 hours
February 2008	Qatar Airways	Shell International Petroleum, Qatar Fuel	40% GTL	Airbus A380	Rolls-Royce Trent 900	1 of 4	3 hours
December 2008	Air New Zealand	UOP, Terasol	50% jatropha	Boeing 747-400	Rolls-Royce RB211-524G	1 of 4	2 hours
January 2009	Continental Airlines	UOP, Terasol, Sapphire Energy	47.5% jatropha, 2.5% algae	Boeing 737-800	CFM56-7B	1 of 2	2 hours
January 2009	Japan Air Lines	UOP, Sustainable Oils	42% camelina, 7.5% jatropha, 0.5% algae	Boeing 747-300	Pratt & Whitney JT9D	1 of 4	1.5 hours
October 2009	Qatar Airways						
2010	Jet Blue	UOP		Airbus A320-200	IAE v2500		
2010	Interjet		Halophyte derived	Airbus A320	CFM56		
To be announced	British Airways						

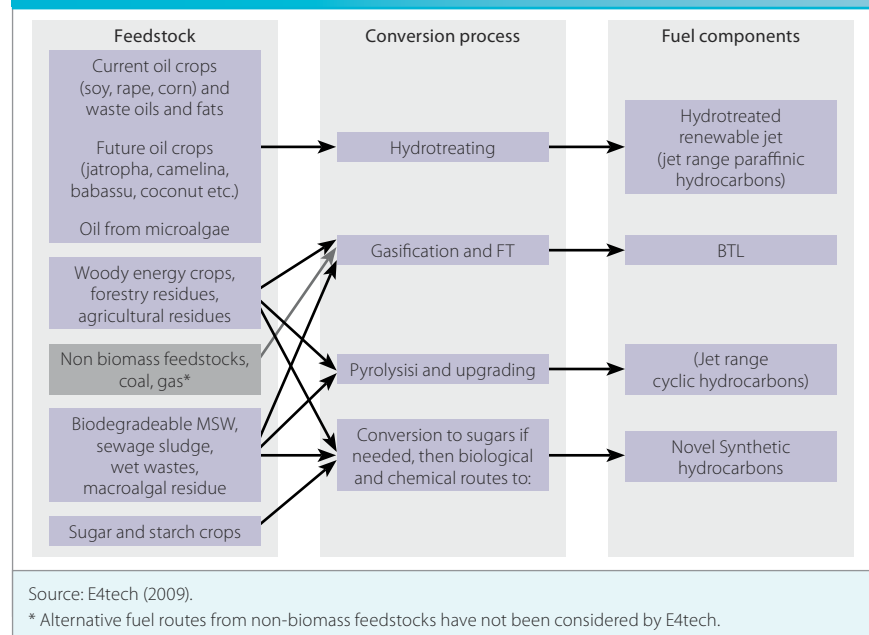
Source: E4tech (2009) based on industry press material.

Routes for production of aviation biofuels

There are several potential routes for producing aviation biofuels (Figure 5.1). In analysis commissioned by the Committee from E4tech, three main routes are identified:

- **Biomass to Liquid (BTL):** this involves gasification of biomass feedstock (e.g. woody crops or wastes), followed by Fischer-Tropsch (FT) synthesis and upgrading steps, to produce jet fuel, diesel or gasoline. A similar process is already used to produce specification-compliant jet fuels from coal (e.g. in South Africa).
- **Hydrogenated Renewable Jet (HRJ):** this involves the conversion of vegetable oils (e.g. conventional oil crops such as palm and soy, but also new oils crops such as jatropha and camelina) and algal oils to aviation fuel through a process including treatment with hydrogen.
- **'Novel synthetic hydrocarbons':** this is a generic term which covers a variety of potential novel routes relying on conversion of biomass to jet fuel via biological or chemical processes.

Figure 5.1 E4tech representation of potential biofuels routes



Current stage of development/addressing technical challenges

The three routes identified above are at different stages of development, with BTL being closest to commercial-scale production, challenges remaining in production of high yield crops for HRJ, and novel synthetic hydrocarbons at an early stage of development:

- Many of the individual technologies required for BTL are commercially available, though their integration into a coherent process is only at the demonstration scale. Commercial-scale plants for road transport BTL fuels are planned from 2012/13².
- Technologies required for HRJ are well known and very similar to those currently used for producing hydro-treated vegetable oil biodiesel for road transport. Small-scale production of jet fuel in existing biofuels plants is expected from 2010, and production in dedicated plants from 2011³. Innovation is required to produce high-yield feedstock from new oil crops such as jatropha and camelina, and to develop algal technology.
- Novel synthetic hydrocarbon technologies are at an earlier stage of development compared to the other two main routes. These technologies are being developed principally by US companies and are currently at pilot-scale testing. Demonstration may occur as early as 2013, but novel synthetic hydrocarbons are unlikely to be commercially available before 2020.

There is therefore a question over the pace at which biofuels could be introduced to aviation given current technical barriers and the required investment to achieve production at scale. These relate, however, primarily to the period to 2030. Going further out in the period to 2050, it is likely that at least some technical barriers could be addressed and that significant use of biofuels in aviation could be technically feasible.

(ii) Sustainability constraints on the use of biofuels

In assessing sustainability constraints on the use of biofuels we consider in turn:

- Emissions of greenhouse gases from growing feedstock and producing biofuels;
- Emissions associated with potential land-use change as a consequence of growing biofuels feedstock;
- Competing demands for available biofuels from other sectors;

² For example, commercial scale plants for BTL diesel are planned by CHOREN in Germany and by TRI in the US from 2012. See E4tech (2009).

³ For example, UOP plans to have a dedicated HRJ plant up and running by Q4 2011 and to commercially produce jet HVO from a diesel plant in 2010. See E4tech (2009).

- Broader sustainability considerations, such as the competing pressure on land-use from biofuels and food production (given the expected increase in population, climate change, water scarcity and therefore possible limits to improvements in agricultural productivity) and possible impacts on biodiversity.

Given that sustainability impacts work through land impacts at the global level, our approach is to consider limits on use of sustainable biofuels in aviation globally, and then to assume that UK aviation biofuels penetration is equal to the global average.

Emissions from growing feedstock and producing biofuels

The degree to which biofuels could deliver lifecycle GHG savings compared with conventional kerosene depends heavily on the type of feedstock used. Table 5.1 sets out E4tech's assessment of possible lifecycle savings for different aviation biofuels routes, based on a review of existing literature and abstracting from possible land-use change effects. This shows that production from conventional oil crops has relatively high emissions compared to production from energy crops (e.g. woody crops and grasses), residues and wastes, low input oil crops, or algae. Specifically:

- For biofuels based on conventional oils, emissions from the use of fertiliser in growth of feedstock and from the production process reduce lifecycle emissions savings by around 50-80%.
- Lifecycle GHG savings could be up to 95% for BTL, 66-89% for new oil crops, up to 98% for algae and up to 90% for novel synthetic hydrocarbons.

Other studies suggest a figure for BTL lifecycle emissions reductions of around 85% (again, abstracting from possible land-use change effects).

Table 5.1 The E4tech assessment of lifecycle savings from biofuels before land use effects

Route	Feedstock	Emissions, g CO ₂ e/MJ fuel	Savings CO ₂ e vs. jet
Fossil jet (baseline)	–	87.5	–
BTL	Energy crops	7.3	92%
	Forestry residues	4.8	95%
HRJ	Conventional oil crops (rapeseed, palm, soy etc)	40-70 (averages)	20-54%
	Jatropha	30	66%
	Camelina	13.5	85%
	Tallow	10	89%
	Algae (Open ponds)	-21 (best case) 1.5 (realistic case)	124% (best case) 98% (realistic case)
Synthetic hydrocarbons	Not specified		70-90%

Source: E4tech (2009).

Emissions from land-use change due to growth of feedstock for biofuels

Lifecycle emissions savings could be reduced if growth of biofuels feedstock were to result in direct or indirect land-use change:

- Direct land-use change occurs where growth of feedstock for biofuels results in deforestation or conversion of other carbon-rich soils.
- Indirect land-use change occurs where growth of biofuels feedstock displaces food production resulting in deforestation or conversion of other carbon-rich soils or cultivation of less productive land requiring greater use of carbon-intense fertilisers.

Direct land-use change has occurred, for example, to support significantly increased production of palm oil in South East Asia⁴. Going forward, the risk of further direct land-use change could be mitigated through introduction of an appropriate regulatory framework.

The risk of indirect land-use change, however, is more difficult to mitigate through regulation, given complexities associated with tracking the chain of impacts from biofuels production on agricultural production.

One key factor in helping to mitigate direct and indirect land-use impacts will be whether or not carbon associated with land-use change and forestry is brought within the scope of a global climate regime.

Estimates of lifecycle emissions reduction including land-use impacts

There is therefore uncertainty about the level of lifecycle emissions reduction of biofuels when land-use change is accounted for, reflected in a wide range of estimates for lifecycle impacts:

- Sustainable Aviation assumes a 50% lifecycle saving in their roadmap.
- IATA assumes a 60-90% saving for BTL biofuels, with a negative 70% saving (i.e. GHG increase) for HRJ biofuels depending on the type of feedstock and where this is grown.

Competing demand for biofuels from other sectors

Analysis by E4tech suggests that biofuels could compete economically with conventional jet fuels in a world of increasing oil and carbon prices, particularly further out in the period to 2050. In particular, conversion of woody crops and wastes (i.e. 'Biomass to Liquid') and use of woody crops such as jatropha and camelina (i.e. 'Hydrogenated Renewable Jet') could become viable from the 2020s.

⁴ See for instance Augustyn (2007). 'A burning issue'. *World Watch Magazine*.

However, even if biofuels could in theory compete in the future with conventional jet fuels there is additional uncertainty about whether supply-constrained biomass should be used in aviation or other sectors:

- Biofuels are currently used in road transport. While, as we set out in our December 2008 report, electrification is likely to be the key technology for decarbonising the surface transport sector, this technology is not applicable to HGVs. In addition, liquid fuels would still be used in hybrid and plug-in hybrid electric vehicles. Biofuels are therefore likely to play a role in road transport in a carbon-constrained world.
- Biomass will continue to be used for cooking and heating in developing countries; currently around two-thirds of global biomass use is for this purpose.
- Biomass could be increasingly used in combined heat and power (CHP) applications or co-firing with coal using CCS technology such that operation results in zero or even negative emissions.
- Biofuels could in principle be used to contribute to emissions reduction from the shipping sector (e.g. first generation biofuels such as biodiesel and vegetable oils can readily be used for ships' diesel). Analysis for our December 2008 report suggested that fuel consumption from the shipping sector in 2050 may exceed fuel consumption from aviation, so potentially this sector could impose a significant extra demand on biomass resource.

The IEA BLUE scenarios⁵ assume that total bioenergy demand will amount to 3.6 billion tonnes of oil equivalent in 2050, with total demand for transport biofuels accounting for around 700 million tonnes (or 19%) of this total and demand from aviation alone accounting for around 165 million tonnes under an assumption of 30% penetration (Box 5.2).

Box 5.2 Land-use requirements from transport biofuels in the IEA BLUE Map scenario

In their Energy Technology Perspectives 2008, the IEA set out global scenarios for penetration of BTL-derived biofuels in aviation, reaching 15% by 2050 in the BLUE Conservative scenario and 30% in the BLUE Map scenario (Figure B5.2a), while noting that rates of penetration could be much higher if sufficient land for growing feedstock became available.

In their recent World Energy Outlook 2009, the IEA presented a more ambitious scenario consistent with stabilisation of atmospheric concentrations of GHG at 450ppm where aviation biofuels achieve a global penetration of 15% by 2030.

⁵ IEA (2008). *Energy Technology Perspectives*.

Box 5.2 continued

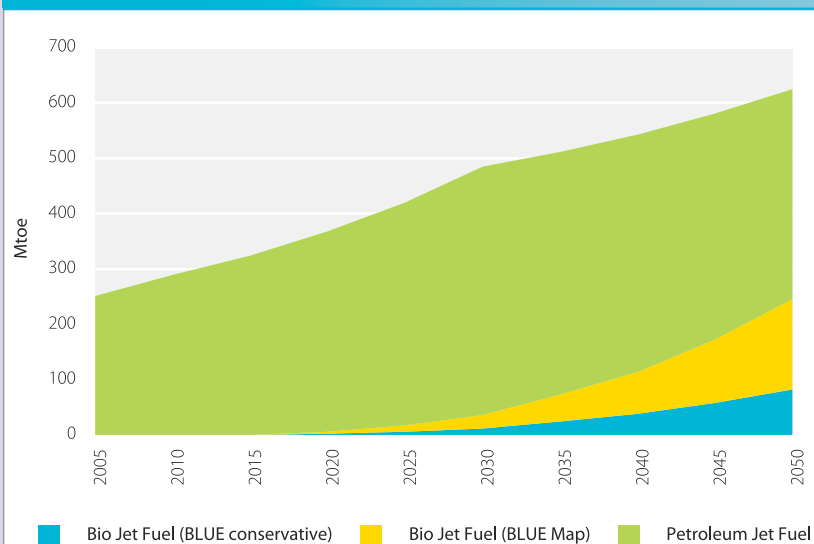
The IEA aviation biofuels scenarios were set in the context of biofuels penetration in the transport sector (including surface transport and shipping in addition to aviation) growing over time to provide energy equivalent to 700 Mtoe by 2050 in the BLUE Map scenario (Figure B5.2b), and of total bioenergy demand (including demand from transport biofuels and from other sectors) increasing to 3.6 billion tonnes of oil equivalent in 2050.

Land requirements for transport biofuels were projected to increase to around 1.6 million km² by 2050 under the BLUE Map scenario (Figure B5.2c).

Land requirements for other biomass uses (e.g. in the power sector and in industry) were projected to increase to between 2.15 and 5.9 million km² by 2050.

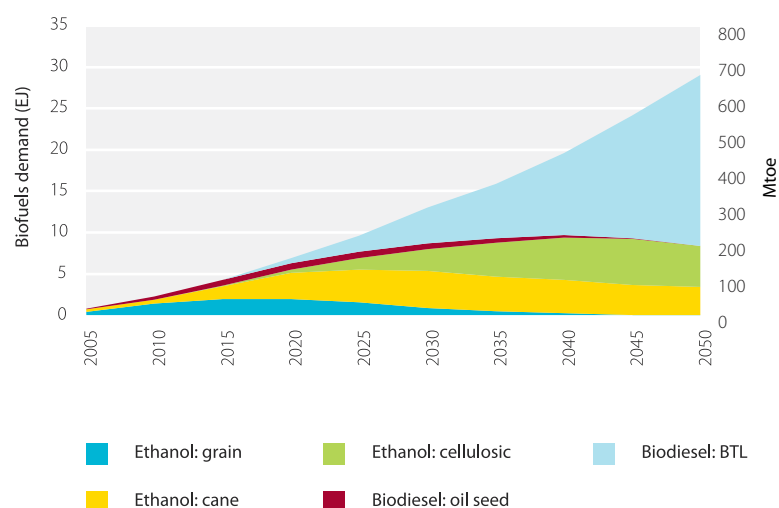
Overall land requirements for biomass production in 2050 in the BLUE Map scenarios were estimated to be between 3.75 and 7.5 million km².

Figure B5.2a The IEA scenarios for biofuel penetration to 2050

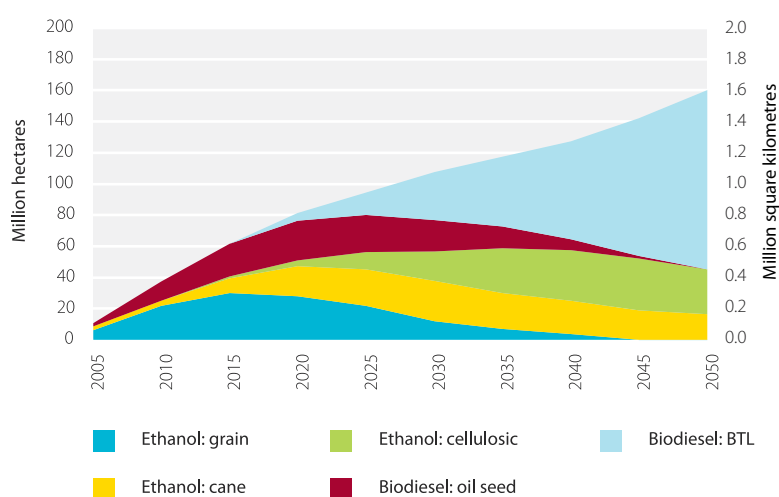


Source: IEA (2009).

Box 5.2 continued

Figure B5.2b Demand for transport biofuels in the IEA BLUE Map scenario

Source: IEA (2008).

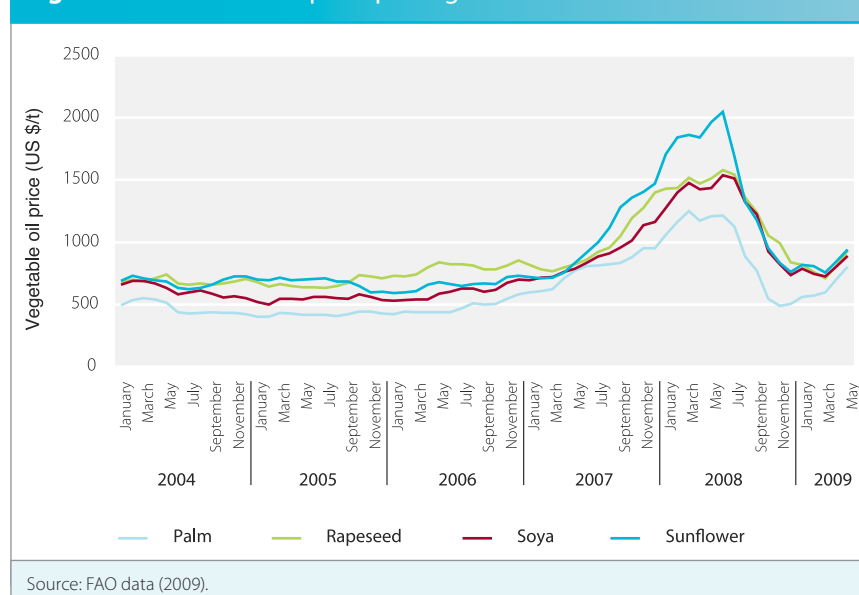
Figure B5.2c Land requirements for biofuel production in the IEA BLUE Map scenario

Source: IEA (2008).

Broader sustainability considerations: tensions between production of biofuels and food, and possible impacts on biodiversity

Increasing use of land for the growth of crops for first generation road transport biofuels (e.g. corn-based ethanol), and the ensuing displacement of food production, was a key driver of the food price shock in 2008⁶. Prices of major staples, such as grains and oilseeds, doubled in just two years between mid-2006 and mid-2008 (Figure 5.2), which in turn led to significant social consequences, particularly for the poor in developing countries. Going forward (and notwithstanding a shift to less land-intensive second and third generation biofuels), there could be further tension between deeper penetration of biofuels and biomass in aviation and other sectors, and increasing agricultural production required to feed a growing global population.

Figure 5.2 Prices of the principal vegetable oils 2004-2009



If 100% of projected aviation fuel use in 2050 were to come from BTL biofuels, E4tech analysis suggests that this would imply a land requirement for growth of feedstock of around 2.5 million km². Together with use of biofuels in other sectors as set out in the IEA's BLUE Map scenario (as described above), the implied land requirement for biofuels feedstock would be around 3.4 million km². In addition, the IEA estimate that there could be an additional demand for other biomass uses of up to 5.9 million km².

This may be compared to the 0.36 million km² that are currently used for biofuel feedstock production, out of the overall 14 million km² currently dedicated to crop production. Going forward, estimates of unused agricultural land vary from very low to nearly 14 million km² depending on assumptions about agricultural productivity improvement, while marginal land that could be converted to biofuel feedstock production may amount to a few million km².

⁶ See Mitchell (2008). *A note on rising food prices*. World Bank Policy Research Working Paper 4682.

Figure 5.3 compares estimates of land requirements for 100% BTL biofuels penetration in aviation by 2050 and other biomass uses with estimates of available idle and marginal land under optimistic assumptions about agricultural productivity improvement⁷, while Figure 5.4 provides more detail on the amount and type of land that may be available in a very optimistic scenario.

Figure 5.3 Potential land requirements in 2050 from aviation biofuels and other biomass uses

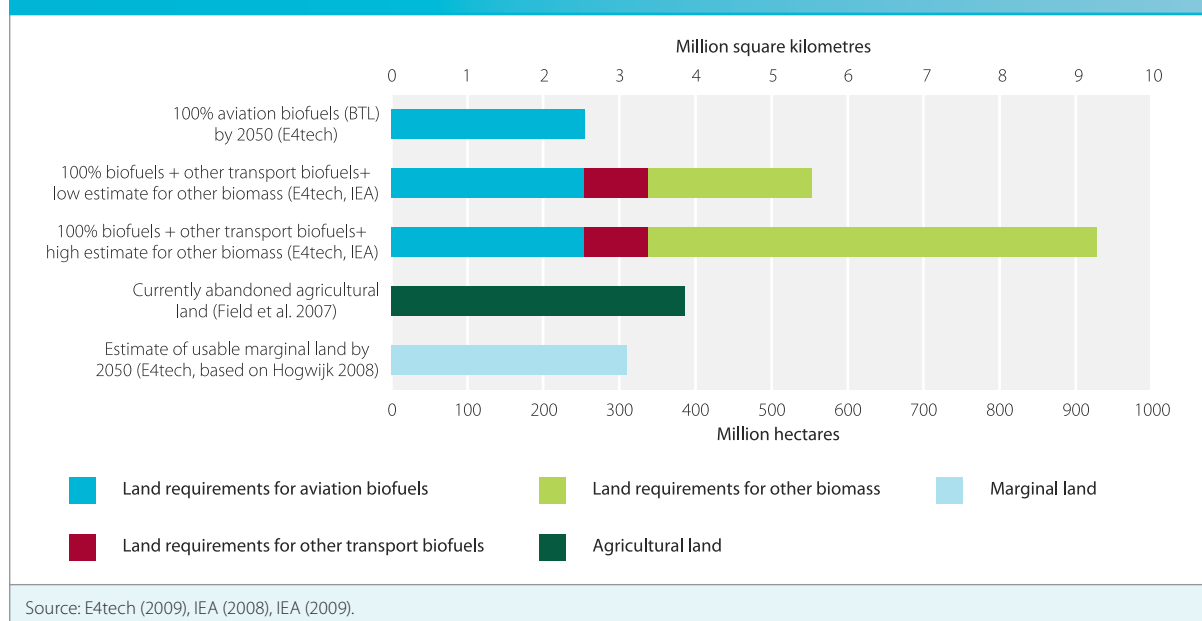
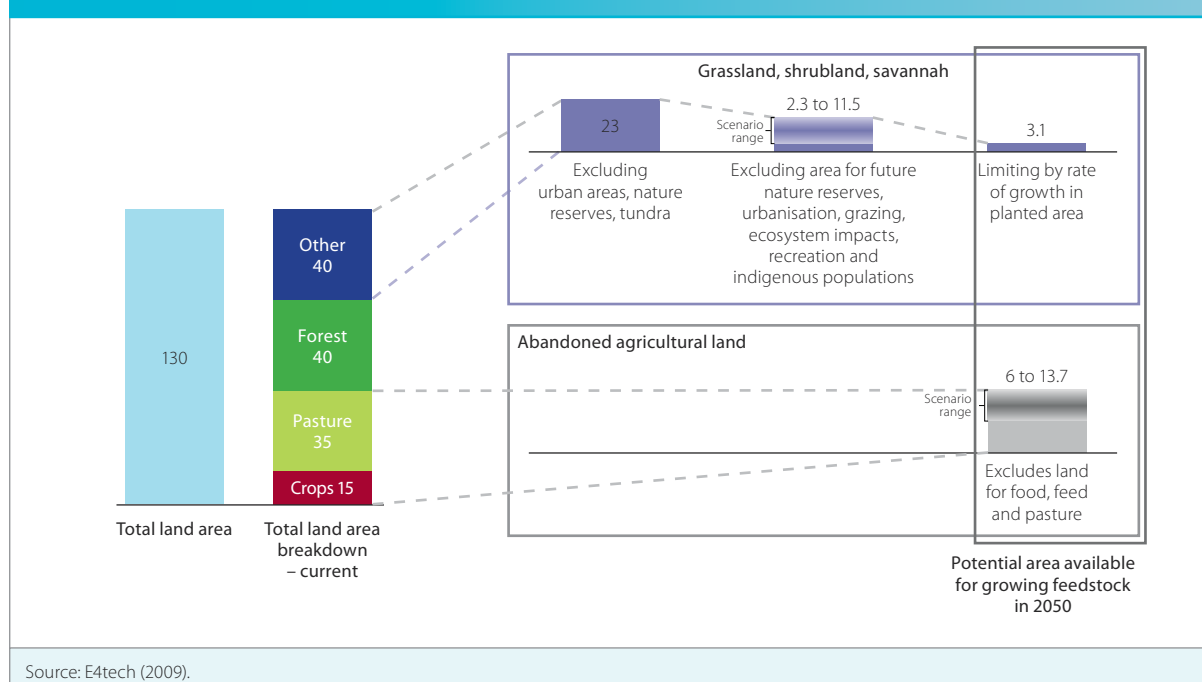


Figure 5.4 E4tech assessment of potential land availability for biomass feedstock (million km²)



⁷ As noted by Field et al. (Field et al (2007). 'Biomass Energy: the scale of the potential resource'. *Trends in Ecology and Evolution*.) the available lands for biomass feedstock are likely to be at the lower end of the spectrum for fertility and climate, with implications for yields.

However, the extent to which unused agricultural land or marginal land will be available depends crucially on global population growth and agriculture productivity improvement:

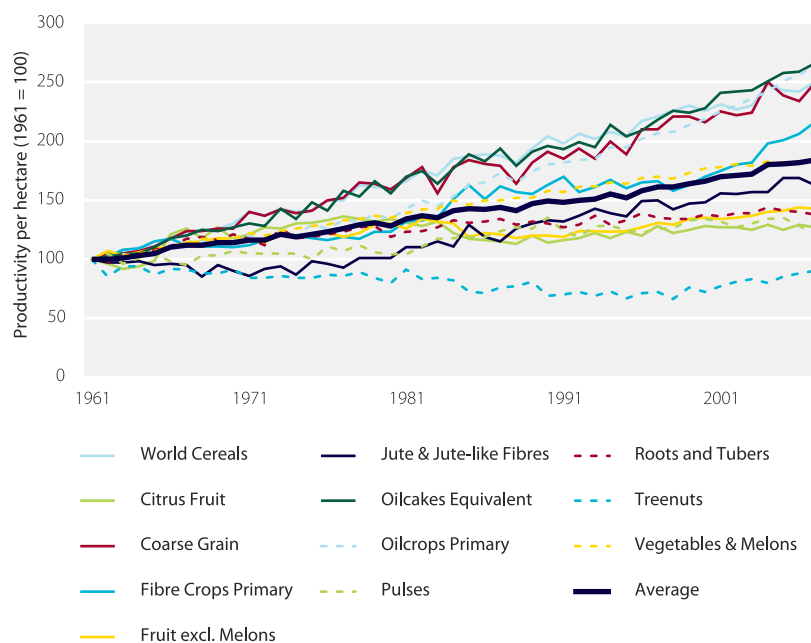
- In the period to 2050, it is expected that the global population will increase from the current level of around 6.7 billion to over 9.1 billion. The FAO estimates that meeting the associated increasing demand for food (and the predicted shift toward western-style diets in developing countries) will require a 70% increase in global food production by 2050⁸.
- Over the last 50 years, agricultural production has increased at rates that have outpaced population growth. FAO statistics show an increase of 138% in gross world food production since 1961, and an increase of more than 200% in overall agricultural production, largely driven by productivity and crop yield improvements (Figure 5.4) and with only a modest increase in cultivated land. Over the same period, population increased by 123%. As a result, the Royal Society estimates that for each person alive today there is, in theory, an additional 29% more food compared with 1960.
- If historical rates of growth in agricultural productivity could be maintained in the period to 2050, then the challenge of feeding a growing population could be met without converting marginal and idle land into agricultural production, which would leave more scope for energy crops. However the 'green revolution' of the early 1960s relied heavily on the use of fertilisers, pesticides and water, and it is uncertain that these rates of growth in productivity can be sustained in the future given greenhouse gas targets, particularly as the impact of unavoidable climate change beyond a point will be to reduce agricultural productivity (Box 5.3).
- In addition to land constraints, there are constraints on available water resource as the global population increases. These have been highlighted for instance by John Beddington, the UK government's Chief Scientific Adviser. He argues that demand for water in 2050 will be 30% above current levels, and that this will limit availability of water for use in agriculture⁹.

Recognising the tension between land-use for growth of biofuels, and possible uses of biofuels in other sectors, the IEA in their Energy Technology Perspectives 2008 set out a range of scenarios for biofuels penetration from 15% to 30% in 2050, while acknowledging the possibility that biofuels may reach much higher penetration levels (and ultimately completely replace conventional aviation kerosene) if sufficient land for growing feedstock were to become available.

⁸ The increase in demand for food will reflect not only increased population but also changes in diet, with a wide range of assumptions possible as to how far developing world diets will converge towards developed world resource intensive patterns (e.g. with higher proportion of meat and dairy). Estimates of total additional agricultural production required range from 50 to 100%.

⁹ Beddington (2009). *Food, Energy, Water and the Climate: A Perfect Storm of Global Events*.

See http://www.dius.gov.uk/news_and_speeches/speeches/john_beddington/~/_media/publications/P/Perfect-Storm-Paper

Figure 5.5 Agricultural productivity per hectare since 1961

Source: FAO data (2009).

Box 5.3 Potential for future productivity improvements in agriculture

A number of major recent studies have looked at the challenges facing the global agricultural sector in meeting the growing demand for food in the period to 2050. A key underlying factor is the extent to which crop yields can keep improving at the same rate as over the past 40 to 50 years in the period to 2050, under a series of additional constraints such as climate change, water scarcity and the need to limit the use of pesticides and nitrogen-based fertilisers.

The **OECD/FAO Outlook¹** offers some medium-term perspectives on these issues. It identifies three critical supply factors that could affect the rate of growth in agricultural productivity:

- Land availability (including the speed with which new land can be brought into production)
- Water availability
- Agricultural productivity, including crop yields and livestock productivity.

Box 5.3 continued

Overall, the OECD/FAO report concludes that agricultural production could be increased considerably. However the report highlights the need for investments (e.g. in water efficiency) and risk management, as well as the potential role that concerns about broader environmental impact, GM technology and food quality may have in shaping the future of the agricultural sector.

A recent **Royal Society** report² looks at these issues over the longer term (to 2050) and focuses more clearly on the need for the agricultural sector to increase food production within clear sustainability boundaries. The report acknowledges the remarkable success of the 'green revolution' in feeding an expanding world population, but also points to its environmental shortcomings (including increasing emissions of nitrates and pesticides and depletion of aquifers) and uneven distribution of the benefits in different regions of the world and among different social groups. It then sets out a blueprint for 'sustainable intensification' of the global agricultural sector.

The constraints on future crop production that need to be addressed according to the Royal Society report are the following:

- Climate change, as a cross-cutting threat which will aggravate the effects on crops of heat, drought, salinity and submergence
- Unsustainable water abstraction
- Temperature extremes
- Increased tropospheric concentrations of ozone, which can damage crops
- Soil quality depletion through erosion, pollution and urbanisation
- The need to maintain adequate levels of crop nutrition while reducing the amount of synthetic nitrogen fertilisers
- The need for effective control of pests, diseases and weed competition
- The need to manage energy and CO₂ implications of agriculture
- The need to maintain genetic diversity in crops.

The report suggests that in order to achieve a sustainable intensification in global agriculture a combination of many different agricultural practices and technologies will be needed, including:

Box 5.3 continued

- Advanced biotechnology and crop genetics (both through GM crops and conventional breeding techniques)
- Improved crop and soil management practices (e.g. integrated pest and nutrient management, soil and water conservation, water harvesting, integration of agroforestry into crop systems).

A recent report by **UNEP**³ (which by contrast with the previous two reports focuses on biofuels) also acknowledges these challenges and points to the importance of fostering sustainable land-use for biomass production, including increasing agricultural yields in an environmentally benign manner (focusing in particular on regions where productivity increases have lagged), directing new fields to degraded land and making more efficient use of biomass, including enhancing the use of waste and residues.

1 OECD/FAO (2009). *Agricultural Outlook 2009-2018*.

2 Royal Society (2009). *Reaping the benefits: science and the sustainable intensification of global agriculture*.

3 UNEP (2009). *Towards sustainable production and use of resources: assessing biofuels*.

An alternative view is set out in scenarios commissioned by the Committee from E4tech (Box 5.4). These assume that agricultural productivity improvement is sufficiently large to offset population increases and/ or that there are technological breakthroughs relating to biofuels with lower land requirements:

- The E4tech analysis is based on primary studies which assume that the growth in agricultural productivity will not slow down in the foreseeable future, so that currently unused agricultural land and marginal land will be available to grow crops for biofuels.
- E4tech envisage that a significant contribution to the aviation biofuel mix could come from the BTL route, which in principle could rely on forest residues and waste and would therefore have a lower land-use impact than woody crops.

