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Growth scenarios for EU & UK aviation: contradictions with climate policy

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Keywords/Phrases: Contraction and Convergence; Stabilisation; Aviation; Carbon dioxide concentration; Scenarios

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Summary

This paper reviews the scientific, policy and economic context to managing greenhouse gas emissions from aviation. It provides a short assessment of the contraction and convergence model developed by the Global Common's Institute (*CCOptions*), finding it both appropriate for the present study and of considerable value for climate policy studies more generally. The report goes on to develop aircraft emissions scenarios for each EU nation over the period 2002-2050, taking into account fuel efficiency improvements and sometimes applying uplift factors[1] relating to radiative forcing. These scenarios are subsequently compared with national carbon contraction and convergence profiles for 450ppmv and 550ppmv carbon dioxide concentration stabilisation levels for EU members states; for the UK, the 550ppmv contraction and convergence profile is consistent with the UK government's 2050 target of reducing carbon emissions by 60%. The results show that a significant portion of annual emissions budget will be attributable to the aviation industry for the aggregated EU25 nations, as is also the case when separated into the original EU15 nations, the 10 new accession states and looking at the UK alone. If the aviation industry is allowed to grow at rates even lower than those being experienced today, the EU could see aviation accounting for between 39% and 79% of its total carbon budget by 2050, depending on the stabilisation level chosen. For the UK, the respective figures are between 50% and 100%.

As a further analysis, the scenarios for the UK were investigated in the context of what the impact on the other sectors of the economy might be. The scenarios show that all of the other sectors of the UK economy would need toreduce their carbon emissions significantly to allow the aviation industry to grow at even moderate rates. This would require a much more substantial investment in renewable energy, carbon sequestration, nuclear power, hydrogen and energy efficiency than would be the case with a low growth aviation sector. Within the 2050 low energy demand scenario within this paper, the energy supply system would be required to make more moderate levels of decarbonisation, with the principal reduction in carbon coming about through other sectors' substantial improvements in terms of energy efficiency and behavioural change, so as to make room for the aviation industry.

1. Introduction

Within the majority of nations in the EU25, greenhouse gas emissions by aviation are growing at a rate far in excess of those of other sectors. The Kyoto Protocol requires a reduction in carbon dioxide emissions to 5.2% below 1990 levels over the period 2008-2012 by Annex 1 parties (the more developed nations that have signed the United Nations Framework Convention). Between 1990 and 2000, Annex 1 Parties did indeed experience an overall decline in greenhouse gas (GHG) emissions. This was in all sectors except transport and the energy industry, where GHG emissions rose by 20% and 10% respectively. However, the 20% rise in emissions from the transport sector as a whole masks the magnitude of the growth due to a rapidly expanding international aviation industry. Between 1990 and 2000, emissions from international shipping remained relatively stable (UNFCCC, 2003) emissions from international aviation rose by 48% (FCCC/SBI, 2003). From 2000-2010, GHG emissions are in aggregate expected to rise above 1990 levels for all parties (ibid). For those nations that have signed the Kyoto Protocol and aim to make more substantial cuts to greenhouse gases in the future, an aviation industry that is allowed to grow unabated will increasingly consume the 'emissions space' within which all their sectors will need to operate.

In December 2003, the UK Department for Transport (DfT) published the UK Government's aviation White Paper, *The Future of Air Transport*, setting out a strategic framework for the development of UK aviation. The White Paper gave support for a new runway at each of Birmingham, Edinburgh, Stansted and Heathrow airports, plus new terminals, apron and runway extensions throughout the UK.

[1] It should be noted that there is substantial scientific uncertainty relating to both the size of the uplift factor that should be used, as well as to the method of simply 'uplifting' carbon values for comparison with carbon emissions profiles. Strictly speaking, such a comparison does not compare like with like.

In addition to the local environmental impacts of aviation expansion, observers have drawn attention to the starkly contradictory direction of aviation White Paper projections and the UK's sustainable development goal (RCEP, 2002), particularly the 2050 UK energy white paper target (Bows & Anderson, 2004; Upham, 2003, 2004; House of Commons Environmental Audit Committee, 2004a, b, c; UK Sustainable Development Commission, 2004). The Energy White paper commits the UK to reducing its carbon dioxide emissions by some 60% from current levels, and observers have commented that it appears unlikely that emissions reductions in other sectors can sufficiently compensate for aviation growth, while meeting the UK's 60% target. The Government is keen to bring *intra-EU* emissions from the flight sector into the EU Emissions Trading Scheme (ETS), which is based on Directive 2003/87/EC and began on 1 January 2005.

The Aviation White Paper states:

> "A greenhouse gas trading scheme is fast developing in Europe. We intend to press for the inclusion of intra-EU air services in the forthcoming EU emissions trading scheme, and to make this a priority for the UK Presidency of the EU in 2005, with a view to aviation joining the scheme from 2008, or as soon as possible thereafter." (Section 3.4, DfT 2003).

The ETS is due to run in two phases: 2005-7 and 2008-12. Aviation would thus join in the second phase. The White Paper expresses a preference for the aviation sector becoming a part of a global ETS, led by the UN International Civil Aviation Organisation (ICAO) (DfT, 2003, Annex B). The 35th triennial ICAO Assembly ended in October 2004 by continuing to affirm the role of ICAO in supporting emissions trading. The Assembly also went further and asked ICAO to provide guidance on aviation greenhouse gas emissions charges by the next ICAO Assembly in 2007. The Assembly's support for emissions trading and guidance on levies were achieved despite strong opposition by non-European parties.

The purpose of this report is to estimate the emissions implications of a Contraction and Convergence policy applied at the EU level, for flights to, from and within the EU, with particular emphasis on the UK. The study explicitly assumes that the EU takes responsibility for half of its flight emissions, regardless of whether these are emitted over EU territories or not – it thus looks beyond the current ambitions of the UK Government for inclusion of only intra-EU flights within EU ETS, and points to the need for further policy measures. While the study assumes that passenger demand is unconstrained by limits on airport development, its projected level of UK air passenger demand up to 2030 is similar to that projected by the UK Department for Transport for the UK in 2030 under high growth assumptions.

Contraction and Convergence is a policy approach to reducing international greenhouse gas emissions at per-capita equality. The approach has been most prominently developed by the Global Commons Institute (GCI) [2] and is both endorsed and used by the UK Royal Commission on Environmental Pollution (RCEP) in its 22nd report *Energy - The Changing Climate*[3]. The DTI Energy White Paper target of reducing UK carbon dioxide emissions by some 60% by 2050 is based on the recommendation of RCEP.

The main hypothesis of this study is that if the EU as a whole commits to substantial long-term cuts in carbon dioxide emissions, as it will need to for stabilisation of atmospheric carbon dioxide concentrations, and these are phased according to a contraction and convergence approach, it is unlikely that the level of UK aviation growth projected by DfT in the aviation White Paper will be accommodated within a European ETS alone. While the study uses simple arithmetic methods to test this, there appears no reason why a more detailed modelling, taking into account fleet- and route-specific factors, would not largely confirm the results presented here. In short, the study is intended to test whether additional policy measures are needed, be these to reduce the rate of

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[2] www.gci.org.uk

[3] Sections 4.47- 4.54 (RCEP, 2000). RCEP describes itself as "an independent body, appointed by the Queen and funded by the government, which publishes in-depth reports on what it identifies as the crucial environmental issues facing the UK and the world" (www.rcep.org.uk).

growth in demand for air transport, or to establish an international emissions trading system that enables EU states (or airlines) to purchase emissions credits (for whatever period this might prove possible under a globally contracting emissions regime).

1.1 Aims and objectives

The main aims of this report are to provide an overview of the Contraction and Convergence climate policy and to broadly estimate the implications of that policy for UK aviation in a European context, given the assumptions stated above. The objectives are:

- To provide an overview of the scientific, aviation and climate policy background to the projected increase in UK aviation greenhouse gas emissions;
- To provide an overview of the contraction and convergence approach to carbon dioxide stabilisation;
- To show the carbon dioxide emissions profiles, based on the contraction and convergence mechanism for each EU nation, for 2002-2050, as output by the Global Commons Institute's contraction and convergence model *CCOptions*, and assuming targets of 450ppmv and 550ppmv global carbon dioxide concentration by 2100;
- To broadly estimate the growth in aviation emissions for each EU nation and relate this to the national emissions contraction profiles, showing the 'emissions space' for aviation growth;
- To show the effects of different 'uplift factors' for EU aviation carbon dioxide emissions;
- To briefly consider the implications of different growth in aviation scenarios on the necessary UK aviation infrastructure

In short, the present study is borne out of the hypothesis that long term European climate policy cannot be reconciled with a European aviation growth, bounded within a European Emissions Trading System (ETS). The study is indicative of the magnitude of the problems faced and summarily reviews relevant literatures for the non-specialist. The report is intended to inform on-going discussion on the inclusion of aviation within the European ETS, an objective set out as a priority by the UK Government in its 2003 Air Transport White Paper.

2. The Need for Extended National Climate Commitments

Contraction and convergence is one policy approach among several that have been suggested as a framework for extending national commitments (GHG emissions reduction targets) beyond the 2008-12 commitment period established in the Kyoto Protocol of the UN Framework Convention on Climate Change (UNFCCC). This section provides an overview of why national climate commitments need to be extended.

2.1 Scientific context

2.1.1 Anthropogenic climate change

The *Third Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC, 2001) is the most recent, complete assessment of the science of climate change. It confirms that anthropogenic global warming is taking place and identifies the rate of this warming as representing a stark disjunction with the past. The latest research shows that globally averaged surface temperature sensitivities to a doubling of carbon dioxide concentrations from pre-industrial levels could be as high, if not higher, than 11K (Stainforth, 2005). Such values expand the headline uncertainty ranges of the IPCC Third Assessment Report (for example, the 1.4-5.8 K range for 1990 to 2100 warming). The projected rate of this warming is much larger than the observed changes during the 20th century and is very likely to be without precedent during at least the last 10,000 years, based on palaeoclimate data (ibid). More recent studies of the cooling effect of aerosols suggest that this cooling may have been substantially underestimated, by 2 to 3 times (Pearce, 2003). As greenhouse gases are expected to continue accumulating in the atmosphere while aerosols stabilise or fall, this may entail "dramatic consequences for estimates of future climate change" (ibid).

2.1.2 Stabilising global atmospheric carbon dioxide concentration

Stabilising the concentration of carbon dioxide and other greenhouse gases at or below 550ppmv is critical to avoiding an 'excessive' increase in global mean surface temperature (and other critical impacts of excess carbon dioxide , notably acidification of the oceans). Article 2 of the UNFCCC states:

> "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

While the IPCC has refrained from recommending an atmospheric concentration for carbon dioxide that should not be exceeded, the Third Assessment Report (IPCC SPM, 2001: 12) states that reductions in greenhouse gas emissions and the gases that control their concentration will nevertheless be necessary to stabilise radiative forcing[4]. It further states that carbon cycle models indicate that stabilisation of atmospheric carbon dioxide concentrations at 450ppmv would require global anthropogenic carbon dioxide emissions to drop below 1990 levels within a few decades, that stabilisation at 650ppmv would require sub-1990 emission levels within about a century, and that 1,000ppmv would require sub-1990 emission levels within about two centuries. All such reductions would require steady decreases thereafter to achieve stabilisation of atmospheric carbon dioxide concentration, with carbon dioxide emissions eventually needing to decline to a very small fraction[5] of current emissions (ibid).

[4] Radiative forcing is the change in the balance of radiation coming into the atmosphere and that going out. Its sign can be positive or negative and it is measured in terms of watts per square metre.

[5] Stated as10% by DEFRA (2003) and less than 5% over a very long timescale by IPCC (2001, in Tuinstra et al: al, 2002: 8).

Although Annex I countries[6] have been responsible for 80% of the cumulative carbon dioxide emissions for fossil fuels from 1900, Annex I country emissions in aggregate have been stable over the last 10 years, with increases in some OECD countries being compensated for by decreases in transitional economy countries. In contrast, emissions of Non-Annex I Parties are increasing rapidly, and their carbon dioxide emissions are expected to exceed those of Annex I in the next few decades. IPCC scenarios show that Kyoto Protocol targets will be far from sufficient to reach stabilisation targets such as 450 or 550ppmv carbon dioxide concentrations.

The choice of climate stabilisation target in terms of the concentration of atmospheric carbon dioxide or its equivalent (i.e. including other greenhouse gases) is not a wholly scientific matter. Given uncertainties regarding the role of feedbacks in the climate system, the choice necessarily includes issues of judgement regarding the degree of precaution individuals want to take in relation to climate change. The choice also requires individuals to judge how much climate change-induced damage they are willing to tolerate – or believe they are willing to tolerate. While this study looks at the implications of targets of 450 and 550ppmv of carbon dioxide alone, it should be remembered that these targets will be judged to involve too high a level of risk by some – arguably for good reason[7].

The EU Council of Environment Ministers, the RCEP and the UK Government in their Energy White Paper cite 550ppmv as a desirable upper limit for atmospheric carbon dioxide (RCEP, 2000: 4.31-2; DTI, 2003: 9, 24). Some paths to stabilisation are provided in the IPCC Third Assessment Report (IPCC, 2001, also in Höhne et al, 2003: 7).

Whatever the pathway, using a contraction and convergence approach to reduce carbon emissions would need begin from points of major national differences: national per-capita emission levels cover a wide range for example, 0.2t carbon dioxide for an individual in Bangladesh, to 25t carbon dioxide equivalent per person in the USA (Höhne et al, 2003: 41, based on the EDGAR database for the three major greenhouse gases and including also emissions from forestry in 1995). The Annex I average is 15t carbon dioxide equivalent/person, the Non-Annex I average is 4t carbon dioxide equivalent/person, and the global average is 6t carbon dioxide equivalent/person (ibid).

2.1.3 Aviation and radiative forcing

In 1999, IPCC published a special report *Aviation and the Global Atmosphere* (IPCC, 1999) following a request from the International Civil Aviation Organization (ICAO) and the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. This considers the effects that aviation has had in the past and may have in the future on both stratospheric ozone depletion and global climate change. IPCC (1999) is widely considered a consensual reference point in the scientific understanding of the climatic impacts of aviation.