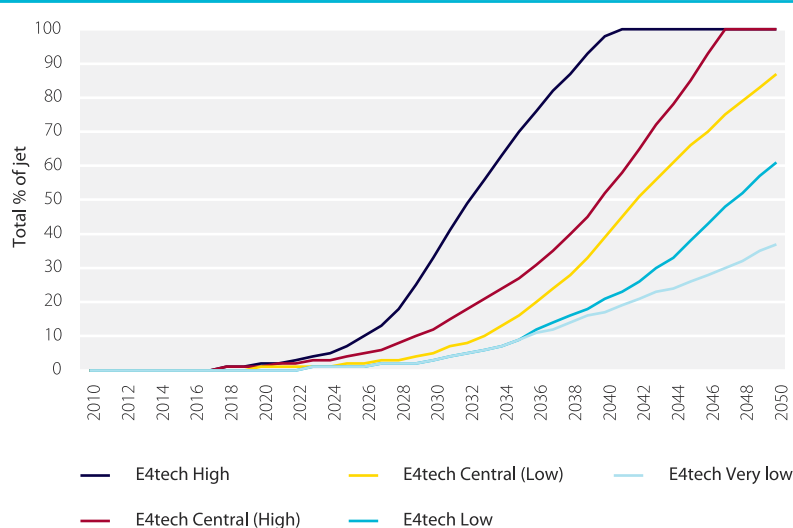
Given these assumptions E4tech set out a range for penetration of sustainable biofuels in aviation from 37% to 100% in 2050 (see Box 5.4).

Box 5.4 E4tech scenarios for aviation biofuels penetration

E4tech considered the technological and economic aspects of use of biofuels in aviation. They then developed scenarios for different combinations of oil prices and carbon prices and different assumptions on the use of conventional vegetable oils and the speed and success of technology development in new oil crops, algae, and novel synthetic hydrocarbons. In all scenarios, uptake was limited by the speed at which new conversion plants could be built, and new crops and algae plants established. Uptake is given as a percentage of the highest global aviation fuel demand scenario used in the IPCC 4th Assessment report (Conserve ULS).

The full set of 18 scenarios was then narrowed down to five summary scenarios illustrated in Figure B5.4. None of the summary scenarios included use of conventional oil crops for HRJ, as a result of potential sustainability impacts, and the likelihood that prices will remain above the level needed to make production competitive with conventional jet fuel. In the Central (Low), Low and Very Low scenarios, commercial introduction of new crops and algae is delayed by five years, and the development of synthetic hydrocarbons is not successful for jet fuels.

Figure B5.4 Proportion of biofuel penetration in aviation in the E4tech scenarios



Source: E4tech (2009).

(iii) Scenarios for use of sustainable biofuels in aviation

Our scenarios for aviation biofuels penetration cover the period to 2050. For the initial part of this period, the binding constraints on biofuels penetration relate to technical barriers (e.g. the need for a technology breakthrough), limits on planting rates for biofuels feedstock, limits on the pace of investment in new plant for biofuels production, and commercial viability of biofuels given relatively high initial costs and relatively low oil and carbon prices.

Further out to 2050, sustainability constraints and use of biofuels in other sectors become increasingly important.

We set out three scenarios covering a range of uncertainty over possible penetration of biofuels in aviation. The scenarios are defined by the penetration of biofuels over time and the lifecycle biofuels emissions reduction.

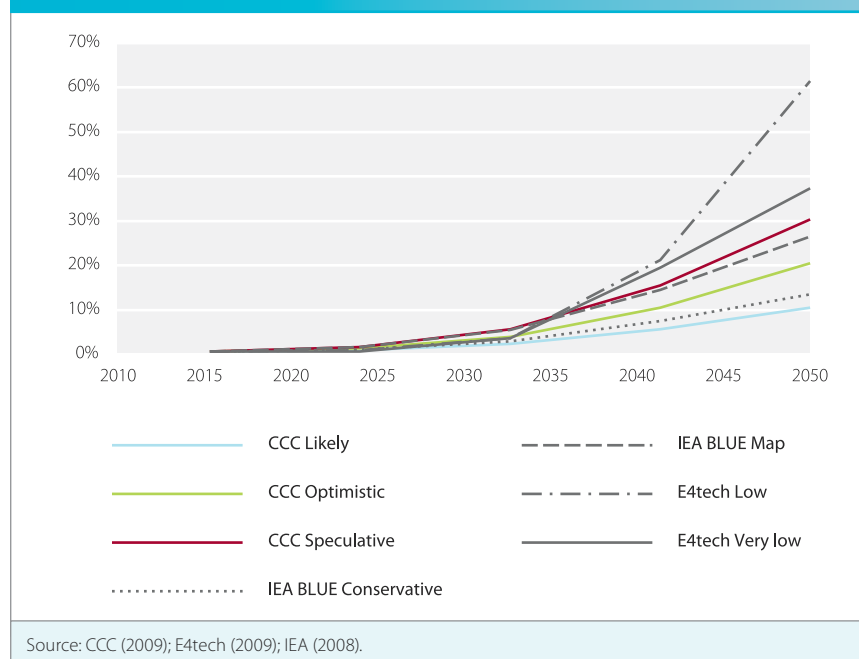
We assume penetration in 2050 from 10% to 30% and lifecycle GHG savings of 50%, which we have chosen to reflect current significant sustainability risks. It is currently prudent to plan for 10% penetration although significantly higher levels of penetration should not be ruled out (e.g. subject to new evidence that there will be abundant supplies of waste or residues, or technological breakthroughs to facilitate mass production of sustainable algae or to allow production of biofuels feedstocks in deserts using solar power and water desalination):

- Under our **Likely** scenario we assume that penetration of aviation biofuels is below 2% in 2030 and reaches 10% by 2050, reflecting a world where there is very limited resource available for use of biofuels in the aviation sector (either due to land constraints, limited progress developing biofuels from routes requiring less land input, or demand for biofuels from other sectors). This is slightly more prudent than the IEA's 'BLUE conservative' scenario, which assumes a 15% penetration of aviation biofuels by 2050. We follow Sustainable Aviation and assume greenhouse gas lifecycle savings of 50% to reflect emissions in production of biofuels and possible land-use change impacts. Under these assumptions, an aviation emissions reduction of 5% is achieved in 2050 compared to a counterfactual where no biofuels are being used.
- Under our **Optimistic** scenario we assume that penetration of aviation biofuels is around 3% by 2030 and 20% by 2050; this scenario reflects constraints on the availability of sustainable biofuels and use of sustainable biofuels in aviation, and is slightly higher than the IEA's 'Blue conservative' scenario. Assuming greenhouse gas lifecycle savings of 50%, these assumptions translate into a reduction of emissions from aviation of 10% by 2050 compared to a counterfactual where no biofuels are used.

- Under our **Speculative** scenario we assume that penetration of aviation biofuels reaches 5% by 2030 and 30% by 2050; this scenario is consistent with the high end of the range from the IEA Blue scenarios, and the low end of the range from the E4tech analysis. Assuming greenhouse gas lifecycle savings of 50%, this would translate into reductions in emissions from aviation of around 15% by 2050 compared to a counterfactual where no biofuels are being used.

Figure 5.6 illustrates our scenarios and compares them to the most relevant scenarios from E4tech and IEA. We use these scenarios in our wider analysis of options for meeting the 2050 UK aviation emissions target in Chapter 7.

Figure 5.6 Proportion of biofuel penetration in aviation: CCC scenarios and comparable scenarios from E4tech and IEA



2. Use of hydrogen in aviation

In the next section we outline the technical status and barriers of using hydrogen-fuelled aircraft. Given challenges and uncertainties for using hydrogen in aviation, we do not reflect any possible emissions reduction in our scenarios.

In our December 2008 report we stated that in addition to biofuels, hydrogen was another potential alternative fuel source to kerosene in the longer term. However, we also highlighted significant infrastructure issues, the need for a sustainable source of hydrogen and that the climate effect of water vapour at altitude would need to be investigated more fully. Taking each in turn:

Technical feasibility

Hydrogen-fuelled engines first ran in the 1930s. Since then research has shown the feasibility of civil aircraft powered by liquid hydrogen and manufacturers suggest that one could be developed in the medium term. Last year, the Committee asked QinetiQ to review the potential for hydrogen use in aviation and their key technical findings were as follows:

- Due to the need for civil aircraft to travel at high speed, liquid hydrogen, as opposed to the gaseous form used in airships, at low temperatures and/or under pressure offers the most potential.
- For the aircraft itself, the key issues surrounding liquid hydrogen are storage and reduction of drag; liquid hydrogen needs four times the size of fuel tank to carry the same energy – this requires a bulkier or longer aerodynamic shape.
- The propulsion can be driven by a gas turbine and the modifications required are relatively straightforward.
- One issue for the aircraft is that of safety, especially as the Hindenburg and R101 airship fires remain in the public memory. However from a technical perspective, in the open atmosphere, hydrogen rises quickly and burns below the detonation limit without explosion. It does not form a burning pool and Airbus suggests, in their CRYOPLANE project, that a hydrogen aircraft could be at least as safe as a conventional aircraft. Public perception, however, may remain an issue.

Availability of sustainably produced hydrogen

Notwithstanding the technical issues described above, there are barriers to hydrogen as a sustainably-sourced energy carrier. Currently, commercial production of hydrogen is dominated by the use of fossil fuels without carbon capture and storage (CCS), primarily natural gas, although the use of low-carbon energy sources for hydrogen production is technically proven. However, in most locations these low-carbon resources can be used in other ways to reduce emissions, often by a greater amount, in more mature applications and at lower cost.

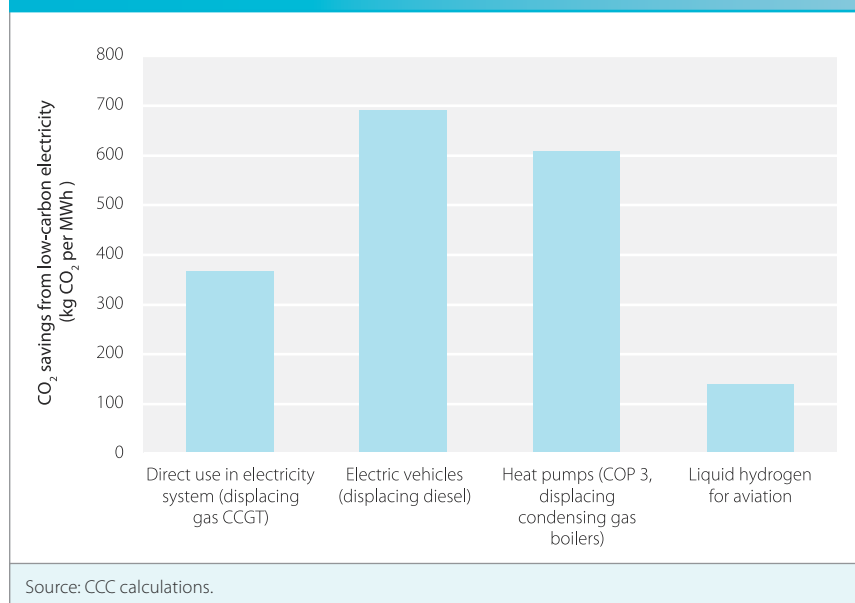
Hydrogen production using low-carbon electricity, via the electrolytic splitting of water, would, in almost all countries in the short to medium-term, reduce emissions by considerably less than the use of the same electricity simply to reduce fossil fuel power generation (see Figure 5.7). There are three main reasons for this:

- i) The extra step of using electricity for hydrogen production involves energy losses of at least 20% that could be avoided by its direct use in the electricity system

ii) Fossil fuel-derived electricity is almost always more carbon-intensive than transport fuels, per unit of energy

iii) The further energy requirement for the liquefaction of the hydrogen for use in aviation would take electricity equivalent to at least a further 30% of the energy content of the hydrogen.

Figure 5.7 CO₂ savings from use of hydrogen produced with low-carbon electricity



Until electricity generation is almost entirely decarbonised, it is difficult to see how electrolytic hydrogen production could be considered genuinely low-carbon. Such levels of electricity decarbonisation are unlikely to occur until 2030 at the earliest in most countries, although there are parts of the world in which 'stranded' renewable electricity resources (i.e. those with limited or no access to an electricity grid) could sensibly be used before then.

The use of biomass for hydrogen production again competes with a variety of other uses, as outlined [in (iii) of section 1], including the production of liquid biofuels.

The most promising medium-term source of low-carbon hydrogen may be the use of fossil fuels with CCS, via processes such as coal gasification and steam methane reforming. Although these processes are mainly being considered as 'pre-combustion' CCS electricity generation options, the production of hydrogen is one of the steps in the generation of electricity within such plants. Indeed, avoiding the subsequent hydrogen combustion step for electricity generation promises significant efficiency advantages in using the hydrogen for transport.

The high energy consumption of the hydrogen liquefaction process will, however, counteract this advantage unless a process with substantially lower energy consumption can be used¹⁰. Furthermore, as CCS has not yet been demonstrated at large scale it is not reasonable to expect significant quantities of low-carbon hydrogen production via this route before 2025 at the earliest.

In addition to the challenge of producing hydrogen sustainably, the introduction of hydrogen-fuelled aircraft poses a significant logistical problem, as either two fuel systems are maintained worldwide, which would be expensive, or a fleet switchover would be required over say five to ten years, which would 'write off' the residual value of any kerosene-powered aircraft.

Climate effects of hydrogen

Hydrogen-fuelled aircraft would not emit any CO₂, the main emission from hydrogen combustion being water. Therefore, sustainably produced hydrogen would for the most part resolve the CO₂ issue, but the water vapour would have significant non-CO₂ climate effects that could well be greater than those from kerosene-powered aircraft:

- The burning of hydrogen generates about 2.6 times as much water as the same energy content in kerosene. Accounting for the additional energy required to lift and propel the bulkier aircraft, this rises to a factor of around 3.
- The greater water content of the exhaust from a hydrogen engine will cause contrails and induced cirrus to form under a wider range of atmospheric conditions. The CRYOPLANE project suggests that cloud cover due to contrails may be up to 50% higher for hydrogen compared to kerosene (see Chapter 6 for a discussion of the relative importance of induced cloudiness and CO₂ on warming).
- It is also possible that a bulkier hydrogen-fuelled aircraft would cruise at higher altitude in order to reduce drag. Water vapour emissions would therefore be delivered into the lower stratosphere, which is very dry. The resulting climate warming effect is estimated to be some 13 times larger than that of CO₂ emissions from a lower flying, kerosene-powered aircraft¹¹.

In conclusion, hydrogen-fuelled aircraft could be and indeed have been built. There are, however, significant technical and logistical barriers including, but not limited to: public perception, sustainably sourcing hydrogen and logistical issues at airports. Even then, the concept should not be pursued until the total climate impacts are more clearly understood.

¹⁰ For example, the pre-cooling of hydrogen via heat exchange with liquefied natural gas (LNG) as outlined in Allam & James (US patent no. 2005/0210914 A1), which is claimed to have the potential to reduce the energy consumption for hydrogen liquefaction by around 70%.

¹¹ See the Royal Commission on Environmental Pollution (2002). *Short Report: The Environmental Effects of Civil Aircraft in Flight*.

Chapter 6

Non-CO₂ climate effects of aviation

120

The report so far has only considered aviation CO₂ emissions. There are, however, potentially significant non-CO₂ effects from aviation which lead to both additional warming and cooling effects on the climate. Overall the consensus is that considered together, these effects have an overall additional warming effect. A comprehensive framework for reducing the climate effects of aviation should account for these non-CO₂ effects. In this chapter we:

- Summarise scientific understanding of aviation non-CO₂ effects;
- Consider at a high level policy options to mitigate these effects;
- Consider possible implications of aviation non-CO₂ effects for UK economy-wide and aviation emissions targets.

The key messages in the chapter are:

- There is high scientific confidence that the total climate warming effect of aviation is more than that from CO₂ emissions alone.
- As scientific understanding develops, aviation non-CO₂ effects are likely to be accounted for in any international framework to address global emissions.
- This could have implications for UK economy-wide and aviation emissions targets, and could require additional emissions reduction effort within aviation.

We set out the chapter in three sections:

1. The non-CO₂ effects of aviation
2. Policy options for reducing the non-CO₂ effects of aviation
3. Possible implications of non-CO₂ effects for UK aviation

1. The non-CO₂ effects of aviation

Types of effects

Non-CO₂ climate effects of aviation arise from emissions of gases and particles, and also from induced cloudiness (see Box 6.1):



- **Emission of gases and particles:** Aside from CO₂, combustion of aviation fuel results in emission of water vapour, nitrogen oxides (NO_x) and aerosols. NO_x are indirect Greenhouse Gases (GHGs), in that they do not give rise to a radiative effect themselves, but influence the concentration of other direct GHGs by enhancing ozone (leading to warming) and suppressing methane (leading to cooling). With the exception of sulphate aerosols, all other emissions cause warming.
- **Induced cloudiness:** Depending on meteorological conditions, the flight of aircraft can also cause formation of linear ice clouds (contrails) and can lead to further subsequent aviation-induced cloudiness. These cloud effects cause additional warming.

Box 6.1 Radiative forcing effects of aviation

The overall effect of aviation on climate is currently the subject of active scientific research. Radiative Forcing (RF) is a standard metric used to compare the contribution of changes in individual atmospheric constituents (forcing agents) to the energy imbalance of the earth-atmosphere system since pre-industrial times. Figure B6.1 shows global average RF from global aviation in the year 2005, with positive RF values indicating warming and negative values indicating cooling.

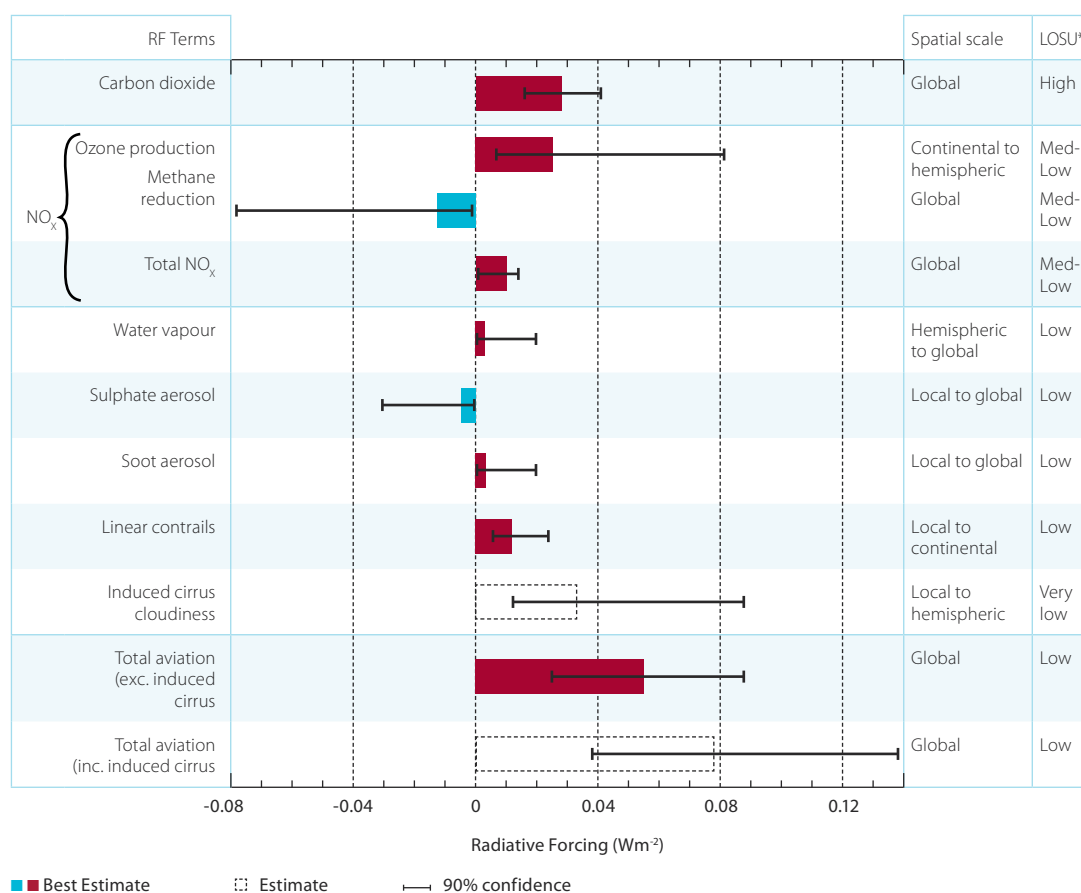
It is important to understand that RF measures the energy imbalance at a given point in time. It is determined in part by the current stock of each forcing agent in the atmosphere, and so depends on the emissions history of that agent and its lifetime. For instance, CO₂ remains in the atmosphere for many centuries, so the CO₂ RF results from the accumulation of emissions since the start of aviation activity. In contrast, contrails only remain for up to several hours, and so the contrail RF is due only to contrails formed by activity in 2005.

RF indicates the current imbalance arising from past activity up until now; it does not give an indication of how current activity will contribute to future climate change. This is because a long-lived forcing agent emitted now will continue to exert RF for much longer than a short-lived agent.



Box 6.1 continued

Figure B6.1 Aviation radiative forcing components in 2005



Source: Reproduced from Lee et al. (2009)¹. Global average radiative forcing (in Watts per square metre, Wm⁻²) in the year 2005 from global aviation. Bars are shown for each of the identified aviation effects, with total bars (with and without induced cloudiness) at the bottom. The right hand columns indicate the spatial scales over which these forcing effects operate and the level of scientific understanding (LOSU) regarding each forcing.

Note: *Level of Scientific Understanding

As can be seen from Figure B6.1, aviation to date has given rise to radiative forcing in the following ways:

- Emissions of CO₂ resulting in a positive RF (warming);
- Emissions of NO_x resulting in the formation of tropospheric ozone (O₃) via atmospheric chemistry, with a positive RF (warming);
- Emissions of NO_x resulting in the destruction of ambient methane (CH₄), also via atmospheric chemistry, with a negative RF (cooling). This destruction of CH₄ leads to further, longer-term loss of tropospheric O₃;
- Emissions of water vapour resulting in a positive RF (warming);
- Emissions of sulphate particles arising from sulphur in the fuel resulting in a negative RF (cooling);
- Emissions of soot particles resulting in a positive RF (warming);
- The formation (depending upon atmospheric conditions) of persistent linear contrails, and further induced cloudiness effects, resulting in an overall positive RF effect (warming).

¹ Lee et al. (2009) 'Aviation and global climate in the 21st century'. *Atmospheric Environment*

Issues in quantifying effects

The UNFCCC already has an agreed framework for comparing the relative effects of specific non-CO₂ GHG emissions covered by the Kyoto Protocol (such as methane and nitrous oxide). This makes use of the 100-year Global Warming Potential (GWP) metric to quantify emissions equivalence¹.

For emissions of gases not covered by the Kyoto Protocol (e.g. NO_x) and for other induced changes (i.e. contrails and cirrus), there are additional complications in quantifying emissions equivalence:

- **Scientific uncertainty:** Their radiative effects have poorer levels of scientific understanding than that for CO₂ (Box 6.1), ranging from 'medium-low' for NO_x effects to 'very low' for aircraft-induced cloudiness. Their assessment requires detailed modelling of atmospheric chemistry and of highly uncertain physical processes that affect aerosol abundance and cloud formation.
- **Spatial and temporal variation:** Kyoto GHGs have long lifetimes (on the order of several years or more) allowing them to become well-mixed in the atmosphere and provide a homogeneous global forcing. In contrast, aviation non-CO₂ effects occur on a range of scales from very short-lived and local (e.g. contrails), to long-lived and global (e.g. effect of NO_x on methane).

Metrics

The importance of additional aviation effects on climate has been widely recognised in policy circles². However, there is ongoing discussion about how these effects can best be quantified (Box 6.2).

Box 6.2 Metrics for aviation climate effects

Metrics

Three common metrics are discussed here. They can be grouped into one that measures current effects as a result of past emissions (Radiative Forcing Index) and those that measure future effects arising from present emissions (Global Warming Potential and Global Temperature Potential):

- **Radiative Forcing Index (RFI):** The Radiative Forcing Index (RFI), introduced by the IPCC in their 1999 report¹, describes the relative contribution to radiative forcing (RF, see Box 6.1) of all forcing agents from aviation, compared with that of carbon dioxide alone. RFI is the ratio of the total RF from aviation to the RF from CO₂. Because RF measures the effect of activity to date, rather than the future effect of current activity, the RFI is not an appropriate measure of emissions equivalence.

¹ See Chapter 9, Box 9.1, from our 2008 report *Building a low-carbon economy* for more details on Kyoto GHGs.

² See for instance DfT (2004) *Aviation and Global Warming*.



Box 6.2 continued

- **Global Warming Potential (GWP):** Global Warming Potential (GWP) is designed as an emissions equivalence metric. It measures the total RF accumulated over a given time horizon arising from a unit emission of forcing agent, relative to that of CO₂. A time horizon of 100 years is used for the international reporting of Kyoto GHG emissions. There are certain theoretical difficulties in producing measures of the GWP of the non-CO₂ effects of aviation, particularly in taking into account short-lived effects, and effects that do not relate to emissions in a straightforward way (e.g. the formation of contrails and cirrus cloud coverage only occurs under certain atmospheric conditions). Nevertheless, the GWP is finding some favour as the only current way of formulating a CO₂ emissions-equivalence for aviation's non-CO₂ effects² that is consistent with the current policy framework. It is also important to note that GWP varies with time horizon, even for long-lived greenhouse gases, and that the choice of 100 years is a policy selection rather than a scientific one. The overall GWPs for aviation effects have been assigned a 'very low' level of scientific understanding (Box 6.3) simply because of the uncertainties in the input data to these metrics (i.e. not an uncertainty in the concept of the metric itself) – this is illustrated by an overall aviation NO_x GWP which ranged from -2.1 to +71.

- **Global Temperature Potential (GTP):** The GTP may be considered analogous to the GWP in that it considers the equivalence of a unit release of emissions to that of CO₂. Rather than calculating the ratio of RFs accumulated over a period of time for that agent and CO₂, however, it calculates the ratio of global mean surface temperature responses at some specific future point in time.

Comparing metrics

The RFI is not intended to measure the equivalence of future non-CO₂ effects. The GWP and GTP are both suitable metrics for this purpose, and recent research has produced estimates of aviation effects using both these metrics (Box 6.3). However, the convention remains under the United Nations Framework Convention on Climate Change (UNFCCC) to express non-CO₂ emissions in terms of CO₂-equivalent using the 100-year GWP metric. A recent workshop of the IPCC³ concluded that it would be inappropriate at the current time to propose replacing the GWP with the GTP as more research was required on the GTP's performance and potential applications.

Finally, none of the global measures fully address the likely importance of localised forcing of the climate system. For example, because of its relatively short timescale, the ozone impact of NO_x is limited mainly to the Northern Hemisphere, whereas the longer timescale of its methane effect means that it is global. Even if a global metric were to imply that these two effects offset each other, they may still in fact lead to climate change if one or the other effect dominated in each hemisphere.

1 IPCC (2009), *Aviation and the global atmosphere*. Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

2 See for instance Forster et al. (2007) Corrigendum to 'it is premature to include non-CO₂ effects of aviation in emission trading schemes'. *Atmospheric Environment*; Fuglestad et al. (2009) Transport Impacts on Atmosphere and Climate: Metrics. *Atmospheric Environment*

3 IPCC (2009), *Summary report of the IPCC expert meeting on the science of alternative metrics* (<http://www.ipcc.ch/meetings/session30/doc13.pdf>).

One approach to quantification has been to use estimates of current radiative forcing of the individual effects relative to that of CO₂ (the Radiative Forcing Index, RFI) as a 'multiplier' of CO₂ emissions to determine future effects. This is now regarded as inappropriate, however (Box 6.2), and more recent estimates based on suitable metrics such as Global Warming Potential and Global Temperature Potential have been proposed (Box 6.3).

Box 6.3 GWP and GTP estimates of aviation climate effects

The recent European Assessment of Transport Impacts on Climate Change and Ozone Depletion (ATTICA, <http://ssa-attica.eu>) was a series of integrated studies investigating atmospheric effects and applicable climate metrics for aviation, shipping and land traffic. Results have been published which provide metrics to compare the different effects across these sectors in an objective way, including estimates of Global Warming Potentials (GWPs) and Global Temperature Potentials (GTPs) over different time horizons (20, 50 and 100 years). Table B6.3 shows the 20-year and 100-year GWPs, plus 100-year GTPs, for each forcing agent from aviation. Based on estimates of fuel usage and emission indices for 2005, the emission equivalent of each agent for these metrics is given on the right, and on the bottom right is the overall ratio of total CO₂-equivalent emissions to CO₂ emissions for aviation in 2005.

**Box 6.3 continued****Table B6.3** Findings of ATTICA project

	Metric values			CO ₂ e emissions (MTCO ₂ e/yr) for 2005			LOSU
	GWP ₂₀	GWP ₁₀₀	GTP ₁₀₀	GWP ₂₀	GWP ₁₀₀	GTP ₁₀₀	
CO ₂	1	1	1	641	641	641	High
Low NO _x	120	-2.1	-9.5	106	-1.9	-8.4	Very low
High NO _x	470	71	7.6	415	63	6.7	Very low
Water vapour	0.49	0.14	0.02	123	35	5.0	–
Sulphate	-140	-40	-5.7	-25	-7	-1.0	–
Black carbon	1600	460	64	10	2.8	0.38	–
Contrail	0.74	0.21	0.03	474	135	19	Low
AIC	2.2	0.63	0.089	1410	404	57	Very low
CO ₂ e emissions/CO ₂ emissions for 2005							
Low NO _x inc. AIC				4.3	1.9	1.1	Very low
High NO _x inc. AIC				4.8	2.0	1.1	Very low
Low NO _x exc. AIC				2.1	1.3	1.0	Very low
High NO _x exc. AIC				2.6	1.4	1.0	Very low

Source: Adapted from Lee et al. (2009)¹. The level of scientific understanding (LOSU) is given for each process in the right column. Values are presented for both high and low GWP values for NO_x reflecting the wide uncertainties in current estimates. The ratios on the bottom right are presented both including and excluding aviation induced cloudiness (AIC) because of uncertainties both in estimates of the magnitude of this effect and in the future incidence of AIC due to air traffic. The different time horizons illustrate how a unit emission of CO₂ increases in importance relative to shorter-lived effects as longer timescales are considered.

¹ Lee et al (2009) Transport impacts on atmosphere and climate; Aviation, *Atmospheric Environment*

The results in Box 6.3 show that the non-CO₂ radiative effects arising from current aviation activity are significant, even when looking over relatively long time horizons. Following the UNFCCC by using 100-year GWPs, the total effect could be up to two times greater than that from CO₂ emission alone; we use these GWPs to illustrate possible implications of aviation non-CO₂ effects for UK emissions targets in section 3 below. We first consider options for reducing the non-CO₂ effects of aviation.

2. Policy options for reducing the non-CO₂ effects of aviation

Demand reduction (e.g. through response to a carbon price, modal shift or increased use of videoconferencing) or controlling fuel burn via Air Traffic Management and operations efficiency improvements could help limit non-CO₂ effects of aviation, as well as CO₂ emissions.

However, other efficiency measures and use of biofuels would not reduce and, in some specific cases, could increase non-CO₂ effects:

- There is an eventual trade-off in engine design and operation between reducing CO₂ and NO_x emissions, i.e. decreasing CO₂ emissions may lead to increased NO_x emissions and vice versa.
- Increased fuel efficiency of planes – through more efficient engines or better aerodynamic design – reduces CO₂ emissions but is unlikely to fully address effects from contrails and induced cloudiness.
- It is likely that the use of biofuels in aviation will have broadly comparable non-CO₂ tailpipe effects to those from conventional kerosene, although there is some uncertainty over this and research is required to provide definitive answers as to whether these are greater, lesser or equivalent.

There are options that could possibly mitigate aviation non-CO₂ effects:

- Engine design to further reduce NO_x emissions (notwithstanding the trade-off highlighted above).
- Airframe design to reduce contrails and induced cloudiness.
- Air Traffic Management options to avoid areas in which contrails and cloudiness may occur. Greater scientific understanding of cloud radiative effects will indicate whether these route changes would be a worthwhile trade-off against the increased CO₂ emission that could arise.

Given possible trade-offs between CO₂ emissions and non-CO₂ effects, it would **not** be appropriate to adopt a policy based around reducing CO₂ emissions only (e.g. cap and trade with non-CO₂ effects included on the basis of a CO₂ multiplier); this could result, for example, in reduced CO₂ emissions and increased non-CO₂ effects, rather than finding an appropriate balance between CO₂ emissions and non-CO₂ effects.

In order to address non-CO₂ effects therefore, flanking instruments could in principle be introduced to complement capping of aviation CO₂ emissions. For example:

- The European Commission has scoped a scheme of NO_x landing and en-route charges as well as NO_x cruise certification that would provide incentives for reduction of NO_x emissions beyond existing regulations.



- As systems for atmospheric monitoring improve, it is plausible that aircraft could be rerouted under or around areas of potential cloud formation.

Further consideration is required, however, before introduction of these options would become practical, particularly as regards contrails and cirrus, where more research is required to understand these effects properly and develop operational methods to reduce them.