In 2002, the RCEP – a standing advisory body to the UK Government - published a special report *The Environmental Effects of Civil Aircraft in Flight* as a contribution to a White Paper on the future of UK aviation. This reconsidered and confirmed the findings of IPCC (1999), but recommended increased demand growth estimates. In 1992, global aviation was responsible for 2% of the carbon dioxide emissions due to the total global burning of fossil fuel, and 13% of that associated with transport (IPCC, 1999, in RCEP, 2002: 3.22). However, the total greenhouse impact was larger than this would suggest. Since the vast majority of the flights were subsonic and therefore in the 9 to 13 km height range, emissions of oxides of nitrogen lead, on average, to an increase in ozone as well as to a decrease in methane. Relative to carbon dioxide, the radiative forcing factors were estimated by IPCC to be +1.3 for ozone and -0.8 for methane. The factor +1.1 was given by IPCC for contrails. The impacts of water vapour, and sulphate and soot particles were given as small and positive. The total radiative forcing was assigned by IPCC a value of 2.7 times that of the carbon dioxide alone, which can be compared with factors generally in the range

[6] The more developed nations, specifically those who have emissions reduction obligations under the Kyoto Protocol.
[7] Such reasons include, for example, the need to account for other GHGs. This study focuses on carbon dioxide alone.

1 - 1.5 for most other activities. Consequently, aircraft were seen as being responsible for 3.5% of the total radiative forcing in 1992 (RCEP, 2002: 3.22).

The radiative forcing from aircraft, excluding cirrus clouds, is estimated to become 3.8 times larger in 2050 than it was in 1992 (IPCC, 1999) – a value of $0.19Wm^{-2}$. To put this into perspective, this figure is about 14% of the total radiative forcing for 1992 (RCEP, 2002: 3.36). However, the IPCC reference scenario used to produce this estimate assumes both lower aviation growth than that seen in the period up to 11 September 2001, and large technological advances (ibid). The RCEP (2002: 3.41) consider the IPCC reference value for the climate impact of aviation more likely to be an under-estimate than an over-estimate of aviation's contribution to radiative forcing. They conclude that unless there is some reduction in growth in the sector or technology improves considerably more than assumed by the 1999 IPCC aviation report, then by 2050, aviation will be contributing at least 6% of a total radiative forcing consistent with climate stabilisation at the 550ppmv level[8]. For the RCEP, a safer working hypothesis is that it will be in the range 6%-10% (RCEP, 2002: 3.41). If significant fleets of sonic or supersonic aircraft are flown, then the aviation contribution would be higher than this (ibid: 3.45). Supersonic aircraft flying at 17-20km have a radiative forcing some 5 times greater than the 9-13km subsonic equivalent. They also contribute to ozone depletion. A subsonic aircraft at 14-15km would be expected to have a radiative forcing between the two values (ibid).

2.2 Conclusions

The overwhelming scientific consensus is that anthropogenic climate change is a reality. Given that this is so, there is an urgent need to reduce greenhouse gas emissions and stabilise the concentrations of greenhouse gases in the atmosphere. While governmental bodies have to date suggested 550ppmv as an upper target for carbon dioxide concentration, there is increasing scientific evidence that 450ppmv should be treated as an upper target. Aviation emissions are unusual in the altitude of their emission. Atmospheric chemistry at this altitude has particular characteristics, and aviation emissions have particular effects. IPCC (1999) – supported by RCEP (2002) - have advocated radiative forcing as an appropriate metric with which to measure those effects, and have estimated the mean radiative forcing of aviation emissions as 2.7 times higher than the radiative forcing of carbon dioxide alone. Our research takes account of IPCC's estimate, but also provides estimates that do not take account of the 2.7 factor (known as uplift when applied).

[8] That is, at an atmospheric concentration of 550ppmv (parts per million by volume), the achievement of which requires a reduction in carbon dioxide emissions of some 60% (by 2050) to 80% (by 2100) for industrialised countries such as the UK, assuming a contraction and convergence policy in which nations approach per-capita equity in carbon dioxide emissions by 2050 [RCEP, 2000: 4.51]. The UK government has recently adopted the 60% target for 2050 (DTI, 2003).

3. Economic and Policy Context

3.1 International, European and UK climate policy

In terms of climate policy, the UK and 183 other countries are signatories to the United Nations Framework Convention on Climate Change (UNFCCC, 1992), which was agreed at the Earth Summit in Rio de Janeiro in 1992. UNFCCC sets out a framework for action to control or cut greenhouse gas emissions. A Protocol to the Convention was adopted in 1997 at the Third Conference of the Parties, held in Kyoto. This Kyoto Protocol (UNFCCC, 1997) commits industrialized countries to achieve quantified targets for decreasing their emissions of six greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) by 5.2% below 1990 levels over the period 2008-2012[9].

The rules for entry into force of the Kyoto Protocol (article 25) require 55 Parties to the Convention to ratify (or approve, accept, or accede to) the Protocol, including Annex I Parties accounting for 55% of that group's carbon dioxide emissions in 1990. As of May 2003, 108 Parties had ratified the Protocol, but this accounted for only 43.9% of Annex 1 Party emissions (UNFCCC, 2003)[10]. In November 2004, Russia (emitting some 17% of global anthropogenic carbon dioxide) ratified the Kyoto Protocol after lengthy debate. The Protocol became a legally binding treaty on February 16th 2005.

The EU accounts for about 24% of Annex 1 GHG emissions. Under the Kyoto Protocol, the EU and its member states can agree to meet their commitments jointly. This 'bubble' arrangement allows the EU's target to be redistributed between member states to reflect their national circumstances. In June 1998, environment ministers agreed how the target should be shared out.

In return for a commitment to reduce GHG's, the Kyoto Protocol also set out 'flexibility mechanisms', intended to be least cost policy instruments. These enable joint reduction (as stated above), transfer of 'Emissions Reduction Units' within a Party's area of jurisdiction, trading of 'emissions allowances' and use of a 'clean reduction mechanism', through which emissions reductions can be earned within a non-Annex 1 Party (Missfeldt, 1998).

In 2000, the European Commission issued a (consultative) Green Paper on greenhouse gas emissions trading within the EU: COM(2000) 87 final (European Commission, 2000). This suggested that a European Community-wide emissions trading scheme should begin by 2005, as a forerunner to emissions trading under the Kyoto Protocol from 2008. It suggested beginning with carbon dioxide for ease of monitoring, and large fixed point sources, and recommended that compatibility between the Community and Kyoto schemes be ensured. The UK initiated the first national GHG emissions trading scheme in 2002. The aviation industry has conducted its own studies into emissions trading for aviation (e.g. Arthur Andersen, 2001; BAA, 2003), and now prominent figures in the sector have expressed support for bringing aviation into the European emissions trading scheme (Clasper, 2004; Jowett, 2004) and thereafter into a global emissions trading scheme. The stated position of the UK Government is to try to bring intra-EU flight emissions into EU ETS in 2008 or soon after.

In the UK, the 2003 Energy White Paper set a target of reducing total UK carbon emissions by 60% from the 1990 level by 2050 (DTI, 2003: 1.10). The White Paper essentially accepted the

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[9] At Kyoto, the EU and its member states agreed to a joint reduction of -8%, the United States to –7%, Japan to –6%, Russia and the Ukraine to return to 1990 levels, and Australia +8%. Targets for individual EU member states ranged from –21% for Germany and Denmark, to –6% for the Netherlands, +13% for Ireland and +27% for Portugal (DEFRA, 2003). However, as of 2003, GHG emissions from the EU had increased for the second consecutive year, moving the EU as a whole further away from meeting its commitment to achieve a substantial emissions cut by the 2008-2012 period (EEA, 2003).

[10] The USA (emitting 36.1% of Annex 1 country carbon dioxide emissions) and subsequently Australia (emitting 2.1%) have so far declined to ratify the Protocol (UNFCCC, 2003).

analysis of the RCEP in their 22nd report *Energy - The Changing Climate.* The RCEP argued that a "contraction and convergence" policy was required for international control of carbon emissions, a consequence of which is a requirement for a 60-90% reduction in carbon emissions by industrialised countries. The principal objective of the RCEP (and by association the Energy White Paper) is to avoid "dangerous climate change" by ensuring the global mean atmospheric concentration of carbon dioxide does not exceed 550*ppmv.* This is understood by the Government and RCEP as being consistent with the goal of the Framework Convention on Climate Change (UNFCCC, 1992).

3.2 European and UK transport policy

For the EU, 'sustainable mobility' was an overarching objective of the 1998-2004 Action Programme for Transport (European Commission, 1998). The European Commission considers an "indefinite continuation of current trends in transport in certain modes (road, air) would be unsustainable in relation to its environmental impact, in particular as regards climate change" (European Commission, 1998: 6). The Commission expresses commitment to the development of 'sustainable forms of transport' (ibid), and, more explicitly, recommends attention be given to ways of de-linking economic growth from increased transport activity (European Commission, 1998: 9).

In the UK, the Government White Paper *A New Deal for Transport - Better for Everyone* (DETR, 1998), which sets a framework for future transport policy, also expresses a commitment to a 'sustainable' transport system. The Department of Environment, Transport and the Regions (DETR) defines this as one that supports employment, a strong economy, increases prosperity, addresses social exclusion, does not damage human health and provides a better quality of life for all now and in the future (ibid).

In July 2002, the UK Department for Transport (DfT) released its consultations on Regional Air Services (DfT, 2002a), which detail specific regional options for where and how airport growth might be accommodated. The mid-range *RASCO* scenario assumes a near trebling of UK air passenger demand by 2030. In March 2003, the DfT and HM Treasury issued a consultative policy document *Aviation and the Environment: Using Economic Instruments* (DfT and HM Treasury, 2003). This was intended to support discussion with stakeholders regarding economic instruments for encouraging the industry to take account of, and where appropriate reduce, its contribution to global warming, local air and noise pollution (ibid).

In December 2003, the DfT issued the aviation White Paper – *The Future of Air Transport*. This largely confirmed the mid-range *RAScarbon dioxide* scenario referred to above, envisaging some 475 million passengers by 2030 (up from 180 million in 2002), requiring a new runway at each of Birmingham, Edinburgh, Stansted and Heathrow airports, plus new terminals, apron and runway extensions throughout the UK.

3.3 Aviation growth trends

During the 20th century, the rate of worldwide energy use increased nine-fold (RCEP, 2000, 1.2), with the most rapid growth in demand arising from electricity use and mobility. In 1995, electricity and final energy demand for mobility accounted respectively for 25% and 17% of global final energy consumption (RCEP, 1.3, after IEA, 1998). Worldwide demand in all sectors will inevitably continue to grow as lower-income countries become increasingly industrialised (ibid).

Aviation has become one of the fastest growing sectors of the world economy (GAO, 2000). Since 1960, air passenger traffic (expressed as revenue passenger-kilometres) has grown at nearly 9% per year, 2.4 times the global average Gross Domestic Product growth rate (IPCC, 1999). Current global passenger transport by air is approximately 50 times greater than it was 50 years ago (Ausubel et al, 1998 in Pastowski, op cit). Notwithstanding periodic shocks and the ongoing restructuring of the industry, the demand for fast and reliable air transport is likely to continue under prevailing market conditions. The rate of growth of global passenger traffic slowed to about

5% in 1997, as the industry matured in some parts of the world. This rate is predicted to continue for at least the next 10 to 15 years (IPCC, 1999).

In the UK, the Department for Transport (DfT) anticipates a near trebling of air passengers by 2030. Current demand is in the region of 180 million air passengers, while the mid point forecast of national demand for 2030 is 500 million passengers per year (mppa) (DfT, 2000: 17). Their mid-range forecasts of passenger numbers are 276 million for 2010, 401 million for 2020 and 500 million for 2030. These represent 45%, 223% and 278% increases respectively from 2002 levels. Regarding air freight, UK demand doubled between 1989 and 1999 and is forecast to grow even more rapidly over the next 10 years (p.45). It currently represents 20% by value of all visible UK trade. DfT forecasts show freight traffic in the SE increasing from 1.8 million tonnes per year today to 6-8 m tonnes per year by 2030. Freight night-time movements may increase from 13,000 today to 40,000 at the four main South East of England airports (ibid).

3.4 Conclusion

Despite the EU having a policy commitment to sustainable mobility, globally, air passenger kilometres have risen steadily over several decades and the UK has recently embarked on an extended period of government-backed aviation growth. This report shows the stark disjunction between aviation growth trends and effective, long term climate policy in both the UK and the wider EU.

4. International Climate Policy Options

4.1 The main policy options

It is clear from the scientific overview above there is an urgent need for extending national commitments beyond Kyoto. In addition to the contraction and convergence policy, with an *a priori* presumption that nations should move towards per-capita equity in their carbon dioxide emissions, there are a number of related but different approaches to extending national commitments post-Kyoto. A study commissioned by the Umweltbundesamt (German Federal Environment Ministry) (Höhne et al, 2003) has assessed these approaches[11], including contraction and convergence, and makes recommendations for increasing their effectiveness and acceptability. Höhne et al's findings on ten alternative approaches to contraction and convergence are summarised below (ibid: 8-9):

- *Intensity targets* can play a role in future commitments as one form of target for a particular group of countries, possibly in parallel to other types of targets for other countries. If applied to all countries, the global emission intensity (emissions per unit of GDP) has to decrease rapidly (2%-4% per year) in order to reach stringent environmental goals. Agreeing on differentiated intensity reductions may be more difficult than agreeing on the level of absolute emissions reductions, as emissions intensity involves country specific knowledge of the relationship between emissions and GDP, which also may evolve with time (Höhne et al, 2003).

- *Contraction and convergence*: since major reductions in emissions are necessary it is likely that per-capita emissions under any policy regime will eventually converge to a very low level. The issue is on which path. Contraction and convergence has the advantages of simplicity and stringency but does not account for the structural differences of countries, their ability to decrease their emissions (nor, directly, for historic emissions) (Höhne et al, 2003).

- *The Triptych approach*: country-specific emissions budgets are calculated that reflect the energy, industrial and household sectors. As the method takes into account existing differences between countries, it can differentiate national emission reduction targets based on need. (Höhne et al, 2003).

- *Multi-stage approaches* "will be the future of the climate regime" (Höhne et al, ibid: ix), but there are many possibilities regarding types of stages and thresholds for moving into a next stage. The current two stages (Annex I and Non Annex I) could be extended. One criterion for moving to a further stage could be emissions per-capita (Höhne et al, 2003).

- *The multi-sector convergence approach* describes a complete set of rules for a future climate regime, defining in essence the path on which sectoral per-capita emissions converge. A major downside of the approach is that sectoral activities are not necessarily directly related to the population (Höhne et al, 2003).

- *Equal mitigation costs*: setting targets so that mitigation costs are equal for all participating countries (e.g. a percentage share of the GDP) seems to be, from a theoretical point of view, a fair option. In practice, however, it may be impossible to agree on a model or calculation method for calculating the cost of countries. It is therefore not a realistic option (Höhne et al, 2003).

- *Policies and measures* can also be a part of a mix. Especially for newly entering countries, policies that combine development and environment objectives are very attractive and could form a first stage of commitments." (Höhne et al, 2003: viii-ix).

[11] For another accessible account of post-Kyoto options, see: www.fiacc.net/app/approachlist.htm Also, models based on some the different approaches can be freely downloaded from research groups.

Höhne et al's analysis necessarily involves subjective judgement in addition to technical analysis – it is difficult to anticipate what will and will not be acceptable in the international political arena. One could also add other policy approaches, notably the Brazilian approach in which emissions reduction responsibilities are allocated on the basis of countries' historical contribution to global temperature change.

Whilst there are clearly many post-Kyoto policy regimes, whatever approach or mix of approaches is chosen, 'dangerous climate change' can only be avoided with major carbon dioxide emissions reductions, and that such reductions need to begin within the coming decades.

4.2 Contraction and Convergence Policy

4.2.1 GCI Contraction and Convergence approach

Notwithstanding the advantages and disadvantages of the various non-contraction and convergence approaches as supported explicitly by the RCEP and implicitly by the Government's Energy White Paper, this study focuses on the implications of a contraction and convergence approach, for UK aviation.

The Global Commons Institute (GCI) has largely been responsible for developing and promoting a contraction and convergence approach to greenhouse gas emissions reduction that is relatively unconcerned with structural differences within the Annex 1 and non Annex 1 groupings. It should also be in the development of the Kyoto protocol[12]. France proposed a formula for Annex I targets in 2010 based on converging global per-capita emissions by 2100. Similarly, in 1997 the EU proposed that emission paths should eventually converge to similar per-capita or per unit of GDP levels, without specifying a timeframe or level (Höhne et al, 2003: 26). Implicit affirmations of contraction and convergence in the UK by RCEP (2000) and DTI (2003) have been referred to above.

The GCI have constructed the spreadsheet model *CCOptions*, downloadable from their website. Based on the IPCC (1995 and 1996), the GCI assume 350ppmv to be a desirable atmospheric concentration target for carbon dioxide , with 450ppmv as an upper target, entailing serious but containable damage[13]. Suggested target years for these are 2050 and 2100 respectively, but other years and target concentrations can be modelled, as can any convergence year between 2001 and 2100.

In terms of algorithms for emissions allocation within the *CCOptions* model, the period between 1990 and 2200 is split into three separate time-periods. An initial stage extrapolates from the most recent year for which actual carbon dioxide emissions data is available up to 2000, the scope of the UNFCCC commitments. Contraction and convergence proper then runs from 2000 to 2100; a global contraction profile being determined first, and then a separate convergence criterion applied to calculate the per-capita emissions for each nation. Finally, the profile is extrapolated up until 2200, slowly reducing global emissions to ensure that the stabilisation level aimed for is attained (Bows & Anderson, 2005)

4.2.2 Multi-sector convergence approach

A multi-sector convergence (MSC) approach has been developed jointly by the Centre for International Climate and Environmental Research, Oslo (CICERO) and The Netherlands Energy Research Foundation (ECN) (Jansen, 2001a, b; Sijm et al, 2001). The approach is relevant to the present study for its sectoral aspect, and has the following characteristics: (i) identification of

[12] The Ad-hoc Group on the Berlin Mandate (AGBM), which resulted in the Kyoto Protocol and its binding quantified reduction targets for Annex I Parties, negotiated during the first review at COP 1 (Conference of the Parties) in 1995.

[13] There is common acceptance amongst climatologists that a 550ppmv atmospheric carbon dioxide concentration is closer to 450ppmv when the basket of 6 greenhouse gases as well as biogeochemical feedbacks in the carbon cycle are included (Exeter, 2005).

sectoral targets; (ii) eventual convergence to emissions levels of global per-capita equity; (iii) assignment of targets to non-Annex 1 countries upon reaching a per-capita GHG emission threshold; (iv) issuing of additional emissions allowances under special circumstances (Sijm et al: 483). It should be noted that the MSC approach as developed by Sijm et al (ibid) uses units of carbon dioxide equivalent, as it includes CH_4 and N_2O emissions. Amongst other possible benefits, the authors argue that use of sectoral divisions may improve insight into the feasibility of global GHG reduction targets, and that use of interim budget periods allows adjustment as economic conditions and scientific knowledge change (ibid: 496).

The MSC approach involves the following stages:
1) The distinction of seven different sectors
2) The determination of global sector emission norms
3) The determination of national emission mitigation targets
4) The inclusion of allowance factors (ibid: 486).

The seven sectors of the MSC approach are: power, households, transportation, industry, services, agriculture and waste. For each sector, per-capita emission allocations ('standards') are set; for the base year of 2010, these are set equal to the global average for each sector. An annual percentage emissions reduction is then set for each sector, by geometric interpolation, until a convergence year. The national target for a given year is determined by summing the per-capita sectoral targets for that year and multiplying by the projected population for that year. Countries take on emissions reduction commitments upon reaching per-capita emissions thresholds. Emissions allowance factors are available, to be applied nationally, to mitigate the effects of emissions control on countries with special needs arising from climate, population density, agricultural and transitional economies and a low potential for use of renewable fuels (Sijm et al: ibid). Sijm et al (ibid) provide numerical illustrations of this approach, in part using an MSC model that can be downloaded from the ECN website[14].

4.2.3 FAIR assessment of Contraction and Convergence policy

Berk and den Elzen (2001) have used the FAIR model (Framework to Assess International Regimes for the differentiation of commitments) (Elzen et al, 2000) to compare alternative regimes of increasing participation. The FAIR model consists of a simple integrated climate model combined with an accounting framework for calculating regional emission allowances resulting from different allocation rules (ibid). The first option assessed was a gradual increase in both the number of Parties involved and their level of emissions reduction. The second option was a contraction and convergence regime with universal participation. Berk and den Elzen (2001) found that, in order to stabilize carbon dioxide concentrations at 450ppmv by 2100, the major industrialising countries must participate in emissions reduction before 2050. If stringent climate targets are set, a convergence regime seemed to provide more incentive for controlling emissions than a regime where nations are gradually incorporated.

As a threshold for a country participating in carbon emissions reductions of 4% per year, Berk and den Elzen (2001) used a per-capita income value of 50% of the 1990 average Annex 1 per-capita income, similar to that of Argentina. Upon reaching 75% of the 1990 average, countries are assumed to join Annex 1 – those countries who have agreed emissions caps – with reduction targets proportional to their per-capita contribution to carbon dioxide-induced temperature rises.[15] As a result, the global emissions ceiling required for 450ppmv is breached after 2020 due to the major developing countries such as China and India participating only after 2050. If the target were 550ppmv, an emission space for Annex 1 would exist but be extremely limited. The corollary is that a 450ppmv target requires major developing countries to participate within a few decades from now, at much lower levels of per-capita income than the 1990 Annex B average (ibid: 473). Berk and den Elzen (ibid: 474) go on to show that 450ppmv is attainable if *per-capita* carbon dioxide emissions are used as a means of differentiating commitments. Under this scenario, Annex

[14] At www.climatepolicy.info/kyoto/burden/

[15] Note that as such, the targets do not take into account climate feedbacks from the carbon cycle and other effects

1 countries would begin with emissions permits well below the global average, China would be permitted an increase from today's levels until 2025, India until 2030 and Africa until 2040.

Berk and den Elzen (ibid: 476) then test a contraction and convergence approach for 450ppmv, with convergence years of 2030 and 2050. The emissions reductions necessary for convergence by 2030, relative to 1990, are relatively high for the time available: 75% for North America and 60% for Europe. For 2050 the reductions are a more plausible 55%, 55% and 40% respectively.

Given these findings, Berk and den Elzen (ibid: 478) consider that a contraction and convergence approach has two main advantages over an increasing participation approach (or *Continuing Kyoto* approach, in terms used by Höhne et al, [2003]). The first concerns the way in which emissions trading, an important component of contraction and convergence, is considered to offer the best opportunity for exploring the cost-reduction potential of the Kyoto Mechanisms. The second is that there would be no 'carbon leakage' (increase in developing country emissions due to business relocations from the developed countries). However, Berk and den Elzen (ibid: 478) also perceive potential problems with emissions trading: once developing countries join the system, prior beneficiaries such as Russia would find a reduced market for their surplus emissions (this could be a general problem with any strongly contractive scenario and is discussed further below). In addition, the concept of per-capita emissions equity has to date been controversial (ibid), despite economic analysis indicating welfare losses of only a few percent by 2050 compared with business as usual (Böhringer and Welsch, 2000, in Berk and den Elzen, ibid)[16].

4.2.4 UBA assessment

As stated above, Höhne et al (2003) have conducted a relatively detailed assessment of the main policy options for international climate negotiations during the next commitment period, for the German Federal Environment Agency (UBA). The following assessment was made of contraction and convergence by Höhne et al (ibid: 62-3) in terms of (italicised) criteria applied to each option.

Environmental criteria
In an illustrative case that would include all countries from 2010, levels of 450 - 550ppmv atmospheric carbon dioxide concentration could be reached by 2100. While there would be certainty over the level of emissions permitted, the approach would imply abrupt changes in the emission trend of many Parties, including major developing countries. Leakage would be avoided since all countries would participate.

Encouragement of early action
Contraction and convergence is one of the few policy approaches that encourages early action (i.e. before 2010), as all countries would know that they must reach equal per-capita emission levels.

Political criteria
With respect to *equity principles*, while the least developed countries would be permitted to increase emissions, most developing countries and all developed countries would be completely emissions-restricted from 2010. The principle of *capability* (ability to pay) is not explicitly addressed. The principle of *responsibility* (polluter pays) is partly addressed, in the sense that the higher emission countries would need to make the largest reductions. The *historic responsibility* of countries is, however, not taken into account. A newly industrialized country with currently high per-capita emissions (e.g. South Korea) would have to reduce emissions by the same degree as an industrialized country with a similar level of per-capita emissions (e.g. France).

Regarding the *fundamental positions of the major political constituencies*, an advantage of contraction and convergence is that most developing countries have clearly indicated their preference for the convergence of per-capita emissions. The G77 and China succeeded in

[16] Similarly the UK Cabinet Office estimates that only 0.02% of annual GDP growth would be foregone over each of the next 50 years if a 60% reduction in carbon dioxide emissions was pursued and achieved by the end of that period (PIU, 2002, in Houghton, 2002).

embedding related language in the Marrakech Accords in the context of the use of the mechanisms: “reducing emissions in a manner conducive to narrowing per-capita differences between developed and developing country Parties”. However, some developed countries are strictly opposed to the concept of per-capita emissions, and the reporting of emissions in per-capita terms in national communications was consequently excluded from UNFCCC reporting requirements.

Economic criteria
Contraction and convergence takes little direct account of the *structural differences between countries*, differentiating only to the extent that high emission countries will need to make the highest emissions reductions. The international emissions trading component of the approach should help to *minimise adverse economic effects* by narrowing the differences in marginal abatement costs in different countries by encouraging emission reductions where they can be obtained for the lowest price.

Technical criteria
*Regarding compatibility with the structure of the UNFCCC and Kyoto Protocol***,** scenarios with targets for convergent per-capita emissions could be based on the structure agreed in the Kyoto Protocol, with all countries participating. In terms of placing *moderate political and technical [demands on] the negotiation process*, Höhne et al (ibid: 43-4) consider contraction and convergence as simple, transparent and easily explained. International agreement would be required on only a few factors: the convergence year and level (through a global stabilisation path), and a decision on which gases and sectors to include. “This low number of decisions would make it relatively easy to reach an agreement from a purely process point of view. The current system of reporting and reviewing GHG inventories would have to be expanded to all countries” (ibid).

Höhne et al (ibid: 44) conclude that while contraction and convergence “is intriguing due to the simplicity of the approach” and is “one of the few approaches that encourage early action by countries that are not yet part of the commitment regime”, its simplicity is also a major disadvantage, in that it does not account for the structural differences between countries that affects their ability to decrease emissions. Moreover, for stabilisation levels of 450 or 550ppmv carbon dioxide , many developing countries would have to decrease emissions below their business as usual path during the coming decades. Consequently, only a few, least developed countries would be able to sell emission allowances to the developed countries, and then only for a short period of time.

4.3 Conclusions

Contraction and convergence is one of several options for a post-Kyoto climate regime. While it has the advantages of simplicity, an element of international equity and would include all countries, it does not in itself allow for structural differences between countries. Nevertheless, it could form a starting point for international negotiations on a post-Kyoto regime. It also enables the national, aggregate implications of the deep cuts required for carbon dioxide emissions stabilisation to be profiled and compared to emissions trends in sub-sectors.

5. The potential for reducing aircraft emissions up to 2050

Minimising the environmental impact of the aviation industry, be it in terms of local noise pollution or climate change impacts is a concern to many within and outside of the aviation industry. Many studies, research programmes and scenarios therefore directly concern prospective aviation fuels, fuel efficiency, improving air traffic management and policy instruments that curb demand. Within this section of the report, a brief summary of the key areas where there is potential for reducing emissions are discussed.

Advances within the aviation industry aimed at having an impact on the aircraft's fuel efficiency or to reduce atmospheric pollutants come in a variety of forms. For example, modifications to the fuel source are likely to require changes to the engine design of an aircraft, the airframe design, or indeed the infrastructure for refuelling. On the other hand, improving the fuel efficiency of aircraft may be done through a more aerodynamic design, engine updates or improvements to the air traffic management system. In the following section the main technological and managerial advances envisaged in the short, medium and long-term are highlighted.