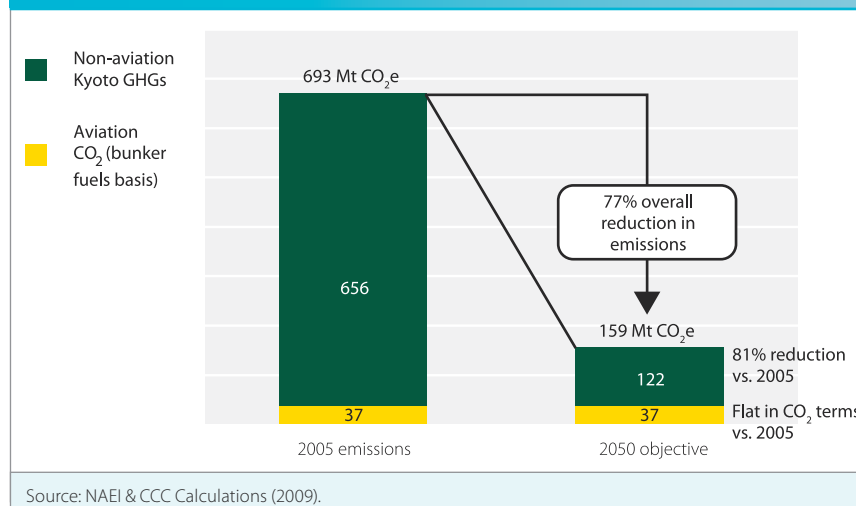
3. Possible implications of non-CO₂ effects for UK aviation

The Kyoto Protocol covers the major long-lived GHGs: carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), sulphur hexafluoride (SF₆) and other fluorinated gases (HFCs and PFCs). Under the Climate Change Act, the UK's framework is consistent with the Kyoto Protocol and therefore does not include aviation non-CO₂ effects as they do not derive directly from emissions of the Kyoto gases.

Accordingly, the Committee's December 2008 advice to Government on the economy-wide 2050 target did not reflect or include aviation non-CO₂ effects, although it did highlight them as an issue. The current long-term target requires that Kyoto GHG emissions should fall from 693 MtCO₂e in 2005 to 159 MtCO₂e in 2050 (80% below 1990 levels), with the possibility of further reductions depending on new scientific evidence; this advice was accepted by Government.

The Committee presented a scenario in its 2008 report that would achieve this 2050 target, with aviation CO₂ emissions not exceeding approximately 2005 levels and cuts of 90% relative to 1990 across all other CO₂ emitting sectors (Figure 6.1). This scenario is broadly consistent with the Government's January 2009 target to reduce UK aviation CO₂ emissions back to 2005 levels in 2050 (i.e. 37.5 MtCO₂).

Figure 6.1 UK emissions in 2005 and target for 2050 as recommended in the CCC's 2008 report, showing contribution from aviation CO₂



In our letter to the Government on international aviation in September 2009, we argued that:

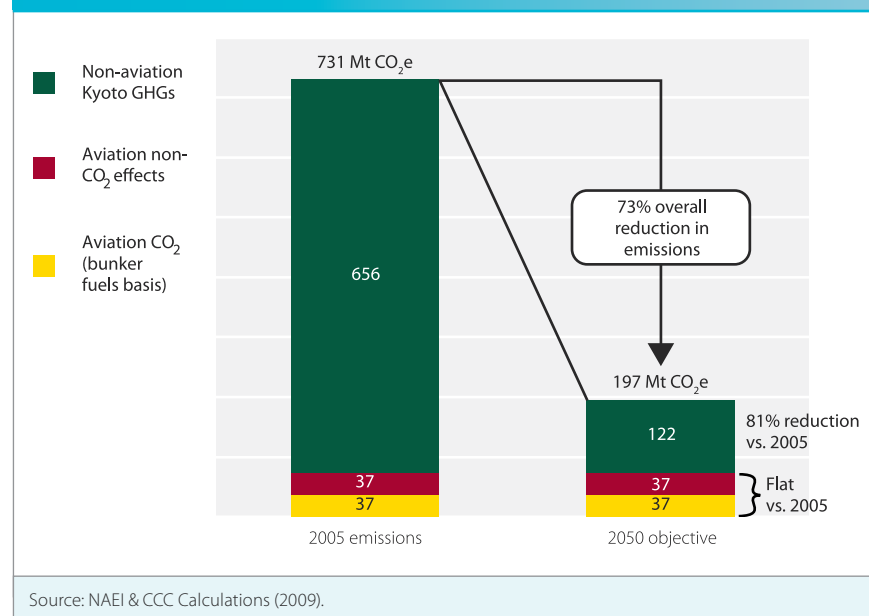
Non-CO₂ effects of aviation must be addressed as part of any international framework through commitment to a schedule for introduction of appropriate policy instruments (e.g. covering NO_x, cirrus and contrails).

More generally, as scientific understanding develops, and to the extent that this confirms the significant additional warming from aviation non-CO₂ effects, it is very likely that these will become fully accounted for in the international framework for limiting climate impacts. We now illustrate the consequences of reflecting the non-CO₂ effects of aviation directly in the UK's targets, based on the GWP estimates in Box 6.3.

Assuming that the total emissions equivalence of aviation in 2005 was two times greater than that from CO₂ emissions alone, and that there is no mitigation of aviation non-CO₂ effects going forward, including this at the UK level would change both historic and projected emissions (Figure 6.2):

- 2005 total UK emissions would become 731 MtCO₂e and aviation emissions 75 MtCO₂e.
- In 2050, achieving the 159 MtCO₂e target as defined under the Climate Change Act would actually result in emissions equivalent to 197 MtCO₂e including aviation non-CO₂ effects.

Figure 6.2 Illustrative addition of aviation non-CO₂ effects onto 2005 emissions and the 2050 target for the UK





Assuming instead that the level of allowable UK CO₂-equivalent emissions in 2050 holds (i.e. remains 159 MtCO₂e even if aviation non-CO₂ effects are included), there would be three options for addressing the impact of aviation non-CO₂ effects:

- Reducing allowed emissions in aviation from 75 MtCO₂e including non-CO₂ effects (i.e. below 2005 levels), see Figure 6.3a.
- Reducing allowed emissions in other sectors from 122 MtCO₂e (i.e. below what we had previously envisaged would be appropriate), see Figure 6.3b.
- A combination of the two above.

Figure 6.3a Illustrative inclusion of aviation non-CO₂ effects with all of the additional reduction effort made in aviation CO₂-equivalent emissions

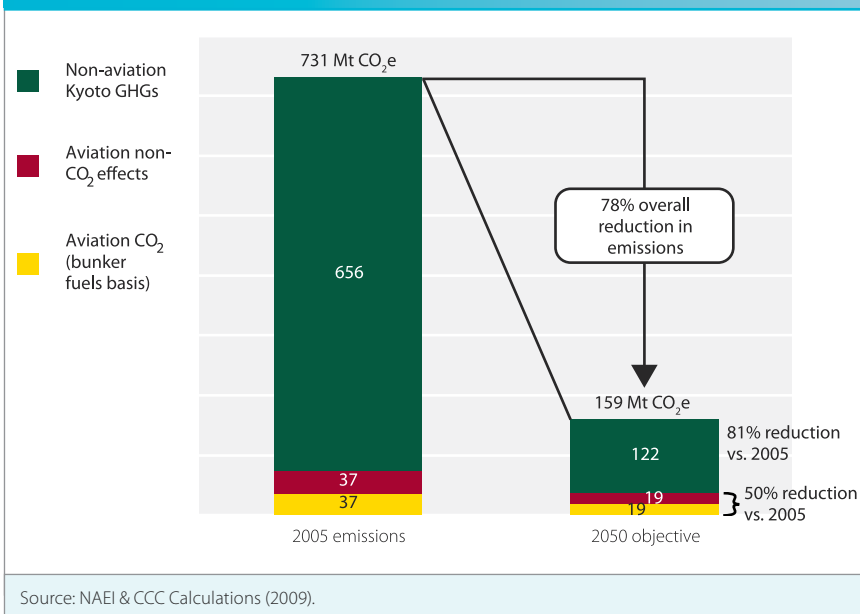
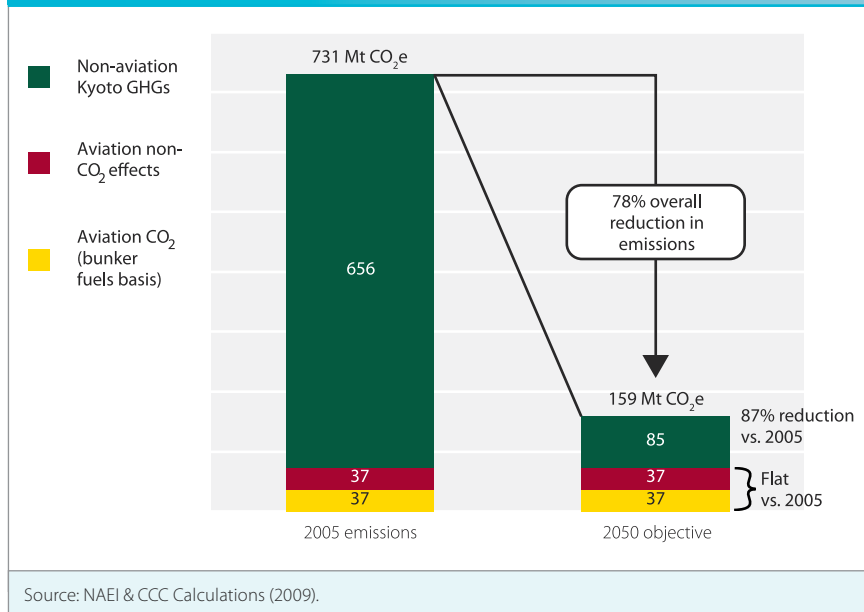


Figure 6.3b Illustrative inclusion of aviation non-CO₂ effects with all of the additional reduction effort made in emissions from other UK sectors



The balance between these options would require detailed analysis of the scope for, and cost of, further emissions reductions in aviation versus other sectors. It is reasonable to assume, however, that some additional emissions reduction effort would be required in aviation.

The Committee is not recommending that the UK aviation target should currently be redefined to include non-CO₂ effects. However, recognising that aviation non-CO₂ effects are likely to become accounted for in any international framework in decades to come, Chapter 7 considers at a high level possible implications for UK aviation expansion in the 2020s.

Chapter 7

Meeting the 2050 aviation target

134

This chapter brings together the analysis in Chapters 1 to 5 and sets out emissions scenarios under alternative assumptions about demand-side factors, improvement in fleet fuel efficiency, and use of sustainable biofuels.

The scenarios are built in the following way:

- **Demand assumptions:** We start with emissions projections reflecting different assumptions on the extent of demand response to carbon prices, modal shift from domestic/short-haul aviation to rail/high-speed rail and reduction in the need for travel through videoconferencing.
- **Fleet efficiency assumptions:** We then overlay alternative assumptions about improvement in fleet fuel efficiency from engine/airframe and Air Traffic Management (ATM) and operations; scenario assumptions on aircraft efficiency differ as regards the pace of innovation.
- **Biofuels assumptions:** We next consider emissions projections which overlay different levels of biofuels penetration onto scenarios for demand-side measures and improvement in fleet fuel efficiency. We model a range of scenarios from 10% to 30% penetration in 2050, on an assumption that lifecycle emissions reductions would be 50%.

We develop three sets of scenarios:

- **Likely scenario:** This reflects demand reductions and carbon intensity reductions likely to be achieved given current policies, investment levels and the pace of technological advance.
- **Optimistic scenario:** This would require both:
 - A significant shift from current policy (e.g. in respect to high-speed rail), and an increase in the level of investment in new aircraft technologies and/or in the pace of fleet renewal as well as improvements in ATM and operations so as to make a 1.0% per annum improvement in carbon efficiency attainable.
 - Progress of biofuel technologies which would make it reasonable to assume that a 20% penetration was compatible with sustainability.
- **Speculative scenario:** This would require both technological breakthroughs and a significant increase in the pace of aircraft fuel efficiency



improvements. In addition, it would require the development of sustainable biofuels which are currently speculative (e.g. biofuels from algae), or an evolution of global population, food demand and agricultural productivity which would make possible the sustainable and large scale use of current agricultural land and water to grow biofuel feedstocks. These developments are assessed today as very unlikely.

We reflect the full range of uncertainty by considering various combinations from these sets of scenarios. In particular, we overlay alternative assumptions about biofuels penetration across each of the scenarios for improvement in fleet fuel efficiency. We then define three core scenarios which combine Likely, Optimistic and Speculative assumptions across each of the options. We consider any gap between projected emissions under these scenarios and the 2050 target, and options for addressing this.

The key messages in this chapter are:

- In our Likely scenario, we assume fleet efficiency improvement of 0.8% annually and biofuels penetration of 10% in 2050. Together these would allow meeting the target with demand growth of around 60% in the period to 2050 (e.g. compared to unconstrained demand growth of over 200%). Demand growth based on planned capacity expansion, with demand response to the carbon price and opportunities for modal shift could be around 115%. Explicit constraints on demand growth in addition to the carbon price would therefore be required to meet the 2050 target.
- There are scenarios with a faster pace of fleet efficiency improvement and higher levels of biofuels penetration where the target is achieved without the need for explicit constraints on demand growth. However, unless and until new evidence is available that the pace of fleet fuel efficiency and the level of sustainable biofuels may be higher than currently envisaged, it is prudent to plan for a world where explicit constraints on demand growth are required to meet the target.
- There are no clear implications of our analysis for specific airports (e.g. Heathrow). The key implication for aviation expansion is that whatever the pattern of capacity development, this should be consistent with constraining demand growth in 2050 to around 60% on 2005 levels if the target is to be achieved.

We set out the analysis that underpins these messages in four sections:

1. Emissions projections including demand response to the carbon price, modal shift, and videoconferencing
2. The impact of improvement in fleet fuel efficiency on emissions
3. Emissions projections including biofuels
4. Options for meeting the 2050 target: planning for demand growth constraint



1. Emissions projections including demand response to the carbon price, modal shift, and videoconferencing

Unconstrained demand growth

We first consider demand response in a context where demand growth is not constrained by runway capacity and where therefore there are further additions to runway capacity beyond what is envisaged in the 2003 Air Transport White Paper (i.e. Heathrow, Stansted, Edinburgh) as required to meet a growing demand.

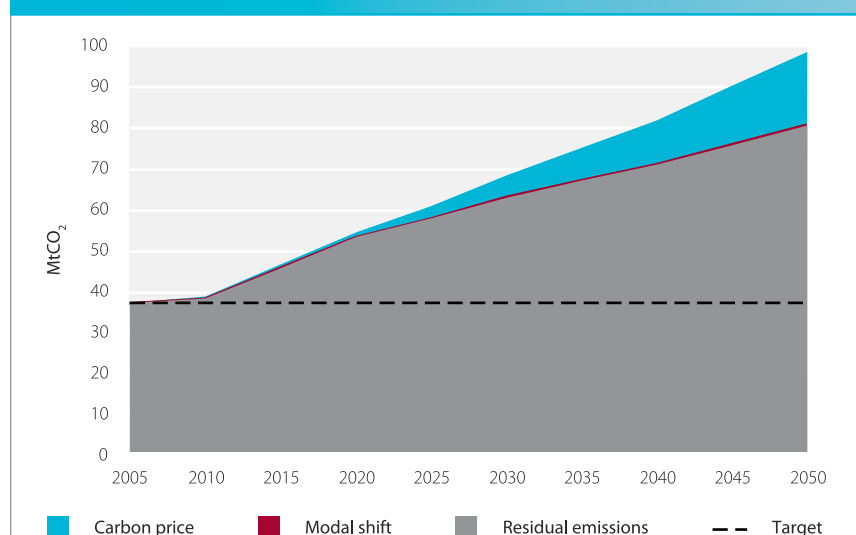
In Chapters 2 and 3 we set out three scenarios for demand response to the carbon price, modal shift and videoconferencing:

- Our **Likely** scenario assumptions result in modal shift equivalent to reducing air demand by 1% of passengers and 2% ATMs in 2050. We assume that videoconferencing has no net impact on aviation demand.
- Our **Optimistic** scenario modal shift and videoconferencing assumptions result in a reduction equivalent to reducing air demand by 7% of passengers and 10% of ATMs in 2050.
- Our **Speculative** scenario modal shift and videoconferencing assumptions result in a reduction equivalent to reducing air demand by 16% of passengers and 19% of ATMs in 2050.

We now overlay these scenarios for demand response to the reference emissions projection for unconstrained demand growth. Emissions projections net of demand response range from 74 MtCO₂ to 81 MtCO₂ in 2050:

- In the Likely scenario, the demand response due to the carbon price results in an emissions reduction of just under 18 MtCO₂ in 2050 from the reference case, with a small additional reduction due to modal shift (Figure 7.1).

Figure 7.1 Likely scenario: demand response with unconstrained runway capacity



Source: CCC modelling.

- In the Optimistic scenario, modal shift and videoconferencing result in a further reduction of just over 2 MtCO₂ beyond the carbon price impact (Figure 7.2).
- In the Speculative scenario, modal shift and videoconferencing result in a further reduction of 7 MtCO₂ beyond the carbon price impact (Figure 7.3).

In none of the scenarios, therefore, does demand response alone result in achieving the 2050 target.

Figure 7.2 Optimistic scenario: demand response with unconstrained runway capacity

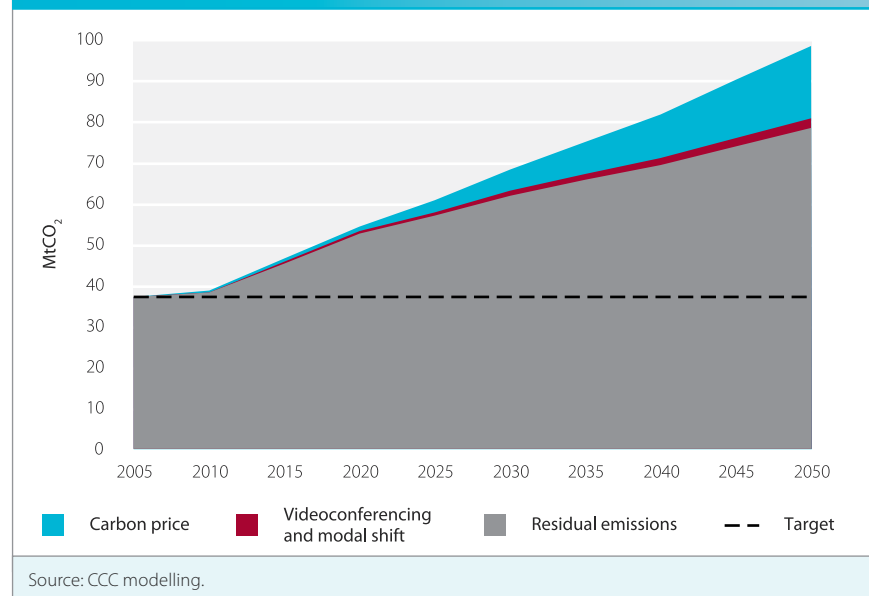
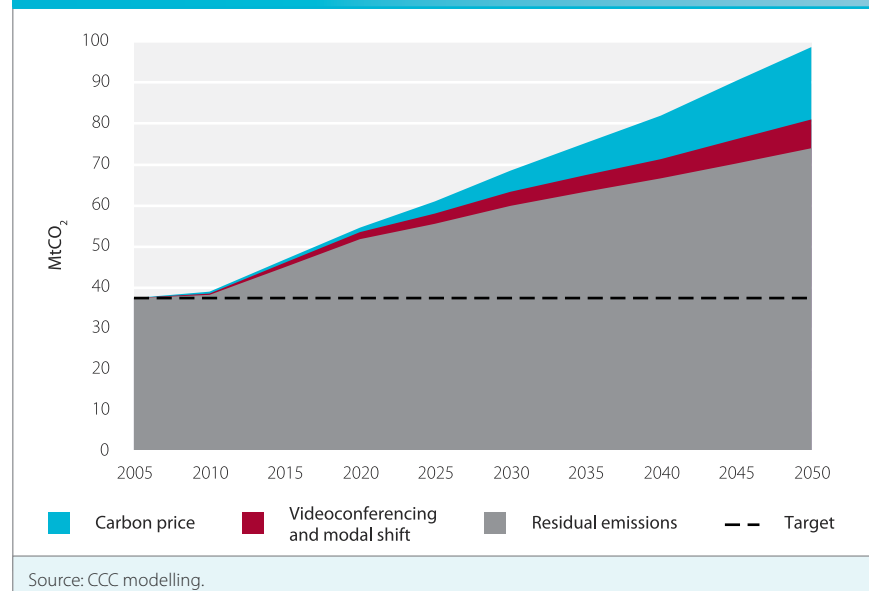


Figure 7.3 Speculative scenario: demand response with unconstrained runway capacity





Demand growth with planned capacity expansion

The DfT modelling approach assumes that no capacity is added beyond that envisaged in the 2003 Air Transport White Paper. There are two implications of this assumption for emissions projections:

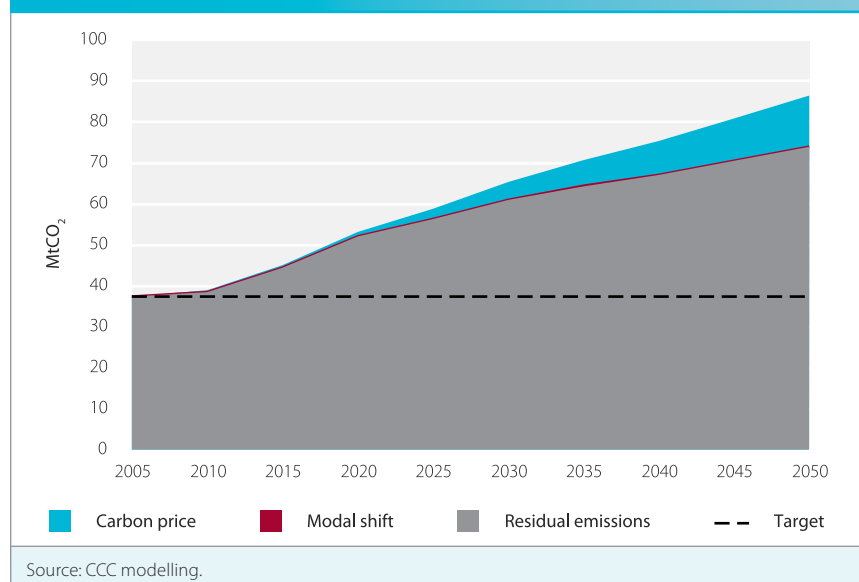
- The reference emissions projection is lower than in the case of unconstrained demand growth (e.g. by around 12 MtCO₂ in 2050).
- The emissions reductions due to modal shift and videoconferencing fall. The reason for this is that where the system operates at capacity, modal shift and videoconferencing free up slots which can therefore be used to meet suppressed demand.

When overlaying scenarios for demand responses to the carbon price, modal shift and videoconferencing, emissions projections in a scenario with only planned capacity additions range from 70 MtCO₂ to 74 MtCO₂ in 2050:

- In the Likely scenario, the demand response due to the carbon price results in an emissions reduction of 13 MtCO₂ in 2050 from the reference case, with a negligible further reduction due to modal shift (Figure 7.4).
- In the Optimistic scenario, modal shift and videoconferencing together result in a further reduction of 1 MtCO₂ beyond the carbon price impact.
- In the Speculative scenario, modal shift and videoconferencing together result in a further reduction of 4 MtCO₂ beyond the carbon price impact.

Demand response alone is therefore still not sufficient to achieve the 2050 target even in a system with capacity constraints; we follow DfT and model a system with planned capacity constraints as envisaged in the 2003 Air Transport White Paper in the remainder of this chapter.

Figure 7.4 Likely scenario: demand response with planned runway capacity



2. The impact of improvement in fleet fuel efficiency on emissions

In Chapter 4 we set out three scenarios for improved fleet efficiency through engine and airframe innovation, air traffic management and operations:

- Our **Likely** scenario reflects annual improvement in fleet average fuel efficiency between 2005 and 2050 of 0.8% per year on a seat-km basis.
- Our **Optimistic** scenario reflects annual improvement in fleet average fuel efficiency between 2005 and 2050 of 1.0% per year on a seat-km basis.
- Our **Speculative** scenario reflects annual improvement in fleet average fuel efficiency of 1.5% per year on a seat-km basis.

We now overlay emissions reductions corresponding to these scenarios onto the emissions projections including demand response to carbon prices/modal shift/videoconferencing in Section 1 above:

- With Likely efficiency improvements and Likely demand response, emissions are above allowed aviation emissions in the period to 2050, and around 13 MtCO₂ above the 2050 target (Figure 7.5).
- With Optimistic efficiency improvement and Optimistic demand response, emissions are around 8 MtCO₂ above the 2050 target (Figure 7.6).
- With Speculative efficiency improvement and Speculative demand response, emissions are around 1 MtCO₂ below the 2050 target (Figure 7.7).

The 2050 target is therefore only achieved in the Speculative efficiency improvement scenario, and not in the Likely or Optimistic scenarios.

Figure 7.5 Likely scenario: impact of fuel efficiency improvements

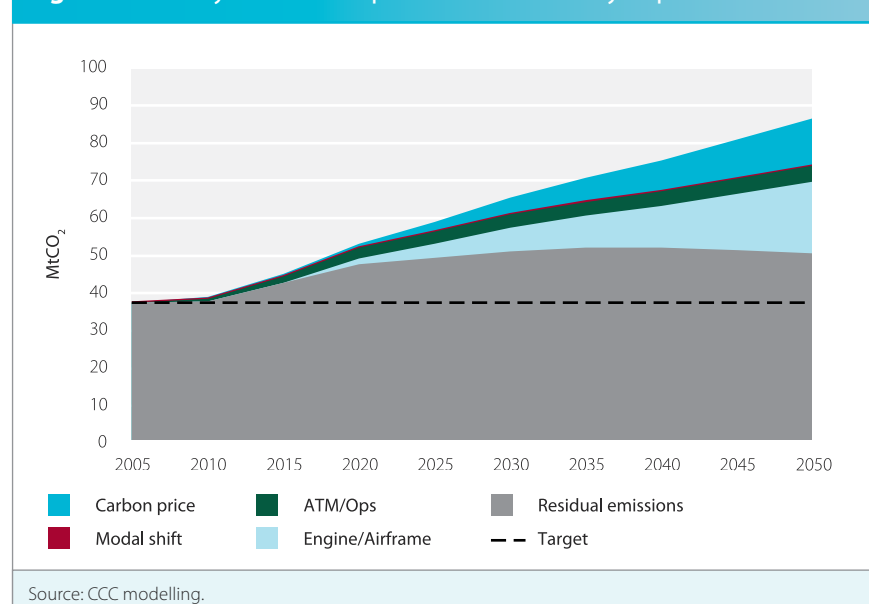
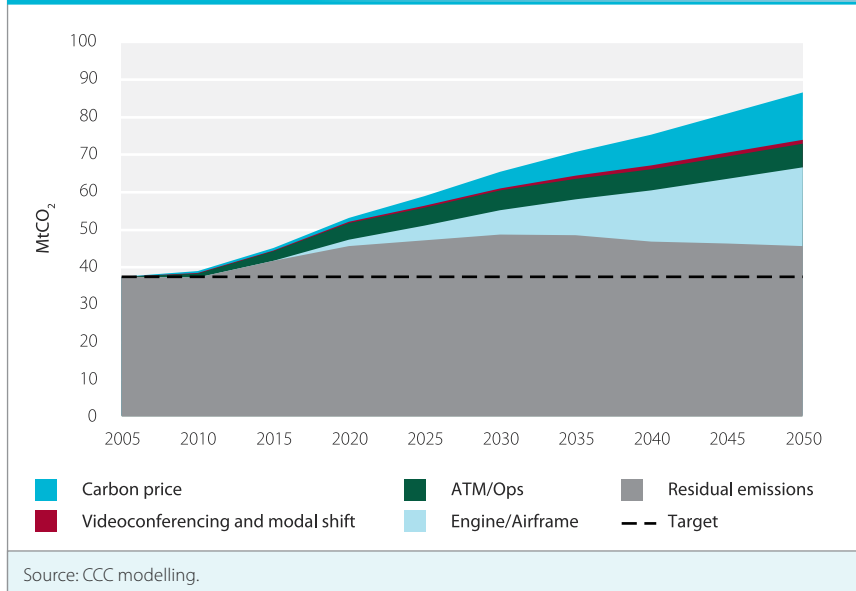
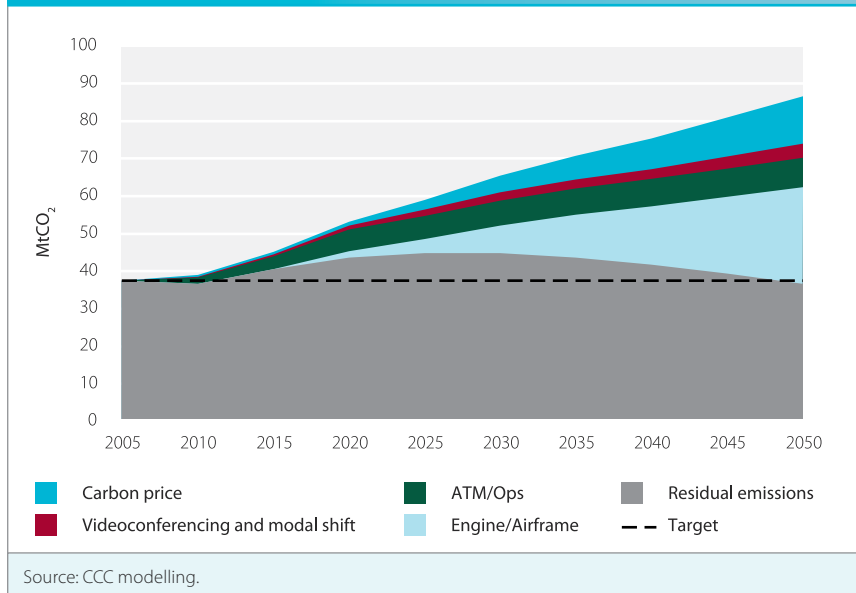


**Figure 7.6** Optimistic scenario: impact of fuel efficiency improvements**Figure 7.7** Speculative scenario: impact of fuel efficiency improvements

3. Emissions projections including biofuels

Scenario assumptions

The next step is to overlay scenarios for biofuels penetration across the scenarios in section 2 above. In Chapter 5, we set out three scenarios for increased biofuels penetration, in each of which we assume a 50% lifecycle emissions reduction:

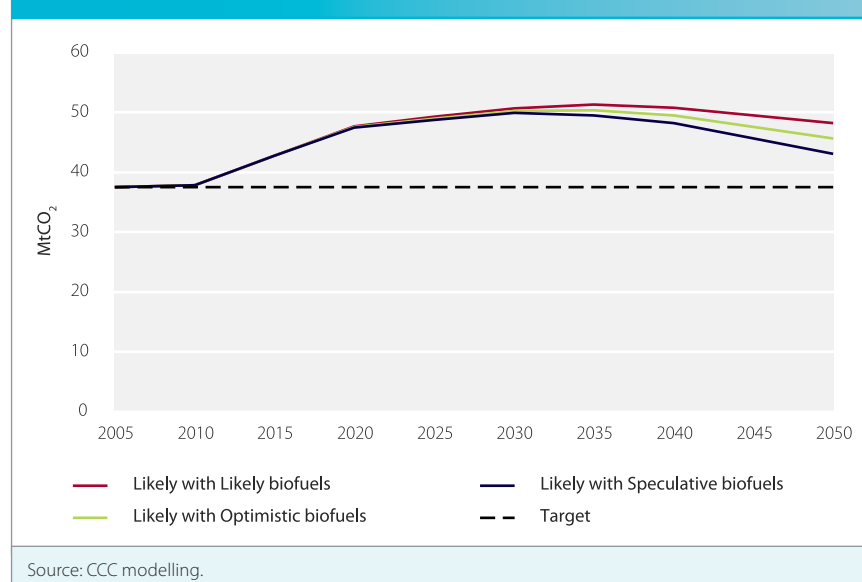
- Under our **Likely** scenario we assume that penetration of biofuels is below 2% in 2030 and reaches 10% by 2050.
- Under our **Optimistic** scenario we assume that penetration of biofuels reaches around 3% by 2030 and 20% by 2050.
- Under our **Speculative** scenario we assume that penetration of biofuels reaches 5% in 2030 and 30% by 2050.

Emissions projections including the impact of biofuels

Combining scenarios for biofuel penetration with the demand responses and fleet efficiency improvement scenarios presented above in Sections 1 and 2 gives the following results for the core set of scenarios:

- The Likely scenario (including Likely demand response, efficiency improvement and biofuels penetration) gives emissions that are 11 MtCO₂ above the 2050 target (Figure 7.8). Triggering the Optimistic and the Speculative scenarios for biofuels on top of Likely scenarios for the other wedges would leave a gap of 8 MtCO₂ and 6 MtCO₂ respectively.
- The Optimistic scenario (including Optimistic demand response, efficiency improvement and biofuels penetration) gives emissions that are around 4 MtCO₂ above the 2050 target (Figure 7.9). Triggering the Speculative scenarios for biofuels on top of Optimistic scenarios for the other wedges would still leave a small gap of 1 MtCO₂.

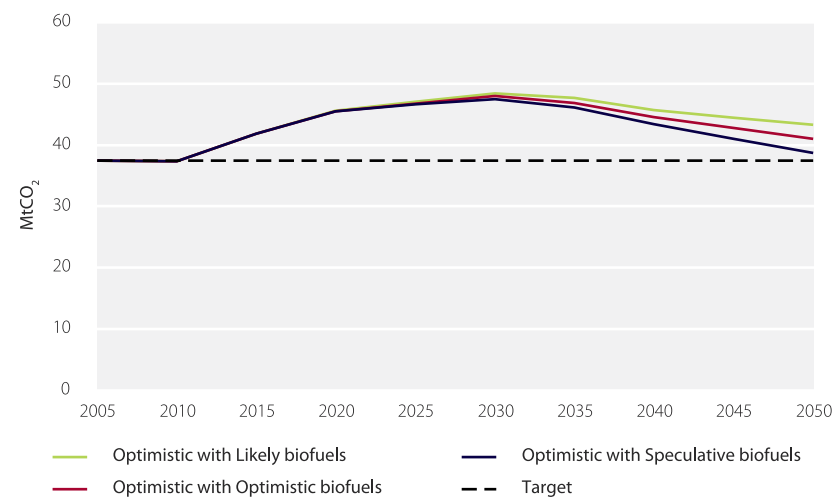
Figure 7.8 Likely scenario: impact of alternative biofuels assumptions





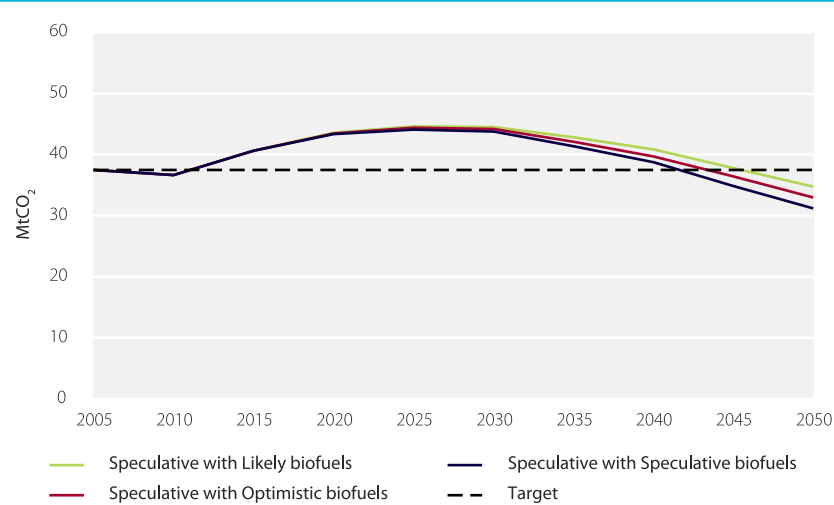
- The Speculative scenario (including Speculative demand response, efficiency improvement and biofuels penetration) gives emissions reductions that are around 6 MtCO₂ below the 2050 target (Figure 7.10). The target would still be exceeded by around 3 MtCO₂ when overlaying the Likely biofuels scenario on top of the Speculative wedges.

Figure 7.9 Optimistic scenario: impact of alternative biofuels assumptions



Source: CCC modelling.

Figure 7.10 Speculative scenario: impact of alternative biofuels assumptions



Source: CCC modelling.

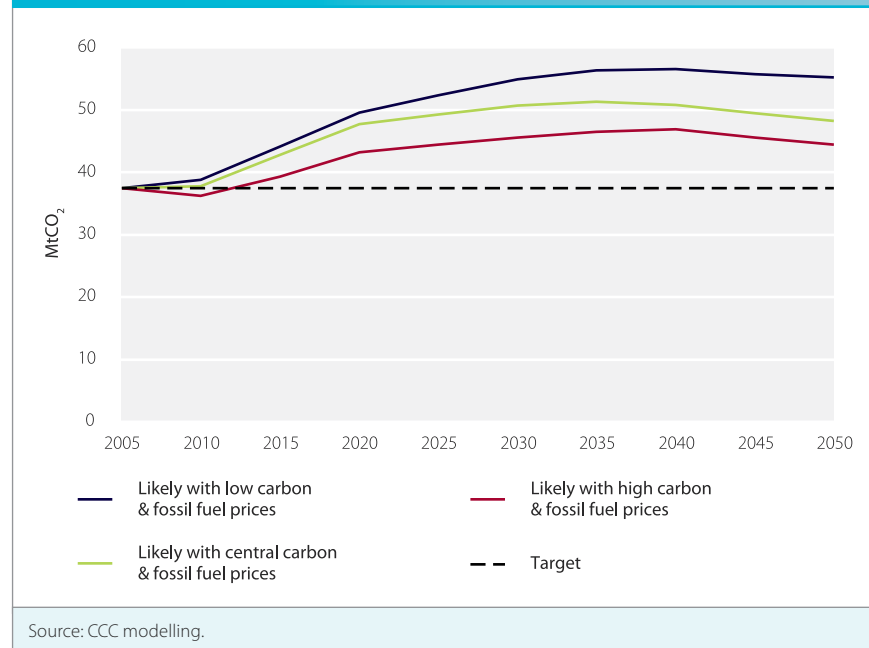
Demand sensitivities: alternative assumptions on fossil fuel and carbon prices

Having looked at sensitivity incorporating a range of biofuels assumptions across different scenarios we now look at the sensitivity of the full Likely scenario (i.e. with Likely biofuels assumptions) to carbon and fossil fuel prices. The Likely scenario with demand sensitivities for low fossil fuel prices and low carbon prices gives emissions that are 18 MtCO₂ above the target, and 7 MtCO₂ above the target with high fossil fuel prices and high carbon prices (Figure 7.11); demand reduction due to high fossil fuel and carbon prices is therefore not sufficiently high to achieve the target.

Summary of biofuels scenarios and sensitivities

The 2050 target is only achieved in those scenarios which combine significant demand-side responses and ambitious efficiency improvements with a significant level of biofuels penetration.

Figure 7.11 Likely scenario: sensitivity to low and high carbon and fossil fuel prices





4. Options for meeting the 2050 target: planning for demand growth constraint

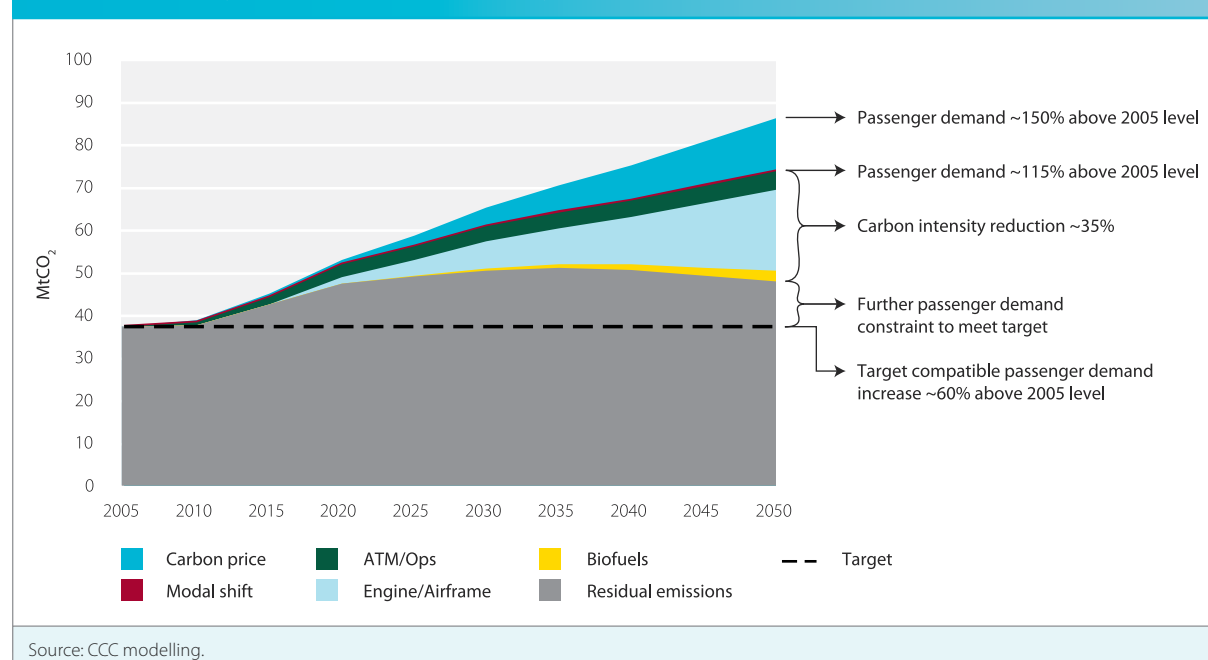
Meeting the target in the Likely scenario

In our Likely scenario we assume annual improvements in fleet fuel efficiency of 0.8% together with 10% biofuels penetration in 2050. This combination of improvement in fleet fuel efficiency and biofuels penetration implies a carbon intensity reduction of around 35% in 2050 relative to the reference projection (Figure ES.6). As a result, an increase in ATMs of around 55% relative to 2005 levels would be compatible with the target of ensuring that 2050 CO₂ emissions did not exceed the 2005 level of 37.5 MtCO₂. Given increasing load factors over time, an increase in passengers of around 60% on 2005 levels by 2050 would be possible, taking total annual passenger numbers from 230 million to around 370 million. This would be equivalent to taking total passenger trips (one departure plus one arrival) from 115 million in 2005 to around 185 million in 2050.

This target-compatible demand growth of around 60% compares with the growth of over 200% which might result in a world where there were no capacity constraints and no carbon price.

On the demand side, however, the Likely scenario incorporates the future capacity limits assumed by the 2003 Air Transport White Paper. It also allows for the impact of carbon price in line with our central projections (rising gradually to around £200/tCO₂ by 2050), and for some modal shift to conventional rail. These assumptions generate a demand growth of 115% relative to current levels by 2050.

Figure 7.12 Likely scenario (planned capacity)



Meeting the 2050 target that CO₂ emissions are no higher than 37.5 MtCO₂ is therefore likely to require policy measures to restrain demand which go beyond our central projected carbon price. The policy instruments which could achieve this restraint include a carbon tax on top of the forecast carbon price, limits to further airport expansion, and restrictions on the allocation of take-off and landing slots even where airports have the theoretical capacity available.

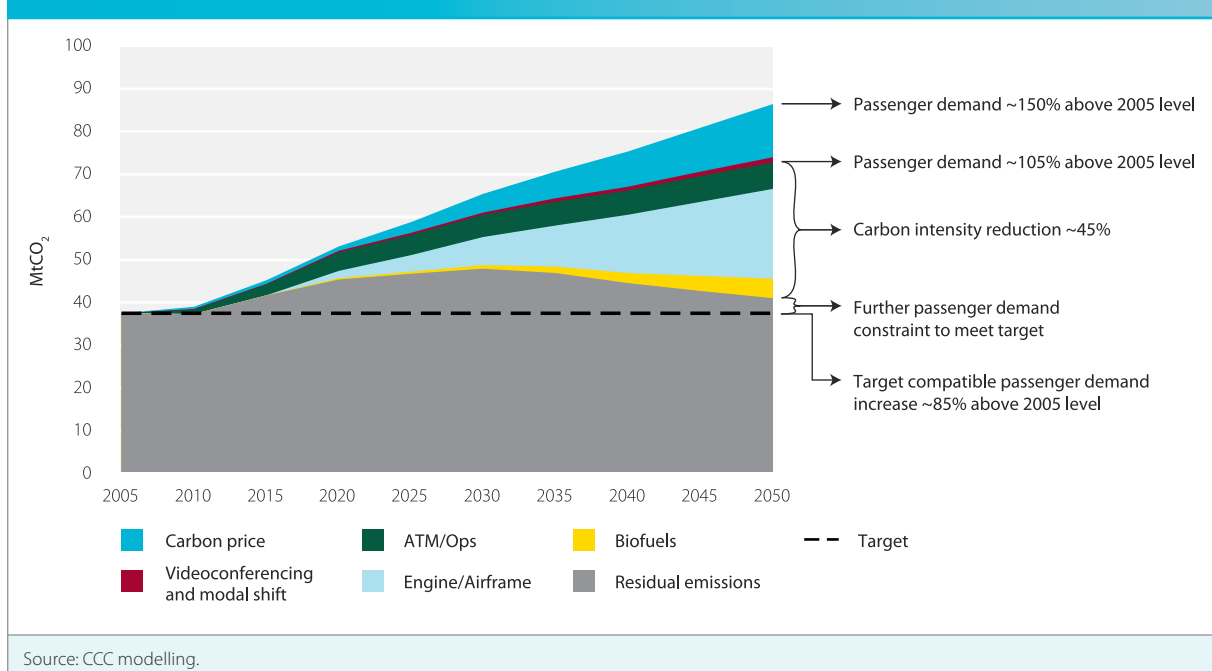
Meeting the target in other scenarios

In the *Optimistic* scenario, we assume 1.0% annual improvement in fleet fuel efficiency and 20% biofuels penetration in 2050. This combination of improvement in fleet fuel efficiency and biofuels penetration implies a carbon intensity reduction of around 45% in 2050. As a result, it would be possible to increase ATMs by around 80% and passenger numbers by around 85% and still meet the target that CO₂ emissions should not exceed 37.5 MtCO₂ in 2050 (Figure 7.13). Passenger trips (one departure plus one arrival) could increase from 115 million in 2005 to around 215 million in 2050.

Given demand growth under this scenario of 115%, meeting the target would still require additional policy measures to constrain demand beyond those implied by the 2003 Air Transport White Paper and the central carbon price projection. But these additional measures would not need to be as restrictive as in the Likely scenario.

In the *Speculative* scenario, we assume annual improvement in fleet fuel efficiency 1.5% and biofuels penetration of 30% in 2050. The implied carbon intensity reduction is around 55% by 2050. This would make an increase in ATMs of around 125% and of passengers of around 135% compatible with

Figure 7.13 Optimistic scenario (planned capacity)





meeting the target. The combination of already planned capacity limits, the demand response to the projected carbon price and opportunities for modal shift and videoconferencing, would produce a demand increase below this 135%. No additional policy measures would therefore be required to meet the target (Figure 7.14).

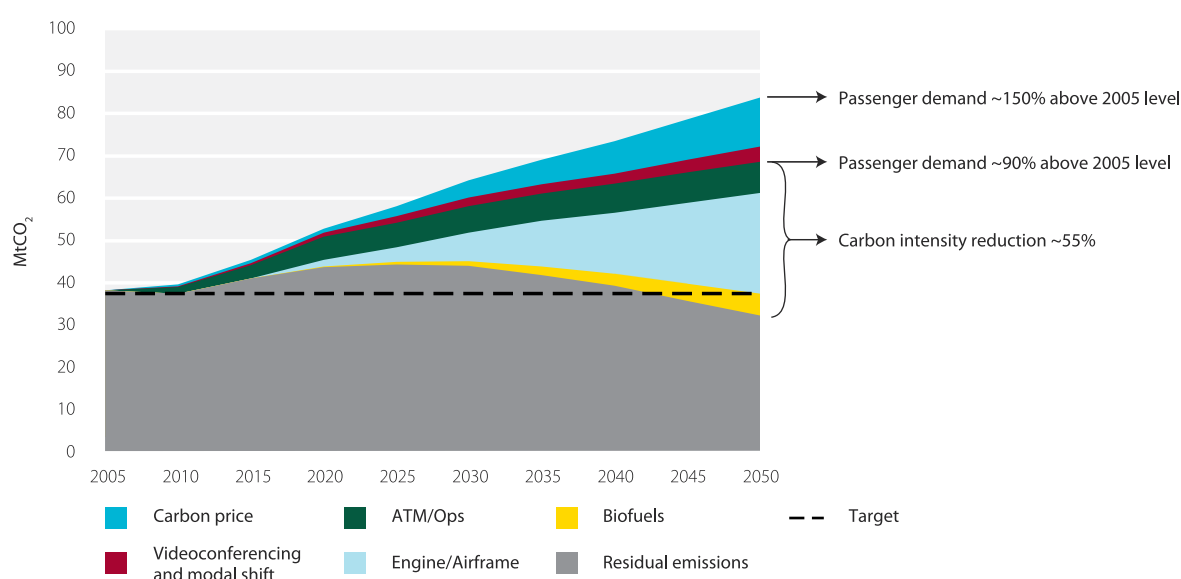
It should be noted however that even in this scenario the maximum demand increase compatible with the target (135% increase in passengers) is much lower than the increase which our projections suggest would occur in a world of no constraints (i.e. with no carbon price and unlimited airport expansion).

The high growth in aviation demand which would occur in an unconstrained environment illustrates the high value which people place on the opportunity to fly, in particular for leisure purposes. If the Optimistic or Speculative scenarios can be achieved, the number of flights compatible with meeting the 37.5 MtCO₂ target increases.

In considering the difference between scenarios, three aspects should be distinguished:

- Achieving greater modal shift to rail and greater use of videoconferencing does not increase the total target-compatible level of demand, but it makes it possible for more of that total to be devoted to other uses (e.g. long-haul leisure) where there are no alternatives to air travel. Investing in a new high-speed rail line and promoting full integration of UK and European high-speed networks can increase the potential for modal shift. Promotion of videoconferencing technologies could ensure higher levels of business travel substitution.

Figure 7.14 Speculative scenario (planned capacity)



Source: CCC modelling.

- Achieving more rapid fuel efficiency improvements directly increases target-compatible demand growth. It could be fostered through increasing investment in R&D, introducing regulatory limits on new aircraft CO₂ performance, exploring possible benefits from early scrappage of older aircrafts, and full implementation of SESAR and NATS initiatives on ATM efficiency improvement.
- The higher the percentage of biofuels use which can be considered sustainable the greater the target-compatible demand increase. Here however it is not clear that higher investment will necessarily drive more rapid improvement, since there is inherent uncertainty about what progress can be achieved, and about the implications of population growth and food demand for land use. We therefore need to observe through time the development of speculative technologies, and trends in agricultural productivity and land availability. Governments could however encourage investment in those technologies most likely to be sustainable. And expanded use of biofuels will need to be underpinned by a global policy framework to mitigate the risks of harmful land-use changes resulting from the growth of biofuel feedstocks.

Several of these developments which might make possible more rapid demand increases than in the Likely scenario are ones over which the UK acting alone has only small influence. EU or broader international action would be required to accelerate the pace of improvement of fleet fuel efficiency and international action would be required to develop a framework to mitigate against risks of indirect land use impacts from biofuels.

The prudent assumption on which to base policy today is therefore that reductions in the carbon intensity of air travel will be limited to the reduction of around 35% achieved in the Likely scenario, implying a maximum allowable increase in ATMs of around 55% and a maximum demand increase of around 60%. If faster technology progress is in fact achieved this can be reflected in adjustments in policy over time.

Implications for airport expansion and slot allocation

The 2003 Air Transport White Paper proposed that there could be airport runway capacity expansions at Edinburgh, Heathrow and Stansted, but at no other airports. In January 2009, the Government decided in favour of a third runway at Heathrow and in favour of increasing slot capacity there from 480,000 to 605,000. It decided however that any decisions on the allocation of further slot capacity (to the maximum theoretical potential of 702,000 with a third runway in place) should be subject to recommendations from the Committee on Climate Change in 2020 on whether further expansion then appears compatible with the target of restricting CO₂ emissions to a maximum 37.5 MtCO₂ in 2050. The Terms of Reference for this report in addition asked the Committee to consider “the implications [for meeting the 2050 target] of further aviation expansion in the 2020s”.



The key implication from our analysis is that future airport policy should be designed to be in line with the assumption that total ATMs should not increase by more than about 55% between 2005 and 2050, i.e. from today's level of 2.2 million to no more than around 3.4 million in 2050. This constraint could be consistent with a range of policies as regards capacity expansion at specific airports.

Total current theoretical capacity at all airports in the UK is about 5.6 million ATMs which is already in excess both of today's actual ATMs and of maximum ATMs compatible with the 2050 target (Table 7.1a and b). But demand cannot be easily switched between different geographical locations, and there is a tendency for demand to concentrate at major hubs, given the advantages of inter-connection between different routes. As a result, capacity utilisation differs hugely between for instance 97% at Heathrow and well below 50% at some smaller airports outside the top ten.

If demand was allowed to grow in line with the demand assumptions of the Likely scenario, with passenger numbers growing 115% ATMs would reach about 4 million by 2050. Our modelling suggests that an allocation of demand at this level would entail Heathrow operating at its maximum 702,000 capacity (with a third runway) with several other airports highly utilised (Table 7.1b). Our analysis suggests however total ATMs need to be restricted to a maximum of about 3.4 million in 2050, about 0.6 million below the level modelled in the Likely scenario.

Table 7.1a: Actual runway capacity and utilisation in 2005

Airport	Maximum runway capacity (ATMs, '000s)	Actual use (ATMs, '000s)	Capacity utilisation	Spare capacity (ATMs, '000s)
Heathrow	480	466	97%	14
Gatwick	260	248	95%	12
Stansted	241	166	69%	75
London City	73	60	82%	13
Luton	100	72	72%	28
Bristol	188	58	31%	130
Birmingham	186	111	60%	75
Manchester	276	213	77%	63
Glasgow	188	93	50%	95
Edinburgh	186	106	57%	79
<i>Other UK Airports</i>	<i>3,400</i>	<i>568</i>	<i>17%</i>	<i>2,832</i>
Total	5,577	2,160	39%	3,417

Source: CCC modelling.

Table 7.1b: Projected runway capacity, utilisation and target compatible ATMs in 2050
(Likely scenario assumptions)^{1,2}

Airport	Maximum runway capacity (ATMs, '000s)	Planned capacity, ATM distribution ('000s)	Capacity utilisation	Spare capacity (ATMs, '000s)
Heathrow	702	702	100%	0
Gatwick	260	260	100%	0
Stansted	480	317	66%	163
London City	120	120	100%	0
Luton	135	135	100%	0
Bristol	226	127	56%	98
Birmingham	206	206	100%	0
Manchester	500	449	90%	51
Glasgow	226	198	88%	27
Edinburgh	450	224	50%	226
Other UK Airports	4,000	1,227	31%	2,773
Total	7,304	3,965	54%	3,339
Target compatible ATMs		3,418		
Difference between the Likely scenario and target compatible ATMs		547		

Source: CCC modelling.

This restriction could be achieved through a range of different policies relating to taxes, capacity expansion or slot allocation at specific airports. Optimal decisions on specific airport capacity do not therefore mechanically follow from national aggregate demand, but need to reflect a wide range of other factors such as customer preference, alternatives to air travel, local environmental impact, competition between UK airports and continental hubs, and economic impacts both local and national. It is not the Committee's role to assess these factors.

The Committee's clear conclusion is, however, that the combination of future aviation policies (combining tax, capacity expansion and slot allocation decisions) should be designed to be compatible with a maximum increase in ATMs of about 55% between now and 2050, and that this should continue to be the policy approach until and unless technological developments suggest that any higher figure would be compatible with the emission target.

¹ The ATM distribution is an indicative model output rather than a definitive view on the distribution in the Likely scenario.

² Stansted utilisation and total demand may be higher in practice when suppressed demand is reallocated from other London airports.



Future work of the Committee on aviation

Further work on aviation emissions by the Committee over the next year will include:

- Assessing whether international aviation emissions should be included in carbon budgets given the final mechanisms agreed by the EU for allocating EU ETS allowances across Member States.
- Assessing the relative costs of emission reductions in different sectors of the economy (including aviation) within the context of the Committee's development of recommendations for the fourth budget period (2023-2027) which will be delivered in December 2010. This will entail consideration of the feasibility of reductions in other sectors sufficient to offset the fact that aviation emissions are likely to grow before falling back to the 37.5 MtCO₂ level.

Over the longer term the Committee will:

- Review any new evidence on improvement in fleet fuel efficiency, sustainable biofuels and aviation non-CO₂ effects and their implications for the maximum demand increase compatible with meeting the emissions target.
- In 2020 advise Government on whether release of the second tranche of slots from Heathrow capacity expansion (from 605,000 to 702,000) is then compatible with meeting the 2050 target.

The Committee's next annual report to Parliament in June 2010 will include an assessment of latest data on UK aviation emissions and will reflect any developments on international aviation policy resulting from the Copenhagen climate change summit.

Glossary

Abatement

Avoiding or reducing pollution or emissions through external intervention.

Advisory Council for Aeronautics Research in Europe (ACARE)

A joint European initiative with the purpose to improve the competitiveness of the European aviation industry through research.

Air Traffic Management (ATM)

A service provided by ground-based controllers who direct aircraft on the ground and in the air.

Air Traffic Movements (ATMs)

Unit of travel referring to a flight.

European Assessment of Transport Impacts on Climate Change and Ozone Depletion (ATTICA)

A series of integrated studies investigating the atmospheric effects of aviation, shipping, land traffic and applicable climate metrics. See Box 6.3 for details.

Biofuel

A fuel derived from biomass and used to power vehicles (can be liquid or gas). Biofuels are commonly derived from cereal crops but can also be derived from other plant material, trees and even algae.

Biomass

Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood and plant and animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

Biomass to liquid (BTL)

Production of jet fuel, diesel or gasoline through gasification of biomass feedstock (e.g. woody crops or wastes), followed by Fischer-Tropsch (FT) synthesis and upgrading steps.

Blended wing body

Radical aircraft design in which airframe dynamics are improved through a flattened profile and wing structures that are smoothly blended to the body.

Bunker Fuel

Fuel consumed for international marine and air transportation.

Bypass ratio

The ratio between the mass flow rate of air drawn in by the fan but bypassing the engine core to the mass flow rate passing through the engine core.

**Carbon Budget**

Allowed emissions under the UK Climate Change Act, defining the maximum level of CO₂ and other Kyoto GHGs which the UK can emit over five year periods.

Carbon Capture and Storage (CCS)

Technology which involves capturing the carbon dioxide emitted from burning fossil fuels, transporting it and storing it in secure spaces such as geological formations, including old oil and gas fields and aquifers under the seabed.

Carbon dioxide equivalent (CO₂e) concentration

The concentration of carbon dioxide that would give rise to the same level of radiative forcing as a given mixture of greenhouse gases.

Carbon dioxide equivalent (CO₂e) emission

The amount of carbon dioxide emission that would give rise to the same level of radiative forcing, integrated over a given time period, as a given amount of well-mixed greenhouse gas emission. For an individual greenhouse gas species, carbon dioxide equivalent emission is calculated by multiplying the mass emitted by the Global Warming Potential over the given time period for that species. Standard international reporting processes use a time period of 100 years.

Carbon Leakage

Displacement of carbon emissions from one country to another due to the existence of (stringent) environmental policy in one country which makes it more attractive or viable for high carbon businesses to operate in a country with less stringent regulations.

Carbon Price

Price at which carbon is traded under an emissions trading scheme (see below).

Climate Change Act

UK law of 26 November 2008. It makes it the duty of the Secretary of State for Energy and Climate Change to ensure that the net UK carbon account for all six Kyoto greenhouse gases for the year 2050 is at least 80% lower than the 1990 baseline.

Combined Heat and Power (CHP)

The simultaneous generation of heat and power, putting to use heat that would normally be wasted. This results in a highly efficient way to use both fossil and renewable fuels.

CONSAVE

Consave 2050 was an EC Accompanying Measure Project that developed scenarios on aviation and emissions, with a particular focus on 2050.

Contrail

Condensation trail (i.e. white line cloud often visible behind aircraft).

Elasticity of demand

The proportion by which demand changes in response to changes in Price (Price Elasticity) or Income (Income Elasticity).

Emissions factor

Constant measure of carbon intensity used for calculation of emissions from some activity, e.g. to calculate emissions from aviation in the knowledge of the number of flights realised the appropriate emissions factor would be the average CO₂ emissions per flight realised.

Emissions trading

Approach to pollution control which leverages economic incentives to deliver emissions cuts in an efficient manner by allowing polluters with the ability to cut their emissions more cheaply to 'sell' emissions credits to other polluters with less flexibility.

European Economic Area (EEA)

Trading group comprising members of the European Free Trade Association (EFTA) and the European Union (EU).

European Union Emissions Trading Scheme (EU ETS)

Cap based emissions trading system covering the power sector and energy intensive industry in the EU.

Exogenous

A variable in an economic model which is determined outside of the model and is not a result calculated by the model, e.g. consumer tastes in a supply and demand model.

Fischer-Tropsch (FT) process

Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.

Fleet rollover model

Technology model which represents the evolution and characteristics of a vehicle fleet taking into account the age and scrappage cycle of the vehicles.

Functional Airspace Block (FAB)

An area of airspace established based on operational requirements and not national boundaries, e.g. Central Europe, Danube, Baltic.

Fossil fuel

A hydrocarbon deposit, such as petroleum, coal, or natural gas, derived from the accumulated remains of ancient plants and animals and used as fuel.

Fuel Efficiency

The efficiency by which a vehicle converts energy contained in a carrier fuel into motion. In the context of aviation this can be expressed in terms of fuel burn per seat-km or per passenger-km.

G8 Countries

A forum for governments of the eight richest countries in the world to discuss key issues. These are the UK, USA, France, Italy, Germany, Russia, Japan and Canada.

**Global Temperature Potential (GTP)**

A means for measuring the radiative effect of emissions based on the effect on the global mean surface temperature at some future point in time. See Box 6.2 for details.

Global Warming Potential (GWP)

A metric for comparing the climate effect of different greenhouse gases, all of which have differing lifetimes in the atmosphere and differing abilities to absorb radiation. The GWP is calculated as the integrated radiative forcing of a given gas over a given time period, relative to that of carbon dioxide. Standard international reporting processes use a time period of 100 years.

GLOCAF

The Global Carbon Finance model was developed by the Office of Climate Change to look at the costs to different countries of moving to a low carbon global economy, and the kind of international financial flows this might generate.

Great Circle Distance (GCD)

A definition of the shortest flight distance between two points, taking the curve of the earth's surface into account.

Greenhouse Gas (GHG)

Any atmospheric gas (either natural or anthropogenic in origin) which absorbs thermal radiation emitted by the Earth's surface. This traps heat in the atmosphere and keeps the surface at a warmer temperature than would otherwise be possible, hence it is commonly called the Greenhouse Effect.

Gross Domestic Product (GDP)

A measure of the total economic activity occurring within a country.

Heavy Good Vehicle (HGV)

A truck over 3.5 tonnes (articulated or rigid).

Hydrogenated Renewable Jet (HRJ)

Conversion of vegetable oils (e.g. conventional oil crops such as palm and soy, but also new oils crops such as jatropha and camelina) and algal oils to aviation fuel through a process including treatment with hydrogen.

International Air Transport Association (IATA)

A trade association comprising 230 airlines with the mission to represent, lead and serve the airline industry.

International Energy Agency (IEA)

Intergovernmental organisation which acts as energy policy advisor to 28 countries.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was formed in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP). It is designed to assess the latest scientific, technical and socio-economic literature on climate change in an open and transparent way which is neutral with respect to policy. This is done through publishing a range of special reports and assessment reports, the most recent of which (the Fourth Assessment Report, or AR4) was produced in 2007.

Kyoto gas

A greenhouse gas covered by the Kyoto Protocol.

Kyoto Protocol/Agreement

Adopted in 1997 as a protocol to the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol makes a legally binding commitment on participating countries to reduce their greenhouse gas emissions by 5% relative to 1990 levels, during the period 2008-2012. Gases covered by the Kyoto Protocol are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Level of Scientific Understanding (LOSU)

This is an index on a 4-step scale (High, Medium, Low and Very Low) designed to characterise the degree of scientific understanding of the radiative forcing agents that affect climate change.

Lifecycle

Lifecycle assessment tracks emissions generated and materials consumed for a product system over its entire lifecycle, from cradle to grave, including material production, product manufacture, product use, product maintenance and disposal at end of life. This includes biomass, where the CO₂ released on combustion was absorbed by the plant matter during its growing lifetime.

Load Factor

Number expressing the degree of occupancy of an aircraft – the higher the number the fuller the aircraft, such that a full aircraft has a load factor of 100%.

Long-haul flight

A flight of distance greater than 3,700km. In practice in this report flights between the UK and destinations outside Europe have been considered long-haul.

MARKAL

Optimisation model that can provide insights into the least-cost path to meeting national emissions targets over the long-term.

Mha

One Million Hectares = 10,000 km².

Mitigation

Action to reduce the sources (or enhance the sinks) of factors causing climate change, such as greenhouse gases.

Modal shift

A change from one means of transport to another e.g. car to cycling, air to rail.

MtCO₂

Million tonnes of Carbon Dioxide (CO₂).

Narrow-body aircraft

An airliner with a fuselage aircraft cabin diameter typically of 3 to 4 metres (10 to 13 ft), and airline seat arranged 2 to 6 abreast along a single aisle.

National Air Traffic Services (NATS)

ATM service provider for aircraft flying in UK airspace, and over the eastern part of the North Atlantic.

National Atmospheric Emissions Inventory (NAEI)

Data source compiling estimates of the UK's emissions to the atmosphere of various (particularly greenhouse) gases.

NO_x

A generic term for mono-nitrogen oxides (NO and NO₂). These oxides are produced during combustion, especially combustion at high temperatures.

Novel synthetic hydrocarbons

Generic term which covers a variety of new methods for the production of biofuels relying on conversion of biomass to jet fuel via biological or chemical processes.

Offset credits

Credits corresponding to units of abatement from projects, such as those generated under the Kyoto treaty's project based flexibility mechanisms, Joint Implementation (JI) and Clean Development Mechanism (CDM).

Passenger-kilometre (Pax-km)

Unit of travel referring to one passenger moved through a distance of one kilometre.

Open rotor engine

Radical engine design in which the rotating fan blades are not surrounded by a casing.

Point-to-point

Modelling term for a journey between two cities. Modelling in this way allows emissions to be calculated on the basis of real trips as opposed to basing them on hypothetical geographical ranges.

Pre-Industrial

The period before rapid industrial growth led to increasing use of fossil fuels around the world. For the purposes of measuring radiative forcing and global mean temperature increases, 'pre-industrial' is often defined as before 1750.

Reference case

Hypothetical projection of a given variable (e.g demand or emissions) which is used as a basis for developing scenarios or for comparison with alternative scenarios.

Radiative Forcing (RF)

A standard metric for measuring the contribution of changes in individual atmospheric constituents to the energy imbalance of the earth-atmosphere system, relative to pre-industrial times (usually dated at 1750).

Radiative Forcing Index (RFI)

An index designed by the IPCC for their 1999 report to measure the total radiative effect of aviation compared to that from CO₂. See Box 6.2 in main body of report for details.

Renewable Energy

Energy resources, where energy is derived from natural processes that are replenished constantly. They include geothermal, solar, wind, tide, wave, hydropower, biomass and biofuels.