5.1 Alternative aviation fuels

5.1.1 Biodiesel

Biodiesel as an aviation fuel would be what is known as a kerosene extender. In other words, biodiesel would be mixed with mineral kerosene to produce a new, lower carbon emitting fuel. A maximum of 10-20 % of biodiesel could be used in aviation fuel, but only in such proportions as biodiesel alters the crystallisation properties of the aviation fuel at low temperatures. Current research efforts can use filtering techniques to remove such crystals in the mixture contains up to 10% biodiesel, so that the fuel continues to meet safety requirements. However, further research will be required for mixtures containing more than 10% biodiesel. Advantages of biodiesel over conventional kerosene include its lower polluting emissions, its biodegradable nature and its relatively simple production from all major biocrop feedstocks. However, mixing mineral kerosene with biodiesel compromises kerosene's ability to perform at cold temperatures, such as those experienced at altitude, even when mixed with a small proportion of biodiesel (Saynor, 2003). Further research is therefore required to improve and build confidence in cold weather performance. Moreover, adding any such material to jet fuel would not be allowed under any current fuel specifications because of compositional considerations (IPCC, 1999).

5.1.2 Fischer-Tropsch Kerosene

As an alternative to biodiesel, kerosene can be manufactured synthetically by Fischer-Tropsch or other fuel production processes from a wide variety of carboniferous feedstocks including caol with carbon capture and biomass, with the advantage of providing fuel-cycle carbon dioxide benefits compared with mineral kerosene, and eliminating oxide of sulphur. Fischer-Tropsch fuels are typically manufactured in a three-step procedure:

- Syngas generation: the feedstock is converted into synthesis gas composed of carbon monoxide and hydrogen.
- Hydrocarbon synthesis: the syngas is catalytically converted into a mixture of liquid hydrocarbons and wax, producing a "synthetic crude".
- Upgradeing: the mixture of Fischer-Tropsch hydrocarbons is upgraded through hydrocracking and isomerization and fractionated into the desired fuels.

This sort of kerosene is chemically and physically similar to mineral kerosene, and therefore broadly compatible with current fuel storage and engines (Saynor, 2003). However, its lack of aromatic molecules and the fact that it is virtually sulphur-free, give it poor lubricity. It also has a lower energy density than mineral kerosene, which would impact on long-haul flights. A few modifications could, on the other hand, improve its lubricity, making it fit for use. This type of kerosene is likely to be a medium-term development within the aviation industry. On a practical note however, the UK could only supply about 10% of the fuel required for its aviation industry (Saynor, 2003).

5.1.3 Hydrogen

Using *hydrogen* to fuel aircraft could be beneficial if derived from the gasification of biomass or electrolysis of water using renewably generated electricity with the potential for reducing the aircraft induced radiative forcing by about 20% if such aircraft were gradually introduced between 2015 and 2050 (Ponater et al., 2003). However, using hydrogen within the aviation industry would require fundamental changes to the jet design. For example, the high energy content, but low density of this gas requires much larger fuel tanks (Saynor, 2003). This would mean that although there would be a weight advantage due to aircraft carrying lighter fuel, this would then be off-set to some degree by the weight of a larger fuel tank. The volume of hydrogen carried would also be some 2.5 times that of the equivalent kerosene. The airframe would therefore need to be larger, and so would have a correspondingly larger drag. The combination of larger drag and lower weight would require flight at higher altitudes. Therefore, if and when hydrogen does come into use as an aviation fuel, it will likely be used in large long-haul, high-altitude aircraft. The requirement to carry a greater fuel volume may present an added difficulty for a hydrogen-fuelled Blended Wing Body aircraft (discussed below), a design otherwise well suited to long-haul flights (RCEP, 2002).

The effects of oxides of nitrogen would still be present when using hydrogen as an aviation fuel, depending on the burn temperature, and the enhanced production of water vapour would likely enhance the contrail effect. Aside from problems of hydrogen storage, transportation and the need for new infrastructure world-wide (IPCC, 1999), hydrogen's main by-product is water vapour – which acts as a greenhouse gas in the upper troposphere. Therefore, the sensitivity to cruising altitude is likely to be very large (Gauss et al., 2004). If, as appears likely, hydrogen fuelled aircraft were to cruise at higher levels, then the increased water emitted into the stratosphere would suggest larger radiative forcing (RCEP, 2002). Since a hydrogen fuelled aircraft produces more water than a kerosene fuelled aircraft, and since the water vapour produced by the latter cruising at 17 - 20 km gives a radiative forcing some 5 times that of a lower flying subsonic aircraft, a hydrogen fuelled supersonic aircraft flying at stratospheric levels would be expected to have a radiative forcing some 13 times larger than for a standard kerosene fuelled subsonic aircraft (RCEP, 2002).

Further research would therefore be required to ensure that any advantage gained in reducing carbon emissions, would not be exacerbated by an increase in global warming due to enhanced water vapour production. Overall, the environmental benefits of using hydrogen rather than kerosene for fuelling aircraft engines are uncertain, and therefore according to the RCEP (2002), hydrogen is likely to be discounted as an aviation fuel for many decades.

5.1.4 Other alternative fuels

Other fuels that have been investigated for the aviation industry that have subsequently been rejected include ethanol and methanol. Their very low heat content, in mass and volume terms render them useless as jet propulsion fuels. Moreover, from a safety standpoint, these alcohols have very low flash points – 12 and 18°C compared with the minimum standard allowed of 38°C (IPCC, 1999; Saynor, 2003). Nuclear powered aircraft are also not currently being considered due to safety concerns over radiation leaks and potential explosions (Saynor, 2003). Finally, bio-methane has been considered as an alternative to kerosene, but it would require similar infrastructure and aircraft design changes to hydrogen, as well as continuing to produce a certain amount of carbon emissions.

5.1.5 Summary

To summarise, although bio-diesel and bio-kerosene could be used in conventional airframe designs and engines, further research is required to make bio-diesel of practical use in cold conditions, and bio-kerosene has large land-use implications. However, bio-kerosene seems to be the most viable option in the medium term. Hydrogen on the other hand is deemed to require too many large-scale changes within the industry in terms of infrastructure and airframe design. It is unlikely that hydrogen will be used to fuel planes therefore for the foreseeable future. Thus, kerosene-type fuels are currently considered to be the only viable option for aircraft within the next 30 years, with some analysts suggesting they will still be in widespread use in 2050 (IPCC, 1999).

When the RCEP conducted a study of the different opportunities for the aviation industry in minimising its impact on climate, they concluded that many of the technically feasible options would likely be used in surface transport in preference to aviation due to cost and easy of implementation (RCEP, 2002). If however, the aviation industry were to use biofuels to reduce the climate change impact of the industry, it is likely that making such fuels unavailable to other modes of transports would have less of a climate impact than allowing the industry to continue to use kerosene. For example, there are a number of options for road transport in terms of hydrogen fuel cells and electricity; whereas it may be the case that bio-kerosene is the only alternative option for the aviation industry. In which case, it would seem unwise not to fully investigate this possibility with continued research.

One general final comment is that many of the alternative fuels mentioned are based on conventional jet engines, whereas alternative engine types, such as the turbo-prop engine, might be able to tolerate a wider range of fuels.

5.2 Airframe and engine design

The design of aircraft can have a big impact on the amount of drag produced and hence on its fuel burn. Novel and innovative aircraft designs have been investigated in the past, for example the blended wing-body (BWB) aircraft and the wing-in-ground effect vehicles (WIGS). However, the latest aircraft being designed and built by Boeing and Airbus, the two largest aircraft manufacturers, continue to use standard airframe designs. Indeed the RCEP (2002) state that aircraft designs up to 2030 are thought likely to be based around conventional airframe configurations, but integrating best practice technology.

5.2.1 Blended wing-body aircraft

In its assessment of the potential for reducing aircraft emissions, the RCEP took special account of a design concept that has considerable potential for a civil airliner, namely the blended wing-body, also known as the 'Flying Wing' (RCEP, 2002). This design has a long history, with precedents in the German Horten aircraft AW-52 and the Northrop YB-49 (Cranfield College of Aeronautics, 1999). The BWB has the body partly or wholly contained within the wing, so that the interior of the wing in the central part of the aircraft becomes a wide passenger cabin (see www.ccoa.aero/themes/airborne/bwb/default.asp for more detail). The Commission has declared itself convinced that the BWB could, as its proponents claim, be significantly lighter and experience very much lower drag than the conventional swept wing-fuselage airframe design. Its fuel usage would therefore be reduced, perhaps by as much as 30%, further reducing aircraft take-off weight. Because of the lower weight and drag, this type of aircraft would have a lower cruise altitude and an extended optimal range (RCEP, 2002).

The Commission regards the BWB concept as a development to be pursued in place of supersonic or near-sonic aircraft, and the concept has been positively explored in the UK by the aviation industry's Greener by Design Steering Group and developed further at Cranfield College of Aeronautics. Other NASA and industry studies suggest that a large commercial BWB aircraft could be developed to carry 800 or more passengers, although studies have also focused on vehicles in the 450-passenger class (NASA, 2002). It is thought that a BWB airliner cruising at high subsonic speeds on flights of up to 7,000 nautical miles would have a wingspan slightly wider than a Boeing 747 and could thus operate from existing airport terminals.

Nevertheless, given the long service lives of aircraft, it would be many decades before BWB aircraft were able to approach their maximum contribution to air travel (RCEP, 2002). It is also likely that the BWB concept will be applicable only to relatively large aircraft, as the embedded passenger cabin must be tall enough to enable passengers to stand up, so implying the need for large wings. The BWB is therefore unlikely to mitigate the impacts of relatively short-distance flights. Moreover, while the Greener by Design team have concluded that a BWB aircraft 50 years hence will likely have only 10% of the greenhouse effect of contemporary high altitude, long range aircraft, the RCEP consider this optimistic and observe that it assumes complete technological and commercial success, the BWB design completely replacing rather than adding to existing aircraft, and reductions in oxides of nitrogen emissions at the high end of the range foreseen by the International Coordinating Council of Aerospace Industries Associations (ICCAIA). These improvements could also only apply to long-haul flights (RCEP, 2002).

RCEP conclude that BWB aircraft could not represent a significant proportion of aircraft movements for many decades, and so would make no significant difference to the total aviation impacts for at least the first half of this century. Two thirds of all the aircraft that will be flying in 2030 are already in use (RCEP, 2002).

5.2.2 Airships

An alternative approach to the problem of reducing the climate impact of aviation is to look at entirely different methods of air transportation. One such suggested form is the airship. Modern airship designs use helium as a much safer alternative to hydrogen, which was used historically in the zeppelin. Helium is heavier and more expensive to produce than hydrogen however and additional lifting power is required on take-off, as 10% lift is lost relative to a hydrogen filled airship.

According to a recent review, (Windischbauer and Richardson, 2005), tasks such as surveillance, airborne early warning (replacing Airborne Warning and Control System aircraft (AWACS)) and long tourist trips are better suited to airships than aeroplanes and helicopters. Small airships, such as the Zeppelin NT, are currently in operation in this capacity, although do not operate economically. On the other hand, larger volume craft are likely to be profitable (Anderson and Wood, 2001).

In relation to the feasibility of airship freighters, despite causing 80-90% less radiative forcing that a conventional jet aircraft, one study concluded that their use was 'un-promising' due primarily to manoeuvrability difficulties in wind during the loading and unloading stages (Anderson and Wood, 2001). Offloading can occur in two ways:

1. The airship hovers where lateral movement (known as drift variation) is less than 1-2% of the vehicle length. Achieving this low level of drift variation is very difficult with such a large surface area against which wind and thermal forces act.
2. The airship descends and is moored to a specially built platform on land or water, although there is still the danger of capsizing in strong side winds

Recently an airship known as the German Cargolifter was designed with the intention of hauling up to 160 tonnes for distances of as far as 10 000 km, but the project failed due to bad financial and engineering management, with large losses despite building one of the world's largest hangars for the construction work, (Windischbauer and Richardson, 2005).

One of the most promising recent designs for a cargo lifter was the Skycat by Airship Technologies Group (UK) (Windischbauer and Richardson, 2005) but again this company has become insolvent as of July 2005 – another set back for the airship's future and illustrating the economic difficulties of making the technology a reality. To date, no successful large cargo lifter has been built, even though reputable firms such as Lockheed have planned projects.

5.2.3 Wing-in-ground effect vehicles (WIGs)

Aerodynamic drag on aircraft can be divided into two categories – that caused by the vortices around the wings (induced drag) and that due to the surface friction. As the distance between the ground and the wing decreases to a length less than an aircraft's wing-span, the ratio of lift to drag increases – this is known as 'ground effect'. For smaller aircraft the increase in surface friction drag due to the denser air at lower altitudes is of roughly equal magnitude to the decrease in induced drag and so any fuel benefit is lost. For large vehicles however, such as the proposed Boeing Pelican a much larger payload can be transported for a given range than for flight at conventional altitudes, or inversely, a given payload can be transported further with equivalent fuel.

The proposed Pelican aircraft would have a wing-span of 150m, will fly as low as 6m above sea level and carry a load of 750 tonnes of cargo for 18 500 km when in 'ground effect' above the sea. At more standard altitude levels, this range for the same fuel burn would be reduced to 12 000km. Whether such a large, heavy aircraft could operate from conventional runways is not certain however. Furthermore, its maximum speed would be lower at low altitude due to air density; therefore the aircraft would take longer to reach their destinations. This might be more appealing for the aviation freight industry than for its passenger industry. There could be a problem with the certification of trans-oceanic flight at low altitude as it would not fit into any current regulation. From the noise point of view, the Pelican has a significant disadvantage over conventional aircraft. Its proposed ~70 separate undercarriages would create much more noise on take-off and landing than its conventional equivalent.

5.2.4 Engine technology

Regarding technological trends, IPCC (1999) state that the most fuel-efficient engines for today's aircraft are high bypass, high-pressure ratio gas turbine engines, for which "no known alternatives are in sight". These engines have high combustion pressures and temperatures and although these features are consistent with fuel efficiency, they increase oxides of nitrogen (NO_x) formation rates – especially at high power take-off and at altitude cruise conditions.

5.3 Management developments

The aviation industry has always had a strong drive towards improving fuel efficiency as fuel costs are a high proportion of the industry's overall costs – particularly for the low-cost genre of airlines. However, as mentioned in the previous section, current aircraft use the same engines and airframe design that have been used since the 1970s. For this reason, although the technology has improved year-on-year, such designs are considered to be mature in terms of their technology, and therefore see only small incremental improvements in fuel efficiency, typically around 1-2% per year for a new aircraft. The aviation industry recognises this fact, and consequently their drive towards improving fuel efficiency in addition encompasses many managerial aspects, as will be discussed in this section.