Riblet

One of a series of microscopic grooves inscribed on the surface of an adhesive backed tape and used on aeroplanes and boat hulls to reduce drag.

Seat-kilometre (Seat-km)

Unit of travel referring to one vehicle seat (occupied or otherwise) moved through a distance of one kilometre.

Sensitivity Analysis

The study of how the variation (uncertainty) in the output of a mathematical model can be apportioned to variation in different input assumptions.

Short-haul flight

A flight of distance less than 3,700km. In practice in this report flights between the UK and Europe have been considered short-haul.

Technical potential

The theoretical maximum amount of emissions reduction that is possible from a particular technology (e.g. What would be achieved if every cavity wall were filled). This measure ignores constraints on delivery and barriers to firms and consumers that may prevent up take.

Turbine Engine Temperature (TET)

Temperature at which air enters a jet engine.

United Nations Framework Convention on Climate Change (UNFCCC)

Signed at the Earth Summit in Rio de Janeiro in 1992 by over 150 countries and the European Community, the UNFCCC has an ultimate aim of 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'

**Videoconferencing**

A means of digital communication by which user(s) are able to interact visually and auditorially with people in geographically distant locations.

Wide-body aircraft

A large airliner with a fuselage diameter of 5 to 6 metres and twin aisles.

Winglet

A short vertical fin on the tip of an aircraft wing for reducing drag.



Committee on Climate Change

4th Floor
Manning House
22 Carlisle Place
London SW1P 1JA

www.theccc.org.uk

natur**ally**responsible[☼]



Printed by **Seacourt** to the most stringent environmental systems using **Waterless** Offset (0% water and 0% Isopropyl alcohol or harmful substitutes), 100% renewable energy and vegetable oil based inks on paper with 100% recycled content. **Seacourt** is registered to EMAS and ISO 14001, prints to ISO12647 Colour Standard, is a CarbonNeutral[®] company and FSC certified TT-COC-2132.

Meeting the UK aviation target – options for 2050

Climate Change | December 2009

Rt Hon Grant Shapps MP
Secretary of State for Transport
Great Minster House
33 Horseferry Road
London SW1P 4DR

24 September 2019

Net-zero and the approach to international aviation and shipping emissions

Dear Secretary of State,

The Government has legislated for the UK to reach net-zero greenhouse gas emissions by 2050. I am pleased the Government clarified to Parliament that the target must cover the whole economy, including international aviation and shipping (IAS) emissions. This letter responds to the Government's request on how to bring IAS emissions formally within the UK's net-zero target, setting out the rationale and the implications for the UK's climate strategy.

Our advice that 2050 is an appropriate date for net-zero is based on formal inclusion of IAS emissions within the target. Without this a more ambitious target is likely to be required.

The rationale for inclusion of IAS emissions in the UK carbon targets

The primary policy approach to reducing IAS emissions should be international. Through the efforts of your Department, the UK has played a key role in progress by both the International Civil Aviation Organisation (to agree a global offsetting scheme for aviation emissions to 2035) and the International Maritime Organisation (to agree to reduce shipping emissions by at least 50% by 2050 compared to 2008 levels and pursue efforts to phase emissions out entirely).

This international framing should not prevent the inclusion of IAS emissions in UK carbon targets, as is already the case for other sectors that are covered by international agreements and potentially exposed to competitiveness pressures (e.g. energy-intensive industry).

Addressing IAS emissions is strategically important. Formal inclusion of IAS emissions in the net-zero target would complement agreed international policies and should not be interpreted as a unilateral UK approach to reducing emissions in these sectors.

- Aviation is likely to be the largest emitting sector in the UK by 2050, even with strong progress on technology and limiting demand. Aviation also has climate warming effects beyond CO₂, which it will be important to monitor and consider within future policies.
- Including IAS emissions in UK carbon targets increases confidence that the Government is appropriately prioritising their reduction. That should include pushing for suitably strong international levers, as well as using supplementary UK measures where these do not impact on the competitiveness of the IAS sectors.
- Inclusion of IAS emissions clarifies the requirements for policy development in other sectors (e.g. the scale of deployment needed for options to offset remaining emissions).
- There are no practical barriers to inclusion. Emissions are already estimated and reported to the UN and should be included in UK emissions targets on the same basis. The uncertainty attached to these estimates is no higher than for other sectors covered by carbon budgets.

- Inclusion can be managed through secondary legislation and without any additional costs for achieving net-zero beyond those already agreed by Parliament.

Formal inclusion of IAS emissions would help to guide long-term policy approaches and infrastructure investment decisions.

Achieving net-zero IAS emissions in the UK

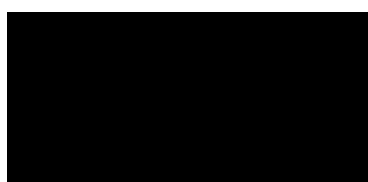
The planning assumption for IAS should be to achieve net-zero emissions by 2050. This should be reflected in your forthcoming Aviation Strategy and as the Clean Maritime Plan is taken forward. It means reducing actual emissions in these sectors and is likely to require some use of greenhouse gas removals (GGRs) to offset remaining emissions:

- **Aviation.** Zero-carbon aviation is highly unlikely to be feasible by 2050.
 - Aviation emissions could be reduced by around 20% from today to 2050 through improvements to fuel efficiency, some use of sustainable biofuels, and by limiting demand growth to at most 25% above current levels. This is likely to be cost-saving. There is potential to reduce emissions further with lower levels of demand.
 - Novel fuels (e.g. synthetic carbon-neutral kerosene, algal biofuels) could allow greater reductions, but their development is highly speculative and should not be relied upon.
 - The Government should assess its airport capacity strategy in this context. Specifically, investments will need to be demonstrated to make economic sense in a net-zero world and the transition towards it.
- **Shipping.** Achieving zero-carbon or near zero-carbon shipping by 2050 is likely to be feasible and cost-effective through use of alternative fuels (e.g. zero-carbon hydrogen or ammonia). A transition to these fuels will need to be well underway globally before 2050, with refuelling infrastructure established and a substantial fraction of the fleet already switched, in order to meet the IMO's current 2050 objective.
- **Greenhouse gas removals (GGRs).** For aviation, and to the extent that shipping emissions cannot be eliminated, measures to remove CO₂ from the atmosphere will be required to offset remaining emissions. They cannot be a substitute for genuine emissions reductions.
 - In the long term offsets can only be based on verifiable emissions removal from the atmosphere. These would ideally be delivered through the international framework (e.g. CORSIA), but may need additional UK policies.
 - However, there will not be unlimited access to GGR offsets since their potential is constrained by global land and other resources. The focus should therefore be on highly scalable GGR options rather than those limited in scope (e.g. afforestation).

The Government can take steps towards enabling IAS to reach net-zero emissions in the UK and internationally by establishing a new market for GGRs. Such a strategy could create a significant new global export opportunity for the UK in GGR technology and expertise.

Further detail on the issues covered in this letter is set out in the accompanying annex.

Yours,



Lord Deben

Chairman, Committee on Climate Change

Annex

Net-zero and the approach to international aviation and shipping emissions

Introduction

In June 2019 the Government legislated for the UK to reach net-zero emissions by 2050, but this formally excluded emissions from international aviation and shipping (IAS).

The Government clarified to Parliament that their plans for net-zero cover the whole economy, including IAS emissions, and that they await the Committee's advice on formal inclusion of these sectors within the target.¹

Our advice is set out in the accompanying letter, which summarises the rationale for formal inclusion of IAS sectors within the net-zero target and sets out how this could be achieved. It reflects the advice in our net-zero report, which incorporated the UK's share of IAS emissions. If these emissions are not formally included then a more ambitious net-zero target is likely to be required.

This annex presents the evidence base underpinning our advice. It explains how and why IAS emissions should be brought formally within the net-zero target, and the implications for the UK's climate strategy.

We set out our assessment in the following four sections:

- (i) Recap of net-zero advice
- (ii) How to include IAS emissions within the net-zero target
- (iii) How to get to net-zero IAS emissions
- (iv) Implications for aviation and shipping policy

(i) Recap of net-zero advice

The Paris Agreement set a long-term goal to hold the increase in global average temperature to well-below 2°C and to pursue efforts to limit the increase to 1.5°C (compared to pre-industrial levels). In order to achieve this long-term temperature goal it also aims to balance 'anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century' (which is widely interpreted as implying net-zero greenhouse gas (GHG) emissions globally).

Global emission pathways consistent with delivering this temperature goal require reducing global CO₂ emissions to net-zero by around 2050, and global GHG emissions to net-zero by around 2070 (Figure A1). This includes all sources of emissions globally, including those from aviation and shipping.

The Paris Agreement also requires that parties pursue their 'highest possible ambition'. At the UK level our analysis currently suggests that 2050 is the earliest credible date for reaching net-zero including IAS emissions, based on capability, equity, and responsibility to lead.

Reducing UK emissions to net-zero will require action across all sectors of the economy (Figure A2). Getting to very-low emissions (e.g. a few million tonnes of CO₂-equivalent - CO₂e) is feasible in most sectors. The greatest challenges are in reducing agriculture and aviation emissions, where there are limited zero-carbon options. These sectors are likely to be a significant source of emissions even in the long-term.

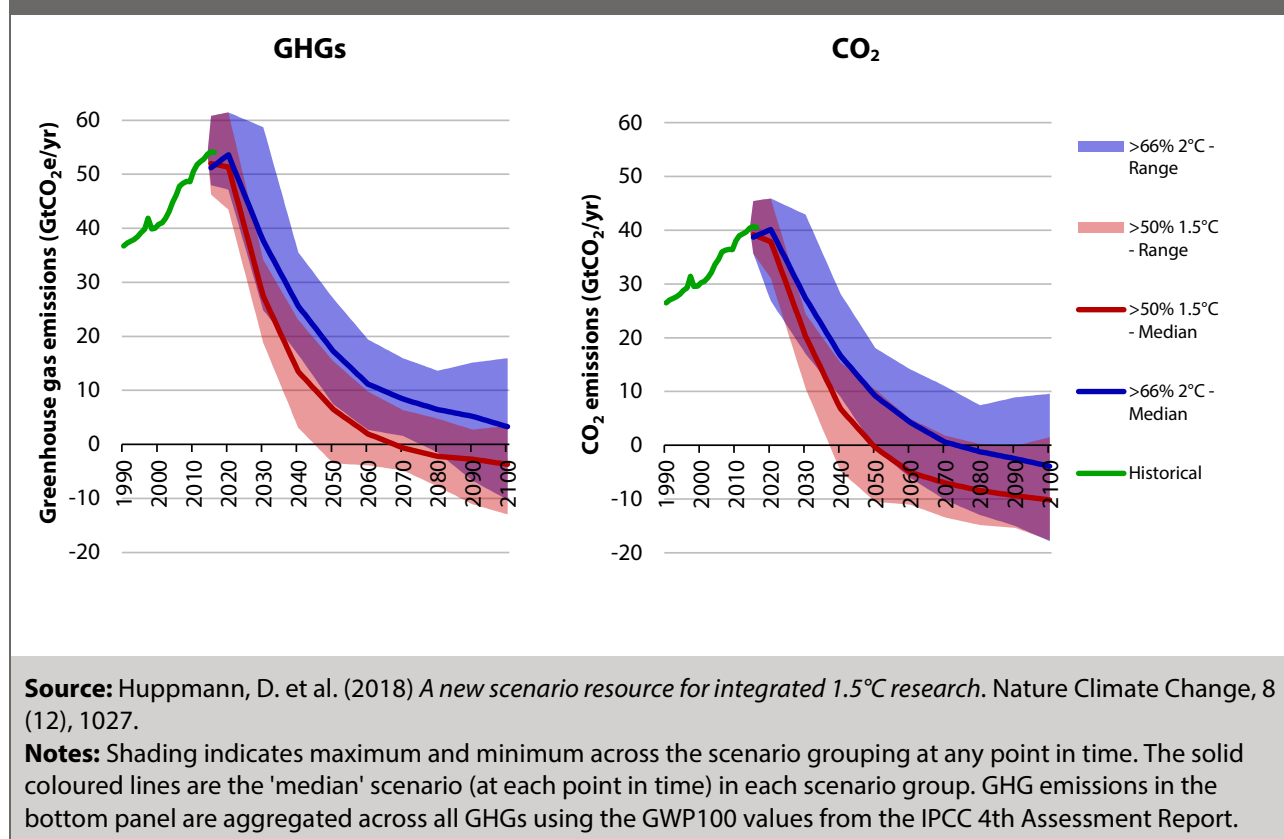
Getting to net-zero emissions overall will therefore require greenhouse gas removals (GGRs) (e.g. bioenergy with carbon capture and storage - BECCS, direct air capture of CO₂ with storage

¹ Hansard HC (12 June 2019) Volume 661 Column 682 *Net Zero Emissions Target*.

– DACCS) in order to offset remaining emissions. We identify sufficient potential for these to be delivered domestically to reach net-zero emissions for the economy as a whole, including IAS.

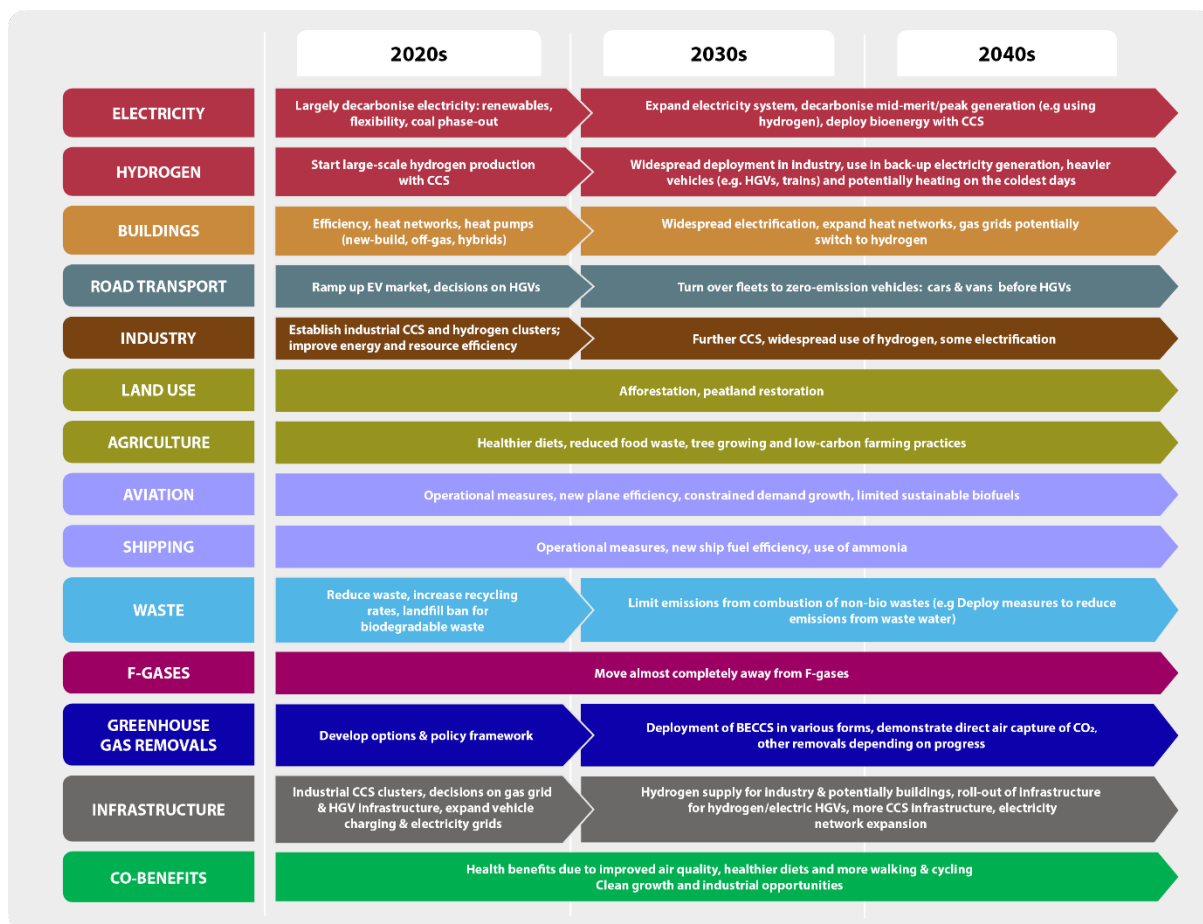
The net-zero target should therefore be met by reducing UK emissions as far as possible (i.e. not by offshoring them), and by using GGRs to offset the emissions that remain (Figure A3). Given potential to achieve this domestically, the aim should be to meet the target without relying on use of international offset credits. The Government confirmed to Parliament that this is its approach.²

Figure A1. Global emissions pathways for CO₂ and GHGs consistent with the Paris Agreement



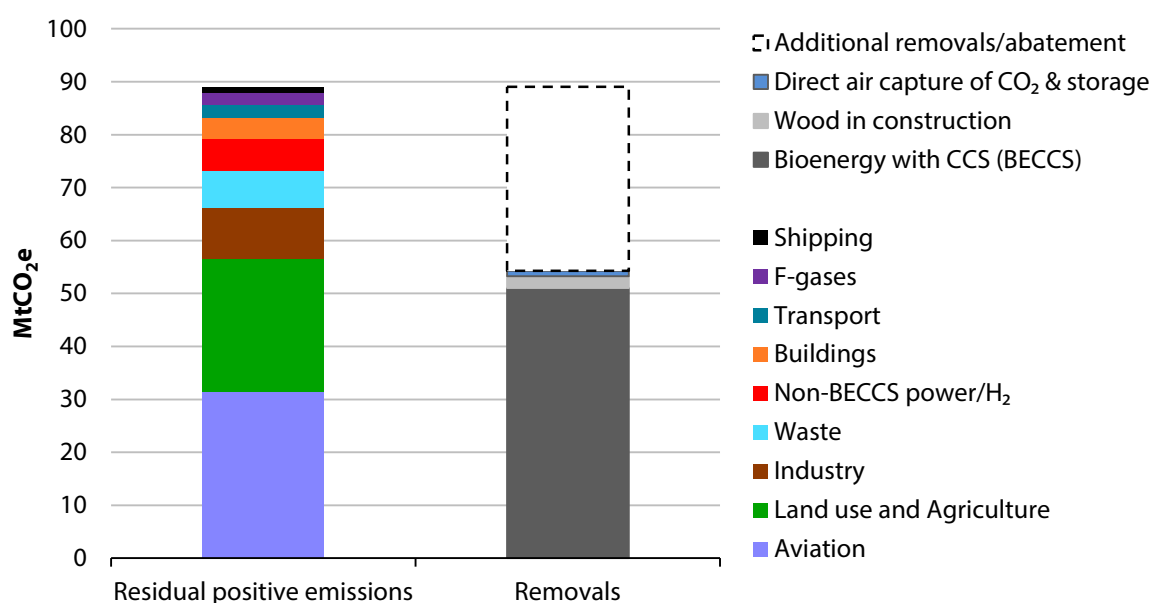
² Hansard HC (12 June 2019) Volume 661 Column 663 *Net Zero Emissions Target*.

Figure A2. Sectoral transitions required over the period to 2050 to reach net-zero



Source: CCC (2019) *Reducing UK emissions – 2019 Progress Report to Parliament*.

Figure A3. Greenhouse gas removals required to balance positive emissions in 2050



Source: CCC (2019) *Net zero – The UK's contribution to stopping global warming*.

Notes: Sectoral emissions and contributions from removals presented for the Further Ambition scenario in our net-zero report. The contribution from 'additional removals/abatement' refers to the options to go beyond the Further Ambition scenario and achieve net-zero emissions, which can be done with additional removals and/or further reductions of positive emissions.

(ii) How to include IAS emissions within the net-zero target

The primary policy approach to reducing IAS emissions should be at the international level, given the global nature of these sectors and the risk of carbon leakage from a unilateral UK approach.

The UK has played a key role in progress by both the International Civil Aviation Organisation (ICAO) and International Maritime Organisation (IMO):

- **Global aviation policy.** The ICAO has agreed a global offsetting scheme for international aviation emissions (the Carbon Offsetting and Reduction Scheme for International Aviation - CORSIA). Airlines flying on routes between countries covered by the scheme are required to offset growth in emissions above 2020 levels. The scheme starts in 2021 and is mandatory from 2027. The policy currently stops in 2035.
- **Global shipping policy.** The IMO has agreed to peak GHG emissions from global international shipping as soon as possible, to reduce them by at least 50% below 2008 levels by 2050, and to pursue efforts to phase them out entirely.

Other voluntary industry initiatives have also been agreed:

- **Aviation.** The International Air Transport Association (IATA), which represents the global airline industry, has adopted a target to reduce net aviation CO₂ emissions by 50% below 2005 levels by 2050. The European airport industry has committed to net-zero CO₂ emissions by 2050 at the latest, covering emissions at airports but not from flights.

- **Shipping.** Maersk, the world's largest shipping company, has announced a goal to reach carbon neutrality by 2050.

At the UK level, addressing IAS emissions is strategically important for the robustness of the net-zero target:

- IAS emissions cause climate change and should therefore be included within the UK's targets and strategies.
- Aviation is likely to be the largest emitting sector in 2050, even after strong progress on technology and measures to limit demand.
- Aviation's true climate impact is likely to be understated, given the existence of short-term non-CO₂ effects (e.g. from contrails) which are not covered in the basket of gases reported to the UN or by the Climate Change Act.

An international framing should not prevent the inclusion of IAS emissions in UK carbon targets, as is already the case for other sectors that are covered by international agreements and potentially exposed to competitiveness pressures (e.g. energy-intensive industry).

Formal inclusion of IAS emissions in the net-zero target would complement agreed international policies and should not be interpreted as a unilateral UK approach to reducing emissions in these sectors:

- **Inclusion increases confidence that the Government is sufficiently prioritising reduction of IAS emissions.** That should include pushing for suitably strong international levers, as well as using supplementary UK measures where these do not impact on the competitiveness of the IAS sectors.
 - At the international level this includes the need for a long-term objective for the aviation sector in line with the Paris Agreement, and future CORSIA caps consistent with this that incentivise GGRs for all emissions, not just emissions growth above 2020 levels.
 - At the UK level, supplementary policies that have limited competitiveness risks include support for developing alternative fuels, managing growth in demand, and kick-starting a market for GGRs.
- **Inclusion clarifies the requirements for policy development in other sectors.** That includes the scale of deployment needed for GGR options, and the need for low-carbon fuel infrastructure to extend to ports.

There are no practical barriers to formal inclusion of IAS emissions. Emissions are already estimated and reported to the UN and should be included in UK emissions targets on the same basis. The uncertainty attached to these estimates is no higher than for other sectors covered by carbon budgets.

- The Climate Change Act requires that inclusion be on the basis of international carbon reporting practice. Bunker fuel sales are the currently agreed methodology by which countries report IAS emissions to the UN.
- While a range of alternative methodologies have been proposed, uncertainty in IAS emissions is no higher than for other sectors already covered by carbon budgets and the net-zero target (Figure A4).
 - Domestic aviation and shipping emissions are already formally included within the net-zero target on the basis of bunker fuel sales.
 - For international aviation, bunker fuel sales are an accurate reflection of aviation activity as airlines do not tend to carry more fuel than needed for a

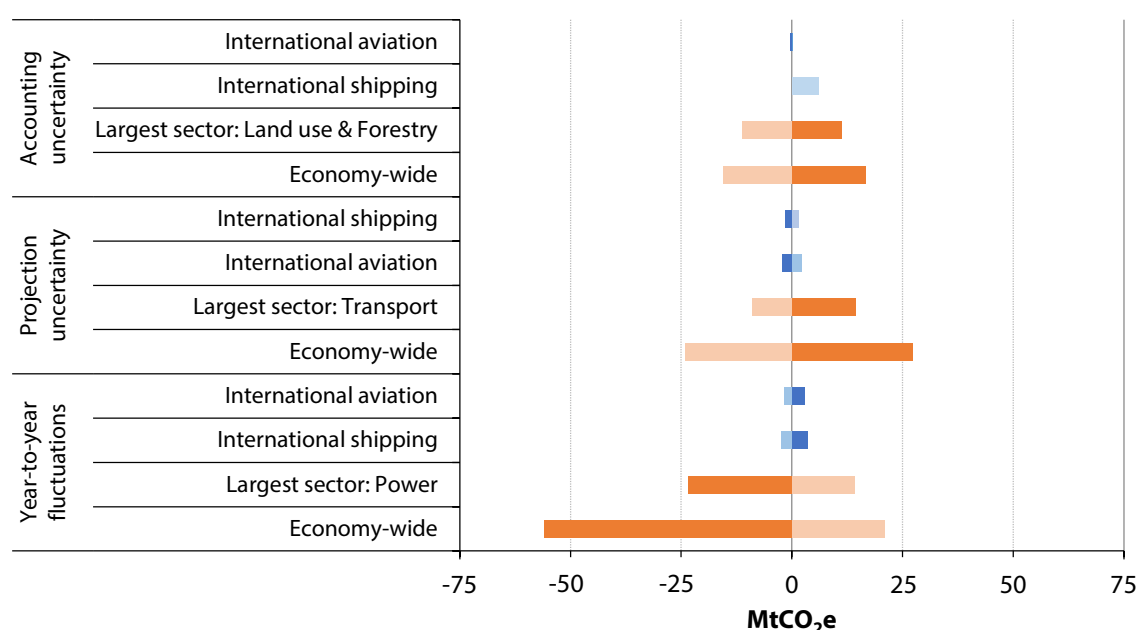
given flight (UK departing-flight emissions modelled by DfT are within 4% of the bunker fuel sales estimate).

- For international shipping, bunker fuels *may* not accurately reflect country-level shipping activity and emissions, given the potential for ships to refuel at multiple ports on routes. However, while imperfect, the difference between this approach and alternative methodologies is unlikely to be material.
- Were alternative methodologies for measuring IAS emissions to be developed and agreed internationally for annual reporting (e.g. by the ICAO, IMO, or UNFCCC) then this could be managed through adjustments to carbon budgets, as allowed under the Climate Change Act.
- Inclusion can be managed through secondary legislation under section 30 of the Climate Change Act, and without any additional costs for achieving net-zero beyond those already agreed by Parliament.

Other countries have already decided to include IAS emissions in their net-zero targets and/or strategies (e.g. in Scotland³ on the basis of bunker fuel sales, and in France⁴).

In the context of international negotiations at ICAO and IMO, inclusion of IAS emissions in the net-zero target should not be interpreted as a rejection of multi-lateral approaches or as prejudicing discussions on burden sharing.

Figure A4. Uncertainty in IAS emissions compared to wider uncertainties in carbon budgets



Source: CCC calculations, BEIS (2019) *2017 UK Greenhouse Gas Emissions, Final Figures*, Lee et al (2005) *Study on the Allocation of Emissions from International Aviation to the UK inventory*, CCC (2011) *Review of UK Shipping Emissions*, CCC (2015) *Sectoral scenarios for the Fifth Carbon Budget – Technical report*, DfT (2017) *UK Aviation Forecasts*, BEIS (2019) *Updated energy and emissions projections 2018*.

Notes: Chart shows uncertainty across three main categories for IAS compared to other sectors already included in carbon budgets and for the economy as a whole. Projection uncertainty is for 2030. Year-to-year fluctuations show the largest annual increase and decrease since 1990.

³ See www.climate.scot

⁴ See http://www.assemblee-nationale.fr/dyn/15/dossiers/energie_climat

Aviation and shipping both emit very small amounts of regulated non-CO₂ greenhouse gases (methane and nitrous oxide) but also have additional warming and cooling effects that are not included in the basket of gases covered by the Paris Agreement and the Climate Change Act (Figure A5):

- **Aviation** produces a range of different pollutants that affect the climate in different ways. The most significant effect is from creation of contrails and high clouds, although the impact of these are short-lived as these clouds are high in the atmosphere. Measuring these effects on an annual basis is challenging, given their short-term nature and dependence on localised conditions. Overall, non-CO₂ effects from aviation warm the climate and approximately double the historic warming effect of CO₂ alone.
- **Shipping** has non-CO₂ effects that come from the emission of sulphur dioxide, which has an overall cooling effect on the climate but causes local air pollution.

In both aviation and shipping these non-CO₂ effects are mainly short-lived, meaning that if they were stopped their effects on the climate would rapidly disappear.

The appropriate approach to policy at this stage is not to include these effects within the net-zero target, but to improve scientific understanding (e.g. for annual reporting) and develop options to markedly reduce them over the coming decades that are not at the expense of GHG emissions.

In aviation, policies are already in place to limit some non-CO₂ effects due to their impact on air quality. In shipping, sulphate emissions are likely to be significantly reduced in future due to global regulations to reduce the sulphur content of shipping fuels. These are expected to come into force in 2020.

While addressing non-CO₂ effects is important, this does not change the need to reduce CO₂ emissions which are the dominant factor contributing to IAS' impact on the climate.

We will continue to monitor progress to reduce the non-CO₂ effects of IAS in our annual progress reports to Parliament and in our advice on setting carbon budgets.

Figure A5. Non-CO₂ effects from aviation and shipping



Source: Lee et al (2010) *Transport impacts on atmosphere and climate: aviation*, Atmospheric Environment; Eyring et al (2010) *Transport impacts on atmosphere and climate: shipping*, Atmospheric Environment.

Notes: Each component of aviation and shipping's effect on climate is shown in terms of radiative forcing, which measures the current atmospheric imbalance (in Watts per square metre, Wm⁻²) due to aviation and shipping activity up until now. Note that it does not give a measure of future effects from current activity - for instance, emitted CO₂ will reside in the atmosphere for many decades, whereas today's contrails and aerosols will only last up to a few hours or days. Whiskers denote 90% confidence intervals (aviation) and range of estimates in the literature (shipping). LOSU indicates the Level of Scientific Understanding regarding each effect. Induced cirrus and aerosol indirect effects are shown as a dotted bar due to high uncertainty.

(iii) How to get to net-zero IAS emissions

The planning assumption for the IAS sectors should be to achieve net-zero emissions by 2050. This reflects the strategic importance of these sectors, and their international nature.

Getting to net-zero emissions will require reducing IAS emissions as far as possible and using scalable GGRs (e.g. BECCS or DACCS) to offset remaining emissions.

Reducing IAS emissions

Reducing aviation emissions will be more challenging than for shipping, given the lack of zero-carbon options in aviation (Figure A7):

- **Aviation.** Our scenarios from our net-zero advice suggest aviation emissions could be reduced from 36.5 MtCO₂ in 2017 to around 30 MtCO₂ in 2050 through a combination of fuel efficiency improvements, limited use of sustainable biofuels, and by managing demand growth. Major technological breakthroughs in commercial aviation are unlikely to make a significant difference to emissions by 2050 given long development and certification lead times, and slow turnover of the fleet.
 - **Fuel efficiency.** Our scenarios reflect a 1.4% annual improvement in fuel efficiency, which is in line with the historical average since 2000 for UK departing flights on a seat-km basis. This rate of improvement could be achieved through:
 - More efficient engines, including both advanced conventional jet designs, and some deployment of hybrid-electric aircraft in the 2040s (e.g. hybrids make up less than 10% of kilometres flown in 2050). There are no full-electric aircraft in the scenario which, particularly for long-haul flights, are unlikely to be feasible by 2050.
 - Improvements in aircraft design including through reductions in design speeds, and use of design elements such as high aspect ratio wings and composite materials.
 - Efficiency improvements in airlines' operations and in airspace management.
 - **Sustainable fuels.** Our scenario has a 10% uptake of sustainable fuels in 2050. It is not appropriate to plan for higher levels of uptake at this stage, given the range of competing potential uses for biomass across the economy (Figure A8) and uncertainty over which use will be most cost-effective. Our scenarios are based around supply of sustainable biomass with strong governance to ensure they reflect genuine emissions savings. We therefore assume high emissions saving from these biofuels. Emissions relating to cultivation, processing and transportation are relatively small and, where relevant, are included elsewhere in our economy-wide scenario.
 - **Demand.** In the absence of a true zero-carbon plane, demand cannot continue to grow unfettered over the long-term. Our scenario reflects a 25% growth in demand by 2050 compared to 2018 levels. This compares to current Government projections which are for up to a 49% increase in demand over the same period.⁵

⁵ DfT (2017) *UK Aviation Forecasts*.

- **Speculative aviation options.** We have identified ‘Speculative’ options in aviation on demand and alternative fuels which could reduce emissions below 30 MtCO₂ in 2050, though these have greater challenges:
 - **Further demand constraint** is possible in order to limit growth to less than 25% above current levels by 2050. We illustrate the potential emission savings from additional demand constraint through a scenario where demand is broadly at 2018 levels in 2050. This could save up to 8 MtCO₂e in 2050, and could, for example, reflect future changes in consumer preferences and social norms, or more ambitious policy.
 - **Alternative fuels.** It is possible that synthetic carbon-neutral fuels (‘power-to-liquid’) could be used to reduce aviation emissions. Production of such fuels would entail recycling captured CO₂ (e.g. via direct air capture, DAC) in conjunction with zero-carbon hydrogen into a drop-in replacement for kerosene. However, costs for DAC are expected to be high (e.g. in our net-zero advice we estimated that it might be around £300/tCO₂ by 2050). On top of this, production of synthetic fuels is likely to have substantial further costs given low thermodynamic efficiency and multiple processing stages, even if the input electricity comes from low-cost renewables. CO₂ captured through DAC is therefore likely to provide emissions reductions at lower cost when combined with CCS rather than it being inefficiently recycled into a fuel:
 - Once CO₂ has been captured, sequestering it geologically can provide abatement at a further cost of up to £20 per tonne of CO₂. By contrast, the cost of recycling it into a carbon-neutral fuel to displace fossil kerosene is estimated to have a further net cost of around £100 per tonne of CO₂ in 2050 (Figure A9).
 - Paying this premium to reduce aviation emissions to net-zero via synthetic fuels rather than sequestering the CO₂ would have an additional cost to the UK of £2-4 billion annually in 2050 under the level of aviation emissions in our net-zero scenario.
- **Shipping.** A range of options exist to reduce shipping emissions, some of which may allow shipping to get to near-zero GHG emissions. These include more fuel-efficient ship and engine designs, improved ship operations, and use of alternative fuels:
 - **Improvements to fuel efficiency** include measures to reduce water resistance (e.g. more efficient hull coatings), measures to improve energy efficiency (e.g. recovery of waste heat), and use of alternative sources of propulsion (e.g. kites, sails and Flettner rotors).
 - **Ship operations.** Reducing speeds at which ships travel can significantly reduce fuel use. Other operational measures include use of software to plan the most efficient routes and to optimise ballast and trim.
 - **Alternative fuels.** Use of hydrogen or ammonia could allow for zero-carbon shipping, but widespread use of biofuels or electrification is unlikely.
 - There is potential for fuel switching in shipping to hydrogen or ammonia, both of which would need to be produced in a low- or zero-carbon way (i.e. from zero-carbon electricity or with CCS). These options can be applied to new ships and retrofitted to existing ships. The potential development of an international market in hydrogen (e.g. as ammonia) shipped from countries with low costs of low-carbon hydrogen production, does raise

the possibility of this being the primary way of supplying low-carbon fuel for refuelling at ports.

- Biofuels are technically feasible in shipping but not likely to be a priority or cost-effective given other competing uses for this resource.
- Electrification is possible for ships, but is likely to be limited to relatively short routes given energy and therefore battery requirements.

Figure A7. Aviation and shipping emission scenarios to 2050

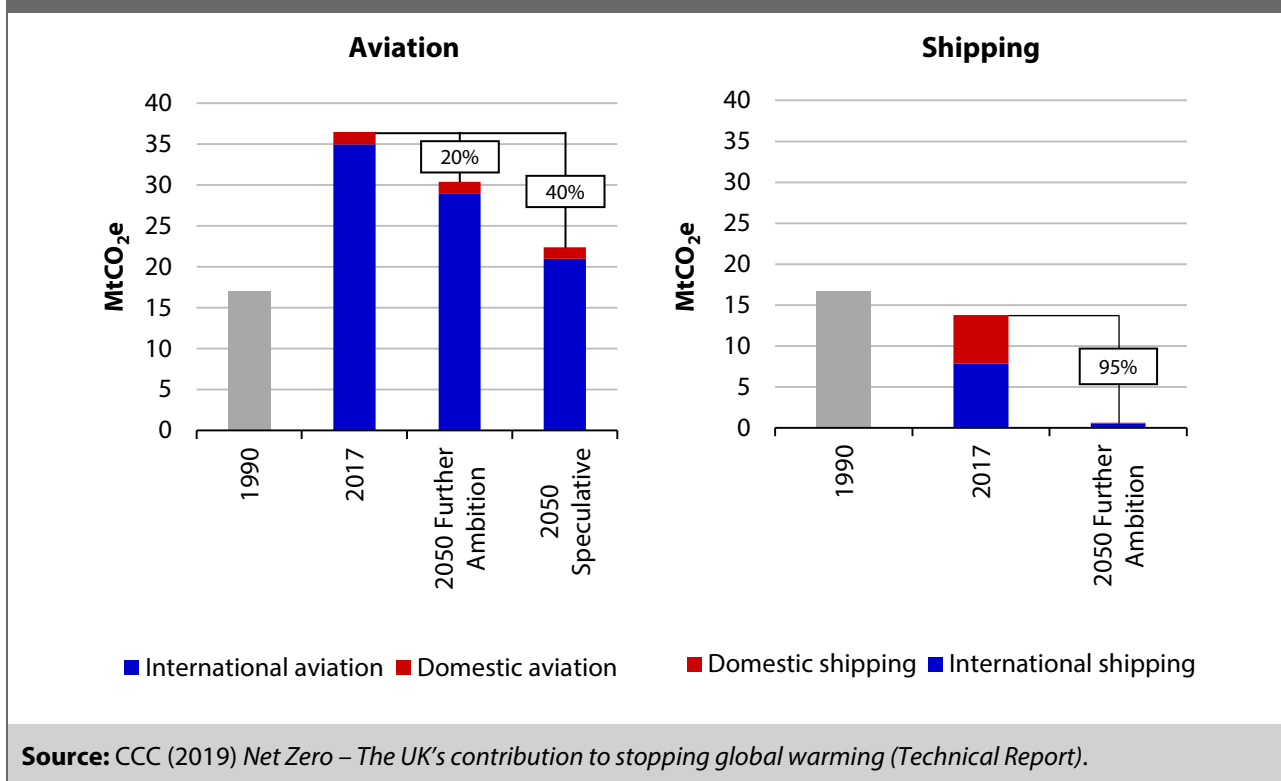
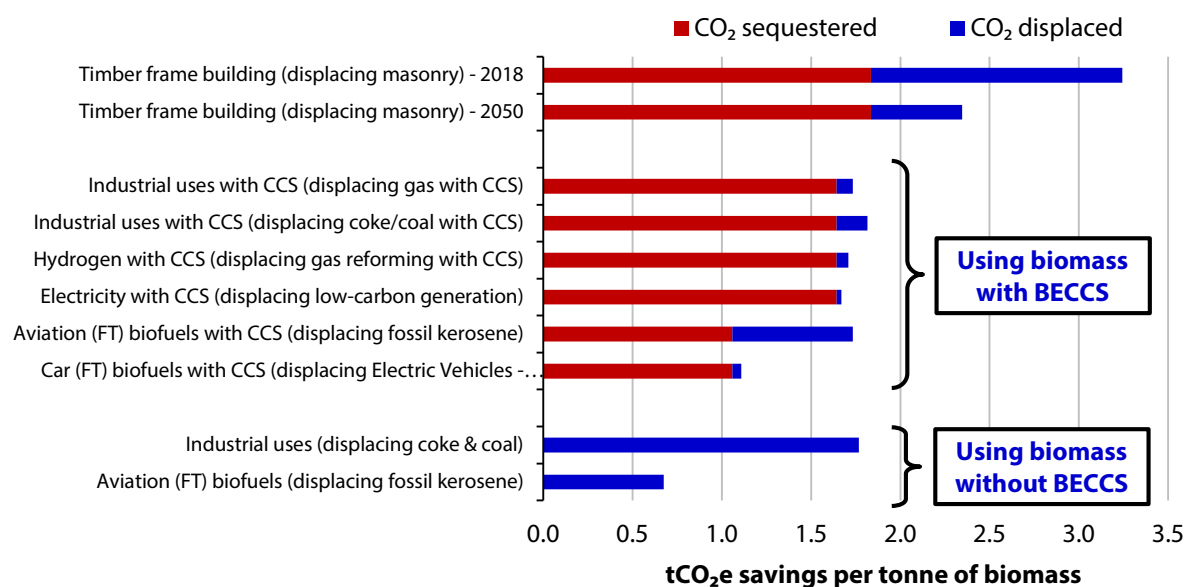


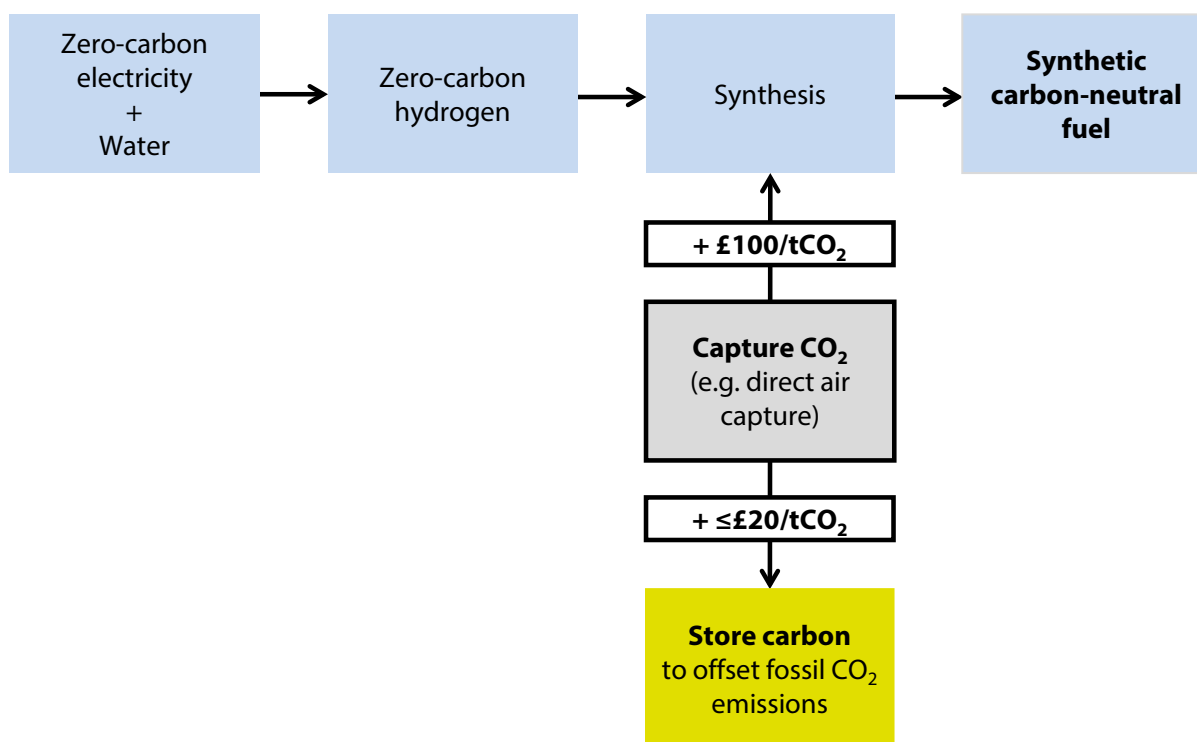
Figure A8. Estimated GHG abatement across different biomass applications



Source: CCC (2018) *Biomass in a low-carbon economy*.

Notes: Shows estimates of GHG abatement provided by an oven dried tonne of biomass used in various sectors, considering an appropriate counterfactual (i.e. what we would expect it to be displacing, long-term).

Figure A9. Cost of storing captured CO₂ compared to cost of using it to produce synthetic fuels



Source: CCC analysis based on Royal Society (2019) *Sustainable synthetic carbon based fuels for transport*.

Getting IAS emissions to net-zero

Achieving net-zero IAS emissions will require limited use of scalable GGR offsets (e.g. BECCS or DACCS), given likely significant remaining IAS emissions in 2050 (primarily from aviation).

- GGR offsets could be funded through a requirement on IAS sectors to pay for removals, or Governments could generate revenues (e.g. through an emissions trading system or carbon tax) that can be used to pay for Government-procured removals.
- GGR offsets could in principle be delivered through international (e.g. CORSIA) or domestic policies, but must demonstrate genuinely additional removals within a robust governance framework. For CCS-based removals it would make sense for a substantial proportion of these to occur domestically, given the UK's advantages relating to availability of CO₂ storage capacity, offshore engineering expertise, and market regulation and design.
- There will not be unlimited access to GGR offsets. The potential for deploying these is limited by global constraints on land and resources. As some GGR options (e.g. afforestation) have relatively low costs but are limited in scope, it should be assumed that these opportunities will be taken in any case and will not provide additional scope to offset positive emissions elsewhere. The GGR options appropriate to offset 'hard to reduce' emissions will therefore generally be those that are highly scalable and towards the higher end of GGR costs (e.g. BECCS or DACCS).
- Offsets that do not offer potential for genuine GGR should not be pursued in the long term.

It may also be possible to deploy synthetic fuels to fully replace fossil fuel use, particularly in aviation. This could reduce emissions to gross (i.e. actual) zero. However, this is likely to be significantly more expensive than a GGR-based approach.

(iv) Implications for aviation and shipping policy

The approach to reducing IAS emissions should be through a combination of international and domestic policies. It will require a co-ordinated cross-government approach to join up the Government's clean growth, industrial strategy, and aviation and shipping objectives.

At the international level, global policies consistent with the ambition in the Paris Agreement are required to provide a level-playing field for airlines and shipping operators, and to guard against the risk of competitive distortions.

But international policies are unlikely to overcome all barriers to decarbonising the IAS sectors. Domestic policies should also be pursued where these can help overcome UK-specific market barriers, and where these do not lead to risk of carbon leakage.

Specific international and domestic policy approaches that should be considered for aviation, shipping, and GGRs include:

- **Aviation.** A package of international and domestic policy measures should be put in place that includes carbon pricing, support for research, innovation and deployment, and measures to manage growth in demand.
 - **A long-term goal for global international aviation emissions.** The ICAO's current carbon policy, CORSIA, has an end date of 2035 and will need to be based on robust rules that deliver genuine emission reductions. A new long-term goal for global international aviation emissions consistent with the Paris Agreement would provide a strong and early signal to incentivise the investment in new, cleaner, technologies that will be required for the sector to

play its role in meeting long-term targets. This is particularly important in aviation given the long lifetimes of assets. A similar approach has been agreed for global shipping emissions in the IMO, which has set a target for greenhouse gas emissions to be at least 50% below 2008 levels by 2050 (although this may need to be tightened further).

– **Support for research, innovation, and deployment in technology and alternative fuels.**

- **Technology.** Our analysis, and that of industry, suggests the largest contribution to reducing aviation emissions will come from new technologies and aircraft designs. Many of these developments are likely to be cost-effective, given their potential fuel savings. The Government should build on the approach set out in the Aerospace Sector Deal and Future Flight Challenge, and set out a clear strategy to ensure these technology solutions are developed and brought to market in a timely fashion.
- **Sustainable biofuels.** Some deployment of sustainable biofuels is likely to be appropriate in aviation (e.g. up to 10% of fuel use in 2050), but higher levels of uptake should be not planned for given competing alternative uses. Development of a UK market for aviation biofuels could be supported by achieving more of the 2030 Renewable Transport Fuel Obligation target through aviation fuels, subject to strong sustainability criteria being put in place. Aviation biofuels will need to be produced with CCS to be competitive against alternative uses of biomass.
- **Synthetic fuels.** Synthetic fuels should not be a priority for government policy, but if the aviation industry wants to pursue them it should focus on demonstrating that these fuels, used in aviation, would be genuinely low-carbon, and could become cost-competitive and scalable in a global market.

– **Managing demand.** Measures should be put in place to limit growth in demand to at most 25% above current levels by 2050. These could include carbon pricing, a frequent flyer levy, fiscal measures to ensure aviation is not undertaxed compared to other transport sectors (e.g. fuel duty, VAT), reforms to Air Passenger Duty, or management of airport capacity. Research commissioned by the Department for Transport concludes that UK demand management policies in aviation are unlikely to lead to carbon leakage in aggregate.⁶

– **Airport capacity.** The Government should assess its airport capacity strategy in the context of net zero. Specifically, investments will need to be demonstrated to make economic sense in a net-zero world and the transition towards it. Current planned additional airport capacity in London, including the third runway at Heathrow, is likely to leave at most very limited room for growth at non-London airports.

⁶ ATA and Clarity (2018) *The carbon leakage and competitiveness impacts of carbon abatement policy in aviation*.

- **Shipping.** The Government's Clean Maritime Plan⁷ sets out many of the steps needed to decarbonise the shipping sector, and commits the UK to 'moving faster than other countries and faster than international standards'. A globally co-ordinated approach will be needed for the transition towards zero-carbon shipping, supported by domestic policies.
 - **Global policy to deliver the IMO 2050 target.** The IMO has agreed to reduce global international shipping emissions by at least 50% by 2050 compared to 2008 levels, and to pursue efforts to phase them out entirely. It must now put in a place a package of policies to deliver that target. That should include carbon pricing, support for research, innovation, and deployment, and a co-ordinated approach to provision of refuelling infrastructure for alternative fuels. Consideration should also be given to increasing the IMO's 2050 ambition, given the potential for much deeper reductions in global shipping emissions (e.g. to nearly zero through use of ammonia or other hydrogen-based fuels).
 - **Domestic policy to support the transition to zero-carbon shipping.** The main focus for domestic shipping policy should be on developing supply chains for zero-carbon fuels (e.g. hydrogen or ammonia), and the refuelling and other port infrastructure required to support this. That should include ensuring availability of key input technologies, including CCS, which will require a co-ordinated cross-government approach. It could also include support for developing and deploying these vessels (e.g. to demonstrate safety standards).
- **Greenhouse gas removal.** The Government can take steps towards enabling IAS to reach net-zero emissions in the UK and internationally by establishing a market for scalable GGR solutions (e.g. BECCS, DACCS). Such a strategy could create a significant new global export opportunity for the UK in GGR technology and expertise. This will require an effective cross-government approach across IAS and GGR policy. It highlights the importance of developing a UK CCS industry, which will be required for production of biofuels in aviation, and hydrogen and ammonia in shipping, as well as for GGRs.

These policy approaches should be reflected in the forthcoming Aviation Strategy and as the Clean Maritime Plan is taken forward.

The Committee will continue to monitor progress in decarbonising aviation and shipping as part of our annual reports to Parliament and as part of our advice on carbon budgets.

⁷ Department for Transport (2019) *Clean Maritime Plan*.



A bottom-up analysis of including aviation within the EU's Emissions Trading Scheme

Alice Bows & Kevin Anderson

November 2008

A bottom-up analysis of including aviation within the EU's Emissions Trading Scheme

Alice Bows & Kevin Anderson

Tyndall Centre for Climate Change Research
Mechanical, Civil and Aerospace Engineering
University of Manchester

Tyndall Working Paper 126, November 2008

Please note that Tyndall working papers are "work in progress". Whilst they are commented on by Tyndall researchers, they have not been subject to a full peer review. The accuracy of this work and the conclusions reached are the responsibility of the author(s) alone and not the Tyndall Centre.

Abstract

European nations agree they must tackle escalating greenhouse gas emissions arising from energy consumption. In response, the EU has set an emission reduction target for 2050 chosen to correspond with stabilising the atmospheric concentration of greenhouse gases at a level likely to avoid 'dangerous climate change' or to not exceed a 2°C rise above pre-industrial levels. By selecting a target related to *global* greenhouse gas concentrations, governments have, perhaps inadvertently, accepted such targets must include *all* greenhouse gas-producing sectors. Furthermore, aiming for a target percentage reduction by a particular date neglects the crucial importance of cumulative emissions. By addressing these two issues, this analysis quantifies the contribution of the aviation industry to future EU climate change targets. Moreover, it assesses the implications of including aviation within the EU's emissions trading scheme. Results indicate that unless the scheme adopts both an early baseline year and an overall cap designed to be in keeping with a 450ppmv cumulative emission pathway, the impact on aviation emissions will be minimal.

1. Introduction

European nations agree they must tackle escalating greenhouse gas emissions arising from energy consumption. In response, several nations have set emission reduction targets for future years. In theory at least, these targets are chosen to correspond with stabilising emissions at levels that are likely to avoid 'dangerous climate change'.

1.1 Global climate targets

Although there is no scientific consensus for what is considered to be 'dangerous' in relation to climate change, it is broadly accepted by the policy community that this relates to global mean surface temperatures not exceeding 2°C above pre-industrial levels. The European Commission acknowledges that stabilising long-term greenhouse gas concentrations at 450ppmv CO₂eq provides around a 50% chance of ensuring global mean temperatures do not exceed the 2°C threshold (COMM, 2007). In response it has set an aspirational target of reducing greenhouse gas emissions by 60%-80% by 2050 from 1990 levels by apportioning global emissions to EU nations.

By selecting a target related to *global* CO₂eq concentrations, governments have, perhaps inadvertently, accepted such targets must include *all* greenhouse gas-producing sectors. Furthermore, aiming for a target percentage reduction by a particular date neglects the crucial importance of cumulative emissions. By addressing these two issues, this analysis quantifies the contribution of the aviation industry to future EU climate change targets. Moreover, it assesses the implications of including aviation within the EU's emissions trading scheme. Results indicate that unless the scheme adopts both an early baseline year and an overall

cap designed to be in keeping with a 450ppmv cumulative emission pathway, the impact on aviation emissions will be minimal.

1.2 Aviation trends

The air transport market within the EU25 nations continues to grow rapidly. Passenger numbers in 2005 exceeded 700 billion, with an 8.5% increase on the previous year's figures (De La Fuente Layos, 2007)¹, illustrating a resurgence of the industry following the events of September the 11th 2001. Inseparable from this resurgence is the continued high levels of growth in carbon dioxide emissions from the industry. Although nations are not required under Kyoto to publish their CO₂ emissions from international aviation within their national inventories, this data is submitted alongside as a memo. Combining the CO₂ emissions from domestic and international aviation provides an estimated CO₂ emission growth rate for the EU's aviation industry of 7% between 2003 and 2004 and 6% between 2004 and 2005. These rates of growth are similar to those produced by the industry since 1993, with the exception of the period affected by the events of September 11th 2001. This rapid growth in emissions, coupled with limited opportunities for other than incremental improvements in fuel efficiency, at least in the short- to medium-term, gives rise to the concern that as EU nations strive to reduce CO₂ emissions, aviation will be responsible for an increasing share of the EU's total.

1.3 EU emissions trading scheme

The EU's emissions trading scheme (EU ETS) began operating in 2005, with the first phase of the scheme complete by the end of 2007. The scheme initially involved some 12,000 installations covering energy activities that exceeded 20MW, as well as a number of process emission activities amounting to around 45% of the EU's CO₂ emissions. The second and expanded phase of the EU ETS began in 2008, and, in recognising the growing issue of emissions generated by the aviation industry, the EU are currently discussing including aviation within the scheme by 2012.

The proposal suggests including all departures and arrivals from EU nations with the aim of internalising some of the costs of the environmental impact of the aviation sector. To explore the implications of aviation's inclusion within the scheme, this paper presents a suite of aviation emission scenarios and compares them with the EU's overall carbon budget.

2. Carbon budgets

One of the key variables of interest to those involved in climate change mitigation and adaptation is the global mean temperature change due to the increase in atmospheric greenhouse gas concentrations. However, there is both confusion and uncertainty as to the relationship between greenhouse gases and the likely resultant temperature change. Some of this confusion stems from errors in the translation of the science into policy. For example, many UK policy documents refer to 550ppmv CO₂ 'alone' being related to the 2°C threshold, when in fact the original work carried out by the UK's Royal Commission on Environmental Pollution (RCEP) linked 550ppmv CO₂ equivalent² (CO₂ eq) to this temperature change (RCEP, 2002). Uncertainty, on the other hand, stems from the inherent range of outputs given by climate models in assessing the impact of altering the atmospheric concentration of greenhouse gases, and the variety of model results available. The methods used in the analysis presented here are consistent with those within '*Living within a carbon budget*' (Bows et al., 2006b), and relate an atmospheric concentration of CO₂ alone and the 2°C temperature threshold, based the work of Meinshausen (Meinshausen, 2006).³

The EU has adopted a target of global mean surface temperatures not exceeding a 2°C rise above pre-industrial levels. To achieve this, recent studies illustrate that a 450ppmv CO₂ eq stabilisation level will provide a reasonable probability of not exceeding this 2°C threshold (Meinshausen, 2006). There are therefore a number of important issues to be addressed in

¹ The latest figures for passenger growth are for the EU27 nations, and are therefore not comparable with the EU25 figures. However, these indicate a 5% growth compared with the previous year (De La Fuente Layos, 2008)

² Equivalent relates to the inclusion of the basket of six greenhouse gases

³ The reasoning behind investigating CO₂ alone can be found in section 2.1 of (Anderson et al., 2007)

relation to the EU's climate change target and in turn how such targets relate to the aviation industry.

The first point to be considered is the ultimate aim of the target – ie for temperatures to not exceed the 2°C threshold. This threshold is associated with atmospheric CO₂ eq levels relating to different probabilities of exceeding 2°C. This type of methodology therefore assumes that all greenhouse gas-producing sectors are included, as the atmosphere does not 'see' what is or is not accounted for. In addition, it assumes that all nations globally comply with the emission reductions required. The Kyoto Protocol and the UK's climate change bill omit international aviation and shipping from their targets. For the EU, it is ambiguous as to whether or not these sectors are or are not included within current policy. If these sectors currently contribute insignificant amounts of greenhouse gases, it might be reasonable to omit them at this stage. However, the data strongly indicates that this is not the case for the aviation sector. Therefore, to institute climate policy that is both proportionate and sufficient to address the issues, there is a need to account for the emissions from international sectors that are, or may in the future represent, a significant proportion of a nation's total emissions.

Secondly, in considering how best to develop a carbon trajectory for a 2°C target, it is important not to become overly focussed on choosing a convenient percentage reduction by a future date. It is the cumulative emissions that are more influential in reaching a desired greenhouse gas concentration than the emission pathway taken (Jones et al., 2006). This is a point that, although very significant, is often overlooked by governments. Accordingly, delaying action to mitigate emissions requires more stringent measures to avoid exceeding the 2°C threshold than is generally recognised (Anderson & Bows, 2008; Bows et al., 2006b; Stern, 2006). The danger of failing to adequately account for the cumulative emissions issue in policymaking is that the resulting policies will be overly focused on the longer-term issues (and hence address energy supply), when in fact it is the short-to-medium term (and hence energy demand) that is of crucial importance [(Bows et al., 2006b): 20]. Clearly, a policy that is out of balance with the variables which it seeks to regulate will not be an efficient policy and may fail.

A third point relates to carbon-cycle feedbacks. These feedback mechanisms have only recently, and still partially, been incorporated in climate change emission budget studies, and are shown to have a very significant effect on the carbon budgets available [(IPCC, 2007): 17]. Carbon budgets that include feedback mechanisms can be some 20% smaller than those that omit feedbacks (Matthews, 2005).

To derive a cumulative carbon budget range for the EU, it is necessary to apportion the global cumulative CO₂ emissions to nations using a modified form of the Contraction & Convergence (Meyer, 2000) approach. The global carbon budgets within Table 1 are taken directly from the IPCC's cumulative carbon budget range presented in (IPCC, 2007) and represent the outer boundaries of the range compatible with a 450ppmv stabilisation derived from a series of modelling studies employing a variety of different global climate models.

Table 1: Global and EU cumulative carbon budgets

Scenario	Global cumulative emissions⁴ GtCO₂ (1990-2100)⁵	EU cumulative emissions GtCO₂ (1990-2100)
450 Low	1431	160
450 High	2257	212

⁴ Not including forestry

⁵ Taken from IPCC, 2007 page 17

This provides a cumulative carbon budget range for the EU, but it is also desirable to be able to understand the impact of this budget on the EU's pathway to a low-carbon future. This is achieved by firstly considering those emissions released for the years 2000-2005, incorporating current EU emission trends, and finally by constraining the pathway to remain within budget. The importance of using empirical data for the period between 2000-2005 cannot be overstated. When considering the cumulative carbon budget, nations emitting at high levels today are 'spending' their budgets very rapidly. As such, those emissions occurring between 2000 and 2005, and also for the short term future, will have a significant impact on the range of pathways available into the longer term. For example, in the case of the '450 High' scenario in Table 1, the emissions represent ~14% of the total budget in just 4 of the 50 years (i.e. 14% spent over only 8% of the timescale).

Emission pathways for the cumulative emissions for the EU from Table 1 are presented in Figure 1; the higher the cumulative target, the easier it is to manoeuvre in later years with the converse true for lower cumulative targets. Hence any policy aiming for levels at or lower than '450 Low' must both stabilise emissions urgently and maintain significant year-on-year reductions for three decades, to allow sufficient 'room for manoeuvre'.

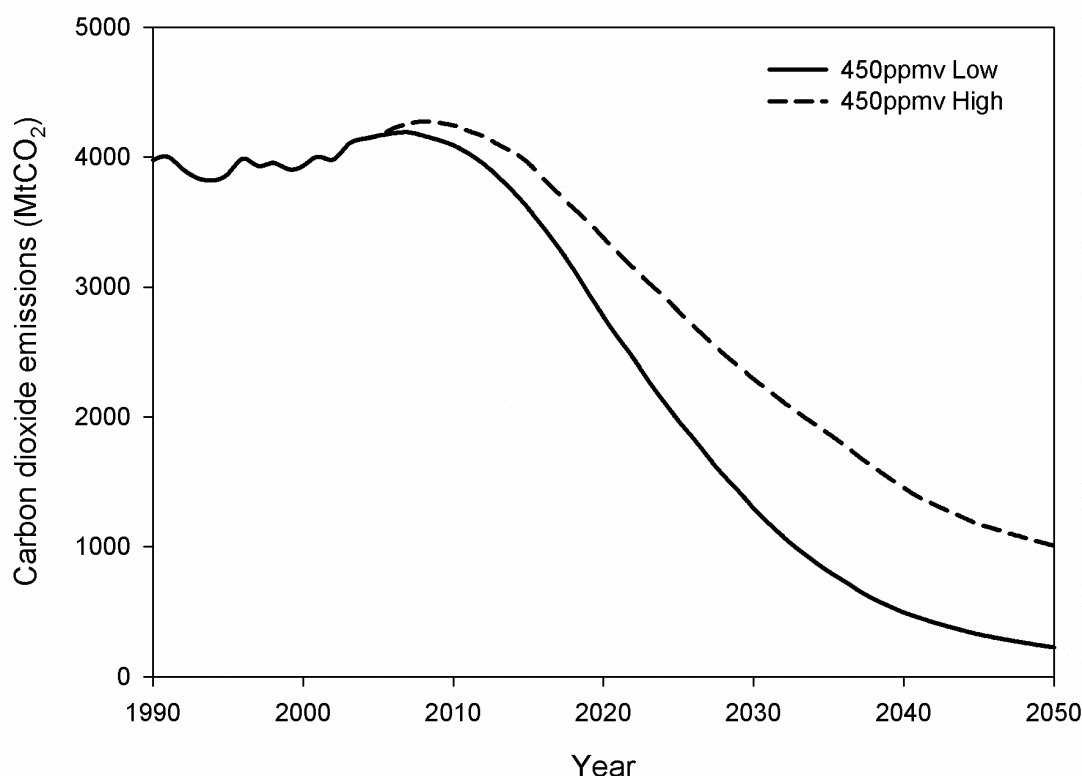


Figure 1: 450ppmv cumulative CO₂ emission profiles for the EU25

3. Aviation emission scenarios

It has been widely publicised that the aviation sector's emissions are growing more rapidly than any other sector in the UK. This is also true for the EU25. Figure 2 presents the CO₂ emissions from the aviation sector in the EU25 from 1993 to 2005.

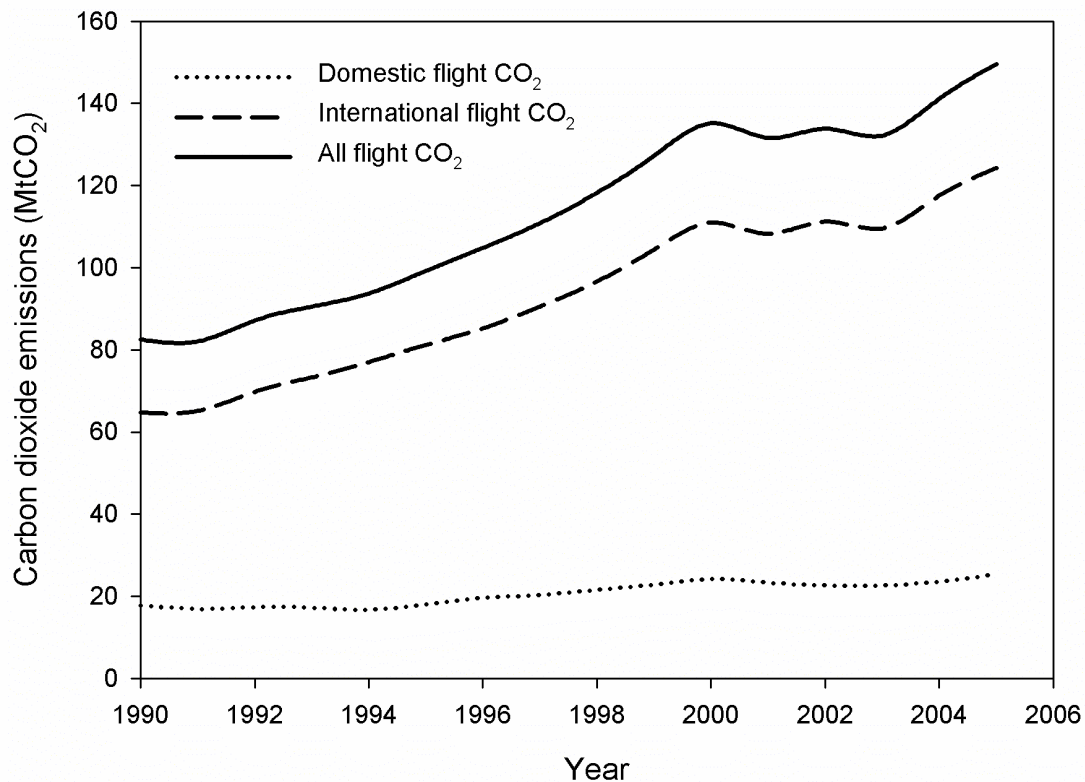


Figure 2: CO₂ emissions from the EU25's aviation sectors, from data submitted to the UNFCCC in 2007 (UNFCCC, 2007). The data incorporates estimates for Greece and Malta in 2005 due to an absence of data. Although not all of the EU25 were in the EU from 1990, all of the nations have been included in the totals from the outset.