5.3.1 Load factors

Increasing the load factor of an aircraft will reduce the amount of fuel spent per passenger, and reduce the need for as many planes to fly, if the same amount of demand is being accommodated for. Consequently, airlines are always looking at ways to push up their load-factors, although some airframe manufacturers on the other hand are less concerned with this aspect of improving fuel efficiency. However, if their customers consider it to be a priority, this might persuade them otherwise. Scheduled airlines struggle more than charter airlines to increase their load-factors, but putting more effort and research into generating sophisticated ticketing technology, differing pricing bands and demand-focussed time-tabling may all lead to load-factor improvements.

5.3.2 Air traffic management

Aircraft burn a substantial proportion of their fuel during take-off and landing, which is why an indirect flight from Manchester to London, London to Madrid, has a much larger environmental footprint than a direct flight between Manchester and Madrid. Therefore an increase in point-to-point flying rather than the commonly used hub-to-hub flights could reduce fuel consumption. Furthermore, to date aircraft have had to fly along a fixed route network when journeying from start to destination airports. This route network is an historic part of the infrastructure, resulting from the days when following a set of ground beacons was the only reliable source of navigation for aircraft. However, with the advent of global positioning satellites (GPS), and modern flight management systems on-board airliners, it is now possible to derive a set of way points which are not necessarily linked to physical locations on the ground. These new technologies enable the introduction of new concepts of operation, such as 'direct routing' whereby the aircraft determines an optimal flight path from the start to the destination airports without reference to fixed points on the ground (AD Little, 2000). Such improvements could translate directly into reductions in fuel consumption and hence a reduced global environmental impact. However, it should be borne in mind that there is also likely to be a trade-off between point-to-point flying and increasing load-factors, as it is likely that a plane that passes through a hub, will be doing so to further fill up the aircraft. This trade-off has not been explored within this work.

Air traffic operations procedures such as alternative approach and departure procedures, for example the Advanced Continuous Descent Approaches (ACDA) also offer improved fuel consumption, reduced emissions and reduced overall approach time (AD Little, 2000). Fuel savings can also be achieved through the operational optimisation of aircraft operations. These include reducing the operational weight of the aircraft, improved taxiing and optimising the aircraft speed. Whilst economic pressures on the industry have dictated that many of these factors have already been optimised by operators, the IPCC (IPCC, 1999) estimate that further optimisation of such measures can result in fuel savings of between 2-6% per trip.

5.4 Fuel efficiency and targets

The aviation industry has itself set research goals for improving fuel efficiency as laid out by the Advisory Council for Aeronautical Research in Europe (ACARE). The targets relevant to climate change are as follows:

1) To reduce fuel consumption and CO_2 emissions by 50%
2) To reduce perceived external noise by 50%
3) To reduce oxides of nitrogen by 80%
4) To make substantial progress in reducing the environmental impact of the manufacture, maintenance and disposal of aircraft and related products.

At first site, targets 2) and 3) appear to be irrelevant for climate change. However, reducing the noise impact of an aircraft will normally require some additional equipment to be added to the engine. Such additionally weight will necessarily translate into an increase in the fuel consumption. There are similar trade-offs to be made to reduce NO_x emissions, hence both targets are indirectly related to the climate change issue.

In relation to the ACARE targets laid out above, the UK's aviation industry has come together to produce a document entitled, 'A strategy towards sustainable development of UK aviation', otherwise known as Sustainable Aviation (Aviation, 2005). Within this document they review these ACARE targets and conclude that the first three ACARE goals could be interpreted as applying to aircraft entering service in 2020, using then current operating procedures, relative to new aircraft entering service using current operating procedures in 2000. Progress towards these targets would include contributions from operational improvements, including those in air traffic management. Therefore, the targets that have been adopted by the UK's aviation industry are laid out in Commitment 10 within the Sustainable Aviation document and are as follows:

1) Improve fuel efficiency by 50% per seat kilometre including up to 10% from air traffic management system efficiencies.
2) Reduce NO_x emissions by 80%

3) By 2020 based on new aircraft of 2020 relative to equivalent new aircraft in 2000

Consequently, each year, a new plane would be 2% more efficient than a new plane in the previous year. Historically there have been significant improvements in fuel efficiency – 70% in the past 40 years through improvements in airframe design, engine technology and rising load factors. More than half of this has come from advances in engine technology (IPCC, 1999). Such improvements give an annual compound fuel efficiency gain of 1.14% in terms of seat-km per kg of fuel consumed. Continued improvements are expected to continue, with airframe improvements likely to play a larger role through improvements in aerodynamic efficiency, new materials and advance in control and handling systems. New, larger aircraft with, for example, a blended-wing body or double-deck cabin offer prospects of further benefits by relaxing some of the design constraints attached to today's large conventional aircraft. But, with the very long total lifetimes of today's aircraft (up to 40 years), replacement rates are low, and the fuel efficiency of the whole fleet is likely to improve slowly; considering that there is limited fleet renewal, and that the efficiency improvements over the previous 20 years have been around 1-2% per year, which would in turn lead to around a 1-2% improvement in efficiency per year for the total fleet. Although AD Little conclude that fuel efficiency improvements to new planes of 2% per annum could in principle be obtained until 2030, the Department for Transport (DfT) are more conservative in their central case emissions forecast (DfT, 2004).

The development of new technologies for improved aerodynamics, materials, engine efficiencies and combustors can reduce global emissions, oxides of nitrogen and noise. In addition, developments in improved air traffic management and operational procedures additionally offer global and local mitigation options. In combination, such future developments could offer fuel efficiency improvements of up to 2% per year until 2030, whilst NO_x reduction technology is forecast to deliver 80% improvements from today's landing and take-off emissions by 2030 (IPCC, 1999). Despite the fact that there are significant opportunities for reducing emissions and other environmental impacts, the RCEP (RCEP, 2002) and the results of this project conclude that their effect is likely to be outstripped by the projected increases in air transport. For emissions from the aviation industry to reduce in real terms, the proposed efficiency gains would have to outstrip growth. With passenger numbers increasing for the UK's aviation industry at 8% between 2003 and 2004 (CAA, 2004), this currently seems highly unlikely.

6. Investigation of the Implications of C & C for European Civil Aviation

6.1 Immediate policy context and debate

The climate change implications of the projected on-going growth in global aviation emissions over the next 50 years are becoming increasingly controversial. This is particularly so in the UK, an island state with both a major international aviation hub in the form of Heathrow airport, and a governmental commitment to reducing carbon dioxide emissions by some 60% by 2050. Add to this ministerial prioritisation of climate change for both the EU and G8 presidencies in 2005[17], an Air Transport White Paper with the stated aim of including intra-EU flight emissions in the second phase of the European Emissions Trading System (i.e. from 2008), and entry into force of the Kyoto Protocol in February 2005, and it is not perhaps surprising that the climate impact of aviation emissions is an increasing focus of attention.

Through 2003-4, the UK House of Commons Environmental Audit Committee vigorously debated projected aviation growth and its impacts with the DfT. The Committee's concern about the impact of aviation emissions on the UK's long term carbon dioxide reduction target was echoed by the House of Lords EU sub-committee on environment and agriculture in November 2004 (House of Lords, 2004), who recommended incorporating the full climatic forcing effects of intra-EU aviation emissions into the European Emission trading Scheme at the earliest possible opportunity.

The UK House of Commons Environmental Audit Committee (2004a, summary point 7, p.7) have questioned whether an EU or international emissions trading system can accommodate global projected aviation growth while "delivering carbon reductions of the order needed" and questioned DfT as to whether and what modelling had been undertaken on this matter. DfT replied that they had not modelled this for the EU emissions trading scheme but would need to.[18] More significant, perhaps, was DfT's response to Q.343 on what modelling had been undertaken: DfT makes it clear that in its view the 60% target relates to 'domestic' emissions only and that if the UK was to be held responsible for its international aviation emissions on the basis, for example, of a 50:50 split between origin and destination countries, then the 60% target would need to be re-examined. Table 7, appended, summarises related estimates of 2030 UK aircraft emissions.

Clearly, aviation emissions are increasingly a high-stakes issue, raising serious technical and policy concerns. For example, the need to properly represent high altitude effects alongside ground level greenhouse gas emissions in an emissions trading system (e.g. Lee and Sausen, 2000; Cames et al, 2004), leading to debates centring on scientific uncertainties, location- and region-specific effects and the need to avoid perverse signals to manufacturers and airlines[19]. More than any other industry sector, aviation emissions threaten the integrity of the world stabilising carbon emissions at a level that avoids dangerous climate change. The UK government response to this challenge will likely influence the reaction of other European states. As Europe's position is in turn important in terms of international progress on a post-Kyoto agreement, modelling the implications of aviation growth under conditions of an international 550ppmv, 450ppmv or other stabilisation commitment is becoming an increasingly pressing issue. This study is an early step in that process.

6.2 Assessment of the GCI Contraction and Convergence model

Contraction and convergence is an international framework for sharing the arrest of global greenhouse gas emissions. In this framework, to reduce emissions, the world's nations would negotiate to set and achieve an overall, contracting, annual emissions target. Furthermore, nations

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[17] See: www.number10.gov.uk/output/page6260.asp

[18] Mr. G. Pendlebury's response to Q.349, uncorrected transcript of oral evidence to be published as HC 233-iv.

[19] For example, applying a multiplier to carbon dioxide to represent radiative forcing, without a flanking instrument such as a tighter NO_x standard for aero-engines, could lead manufacturers to raise engine efficiency at the expense of higher NO_x emissions, so increasing the formation of ozone, a greenhouse gas. On location specificity: contrails form in a vertically narrow zone of the atmosphere and under particular conditions; regionally, ozone formation varies by latitude in response to temperature and ambient pollution.

converge towards equal per-capita emissions by a certain year – e.g. 2050 – that enables a climate stabilisation target to be met, as informed by climate change models. By simultaneously contracting and converging, such a policy requires all nations to impose targets from the outset (Cameron, 2003). Although it can be argued that some countries should be permitted to emit more than others for reasons such as a cold environment or extended transport network across a large land mass, proponents of contraction and convergence tend to consider that if many allowances are made for such differences, this will interminably delay climate negotiations. As stabilising the carbon dioxide concentration at 450-550[20]ppmv demands a reduction strategy that is initiated as a matter of urgency, proponents of contraction and convergence consider that the simplicity of the idea gives it an important practical appeal.

To support the contraction and convergence regime, the Global Commons Institute have produced a spreadsheet model – *CCOptions* – to facilitate the investigation of varying the contraction year, the convergence year and the target carbon dioxide stabilisation level. The strengths and weaknesses of the *CCOptions* model are summarised below (Bows & Anderson, 2005).

6.2.1 Suitability of the CCOptions model for the present study

The assumptions and calculations of *CCOptions* are visible within an Excel worksheet, enabling the user to make modifications to the model and offering a reasonable degree of flexibility. However, whilst data used within the model is taken from a reliable source, (the carbon dioxide Information Analysis Centre - CDIAC), it is currently based on year 1999 figures. Provision of carbon dioxide and population data for 2003 would be advisable.

The user selects the cumulative 110-year carbon emissions value to enable the contraction profile to be calculated. This value is crucial to achieving a desired stabilisation concentration level, and therefore choosing a suitable value has, in the past, required some guidance. In the original version of the model, a range of cumulative 110-year carbon values related to an atmospheric carbon dioxide concentration of between 330 and 750ppmv were provided for the user. The range given was taken from data published in IPCC (1996).

GCI no longer consider that recommended values are appropriate, as their model now includes the addition of a second relationship between the carbon dioxide concentration and carbon emissions, based on Hadley Centre data on climate feedback (Hadley, 2002). The inclusion of this data, which takes into account some additional feedback mechanisms that were previously ignored when calculating appropriate carbon dioxide stabilisation targets, encourages the user to choose their own 110-year cumulative carbon emission value, depending on whether or not they wish to meet the feedback or non-feedback carbon dioxide concentration profile.

According to the Hadley model (Hadley, 2002), the quantity of cumulative carbon dioxide emitted into the atmosphere that is likely to lead to stabilisation at 550ppmv is likely to be nearer to 680 GTC than the 870 to 990 GTC range published in IPCC (1996). The difference between the results is primarily due to the use of a more sophisticated carbon-cycle model to calculate the stabilisation concentration-emission relationship[21]. Within the latest version of the *CCOptions* model, the new relationship between carbon emissions and carbon dioxide concentration established by the Hadley Centre is used to calculate the contracted emissions. The results show that a much lower

[20] Reaching 450 or 550ppmv requires there to be a strict limit on the amount of carbon emissions released over the next 100 years. The long life-time of carbon in the atmosphere mean that any action taken today, will need to continue for at least 100 years.

[21] The atmospheric concentration of carbon dioxide depends not only on the quantity of carbon dioxide emitted into the atmosphere (natural and anthropogenic), but also on changes in land use and the strength of carbon sinks, such as the ocean and biosphere. As the atmospheric concentration of CO2 increases (at least within reasonable bounds), so there is a net increase in the take-up of CO2 from the atmosphere by vegetation (carbon fertilisation). Changes in temperature and rainfall induced by increased CO2 affect the absorptive capacity of natural sinks. Climate change alters the geographical distribution of vegetation and hence its ability to store carbon dioxide. Changes in ocean circulation and mixing brought on by climate change also alter its ability to take up CO2 from the atmosphere and a warmer ocean absorbs less carbon dioxide. To incorporate all of these feedbacks, the Hadley Centre used a simple climate carbon-cycle model which includes the feedbacks from vegetation, soils and the ocean (Cox, 2002).

cumulative carbon dioxide amount can be released into the atmosphere if a stabilisation level of 550ppmv is to be achieved and if the feedback carbon dioxide profile is the target.

In this new version of *CCOptions*, the emphasis has been moved from ensuring that the user inputs a recommended 110-year cumulative carbon value as suggested by the IPCC, and instead focuses on the concentration curves, encouraging the user to find suitable cumulative carbon values, depending on the stabilisation level required. The difference between the 110-year cumulative emissions required within the new version of the model for a non-feedback carbon dioxide concentration profile, and one that incorporates the feedbacks is as much as 460GTC for a stabilisation level of 550*ppmv*. This has a significant effect on any calculations carried out using *CCOptions* regarding the percentage cuts that individual nations may have to meet if they are to achieve a given stabilisation level.

It should be noted that in all cases, the actual relationship between carbon dioxide concentrations and emissions is far more complicated than suggested in the *CCOptions* model, which reproduces these relationships using simple regression formulae. The *CCOptions* model is attempting to reproduce model data that incorporates many more variables than are available within its own structure. Equations within *CCOptions* are simply good estimates of the sophisticated climate model data, and only suitable for indicating the level of stabilisation required for particular emission paths.

The *CCOptions* model is further limited by its exclusion of any of the other greenhouse gases, as well as neglect of the effects of aircraft releasing emissions at altitude. While a simple ‘uplift factor’ can be applied to carbon dioxide values to approximate the effects of other gases and particles for aviation, it needs to be remembered that some ground level emissions will have additional warming effects at both low and high levels in the atmosphere. In other words, a wholly commensurate comparison of the effects of all greenhouse gases cannot be achieved with *CCOptions*. Other simplifications in the model include the treatment of deforestation and bunker fuels which are both assumed to be world overheads; currently no data on bunker fuels is provided.

In short, *CCOptions* is a simple and useful tool for policy studies, providing its nature is properly understood. It uses a familiar software package (Microsoft Excel) and its results are presented in a plain and relatively unambiguous manner, allowing the user to make a quick evaluation of their experiment without involved data manipulation. Experiments are easily set up and modified and the model predicts sensible emissions profiles for different nations between today and 2200 based on the contraction and convergence regime. The model generally avoids making over complicated assumptions, but rather attempts to show the most basic apportionment of emissions between nations, with the intention of minimising the need for detailed, lengthy and potentially fruitless debates on carbon emission targets. A more detailed account of the *CCOptions* model can be found in Bows & Anderson (2004).

Based on this assessment of the *CCOptions* model, the decision was taken to use the older version of the model for the project experiments. This decision was essentially based on two key drivers. Firstly, although *CCOptions* adequately reproduces widely accepted Hadley Centre model relationships between carbon dioxide concentrations and cumulative carbon values for all nations between today and 2200, releasing the latest version was perhaps premature as it attempts to reproduce Hadley Centre results that incorporate biogeochemical feedbacks from the carbon-cycle whilst the magnitude of such feedbacks remains uncertain. Arguably, the latest *CCOptions* model, in attempting to capture elements of the climate change science still characterised by considerable uncertainty, jeopardises its credibility as a relatively objective policy tool. Secondly, updates to the model render it different from that used to calculate the UK Government’s 60% carbon reduction target.

6.2.2 Experimenting with *CCOptions*

Having established the suitability of the model for the present study, the second research phase produced a series of model runs, with differing carbon dioxide stabilisation targets, to apportion global carbon emissions between nations. One of these model runs replicated the RCEP's (RCEP, 2000), and subsequently the Energy White Paper's claim that the UK would have to cut its emissions by 60% by 2050 to stabilise carbon dioxide concentrations at 550ppmv. The 60% target was essentially derived from an early version of *CCOptions* with the relationship between the carbon dioxide concentration and global carbon emissions based on the Met. Office's 2D modelling data, incorporating only basic carbon-cycle feedbacks.

6.3 Indicative scenarios for European aviation emissions to 2050

6.3.1 Method

The availability of detailed public domain data relating to the growth in carbon emissions from the aviation industry is limited, particularly for nations other than the UK. Moreover, detailed aviation emissions modelling requires access to not only to a range of data, but also to aero-engine and route models. The present study uses a methodology for forecasting emissions that is simple, transparent and based on publicly available information. The objective is to highlight the likely scale of the problems to be faced if demand is not explicitly constrained through either a moratorium on additional airport infrastructure or further demand management measures (for example, through a fuel or emissions charge). A closed EU ETS is assumed, ie one where sectors can only trade with other sectors under the EU ETS umbrella, to demonstrate the implications of current European growth trends and hence any requirement for policy responses.

Given the requirement of this project to construct a carbon emissions scenario from relatively simple public domain information, three options exist. The first option is to base emission scenarios on forecasts of future air traffic movement numbers, or to extrapolate on the basis of current flight growth figures. EUROCONTROL's *Air Traffic Statistics (EUROCONTROL Air Traffic Statistics and Forecasts Service (STATFOR), Forecast of Annual Number of IFR Flights (2003-2010)* provides air traffic growth estimates up to 2010 for International Flight Rules (IFR) flights (EUROCONTROL, 2004a). [22] Although this dataset has figures for all the EU nations, it was not used for this project for the following reasons: 1) the scenarios are only up until 2010, 40 years short of this project's timeframe, and 2) the dataset makes assumptions that are not explicit regarding, for example, engine efficiency, airframe design, load factors, flight distances and different fleet mixes.

In terms of the second option, carbon emissions data from the aviation industry for each EU nation is available from the United Nations Framework Convention on Climate Change (UNFCCC)[23]. For each nation, the data are split into civil aviation and international bunker fuels for international travel. Bunker fuel data are an approximation to each nation's international aviation emissions split 50:50 between arrival and departure. If a projected or historical growth figure for aviation fuel use in each EU nation for aircraft carbon emissions were available, then this could be applied to the UNFCCC data to project emissions up to 2050. However, the only figure widely available in terms of fuel burn growth is the 1.7% world average growth figure which appears in the IPCC (1999). Growing all EU emissions at this rate – which naturally includes many nations where growth is much lower than the current European average – would likely underestimate the true impact of the industry in Europe.

The third option of using passenger growth rates is used in this project as it is relatively transparent and relates most clearly to demand and hence to policy options. Although it is aircraft that directly

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[22] In December 2004, mid-way through the present research, STATFOR also produced air traffic growth estimates for 2004-25 (EUROCONTROL, 2004b).

[23] unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/2761.php Tables 1.A(a) sheet 3 and Table 1.C), apart from values for Cyprus and Malta. Some data on Maltese aviation emissions can be found at unfccc.int/parties_and_observers/parties/items/2142.php

emit greenhouse gases, not passengers, passengers are obviously the key driver for aircraft traffic (we have not considered freight at all here, but plan to do so in future work). If demand management proves necessary, then it is passengers who must be directly influenced. Having an indication of future passenger numbers and growth rates is useful in this regard, and passenger numbers are also likely to be more readily comprehensible to the wider public when considering aviation policy options. Moreover, initial use of historical passenger growth rates as a basis for constructing our emissions scenarios reveals the consequences of permitting on-going and relatively unconstrained growth in demand. We have tempered national historical passenger growth rates with a second growth rate for the latter period of the study, representing a mature air market. It is important to note that use of passenger growth rates as a basis for carbon emissions growth requires the assumption that the mean length of flights remains unchanged.

Historical passenger data for the UK is available from the UK Civil Aviation Authority (CAA, 2002), but the CAA do not hold data for the other European nations. However, passenger number data for 2002 for all EU nations is available from Eurostat (Statistics in Focus, Transport 11/2004). For consistency therefore, this dataset was chosen for all the EU nations, including the UK. Comparing the CAA data with the Eurostat data for the UK shows that results are similar but not identical: the discrepancy is likely to be one reason for differences between the values for carbon emissions and passenger numbers found in *The Future of Air Transport* White Paper and the present study.

Historical growth figures for passenger numbers in the old EU nations is also available for 1997 to 2001 and in an older version of the Eurostat data (Eurostat, Statistics in Focus, Transport 1/2000) for 1993 to 1997. For the accession nations, growth data for 1995 to 2000 are also available from Eurostat (*Aviation and Maritime statistics in the Candidate Countries 1995-2000*). Using these sources, a comprehensive dataset for passenger growth can be calculated for 1993-2001 for old EU nations, and 1995 to 2000 for the new nations. Due to the events on 11 September having a temporary but significant impact on the growth figures between 2001 and 2002, the above dataset arguably gives a better basis for estimating future passenger growth than would a dataset that includes 2001-2.

In constructing the 2050 scenario from this passenger dataset, it was decided to limit the period over which current trends should be extrapolated, particularly given the extremely high growth figures of some nations: for example, in Spain passenger numbers are currently increasing at about 12% per year. Given that many of the EU15 nations have what can be considered to be relatively mature aviation industries, and the new EU nations have much younger aviation industries, and hence generally more potential for growth, two distinct time limits were placed on the extrapolation of current trends. Consequently, for the EU15 nations, current trends were continued until 2015. Whilst for the new EU nations, trends were continued until 2025.

Without deliberate policy decisions for curbing the rate of air traffic and passenger growth, there is no reason to assume that the industry will stop growing within the timeframe of our analysis (i.e. to 2050). For the UK, the aviation white paper suggests, by way of its mid-level forecast, that growth in the UK – a country with a relatively mature aviation industry – will average 3.3% per year between today and 2030. This figure is based on a growth of around 3.8% per year in terms of passenger numbers until 2020, then a further growth of 1.8% per year from 2020 to 2030. DfT's high-level forecast shows average growth of 4% per year up to 2030 – 4.5% between 2000 and 2020, and around 2.7% from 2020 to 2030. Historically, Figure A4 of the Civil Aviation Authority's supporting document for the aviation white paper (CAA, 2003) indicates that growth in passenger numbers at UK airports has been around 5.8% from 1973 to 2003, substantially higher than DfT's future projections. Moreover, the Eurostat dataset suggests that the current rate of growth in the UK is actually 6.4%, based on the trend between 1993 and 2001 (eliminating the short-term effects following the events of 11 September), again, significantly larger than the 3-4% assumption used in the white paper. Incidentally, road transport is currently growing at around 2.5% per year – close to the UK's GDP growth figure.

Given the information available, we have assumed that the aviation sectors of all EU nations will continue to grow after they reach maturity (2015 – EU15, 2025 – New EU). The growth rate for all nations is the same as that assumed for the UK (2000-2030) in the Aviation White Paper. While this specificity would be unlikely in practice, it is not an unreasonable assumption for present purposes, particularly given the global nature of the industry. DfT assumes an average of a 3.3% per year increase in passenger numbers between 2000 and 2030. Considering the current high rates of growth within the industry, around 8% in the UK, this figure appears to assume an overambitious rate of maturity. Further justification for assuming this to be a *conservative* growth rate in the absence of airport capacity constraints is that:

a) the UK has a relatively mature aviation industry, yet contemporary passenger number increases per year are still substantially higher than 3.3%: an on-going annual increase of 3.3% per year is well within the bounds of possibility;
b) all EU nations, other than Latvia and Malta, are currently showing much higher annual rates of change in passenger numbers, and 3.3% represents a significant reduction in growth from current levels;
c) 3.3% is only 0.5% above current levels of GDP annual growth in the UK, and the aviation industry has historically grown at levels well above GDP. A similar study also recently projects UK passenger numbers increasing at 3, 4 and 5% per year up until 2050 (Lim, 2004), with no explicit airport capacity constraint.

Table 1 Comparison of passenger growth for the UK and an exemplar accession nation. Growth figures are compound rates.

Nation	Annual growth1 (up to 2015 for UK, 2025 for PL)	Annual growth2 (from 2015 for UK, 2025 for PL)	2002 (million passengers (mil pax)	2010 (mil pax)	2020 (mil pax)	2030 (mil pax)	2040 (mil pax)	2050 (mil pax)
UK	6.4%	3.3%	168.7	277.2	444.6	615.1	851.1	1,177.5
Poland	11.9%	3.3%	6.5	16.1	49.5	102.2	141.4	195.5

Table 1 provides an example of the implications of this methodology for two exemplar nations - the UK and Poland (an exemplar accession nation). It is worth noting that our 2030 passenger value for the UK is similar to DfT’s 2030 extrapolated (no capacity constraints) forecast of some 600 million passengers, based on DETR’s 2000 air traffic forecast and provided in RASCO consultation documents (e.g. DfT, 2002b, Table 4.1). Figure 1 shows the consequent passenger growth graphically for selected EU nations.

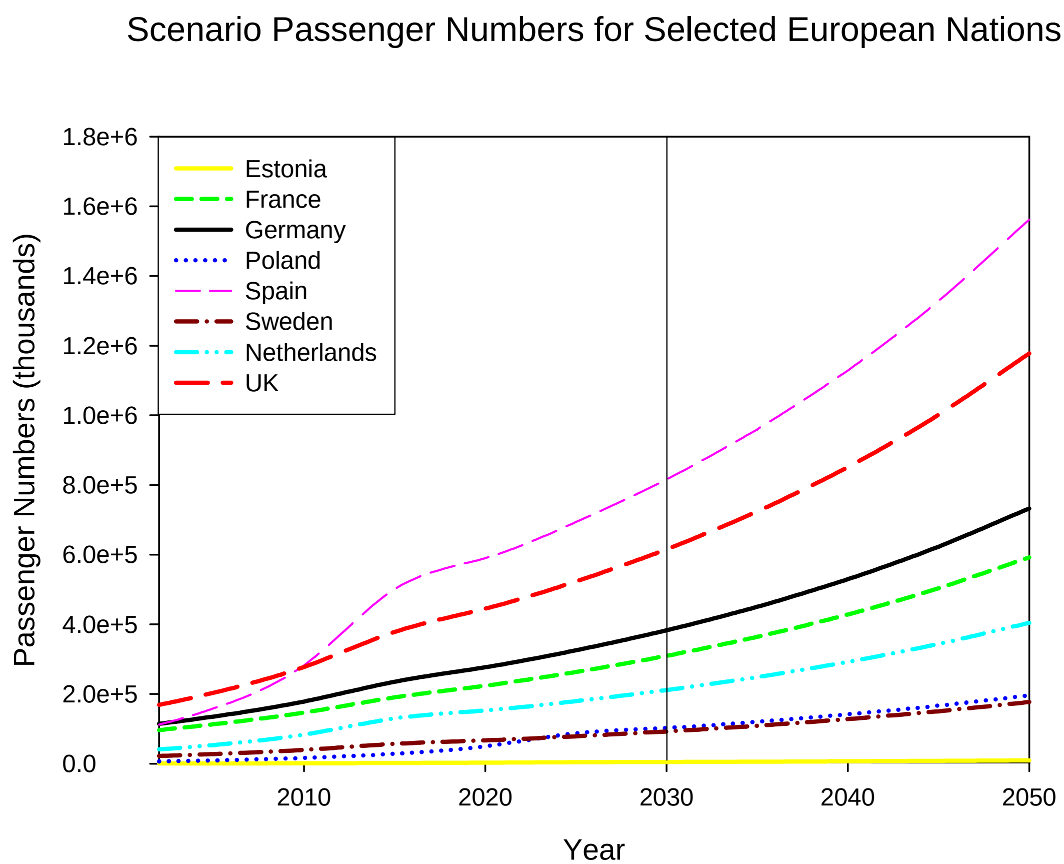

Figure 1: Forecast passenger numbers for selected European nations. The passenger scale is a linear scale in thousands (i.e. 1.0e+6=1 billion passengers).