The emissions from international flights clearly dominate. CO₂ emissions from domestic flights have increased at an average of 2.5% per year since 1990 while the corresponding figure for international flights is 4.5%. However, the events of September 11th 2001 had a marked impact on the growth rate of aviation emissions as illustrated. If the period between 1990 and 2000 is assessed, domestic aviation's annually averaged CO₂ growth was 3.2%, with international air travel at 5.6%.⁶ From 2003 to 2004, and 2004 to 2005, the total amount of CO₂ from the EU25's aviation industries increased by 7% and 6% respectively.

In addition to emitting CO₂, aircraft release soot and water vapour that lead to the formation of contrails and possibly cirrus clouds, and NO_x emissions which acts as a precursor for ozone formation and methane depletion. All of these emissions alter the radiative properties of the atmosphere either globally, in the case of well-mixed greenhouse gases (this does not include ozone), or at a local level in relation to contrails and cirrus clouds. However, there is much debate over the appropriate metric to account for these additional impacts. One metric that has been used to calculate the total impact on the climate of these emissions (in addition to CO₂) is radiative forcing. Radiative forcing is the total globally and annually averaged impact of anthropogenic emissions on the climate in terms of Watts per square metre (Wm⁻²) in relation to an assumed zero Wm⁻² in pre-industrial years (1750). For total global anthropogenic activities – ie from all sources, the figure stands at 1.6 Wm⁻² (IPCC, 2007). If this metric is applied to the aviation sector, the emissions of CO₂, NO_x and contrails amount to a total radiative forcing impact in the year 2000 of around 0.048 Wm⁻²⁷ (Sausen et al., 2005).

⁶ This period also incorporated the first gulf war, which understandably impacted on the industry.

⁷ This figure does not include contrail-induced cirrus cloud

Whilst this metric has a clear role to play in the scientific analysis of climate change, it has limitations for developing current and future mitigation policies. Radiative forcing is often used to relate the CO₂ impact to the impact from NO_x and contrails through the use of an 'uplift factor' developed initially by the IPCC, (Penner et al., 1999) and since updated (Sausen et al., 2005). However, radiative forcing compares the impact of emissions from 1750 to date, to illustrate the historical impact of the different sectors on the overall temperature rise. When using it to look at future impacts, this measure can lead to inappropriate policy messages if it guides policy mitigation. Furthermore, the metric could lead to unhelpful policy conclusions in certain situations. For example, if applied to shipping emissions, the policy conclusion may be to increase the sulphur emissions from ships to mitigate the warming caused by their release of CO₂ emissions⁸. Consequently, the cumulative approach is more useful in the context of this research, given its importance in policy terms. Therefore, to be consistent with the cumulative carbon budget approach being taken here, the analysis of the aviation sector will address CO₂ alone, requiring no additional metric.

3.1 Aviation emission baselines

To include aviation within the EU ETS, the Commission propose a baseline above which the industry must buy emission allowances be placed at the 2004-2006 level. In other words, any CO₂ emitted above the 2004-2006 level will need to be purchased by the industry from the market. However, the UK Government has also explored the possibility of employing alternative baseline dates.

To illustrate the impact of the baseline date choice, three different baselines are explored here – one for 1990, one for 2000 and one for 2005. Aviation scenarios for the short-term period of 2006-2012 are compared with these baselines to illustrate the levels of emissions needed to be purchased if all departing and arriving flights are included within the scheme. Following on from this, a suite of aviation scenarios from 2013 to 2050 commensurate with a world striving to live within the 450ppmv carbon budget are developed. These scenarios incorporate a range of growth rates and assumptions related to fuel efficiency and, in the longer term, the inclusion of alternative low-carbon fuels. The cost implications of these different scenarios under a range of carbon allowance prices is considered for selected exemplar flights. Finally, the aviation scenarios are compared with the overall 450ppmv carbon budget for the EU25.

To develop the scenarios, the baselines must be quantified. One important distinction to make at this stage is the difference between the CO₂ baselines for emissions submitted to the UNFCCC, and the emissions that will be included in the EU ETS. For the UNFCCC, domestic aviation's CO₂ is submitted separately from the CO₂ from international aviation (where domestic aviation refers to flights within a nation, and international for flights from one nation to another). The latter broadly approximates to 50% of all flights to and from each nation within the EU to either another EU nation or an extra-EU nation. Therefore, the total domestic and international CO₂ for aviation submitted to the UNFCCC is an estimate of the CO₂ associated with all domestic flights within the EU25 and 50% of international flights to and from EU nations, giving a baseline for 2005 of 150MtCO₂; 25MtCO₂ from domestic and 125MtCO₂ from international. However, to incorporate aviation within the EU ETS, the Commission proposes CO₂ emissions from *all* departures and arrivals from and to EU nations are included. Therefore, the UNFCCC data alone is not sufficient but requires supplementary information to form the baseline. This is because it is not appropriate to simply double the CO₂ emissions submitted to the UNFCCC to account for these additional flights, as double counting for domestic and intra-EU flights will occur. The EU ETS baseline is therefore higher than the 2005 UNFCCC baseline, standing at some 225MtCO₂ in 2005. The method used to derive this alternative baseline uses empirical data for UNFCCC international and domestic flights in addition to some model data (Wit et al., 2005) to calculate those flights associated with intra-EU flights. This data is modelled because aggregated information for intra-EU flights is not currently submitted to the UNFCCC. The breakdown of EU aviation CO₂ emissions are presented in Table 2 for baselines in 1990, 2000 and 2005. For more information on the method see section 3.1 in (Anderson et al., 2007).

⁸ This is a conclusion that was referred to during a Waterfront Shipping meeting with industry stakeholders.

Table 2: CO₂ emissions from all flights that either depart or arrive in the EU

UNITS: MtCO₂	Data type	1990	2000	2005
UNFCCC international aviation bunker CO ₂ ⁹	Empirical	64.8	111.0	124.3
UNFCCC domestic aviation CO ₂	Empirical	17.8	24.2	25.3
Intra EU flight CO ₂ (EU to EU, not domestic)	Modelled	19.3	36.0	40.2
EU to EU ultra peripheral regions CO ₂	Modelled	4.8	8.9	8.1
EU to EU overseas countries & territories CO ₂	Modelled	0.5	0.9	0.9
Derived starting aviation CO ₂ value	Empirical & model	122.8	200.4	224.7

3.2 Short-term

Following the baseline quantification, aviation scenario development requires quantification of the aviation CO₂ from now until the estimated commencement date of the revised scheme (2012). A number of assumptions are made leading to a range of growth rates. In addition to available passenger number and CO₂ data, factors influencing the choice of scenarios include:

- ** The current continued success of the low-cost air model;
- ** Access to a network of growing regional airports;
- ** The low-cost model extending in modified form to medium and longer-haul routes;
- ** No significant economic downturn between the 2005 data and 'today' (2007); and
- ** High growth routes between the EU and industrialising nations.

For the years from 2006 to 2012, recent and longer-term trend data significantly influences the choice of scenarios. According to the submissions to the UNFCCC, there has been a long-term trend of increasing CO₂ emissions from EU25 nations of the order of 6% per year. More recent emissions have also increased at 6% per year, once allowance is made for the period affected by the events of 11th September 2001. Reinforcing this 6% figure is Eurocontrol's forecast of strong growth for 2007-2008 (EUROCONTROL, 2007). The range of scenarios considered for the period from 2006 to 2012 therefore uses 6% annual emission growth as a mid-range value, with 4% for the lower-range and 8% for the higher-range. Assuming no radical step changes in the short-term, the scenarios all use a 1% per year improvement in fuel efficiency across the fleet for this short-term period.

⁹ 2007 submission (UNFCCC, 2007)

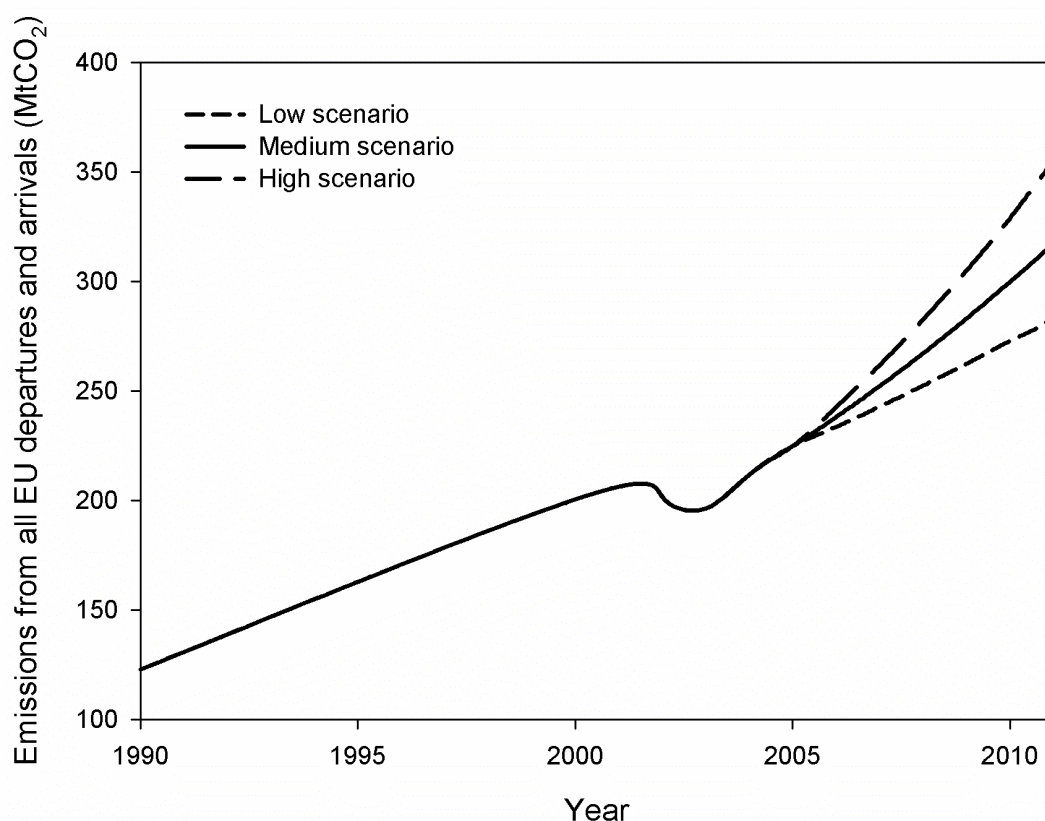


Figure 3: Aviation CO₂ emissions for all departures and arrivals under a range of growth rates. This range is the same as that applied to the UNFCCC data presented in

Based on these scenarios, by the end of 2011, the aviation sectors emissions range between around 284 and 355 MtCO₂, (Figure 3). Of the three initial baselines of 1990, 2000 and 2005 for aviation emissions considered here (Table 2), Table 3 presents the allowances that need to be purchased in 2012.

Table 3: Emissions allowances to be purchased in 2012 under the range of Tyndall scenarios

Baseline year	Emissions in baseline year (MtCO ₂)	Emissions in 2012 (MtCO ₂)	Emissions to be purchased (MtCO ₂)
1990	123	284 - 355	161-232
2000	200	284 - 355	84-155
2005	225	284 - 355	59-130

The earlier the baseline year, the more allowances must be purchased by the industry. In fact, the aviation sector has grown so significantly since 1990 that the emissions allowances required by 2005 under the 1990 baseline are in excess of the total amount of emissions released in 1990. The range is somewhat lower for the 2005 baseline, where between 59 and 130 million allowances must be purchased by the industry. The cost to the industry will depend on the price of carbon on the market and will be discussed in the next section.

3.3 Medium to long-term

In considering aviation emission scenarios for the medium (2017-2030) to long-term (2031-2050), not only must a range of assumptions be made in relation to the aviation industry, but attention must also be paid to the overarching EU policy climate.

In aiming for a 450ppmv stabilisation level, it is assumed that:

- ** The EU adopts a comprehensive and scientifically literate basis for its climate policy derived from a cumulative carbon budget approach;
- ** It has a complete account of all sectors; and
- ** It uses a Contraction and Convergence regime for emission apportionment.

From 2011 onwards, three suites scenarios commensurate with 450ppmv are considered alongside one illustrative suite outside of the 450ppmv regime. Given that the core scenarios are required to be commensurate with the cumulative emissions budget for 450ppmv, the sooner the EU responds, the less demanding will be the emissions pathway from that point onwards.

Future aviation emissions are subject to a number of factors including the rate of growth in the short, medium to long-term (i.e. after 2012) and the rate of introduction of new technologies and operational measures that may improve the efficiency and carbon intensity of the industry. Accordingly, building on the three near-term scenarios to 2012 (Figure 3) a series of scenarios that reflect the range of reasonable and optimistic possibilities for the short, medium and long-term are developed. These scenarios are called *Indigo*, *Aqua*, *Violet* & *Emerald*.

In each case, the four scenarios are divided into three time periods after 2012:

Short-term	Start of 2012 to the start of 2017
Medium-term	Start of 2017 to the start of 2031
Long-term	Start of 2031 to the start of 2051

All but the *Emerald* scenario are based on an assumption that the EU is committed to meaningful 450ppmv carbon budget, and that aviation will play its part in that process, including a modification to the growth rate. Consequently, all these scenarios assume the significant reductions in the CO₂ emitted per passenger-km flown (CO₂/pax), as presented in Table 4; these combine to give a reduction in CO₂/pax for 2012-2050 of 68.5%. The overarching context of this reduction in carbon intensity is society's explicit and genuine commitment to a 450ppmv pathway.

Table 4: CO₂/pax improvement per period

	Short	Medium	Long
Mean annual improvement in CO ₂ /pax	1.5%	2%	4%
Total improvement of the period	7% in 5 yrs	23% in 14yrs	56% in 20 yrs

The *Greener by Design* (Greener by Design, 2005) study highlights a number of areas that could offer substantial improvements in terms of the fuel burn saved per seat km. For example, in the short to medium-term, air traffic management improvements could offer an 8% reduction in fuel burn, open rotor engines could improve fuel efficiency by some 12% and the use of lighter materials such as carbon-fibre could offer an additional 15-65% improvement. In the longer term, laminar flow-type aircraft designs could reduce fuel burn by over 50% and alternative fuels, although generally believed unlikely to be used across the fleet prior to 2030 perhaps even 2050, could play a role to reduce aviation's CO₂ emissions, if the drive towards a low-carbon economy was strong enough. It is the timescale over which

the gains in fuel efficiency and the incorporation of low-carbon fuels into the mix can be achieved that is of key importance.

In terms of these Tyndall scenarios, technological improvements in efficiency coupled with a variety of air traffic management and operational changes provide the principal components of the reducing CO₂/pax during the first two periods (2012-2017 and 2018-2030). Typical changes include continued incremental jet-engine improvements and the incorporation of rear-mounted open rotor engines particularly for shorter-haul flights. In addition, improvements are made through airframe modifications to wing design to improve air flow and reduce fuel burn and increasing amounts of lighter materials. It is assumed there will be additional load-factor increases, and a series of efficiency gains across the air traffic management system through more direct routing, reduced taxiing, waiting and circling, and reduced use of the auxiliary power unit.

Fuel switching is considered to be a minor component within the two earlier periods. In the long-term period, fuel efficiency improvements across the fleet continue to be of the order of 2% per year, with the remaining 2% being derived from fuel switching to a low carbon fuel such as biofuel or hydrogen for example. In considering these assumed efficiency savings and the introduction of low-carbon fuels, it must be noted that these reflect a situation where the aviation industry goes well beyond its achievements over the previous two decades. However, such significant improvements to the technical, operational and managerial efficiency of aviation are only considered possible when driven by a concerted effort on the part of the industry (and society) to deliver them.

In terms of drivers for such a change, the three scenarios reflect a society whose focus is very different from that of today. Within this society, low-carbon innovation, not only on aircraft themselves, but in addition in relation to video-conference etc. receives very significant funding and policies would be in place to regulate low-carbon behaviour and operation within companies. The difference in emphasis of this world from ours is central to these scenarios. Therefore it is worth reiterating that the carbon intensity improvements envisaged are well in excess of what has occurred within most fleets in recent times yet in keeping with what is possible (Green, 2005) if the right suite of incentives were in place.

In terms of the other variables reflected in the scenarios, while three of the scenarios all have the same level of carbon intensity improvement, each differs in the rate of passenger growth. These factors combine to produce different emission changes between 2012 and 2050 which, in combination with the range of short-term scenarios, produce a range of possible net CO₂ emissions from aviation.

A fourth scenario (*Emerald*) differs from the others in terms of both passenger growth and technological efficiency improvements. This scenario reflects only partial commitment to both curbing passenger growth rates and instigating the technological efficiency improvements described above, and is highly unlikely to be compatible with a 450ppmv pathway.

Table 5: Scenario passenger-km growth and carbon intensity improvements

Parameter	Scenario	Short	Medium	Long
Annual pass-km growth	<i>INDIGO</i>	3%	1.5%	1%
	<i>AQUA</i>	4%	3%	2%
	<i>VIOLET</i>	5%	4%	3%
	<i>EMERALD</i>	6%	5%	3%
Annual CO ₂ /pax improvement	<i>INDIGO/AQUA/VIOLET</i>	1.5%	2%	4%
	<i>EMERALD</i>	1%	1.5%	2%
Annual emissions change	<i>INDIGO</i>	1.5%	-0.5%	-3%

AQUA	2%	1%	-2%
VIOLET	3.5%	2%	-1%
EMERALD	5%	3.5%	1%

The scenario emission growth rates are presented in Table 5. *Indigo* is the most responsive to the climate change issue and the EU ETS and shows a significant, comprehensive and early drive towards a low-carbon aviation industry within the EU. The net aviation emission change between 2012 & 2050 equates to a *45% reduction*, though compared with 1990, it still represents a 24%- 55% increase.

In *Aqua*, aviation responds more slowly to the EU ETS scheme, compensated by slightly larger reductions by other sectors. Net aviation emission change between 2012 & 2050 equates to a *16% reduction*, though compared with 1990, it represents a 95% to 144% increase.

In *Violet*, the aviation industry continues to grow its emissions at a higher rate than in the *Indigo* and *Aqua* scenarios at the expense of the other sectors in the EU ETS. The net aviation emission change between 2012 & 2050 equates to a *26% increase*, and compared with 1990, a 184% to 256% increase.

Emerald is an additional scenario used to illustrate a future where the current rhetoric on climate change is only partially converted into meaningful action. Such a future would be more attuned to cumulative emissions associated with much higher CO₂ concentrations and a failure to respond to the 2°C commitment. In this case, the net aviation emission change between 2012 & 2050 equates to a *146% increase*, and compared with 1990, a 278% to 373% increase. Assumptions behind these growth rates include new EU nations expanding their aviation industries towards per capita rates of old EU nations, and a modified version of the low-cost model assumed to extend to medium and long-haul flights. Point-to-point aircraft, in combination with the expansion of regional airports are assumed to provide much quicker and convenient air travel for all. Security becomes less of an obstacle to flying and big improvements in check-in improve the quality of experience for the traveller. Increasing globalisation stimulates more migration and consequently international travel to maintain family ties. In economic terms, world GDP growth continues and the EU's economy grows at 2.5 – 3% p.a. Although it is impossible to paint an accurate picture of a business as usual future for aviation emissions, the *Emerald* scenario represents the closest to an extrapolation of current trends of all the scenarios.

When combined with the three near term growth scenarios (Figure 3), the full scenarios result in nine core scenarios, with a further three for the *Emerald* set. The resulting net CO₂ emissions for all twelve scenarios are provided in Figure 4.

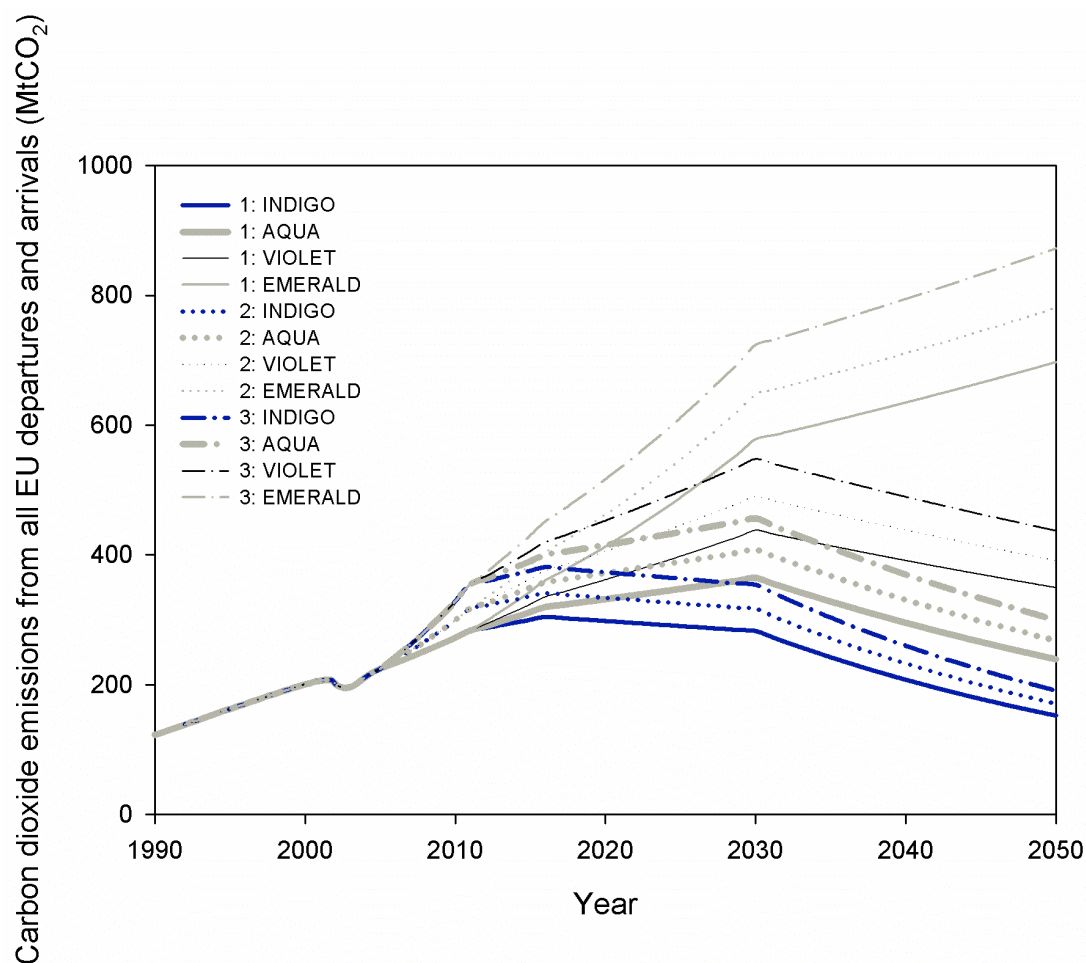


Figure 4: CO₂ emissions from the nine core scenarios (Indigo, Aqua and Violet for pre-2012 near term growth scenarios low-1, medium-2 and high-3) in blues and purples, and the three illustrative higher growth scenarios (Emerald for pre-2012 near term growth scenarios low-1, medium-2 and high-3).

To compare the scenarios with total emissions consistent with a 450ppmv budget, the scenario assumptions are applied to the UNFCCC baseline figure of 150MtCO₂ (Figure 5).

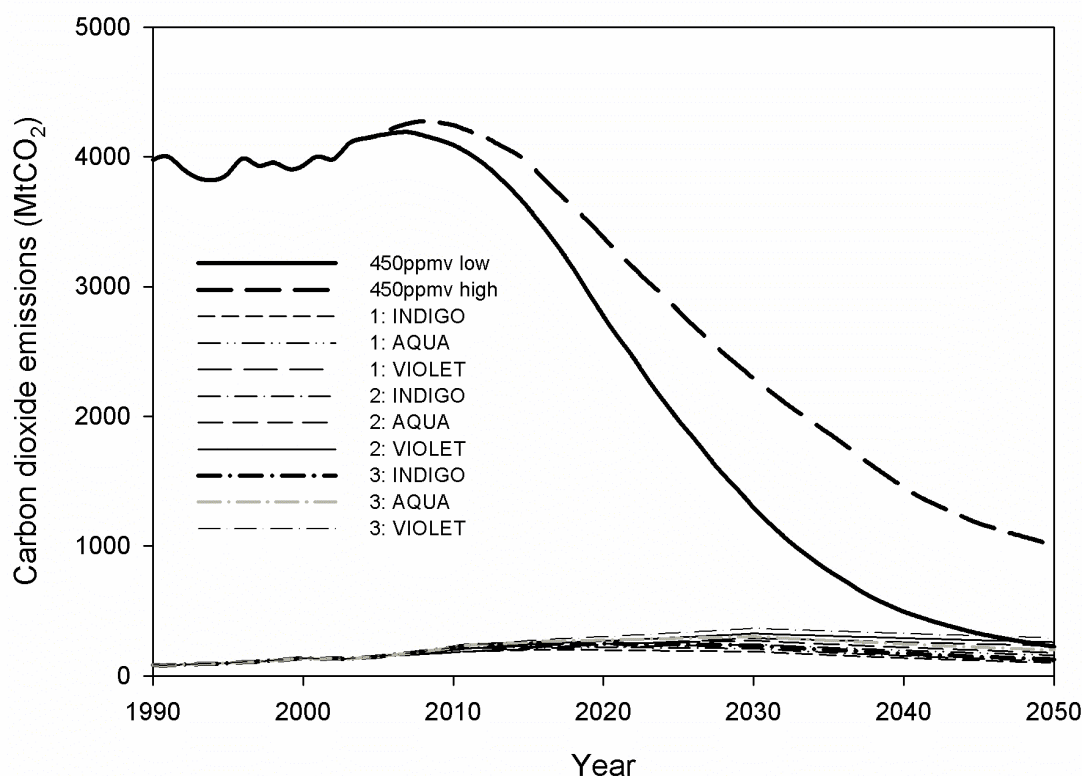


Figure 5: CO₂ emission budgets for 450ppmv compared with aviation emissions scenarios based on the UNFCCC data to account for 50% of international flights and all domestic and intra-EU flights.

Unless very low growth rates and substantial improvements to carbon efficiency are achieved, aviation emissions could exceed the 450ppmv 'low' pathway by the late 2040s. For the 450ppmv 'high' pathway, the emissions from aviation account for at best 10% and at worst 29% of the total budget for all sectors and all emissions.

All of the aviation industry scenarios, within a world striving to achieve a 450ppmv future, reflect an increase in CO₂ levels in 2050 compared with 1990. This is in sharp contrast to the other sectors of the economy, where 75 to 90% reductions from 1990 levels have been required to remain within budget.

4. Economic analysis

To investigate the likely scale of carbon price necessary to bring about the growth and efficiency changes embedded in the scenarios, a basic and illustrative analysis is presented in relation to three different emission baseline levels, for three typical flight lengths. Note that price elasticities are not presented here given the changes being investigated are step changes in prices, whereas price elasticities are useful only in investigating the impact of increment price changes. The price of carbon is varied to provide a range of possible impacts on flight price.

The first stage compares the emissions over different time periods with the baseline results for 1990, 2000 and 2005. The choice of baseline significantly impacts the amounts of carbon permits required. For example, by the end of 2011, between 57% and 65% of emissions must be purchased if 1990 is to be the chosen baseline. Whereas, 21% to 37% would need to

purchased if 2005 were the baseline (Table 6). The carbon intensity improvements are assumed to be the same across all types of flight.¹⁰

Table 6: Percentage of permits that would need to be purchased for the lowest Indigo and highest Violet scenarios.

INDIGO			
Baseline dates	Percentage of the carbon on a flights that needs to be purchased		
	End 2011	End 2016	End 2050
1990	57%	60%	20%
2000	29%	34%	-31%
2005	21%	26%	-47%

VIOLET			
Baseline dates	Percentage of the carbon on a flights that needs to be purchased		
	End 2011	End 2016	End 2050
1990	65%	71%	72%
2000	44%	52%	54%
2005	37%	46%	49%

To estimate the additional cost of a typical flight (assuming that *all* costs are passed on to the passenger) a range of carbon prices for these permits is considered. Although carbon prices above €50 have yet to materialise, the premise of this report is that the EU is genuinely committed to 450ppmv. Within this in mind, it is assumed that between 2012-2017 carbon prices are €50-€100, increasing in the longer term to €100 to €300. These prices broadly reflect the higher ranges of values discussed within the literature [p.323 (Stern, 2006)];(Uyterlinkde et al., 2006).

Typical emissions per passenger data is used to provide indicative costs per passenger for flights. As carbon intensity improves over time in line with the figures presented in Table 5, so the carbon emissions per passenger will fall for the same flight. For three exemplar flights, Table 7 presents the carbon emissions over time relating to the carbon efficiency improvements.

Table 7: Tonnes of CO₂ per passenger for 3 example flights in 2005, 2011 and 2050 with carbon efficiencies taken from Table 5

One way flight ¹¹	2005	End 2011	End 2050
Short-haul (e.g. London – Barcelona)	0.25	0.235	0.073
Medium-haul (e.g. London – Washington)	1	0.941	0.291
Long-haul (e.g. London – Sydney)	2	1.883	0.582

¹⁰ Tables 12 and 14 in (Anderson et al., 2007) give more details.

¹¹ These figures do not reflect actual flights but are typical values associated with 'short, medium and long-haul' flights within an appropriate range.

To estimate the typical indicative cost per passenger, the percentage of a flight's carbon emissions for which permits are required to be purchased can be applied to the data in Table 7 for the lowest growth scenario, *Indigo*, and the highest growth scenario, *Violet*. Using the percentages, the typical costs per flight are presented in Table 8 for *Indigo* and *Violet*.

Table 8: Typical prices for exemplar flights over different periods and baselines for the lowest Indigo scenario and Highest Violet scenario. The '--'s in the table below illustrate that, within a 450ppmv budget, a value of € 50 per tonne is unrealistic post-2030. Similarly, much higher carbon prices of € 300 are unlikely in the period prior to 2012.

Carbon prices for different types of typical flights							
INDIGO							
Carbon price		End 2011		End 2016		End 2050	
	Baseline years	1990	2005	1990	2005	1990	2005
€ 50	Short-haul	€ 7	€ 2	€ 7	€ 3	--	--
	Medium-haul	€ 27	€ 10	€ 26	€ 11	--	--
	Long-haul	€ 53	€ 20	€ 52	€ 23	--	--
€ 100	Short-haul	€ 13	€ 5	€ 13	€ 6	€ 1	-€ 3
	Medium-haul	€ 53	€ 20	€ 52	€ 23	€ 6	-€ 14
	Long-haul	€ 107	€ 39	€ 104	€ 46	€ 11	-€ 27
€ 300	Short-haul	--	--	€ 39	€ 17	€ 4	-€ 10
	Medium-haul	--	--	€ 156	€ 69	€ 17	-€ 41
	Long-haul	--	--	€ 313	€ 138	€ 34	-€ 82
VIOLET							
		End 2011		End 2016		End 2050	
	Baseline years	1990	2005	1990	2005	1990	2005
€ 50	Short-haul	€ 8	€ 4	€ 8	€ 5	--	--
	Medium-haul	€ 31	€ 17	€ 31	€ 20	--	--
	Long-haul	€ 62	€ 35	€ 62	€ 41	--	--
€ 100	Short-haul	€ 15	€ 9	€ 15	€ 10	€ 5	€ 4
	Medium-haul	€ 62	€ 35	€ 62	€ 41	€ 21	€ 14
	Long-haul	€ 123	€ 69	€ 124	€ 81	€ 42	€ 28
€ 300	Short-haul	--	--	€ 46	€ 30	€ 16	€ 11
	Medium-haul	--	--	€ 185	€ 122	€ 63	€ 42
	Long-haul	--	--	€ 371	€ 243	€ 125	€ 85

¹² These figures do not reflect actual flights but are typical values associated with 'short, medium and long-haul' flights within an appropriate range.

Table 8 illustrates the typical additional costs per passenger for a one-way flight under the *Indigo* and *Violet* Scenarios. Again, the earlier the baseline, the higher the additional cost.

Even in the case of the higher growth scenario (*Violet*) and even assuming that *all* costs were passed on to the passenger, the additional €8 to €15 for a short-haul flight is unlikely to significantly influence passenger growth rates (the €15 figure, equates to a carbon price of €100 per tonne).

For the longer-haul flights, the maximum additional premium would be €371 if 1990 were to be the baseline. The permit price in this case is €300 – an order of magnitude higher than other studies typically expect in the future. Only at such a level, and with an early baseline, is there likely to be a sufficient price signal to significantly curb the growth in emissions from the aviation sector. When considering the 2005 emission baseline, it is probable that carbon prices would have to rise well above €300 per tonne to have a significant influence on growth.

The *Violet* scenario adds an additional €30 to a short-haul flight by the end of 2016, €122 to a medium-haul flight and €243 to a long-haul flight (all at €300 per tonne). The respective figures are €5, €20 and €41 at the lower carbon price of €50 per tonne. Here, again, price signals from even high estimates of carbon prices would not seem to be sufficient to produce the required effect.

5. Discussion & conclusions

In March of this year the EU reaffirmed its commitment to not exceeding the 2°C target. Drawing on this commitment, this paper illustrates the EU's associated emission-reduction pathway over the next fifty years, with particular focus on what this means for the aviation sector. Three of the scenario suites presented reflect emission pathways for the aviation sector that, although representing a growing share of the EU's emissions, could nevertheless be reconciled with a 450ppmv CO₂ pathway. However, in all cases, these scenarios reflect the situation where there is a concerted effort to produce not only very significant increases in the carbon efficiency of aviation, but a curbing of passenger-km growth rates. Furthermore, even though the aviation emissions pathways implied by the scenarios can be reconciled with the 450ppmv CO₂ pathway, the other sectors would have to significantly compensate for aviation to remain within the carbon budget available. Whilst these scenarios are, in principle, achievable, they also represent an urgent and radical departure from the current level of aviation's emission growth and the majority of analyses and passenger growth forecasts for the future of aviation.