If it is assumed that the underlying structure of the aviation industry remains unchanged (i.e. routes, load factors, air-traffic management, fleet and engine efficiency) then an increase in passenger numbers would result in a proportional increase in carbon emissions. However, reductions in the amount of carbon emitted per passenger-km are likely to arise from a combination of load factor improvement, aircraft design, aircraft size, air transport management and engine efficiency. The IPCC Special Report on aviation (1999), estimates that a combination of these improvements up to 2050 will be equivalent to a 1.2% decrease in per passenger-kilometre emissions per year. This value is a mean of the efficiency improvements estimated by the IPCC in their seven scenarios. A slightly lower rate, of 1% per year, has been suggested and used by the DfT in the aviation White Paper, but here we have assumed IPCC's 1.2% value.

To estimate the growth in aviation emissions for all EU nations between today and 2050, the 2002 carbon dioxide emission figures from the UNFCCC have been grown by a combination of the percentage increase in passenger numbers and the likely upper bound of an improvement in fuel efficiency etc (i.e. 1.2% pa). So, for example, carbon emissions for the UK are grown at 6.3% minus 1.2% = 5.1% up until 2015, and then at 3.3% minus 1.2% = 2.1% between 2015 and 2050. Similarly Poland's emissions are grown at 11.9% minus 1.2% = 10.7% up until 2025, and then at 3.3% minus 1.2% - 2.1% from 2025 to 2050, as illustrated in Table 1. All annual growth rates refer to compound growth.

6.3.2 Results and Discussion

The carbon emissions, with the inclusion of efficiency and other improvements are plotted in Figure 2 for selected exemplar nations. This figure shows aviation emissions from international and domestic aviation for a selected number of nations in the EU.

Carbon emissions from the aviation industry for selected European nations

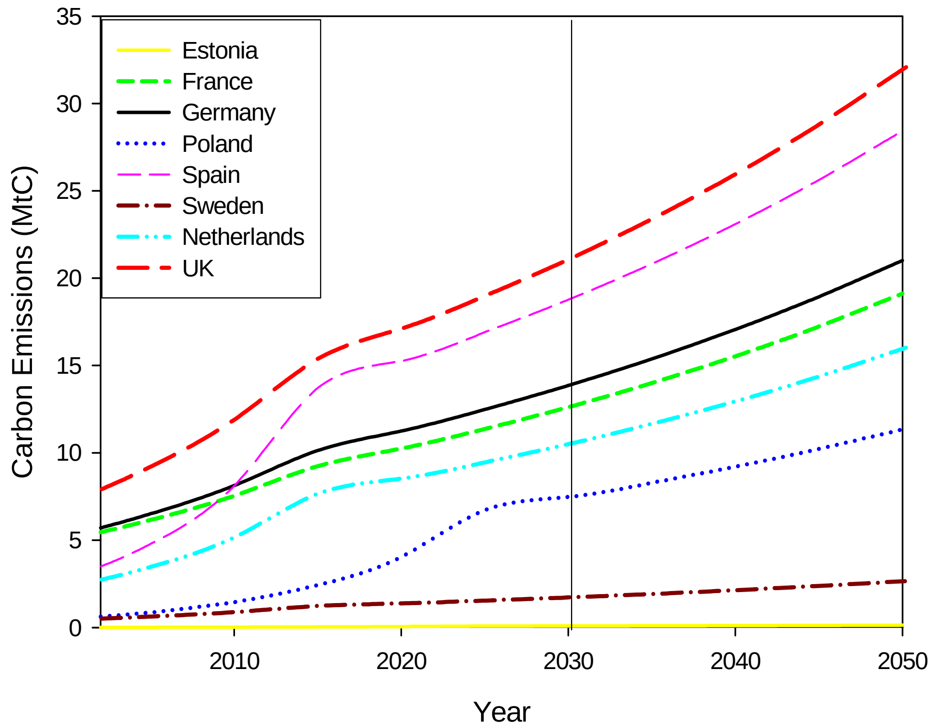

Figure 2: Carbon emissions for the aviation industry for selected European nations. Carbon values are in million tonnes of carbon.

It is notable that although growth in passenger numbers in Spain leads to a higher number of passengers than for the UK, (Figure 1), Figure 2 shows the UK having the largest emissions of all nations. This reflects the fact that, according to the UNFCCC data, aviation emissions in the UK are currently the highest in Europe by some margin. This in turn is likely to reflect a higher proportion of international traffic serviced by the UK, principally by the Heathrow hub. In Figure 2, the kinks in the profiles are due to the step change in growth described as a nation's aviation industry matures. According to Figure 2, UK aviation emissions are 21MtC by 2030 and 32MtC by 2050, assuming no significant changes to aircraft design etc. By comparison, the UK government forecasts that emissions will be around 18MtC by 2030, at which point they start to level out, assuming limited UK airport capacity, particularly in SE England. However, while the aviation white paper only extends to 2030 in terms of its planned infrastructure changes, it cannot be assumed that future UK governments (or those in other EU states) will not commit to further infrastructure provision. For comparison, the Lim (2004) study finds that carbon emissions could be between 15MtC and 40MtC by 2050, depending on the growth rate assumed. Table 2 compares our passenger-based emissions estimates with those produced by DfT (2004) and DUKES (Digest of UK Energy Statistics).

Table 2: Comparison of DfT projections & Tyndall scenarios for aircraft carbon emissions

UK Aviation Emissions Summary Table	**1990 (MtC) (DUKES bunker fuel and kerosene)**	**2000 (MtC) (DUKES bunker fuel and kerosene)**	**2010 (MtC) DfT Projection/Tyndall projection**	**2020 (MtC) DfT Projection/Tyndall projection**	**2030 (MtC) DfT Projection/Tyndall projection**
UK total aviation emissions	5.1	9.69	13 (DfT) 12 (Tyndall)	16 (DfT) 17 (Tyndall)	18 (DfT) 21 (Tyndall)

6.4 Comparison with Contraction and Convergence profiles

Contraction and convergence profiles for the different European nations are calculated using the Global Common's Institute contraction and convergence Model, *CCOptions* version 1 (described in section 6.2 and excluding biogeochemical feedbacks). Whilst a newer version of the *CCOptions* model produces results indicating that emissions will need to reduce by around 75% by 2050 to meet a carbon dioxide stabilisation concentration of 550ppmv, it is the older version of the model that is used for this study to provide consistency with the UK government's target of a 60% reduction in carbon emissions by 2050. While this ensures conservative results in terms of the comparison of contraction and convergence profiles and aviation emissions, it should be borne in mind that the carbon target (i.e. 60%) used in this study is likely to increase if a 550ppmv carbon dioxide concentration is the policy goal.

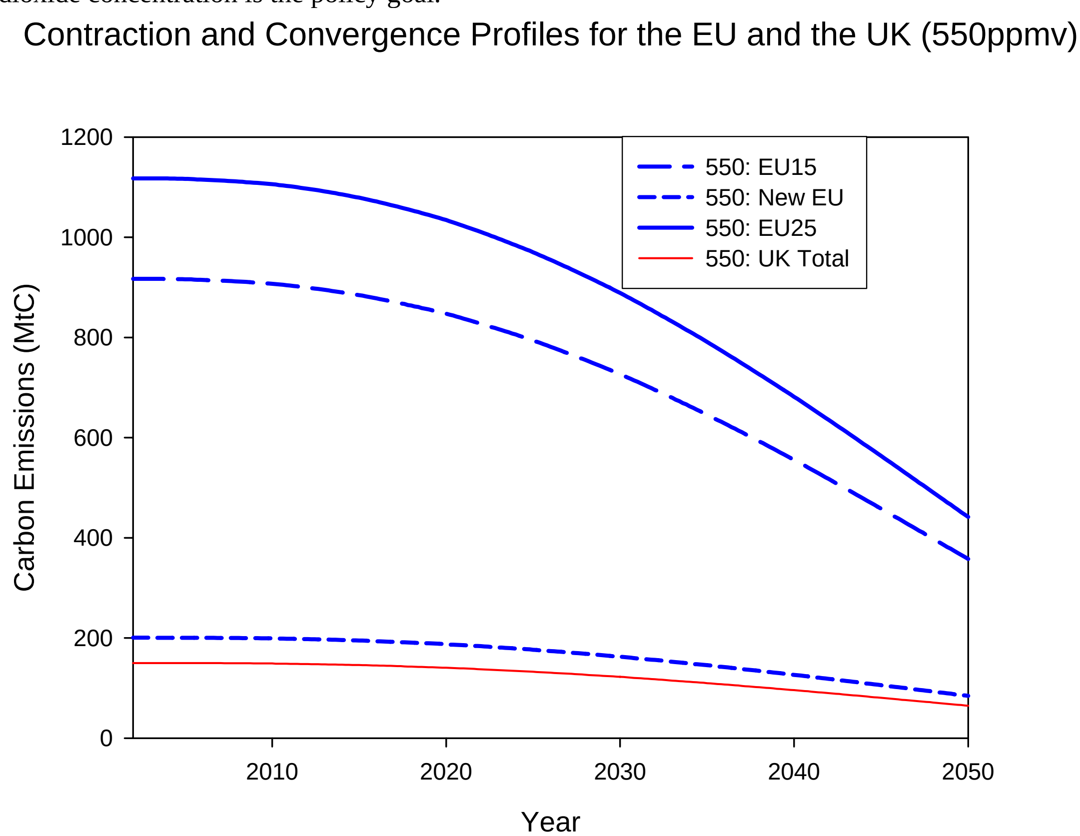

Figure 3: Contraction and convergence profile to meet a 550ppmv carbon dioxide concentration. The emissions profile shown as a blue solid line (thick solid line for black and white) is for the whole of the EU, the long dashed line is for the EU15 nations, short dashed line for New EU nations (accession nations) and in red (thin solid) for the UK.

Figure 3 shows the contraction and convergence profile for 550ppmv for the EU, split into a total for the original EU15 nations (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Portugal, Spain, Sweden, United Kingdom and The Netherlands), a total for the New EU nations (Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovenia, Slovakia) and also for comparison for the UK alone. Whilst the more industrialised nations together produce the largest share of the EU25 emissions in 2002, when separated out, both the EU15 and New EU states require percentage cuts to stabilise carbon dioxide emissions at 550ppmv of around 60% from 2002 levels.

As Figure 3 shows, the UK is required to reduce its emissions from around 150MtC today to around 60MtC by 2050 – equivalent to the government's 60% target, if it is to contribute towards stabilising carbon dioxide concentrations at 550ppmv. Similarly, to reach 550ppmv, the whole of the EU needs to reduce emissions from around 1100MtC in 2002 to close to 450MtC by 2050 – again about a 60% reduction.

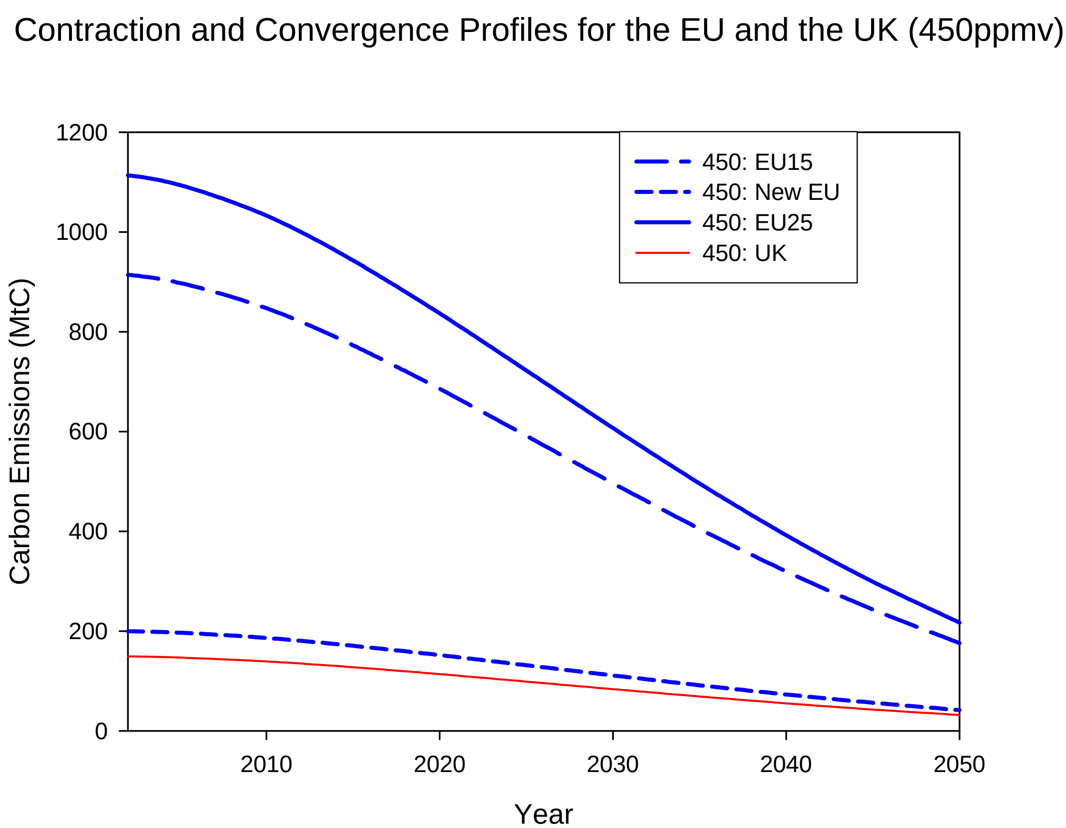

Figure 4: Contraction and convergence profile to meet a 450ppmv carbon dioxide concentration. Emissions profile in blue (thick) solid line for the whole of the EU, long dash for the EU15 nations, short dash for New EU nations and in red (thin) for the UK.

Figure 4 shows a similar picture to Figure 3, but on this occasion the contraction and convergence profiles are designed to reach a carbon dioxide concentration of 450ppmv. All the profiles start from the same levels in 2002, but then drop more rapidly to much lower values by 2050. For example, the EU25 profile drops to a Figure of just over 200 MtC – a cut of 80% from 2002 levels compared with 60% to reach 550ppmv. Similarly, the EU15, New EU as well as the UK require 80% cuts in emissions by 2050 to reach a carbon dioxide concentration of 450ppmv.