5.1 Current aviation emissions are significant

In 2005 aviation emissions were approximately 150MtCO₂, representing 4% of the EU's total CO₂ emissions. It is such percentages that give rise to the repeated and dangerously misleading claim that "aviation is not a major greenhouse gas polluter" (IATA, 2007). Making simplistic comparisons with other emissions sources conveniently chosen to underplay aviation's contribution to total emissions only serves to confuse an already confusing issue [see (IATA, 2007) p.12]. The same basis of analysis would suggest that the UK's total transport and power station emissions are not major sources when compared with global totals; similarly the emissions from nations such as Belgium, Portugal and the Netherlands are too small to be the focus of concerted low-carbon action. Unfortunately, this view is all too prevalent in discussions over climate change. The UK's proportion of world emissions is often cited as only 2% of the global total and, so the argument goes, whatever the UK does in terms of carbon emissions is of little relevance. Similarly, Beijing, New York, Delhi, Paris, and all the other major cities of the world are respectively less than 2% of total emissions. This apparent logic would suggest there is little benefit in their implementing stringent carbon-reduction strategies. *All* emissions are inevitably the aggregate of smaller percentages; using this as an excuse for relative inaction will collectively lead to individual, sectoral, national and, ultimately, global apathy. The aviation sector's 4% of EU emissions is therefore already a significant proportion of total EU emissions, and it is essential this is recognised.

5.2 EU Aviation scenarios within a 450ppmv budget

Most of the scenarios presented within this paper, unlike many existing aviation scenarios, are expressly designed to be compatible with a 450ppmv CO₂ pathway. Understanding the importance of this emphasis is essential if the scenarios are to provide a useful heuristic for policy makers and other stakeholders. Seriously exacerbating the aviation sector's already significant level of emissions is the sector's rate of growth. Whilst emissions from most sectors are broadly stable,¹³ the latest EU aviation data show increases in emission of between 6% and 7% per annum, consistent with long-run trends. Such growth rates are often ignored or underestimated by those with a vested interest in the sector's continued prosperity. Currently, the limited constraints on the expansion of the EU's aviation sector are being dwarfed by the drivers for expansion. In the absence of explicit and coordinated action to both constrain growth and increase efficiency it is difficult to envisage the current situation changing appreciably. Previous Tyndall scenarios demonstrated the dangers of relative inaction in relation to emissions growth (Anderson et al., 2005; Bows et al., 2006a); by contrast these scenarios illustrate what viable aviation emission-pathways may look like, provided radical policies are implemented to constrain emissions growth as a matter of urgency.

These latest scenarios contain reductions in carbon intensity per passenger-km well above those assumed within all but the industry's more optimistic predictions. This is a consequence of the latest scenarios being developed for an explicit 450ppmv CO₂ future. There is a raft of opportunities for reducing the carbon intensity at levels not dissimilar to those used within this report. However, the scope and scale of policies necessary to bring about such changes and the more immediate and short-term benefits of behavioural and operational adjustments are often ignored.

The analysis presented within this paper begins to sketch out the necessary scope and scale of policies; with an inevitably conditional conclusion, being that if price is to be the principal driver, the € per tonne carbon prices currently being discussed are an order of magnitude too low. Carbon prices of €50 to €100 per tonne in 2012 equate to a typical short-haul flight price increase of €2-€15 per passenger, medium-haul €10-€60, and flights from, for example, the UK to Australia, €40-€120. It is difficult to envisage such small price signals having other than marginal impacts on the rate of growth of aviation emissions. In relation to the more demanding of the report's scenarios (*Indigo*), the €300 carbon price in 2017 equates to a per passenger supplement for typical short, medium and long-haul flights of €15-€40, €70-€155 and €140-€310 respectively. Given the radical departure from aviation's current high emission growth represented by the *Indigo* scenario, these additional costs are still likely to be insufficient. Current discussions often refer to carbon prices well below €50/tonne, with the latest IATA report [(IATA, 2007) p.3] focussing on values per tonne of CO₂ of between €15 and €33. Such low prices are considered inconsistent with a genuine drive towards an EU 450ppmv CO₂ pathway, and consequently the prices are revised upwards significantly. Only with carbon prices an order of magnitude higher than those currently being considered by the industry (i.e. €100 to €300 per tonne as opposed to €15 to €33 per tonne), and with an early baseline year, can the scheme have sufficient impact on reducing current levels of emission growth.

5.3 Aviation remains privileged

On first reading of this paper, the scenarios may appear to place undue constraints on the aviation sector. However, even under the most demanding scenario (*Indigo*), aviation remains highly privileged in relation to emissions. The 450ppmv CO₂ pathway demands aggregate emission reductions from all sectors, compared with 1990, of approximately between 75% and 90% by 2050. By contrast, even the *Indigo* scenario has an emissions increase from the aviation sector in 2050 of between 23% and 53%, compared with 1990. This growth is despite the exceptionally high levels of efficiency and unprecedented reduction in passenger-km growth assumed within the scenario. Such findings illustrate the scale of the challenge facing the EU and its member states and reveal the failure of existing policy instruments to address the rapid growth in aviation emissions. Moreover, it exposes the

¹³ Seldom increasing or decreasing at more than 1-2% per annum.

politically-expedient rather than scientifically-literate basis of discussions informing and framing the scale of forthcoming policy instruments. It is imperative this reluctance to actively engage in evidence-based analysis of current and future emissions be reversed if the EU is to meet even the higher 450ppmv emission pathway, let alone the EU's own 2°C commitment.

5.4 Conclusion

From the relatively simple 'what-if' economic analysis presented in this paper, a series of options for reconciling aviation with a 450ppmv CO₂ pathway are evident. Firstly, the EU ETS cap must be designed in keeping with a cumulative 450ppmv pathway. A reconsideration of an early baseline year should be a prerequisite for aviation's inclusion in the EU ETS and early inclusion in the scheme is highly desirable, with stringent constraints on the sector's emission growth implemented in the interim. In relation to the carbon price, the overall EU ETS cap needs to be sufficiently tight that carbon prices well in excess of €300/tonne are achieved. Finally, in relation to non-CO₂ climate change impacts, additional and substantial flanking instruments must be implemented. Constrained and responsible growth of the aviation sector can be reconciled with a 450ppmv CO₂ future, but the carbon price currently being discussed is an order of magnitude too low to stimulate the necessary changes.

For the EU to achieve its climate targets, all sectors require mitigation policies. If a realistically high carbon price is considered unachievable, there are a number of alternative mechanisms available for consideration. For example, the aviation sector could operate within a sector-specific cap; either for aviation only, or for all transport modes, based on the sector making its fair contribution to a 450ppmv cumulative CO₂ pathway. Or, a very high carbon-related price could be placed on the industry in the form of a fuel tax, air passenger duty, or some other innovative charging instrument. One other mechanism is for a stringent carbon rationing regime to be introduced, such as personal carbon allowances, with the quantity of allowances in line with a cumulative 450ppmv CO₂ pathway. If a stringent policy mechanism is not chosen, the EU must prepare to adapt to climate change impacts in excess of a +2°C future. The transition from the EU's rhetoric on climate change to a scientifically-literate policy agenda demands a reframing of the debate in terms of cumulative carbon budgets and accompanying carbon-reduction pathways. Within such a framing, addressing urgently aviation's rapidly escalating emissions becomes a prerequisite of any meaningful carbon-reduction strategy.

Anderson, K., and Bows, A., 2008 Reframing the climate change debate in light of post-2000 emission trends, *Philosophical Transactions of the Royal Society A*, 366, 3863-3882.

Anderson, K., A. Bows and A. Footitt, 2007. Aviation in a low-carbon EU. Report for Friends of the Earth, Tyndall Centre Manchester.

Anderson, K., S. Shackley, S. Mander and A. Bows, 2005. Decarbonising the UK: Energy for a climate conscious future, The Tyndall Centre for Climate Change Research, Manchester.

Bows, A., K. Anderson and P. Upham, 2006a. Contraction & Convergence: UK carbon emissions and the implications for UK air traffic. Tyndall Centre Technical Report. Norwich, Tyndall Centre for Climate Change Research.

Bows, A., S. Mander, R. Starkey, M. Bleda and K. Anderson, 2006b. Living within a carbon budget. Report commissioned by Friends of the Earth and the Co-operative Bank. Tyndall Centre. Tyndall Centre, Manchester.

De La Fuente Layos, L., 2007. Air transport in Europe in 2005. Statistics in focus. European Communities, EU.

De La Fuente Layos, L., 2008. Air transport in Europe in 2006. Statistics in focus. European Communities, EU.

EUROCONTROL, 2007. Flight Movements 2007-2008. Short-Term Forecast. EUROCONTROL, STATFOR.

Green, J. E., 2005. Future aircraft - greener by design? Meteorologische Zeitschrift. 583-590.

Greener by Design, 2005. Mitigating the environmental impact of aviation: opportunities and priorities. Air Travel - Greener by Design, Royal Aeronautical Society.

IATA, 2007. Financial impact of extending the EU ETS to airlines, from www.iata.org/economics.

IPCC, 2007. Climate Change 2007: the physical science basis. Report of Working Group 1 to the Fourth Assessment report of the Intergovernmental Panel on Climate Change.

Jones, C. D., P. M. Cox and C. Huntingford, 2006. Impact of climate-carbon cycle feedbacks on emissions scenarios to achieve stabilisation, in: Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. and Yohe, G. (Eds.), Avoiding dangerous climate change. Cambridge University Press, Cambridge, pp. 323-331.

Matthews, H. D., 2005. Decrease of emissions required to stabilise atmospheric CO₂ due to positive carbon cycle-climate feedbacks. Geophysical Research Letters. 32,(L21707), DOI:10.1029/2005GL023435.

Meinshausen, M., 2006. What does a 2C target mean for greenhouse gas concentrations? a brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates, in: Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. and Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, pp. 253-279.

Meyer, A., 2000. Contraction & Convergence - the global solution to climate change, Green books, Devon.

Penner, J. E., D. G. Lister, D. J. Griggs, D. J. Dokken and M. McFarland, Eds., 1999. Aviation and the global atmosphere; a special report of IPCC working groups I and III Cambridge University Press, Cambridge.

RCEP, 2002. The environmental effects of civil aircraft in flight. Special report of the Royal Commission on Environmental Pollution, Royal Commission on Environmental Pollution.

Sausen, R., I. Isaksen, V. Grewe, D. Hauglustaine, D. S. Lee, G. Myhre, M. O. Kohler, G. Pitari, U. Schumann, F. Stordal and C. Zerefos, 2005. Aviation radiative forcing in 2000: An update on IPCC (1999). Meteorologische Zeitschrift. 14,(4), 555-561.

Stern, N., 2006. Stern Review on the Economics of Climate Change. Her Majesty's Treasury. Cambridge, Cambridge University Press.

Uyterlinkde, M. A., G. H. Martinus, H. Rosler, B. C. C. Van der Zwaan and et al, 2006. The contribution of nuclear energy to a sustainable energy system. CASCADE MINTS.

Wit, R. C. N., B. H. Boon, A. van Velzen, A. Cames, O. Deuber and D. S. Lee, 2005. Giving wings to Emissions Trading - Inclusion of Aviation under the European Trading System (ETS): Design and Impacts, CE, Delft.

UNFCCC, 2007. Greenhouse Gas Submissions to the United Nations Framework Convention on Climate Change, <http://unfccc.int>

The Tyndall Centre working paper series presents results from research which are mature enough to be submitted to a refereed journal, to a sponsor, to a major conference or to the editor of a book. The intention is to enhance the early public availability of research undertaken by the Tyndall family of researchers, students and visitors. They can be downloaded from the Tyndall Website at:

http://www.tyndall.ac.uk/publications/working_papers/working_papers.shtml

The accuracy of working papers and the conclusions reached are the responsibility of the author(s) alone and not the Tyndall Centre.

Papers available in this series are:

- Al-Saleh Y., Upham P., Malik K., (2008) **Renewable Energy Scenarios for the Kingdom of Saudi Arabia:** Tyndall Working Paper 125
- Scrieciu S., Barker T., Smith V., (2008) **World economic dynamics and technological change: projecting interactions between economic output and CO2 emissions :** Tyndall Working Paper 124
- Bulkeley H., Schroeder H., (2008) **Governing Climate Change Post-2012: The Role of Global Cities - London:** Tyndall Working Paper 123
- Schroeder H., Bulkeley H., (2008) **Governing Climate Change Post-2012: The Role of Global Cities, Case-Study: Los Angeles:** Tyndall Working Paper 122
- Wang T., Watson J., (2008) **Carbon Emissions Scenarios for China to 2100:** Tyndall Working Paper 121
- Bergman, N., Whitmarsh L., Kohler J., (2008) **Transition to sustainable development in the UK housing sector: from case study to model implementation:** Tyndall Working Paper 120
- Conway D, Persechino A., Ardoin-Bardin S., Hamandawana H., Dickson M, Dieulin C, Mahe G, (2008) **RAINFALL AND WATER RESOURCES VARIABILITY IN SUB-SAHARAN AFRICA DURING THE 20TH CENTURY:** Tyndall Centre Working Paper 119
- Starkey R., (2008) **Allocating emissions rights: Are equal shares, fair shares? :** Tyndall Working Paper 118
- Barker T., (2008) **The Economics of Avoiding Dangerous Climate Change:** Tyndall Centre Working Paper 117
- Estrada M, Corbera E., Brown K, (2008) **How do regulated and voluntary carbon-offset schemes compare?:** Tyndall Centre Working Paper 116
- Estrada Porrua M, Corbera E., Brown K, (2007) **REDUCING GREENHOUSE GAS EMISSIONS FROM DEFORESTATION IN DEVELOPING COUNTRIES: REVISITING THE ASSUMPTIONS:** Tyndall Centre Working Paper 115
- Boyd E., Hultman N E., Roberts T., Corbera E., Ebeling J., Liverman D, Brown K, Tippmann R., Cole J., Mann P, Kaiser M., Robbins M, (2007) **The Clean Development Mechanism: An assessment of current practice and**

future approaches for policy: Tyndall Centre Working Paper 114

- Hanson, S., Nicholls, R., Balson, P., Brown, I., French, J.R., Spencer, T., Sutherland, W.J. (2007) **Capturing coastal morphological change within regional integrated assessment: an outcome-driven fuzzy logic approach:** Tyndall Working Paper No. 113
- Okereke, C., Bulkeley, H. (2007) **Conceptualizing climate change governance beyond the international regime: A review of four theoretical approaches:** Tyndall Working Paper No. 112
- Doulton, H., Brown, K. (2007) **'Ten years to prevent catastrophe'? Discourses of climate change and international development in the UK press:** Tyndall Working Paper No. 111
- Dawson, R.J., et al (2007) **Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change:** Tyndall Working Paper No. 110
- Okereke, C., (2007) **A review of UK FTSE 100 climate strategy and a framework for more in-depth analysis in the context of a post-2012 climate regime:** Tyndall Centre Working Paper 109
- Gardiner S., Hanson S., Nicholls R., Zhang Z., Jude S., Jones A.P., et al (2007) **The Habitats Directive, Coastal Habitats and Climate Change – Case Studies from the South Coast of the UK:** Tyndall Centre Working Paper 108
- Schipper E. Lisa, (2007) **Climate Change Adaptation and Development: Exploring the Linkages:** Tyndall Centre Working Paper 107
- Okereke C., Mann P, Osbahr H, (2007)

Assessment of key negotiating issues at Nairobi climate COP/MOP and what it means for the future of the climate regime: Tyndall Centre Working Paper No. 106

- Walkden M, Dickson M, (2006) **The response of soft rock shore profiles to increased sea-level rise. :** Tyndall Centre Working Paper 105
- Dawson R., Hall J, Barr S, Batty M., Bristow A, Carney S, Evans E.P., Kohler J., Tight M, Walsh C, Ford A, (2007) **A blueprint for the integrated assessment of climate change in cities. :** Tyndall Centre Working Paper 104
- Dickson M., Walkden M., Hall J., (2007) **Modelling the impacts of climate change on an eroding coast over the 21st Century:** Tyndall Centre Working Paper 103
- Klein R.J.T, Erickson S.E.H, Næss L.O, Hammill A., Tanner T.M., Robledo, C., O'Brien K.L.,(2007) **Portfolio screening to support the mainstreaming of adaptation to climatic change into development assistance:** Tyndall Centre Working Paper 102
- Agnolucci P., (2007) **Is it going to happen? Regulatory Change and Renewable Electricity:** Tyndall Centre Working Paper 101
- Kirk K., (2007) **Potential for storage of carbon dioxide in the rocks beneath the East Irish Sea:** Tyndall Centre Working Paper 100
- Arnell N.W., (2006) **Global impacts of abrupt climate change: an initial assessment:** Tyndall Centre Working Paper 99
- Lowe T.,(2006) **Is this climate porn? How does climate change communication affect our perceptions**

and behaviour?, Tyndall Centre Working Paper 98

- Walkden M, Stansby P, (2006) **The effect of dredging off Great Yarmouth on the wave conditions and erosion of the North Norfolk coast**. Tyndall Centre Working Paper 97

- Anthoff, D., Nicholls R., Tol R S J, Vafeidis, A., (2006) **Global and regional exposure to large rises in sea-level: a sensitivity analysis**. This work was prepared for the Stern Review on the Economics of Climate Change: Tyndall Centre Working Paper 96

- Few R., Brown K, Tompkins E. L, (2006) **Public participation and climate change adaptation**, Tyndall Centre Working Paper 95

- Corbera E., Kosoy N, Martinez Tuna M, (2006) **Marketing ecosystem services through protected areas and rural communities in Meso-America: Implications for economic efficiency, equity and political legitimacy**, Tyndall Centre Working Paper 94

- Schipper E. Lisa, (2006) **Climate Risk, Perceptions and Development in El Salvador**, Tyndall Centre Working Paper 93

- Tompkins E. L, Amundsen H, (2005) **Perceptions of the effectiveness of the United Nations Framework Convention on Climate Change in prompting behavioural change**, Tyndall Centre Working Paper 92

- Warren R., Hope C, Mastrandrea M, Tol R S J, Adger W. N., Lorenzoni I., (2006) **Spotlighting the impacts functions in integrated assessments. Research Report Prepared for the Stern Review on the Economics of Climate Change**, Tyndall Centre Working Paper 91

- Warren R., Arnell A, Nicholls R., Levy P E, Price J, (2006) **Understanding the regional impacts of climate change: Research Report Prepared for the Stern Review on the Economics of Climate Change**, Tyndall Centre Working Paper 90

- Barker T., Qureshi M, Kohler J., (2006) **The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature**, Tyndall Centre Working Paper 89

- Kuang C, Stansby P, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 3: wave modelling**, Tyndall Centre Working Paper 88

- Kuang C, Stansby P, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 2: current and morphological modelling**, Tyndall Centre Working Paper 87

- Stansby P, Kuang C, Laurence D, Launder B, (2006) **Sandbanks for coastal protection: implications of sea-level rise. Part 1: application to East Anglia**, Tyndall Centre Working Paper 86

- Bentham M, (2006) **An assessment of carbon sequestration potential in the UK – Southern North Sea case study**: Tyndall Centre Working Paper 85

- Anderson K., Bows A., Upham P., (2006) **Growth scenarios for EU & UK aviation: contradictions with climate policy**, Tyndall Centre Working Paper 84

- Williamson M., Lenton T., Shepherd J., Edwards N, (2006) **An efficient numerical terrestrial scheme (ENTS) for fast earth system modelling**, Tyndall Centre Working Paper 83

- Bows, A., and Anderson, K. (2005) **An analysis of a post-Kyoto climate policy model**, Tyndall Centre Working Paper 82
- Sorrell, S., (2005) **The economics of energy service contracts**, Tyndall Centre Working Paper 81
- Wittneben, B., Haxeltine, A., Kjellen, B., Köhler, J., Turnpenny, J., and Warren, R., (2005) **A framework for assessing the political economy of post-2012 global climate regime**, Tyndall Centre Working Paper 80
- Ingham, I., Ma, J., and Ulph, A. M. (2005) **Can adaptation and mitigation be complements?**, Tyndall Centre Working Paper 79
- Agnolucci, P. (2005) **Opportunism and competition in the non-fossil fuel obligation market**, Tyndall Centre Working Paper 78
- Barker, T., Pan, H., Köhler, J., Warren, R. and Winne, S. (2005) **Avoiding dangerous climate change by inducing technological progress: scenarios using a large-scale econometric model**, Tyndall Centre Working Paper 77
- Agnolucci, P. (2005) **The role of political uncertainty in the Danish renewable energy market**, Tyndall Centre Working Paper 76
- Fu, G., Hall, J. W. and Lawry, J. (2005) **Beyond probability: new methods for representing uncertainty in projections of future climate**, Tyndall Centre Working Paper 75
- Ingham, I., Ma, J., and Ulph, A. M. (2005) **How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning?**, Tyndall Centre Working Paper 74
- Walkden, M. (2005) **Coastal process simulator scoping study**, Tyndall Centre Working Paper 73
- Lowe, T., Brown, K., Suraje Dessai, S., Doria, M., Haynes, K. and Vincent, K. (2005) **Does tomorrow ever come? Disaster narrative and public perceptions of climate change**, Tyndall Centre Working Paper 72
- Boyd, E. Gutierrez, M. and Chang, M. (2005) **Adapting small-scale CDM sinks projects to low-income communities**, Tyndall Centre Working Paper 71
- Abu-Sharkh, S., Li, R., Markvart, T., Ross, N., Wilson, P., Yao, R., Steemers, K., Kohler, J. and Arnold, R. (2005) **Can Migrogrids Make a Major Contribution to UK Energy Supply?**, Tyndall Centre Working Paper 70
- Tompkins, E. L. and Hurlston, L. A. (2005) **Natural hazards and climate change: what knowledge is transferable?**, Tyndall Centre Working Paper 69
- Bleda, M. and Shackley, S. (2005) **The formation of belief in climate change in business organisations: a dynamic simulation model**, Tyndall Centre Working Paper 68
- Turnpenny, J., Haxeltine, A. and O'Riordan, T., (2005) **Developing regional and local scenarios for climate change mitigation and adaptation: Part 2: Scenario creation**, Tyndall Centre Working Paper 67
- Turnpenny, J., Haxeltine, A., Lorenzoni, I., O'Riordan, T., and Jones, M., (2005) **Mapping actors involved in climate change policy networks in the UK**, Tyndall Centre Working Paper 66

- Adger, W. N., Brown, K. and Tompkins, E. L. (2004) **Why do resource managers make links to stakeholders at other scales?**, Tyndall Centre Working Paper 65
- Peters, M.D. and Powell, J.C. (2004) **Fuel Cells for a Sustainable Future II**, Tyndall Centre Working Paper 64
- Few, R., Ahern, M., Matthies, F. and Kovats, S. (2004) **Floods, health and climate change: a strategic review**, Tyndall Centre Working Paper 63
- Barker, T. (2004) **Economic theory and the transition to sustainability: a comparison of approaches**, Tyndall Centre Working Paper 62
- Brooks, N. (2004) **Drought in the African Sahel: long term perspectives and future prospects**, Tyndall Centre Working Paper 61
- Few, R., Brown, K. and Tompkins, E.L. (2004) **Scaling adaptation: climate change response and coastal management in the UK**, Tyndall Centre Working Paper 60
- Anderson, D and Winne, S. (2004) **Modelling Innovation and Threshold Effects In Climate Change Mitigation**, Tyndall Centre Working Paper 59
- Bray, D and Shackley, S. (2004) **The Social Simulation of The Public Perceptions of Weather Events and their Effect upon the Development of Belief in Anthropogenic Climate Change**, Tyndall Centre Working Paper 58
- Shackley, S., Reiche, A. and Mander, S. (2004) **The Public Perceptions of Underground Coal Gasification (UCG): A Pilot Study**, Tyndall Centre Working Paper 57
- Vincent, K. (2004) **Creating an index of social vulnerability to climate change for Africa**, Tyndall Centre Working Paper 56
- Mitchell, T.D. Carter, T.R., Jones, J.P.D, Hulme, M. and New, M. (2004) **A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100)**, Tyndall Centre Working Paper 55
- Turnpenny, J., Carney, S., Haxeltine, A., and O'Riordan, T. (2004) **Developing regional and local scenarios for climate change mitigation and adaptation Part 1: A framing of the East of England** Tyndall Centre Working Paper 54
- Agnolucci, P. and Ekins, P. (2004) **The Announcement Effect And Environmental Taxation** Tyndall Centre Working Paper 53
- Agnolucci, P. (2004) **Ex Post Evaluations of CO2 -Based Taxes: A Survey** Tyndall Centre Working Paper 52
- Agnolucci, P., Barker, T. and Ekins, P. (2004) **Hysteresis and Energy Demand: the Announcement Effects and the effects of the UK Climate Change Levy** Tyndall Centre Working Paper 51
- Powell, J.C., Peters, M.D., Ruddell, A. and Halliday, J. (2004) **Fuel Cells for a Sustainable Future?** Tyndall Centre Working Paper 50
- Awerbuch, S. (2004) **Restructuring our electricity networks to promote decarbonisation**, Tyndall Centre Working Paper 49
- Pan, H. (2004) **The evolution of economic structure under**

technological development, Tyndall
Centre Working Paper 48

- Berkhout, F., Hertin, J. and Gann, D. M., (2004) **Learning to adapt: Organisational adaptation to climate change impacts**, Tyndall Centre Working Paper 47
- Watson, J., Tetteh, A., Dutton, G., Bristow, A., Kelly, C., Page, M. and Pridmore, A., (2004) **UK Hydrogen Futures to 2050**, Tyndall Centre Working Paper 46
- Purdy, R and Macrory, R. (2004) **Geological carbon sequestration: critical legal issues**, Tyndall Centre Working Paper 45
- Shackley, S., McLachlan, C. and Gough, C. (2004) **The Public Perceptions of Carbon Capture and Storage**, Tyndall Centre Working Paper 44
- Anderson, D. and Winne, S. (2003) **Innovation and Threshold Effects in Technology Responses to Climate Change**, Tyndall Centre Working Paper 43
- Kim, J. (2003) **Sustainable Development and the CDM: A South African Case Study**, Tyndall Centre Working Paper 42
- Watson, J. (2003), **UK Electricity Scenarios for 2050**, Tyndall Centre Working Paper 41
- Klein, R.J.T., Lisa Schipper, E. and Dessai, S. (2003), **Integrating mitigation and adaptation into climate and development policy: three research questions**, Tyndall Centre Working Paper 40
- Tompkins, E. and Adger, W.N. (2003). **Defining response capacity to enhance climate change policy**, Tyndall Centre Working Paper 39
- Brooks, N. (2003). **Vulnerability, risk and adaptation: a conceptual framework**, Tyndall Centre Working Paper 38
- Ingham, A. and Ulph, A. (2003) **Uncertainty, Irreversibility, Precaution and the Social Cost of Carbon**, Tyndall Centre Working Paper 37
- Kröger, K. Fergusson, M. and Skinner, I. (2003). **Critical Issues in Decarbonising Transport: The Role of Technologies**, Tyndall Centre Working Paper 36
- Tompkins E. L and Hurlston, L. (2003). **Report to the Cayman Islands' Government. Adaptation lessons learned from responding to tropical cyclones by the Cayman Islands' Government, 1988 – 2002**, Tyndall Centre Working Paper 35
- Dessai, S., Hulme, M (2003). **Does climate policy need probabilities?**, Tyndall Centre Working Paper 34
- Pridmore, A., Bristow, A.L., May, A. D. and Tight, M.R. (2003). **Climate Change, Impacts, Future Scenarios and the Role of Transport**, Tyndall Centre Working Paper 33
- Xueguang Wu, Jenkins, N. and Strbac, G. (2003). **Integrating Renewables and CHP into the UK Electricity System: Investigation of the impact of network faults on the stability of large offshore wind farms**, Tyndall Centre Working Paper 32
- Turnpenny, J., Haxeltine A. and O'Riordan, T. (2003). **A scoping study of UK user needs for managing climate futures. Part 1 of the pilot-phase interactive integrated assessment process (Aurion Project)**, Tyndall Centre Working Paper 31

- Hulme, M. (2003). **Abrupt climate change: can society cope?**, Tyndall Centre Working Paper 30
- Brown, K. and Corbera, E. (2003). **A Multi-Criteria Assessment Framework for Carbon-Mitigation Projects: Putting "development" in the centre of decision-making**, Tyndall Centre Working Paper 29
- Dessai, S., Adger, W.N., Hulme, M., Köhler, J.H., Turnpenny, J. and Warren, R. (2003). **Defining and experiencing dangerous climate change**, Tyndall Centre Working Paper 28
- Tompkins, E.L. and Adger, W.N. (2003). **Building resilience to climate change through adaptive management of natural resources**, Tyndall Centre Working Paper 27
- Brooks, N. and Adger W.N. (2003). **Country level risk measures of climate-related natural disasters and implications for adaptation to climate change**, Tyndall Centre Working Paper 26
- Xueguang Wu, Mutale, J., Jenkins, N. and Strbac, G. (2003). **An investigation of Network Splitting for Fault Level Reduction**, Tyndall Centre Working Paper 25
- Xueguang Wu, Jenkins, N. and Strbac, G. (2002). **Impact of Integrating Renewables and CHP into the UK Transmission Network**, Tyndall Centre Working Paper 24
- Paavola, J. and Adger, W.N. (2002). **Justice and adaptation to climate change**, Tyndall Centre Working Paper 23
- Watson, W.J., Hertin, J., Randall, T., Gough, C. (2002). **Renewable Energy and Combined Heat and Power Resources in the UK**, Tyndall Centre Working Paper 22
- Watson, W. J. (2002). **Renewables and CHP Deployment in the UK to 2020**, Tyndall Centre Working Paper 21
- Turnpenny, J. (2002). **Reviewing organisational use of scenarios: Case study - evaluating UK energy policy options**, Tyndall Centre Working Paper 20
- Pridmore, A. and Bristow, A., (2002). **The role of hydrogen in powering road transport**, Tyndall Centre Working Paper 19
- Watson, J. (2002). **The development of large technical systems: implications for hydrogen**, Tyndall Centre Working Paper 18
- Dutton, G., (2002). **Hydrogen Energy Technology**, Tyndall Centre Working Paper 17
- Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. (2002). **Adaptation to climate change: Setting the Agenda for Development Policy and Research**, Tyndall Centre Working Paper 16
- Köhler, J.H., (2002). **Long run technical change in an energy-environment-economy (E3) model for an IA system: A model of Kondratiev waves**, Tyndall Centre Working Paper 15
- Shackley, S. and Gough, C., (2002). **The Use of Integrated Assessment: An Institutional Analysis Perspective**, Tyndall Centre Working Paper 14
- Dewick, P., Green K., Miozzo, M., (2002). **Technological Change, Industry Structure and the Environment**, Tyndall Centre Working Paper 13
- Dessai, S., (2001). **The climate regime from The Hague to Marrakech:**

Saving or sinking the Kyoto Protocol?, extreme weather events, Tyndall
Tyndall Centre Working Paper 12 Centre Working Paper 6

- Barker, T. (2001). **Representing the Integrated Assessment of Climate Change, Adaptation and Mitigation,** Tyndall Centre Working Paper 11
- Barnett, J. (2001). **The issue of 'Adverse Effects and the Impacts of Response Measures' in the UNFCCC,** Tyndall Centre Working Paper 5
- Gough, C., Taylor, I. and Shackley, S. (2001). **Burying Carbon under the Sea: An Initial Exploration of Public Opinions,** Tyndall Centre Working Paper 10
- Barker, T. and Ekins, P. (2001). **How High are the Costs of Kyoto for the US Economy?,** Tyndall Centre Working Paper 4
- Barnett, J. and Adger, W. N. (2001). **Climate Dangers and Atoll Countries,** Tyndall Centre Working Paper 9
- Berkhout, F, Hertin, J. and Jordan, A. J. (2001). **Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines',** Tyndall Centre Working Paper 3
- Adger, W. N. (2001). **Social Capital and Climate Change,** Tyndall Centre Working Paper 8
- Hulme, M. (2001). **Integrated Assessment Models,** Tyndall Centre Working Paper 2
- Barnett, J. (2001). **Security and Climate Change,** Tyndall Centre Working Paper 7
- Mitchell, T. and Hulme, M. (2000). **A Country-by-Country Analysis of Past and Future Warming Rates,** Tyndall Centre Working Paper 1
- Goodess, C.M., Hulme, M. and Osborn, T. (2001). **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of**

© Copyright 2008

Tyndall°Centre
for Climate Change Research

For further information please
contact

[Javier Delgado-Esteban](#)

Stansted Airport planning application

Plans to increase the passenger cap at Stansted Airport have been refused by Uttlesford District Council's Planning Committee at an extraordinary meeting today (24 January).

This comes after a Planning Committee meeting in November 2018 at which the committee resolved to grant approval of the application subject to the S106 Agreement.

The reasons for today's refusal were made in relation to noise, air quality and climate change, matters that the committee agreed were material planning changes since the approval was granted.

Audio recording

Unfortunately the broadcasting of today's meeting failed. Officers worked throughout the day, in liaison with the supplier, to identify and rectify the problem without success.

It has now been established that the back-up local recording of the meeting also failed, meaning an audio recording of the meeting will not be available on the council's website.

We sincerely apologise to those who had wanted to 'listen in' or 'listen again' to the meeting.

24 January 2020