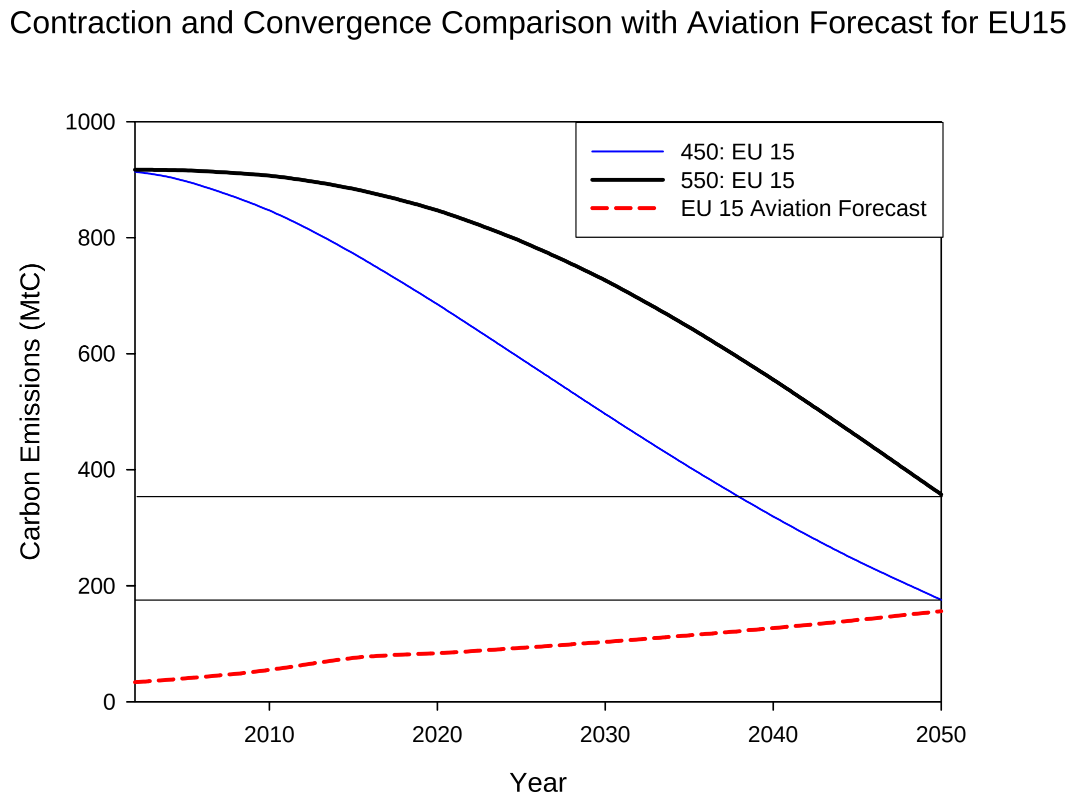

Figure 5: Contraction and convergence profiles to meet 450ppmv and 550ppmv carbon dioxide concentrations for the EU15 nations, compared with projected aviation emissions for those nations. Emissions profile in thick black solid line for 550ppmv, blue (lighter) solid for the 450ppmv and dashed for the forecasted aviation emissions for the EU15 nations.

Comparing the contraction and convergence profiles for both the 450ppmv and 550ppmv cases with the aviation forecast for the EU15 nations shows that as time goes by, a larger proportion of the emission allowance under this regime is taken up by the aviation industry. Indeed by 2030, over 100MtC of the 500MtC to 725MtC is emitted by the aviation industries of the EU15. If such values were to remain constant from 2030 onwards, as the DfT suggest for the UK in their capacity constrained analysis for the UK (DfT, 2003, 2004), these static EU aviation emissions would account for some 59% of emissions to reach 450ppmv and 29% of 550ppmv. However, if emissions continued to rise, almost all of the 200MtC permissible to meet 450ppmv would be emitted by the aviation industry by 2050, and some 44% of the 550ppmv limit would be consumed.

Figure 6 shows the same profile as Figure 5, but for the New EU nations. As aviation emissions from these nations start from a much lower base, the growth rates applied result in a lower proportion of the permissible allowance of carbon emissions being taken up by the aviation industry. In this case, the emissions in 2030 are around 10% of the 450ppmv total and 6% of the 550ppmv total. However, this needs to be seen in the context of the air transport sector of the new EU nations accounting for only 0.1% total emissions in 2000. If emissions continue to rise beyond 2030 and up to 2050, aviation emissions would account for just less than 50% of the quantity prescribed by a 450ppmv profile.

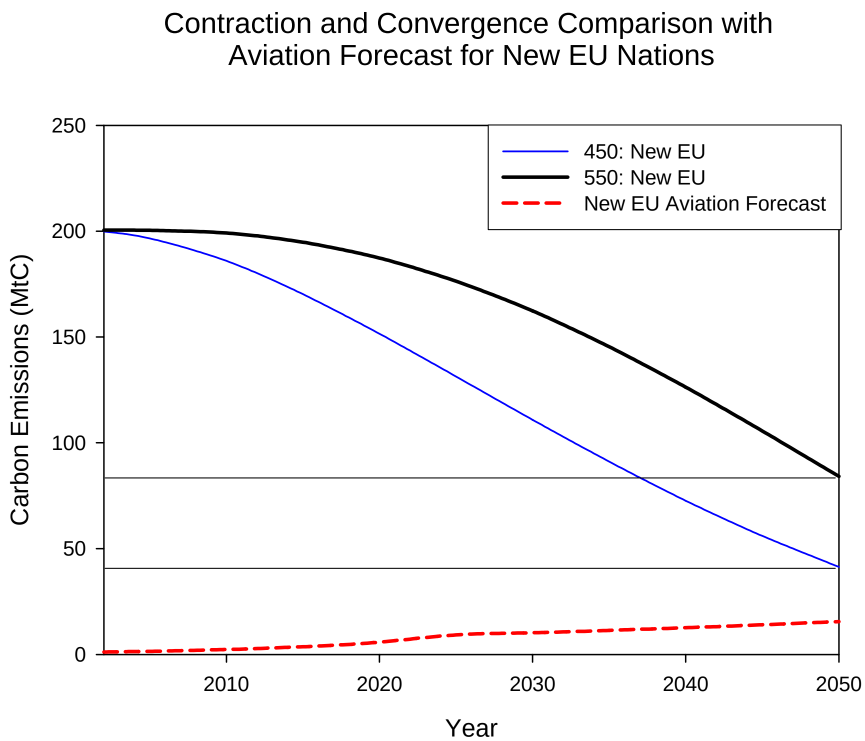

Figure 6: Contraction and convergence profiles to meet 450ppmv and 550ppmv carbon dioxide concentrations for the New EU nations compared with projected aviation emissions for those nations. Emissions profile in black thick solid line for 550ppmv, blue (thin) solid for the 450ppmv and dashed for the forecasted aviation emissions for the New EU nations.

Again Figure 7 shows contraction and convergence profiles for 450ppmv and 550ppmv, but in this case for the whole of the EU. The general picture is similar to that seen for the EU15 nations in Figure 5, as these nations dominate the European aviation scene. For 2030 emissions relative to 2030 contraction and convergence targets, EU aviation would account for 19% of the 450ppmv value and 13% for 550ppmv. If growth continued up to 2050, the industry would account for some 80% of the 450ppmv profile value for 2050 and 39% of the 550ppmv profile value for 2050. It should be emphasised that these values are for carbon emissions alone, and do not take into account any additional radiative effects such as those due to contrails and cirrus clouds.

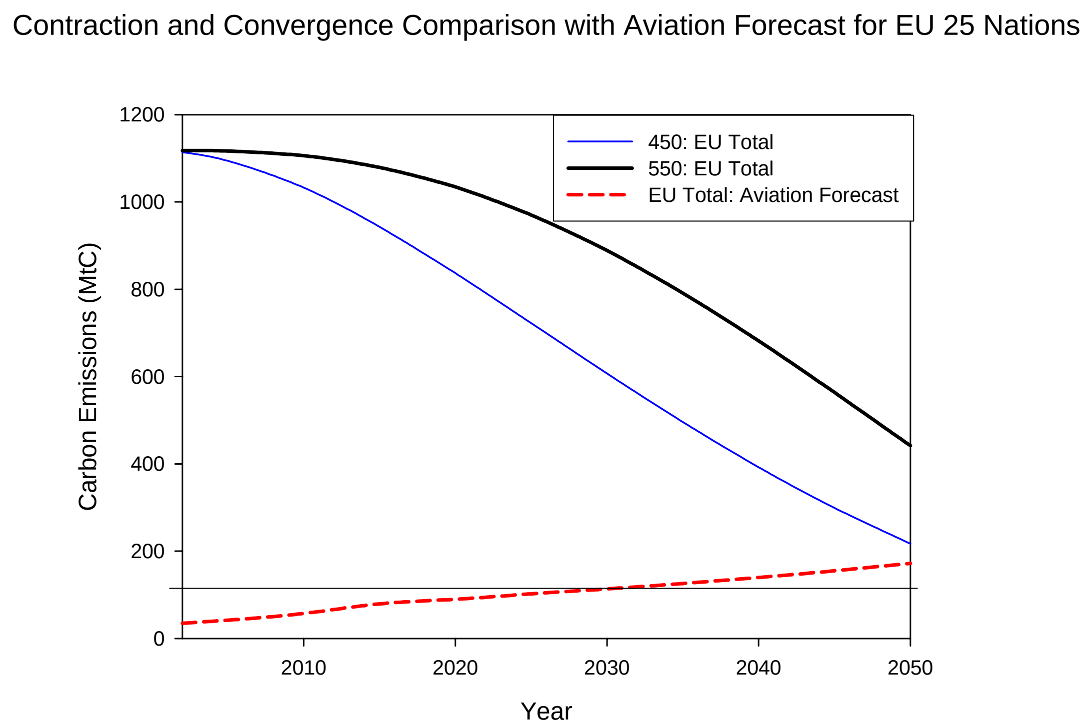

Figure 7: Contraction and convergence profiles to meet 450ppmv and 550ppmv carbon dioxide concentrations for the EU25 nations compared with projected aviation emissions for those nations. Emissions profile in black thick solid line for 550ppmv, blue (thin) solid for the 450ppmv and dashed for the forecasted aviation emissions for the EU25 nations.

6.5 Investigation of alternative carbon dioxide 'uplift' factors

As stated, aviation's contribution to climate change is not restricted to the carbon dioxide released by the aircraft. The altitude of the emissions and the types of emissions released are thought to have an impact on radiative forcing and hence warming of up to 2-4 times that of the carbon dioxide alone (DfT, 2002b, RCEP, 2002 IPCC, 1999). An uplift factor is therefore typically applied to carbon dioxide quantities to estimate the full impact of the aircraft emissions on the climate. *However, it should be noted that there is very substantial uncertainty and disagreement surrounding both the size of the factor that should be used, as well as the method of simply 'uplifting' carbon values, and comparing these with carbon emissions profiles. Strictly speaking, such a comparison does not compare like with like.*

Nevertheless, using an uplift factor provides at least a means by which the total contribution to climate change of aircraft emissions can be assessed. The inclusion of such factors make it necessary to revisit the contraction and convergence profiles to estimate the aviation industry's likely impact. In this study, the uplift factors chosen are both within IPCC's 2-4 range. The figure of 2.7 is chosen, as it is the most widely used figure, and was adopted by the IPCC (1999). The second uplift value chosen is 3.5. This value is at the higher end of the IPCC range, and is used because more recent studies and commentary suggest that an appropriate value may be higher than IPCC's 2.7 average (RCEP, 2002; Stordal et al. 2004).

Contraction and Convergence Profile for EU25 Compared with Aviation Forecasts

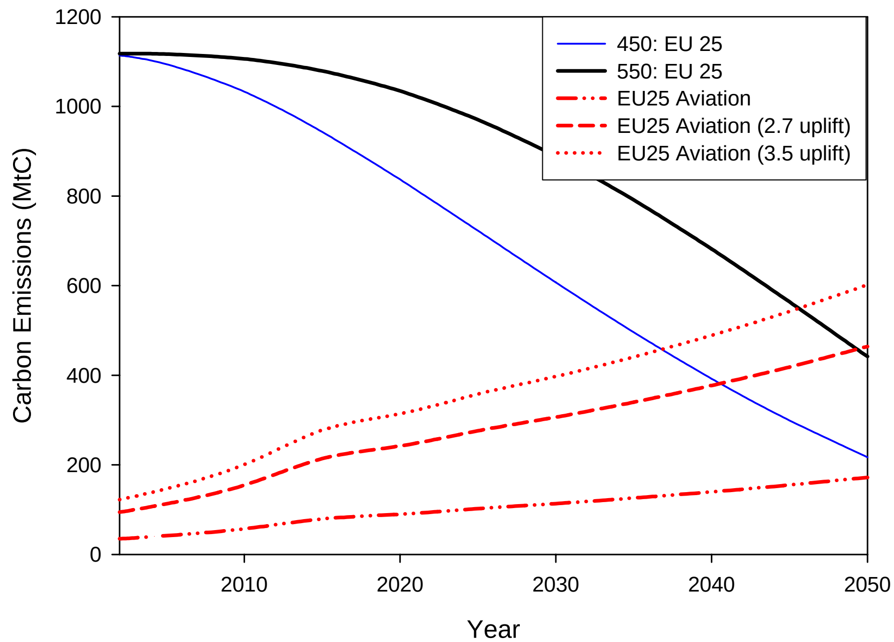

Figure 8: Contraction and convergence profiles to meet 450ppmv and 550ppmv carbon dioxide concentrations for the EU25 nations compared with their projected aviation emissions with no uplift, uplifted by 2.7 and uplifted by 3.5. Emissions profile in black thick solid line for 550ppmv, blue (thin) solid for the 450ppmv, dash-dot-dot for no uplift, short dash for an uplift of 2.7, and dotted for 3.5 uplift.

Figure 8 shows profiles for 450ppmv and 550ppmv carbon dioxide concentration levels as well as two uplifted aviation scenarios and one scenario without uplift. By 2030, uplifted EU aviation emissions account for between some 34% and 45% of the contraction and 550ppmv convergence target for that year, depending on choice of factor and between some 50% and 65% to stabilise emissions at 450ppmv. If aviation growth continues to 2050, and were to have an impact on the climate as high as the uplifted value of 3.5, then, by 2045 current growth in the EU aviation industry could not be accommodated within the EU contraction and convergence profile consistent with stabilisation of global atmospheric carbon dioxide emissions of 550ppmv (and this is with the conservative version of the GCI model, excluding carbon cycle feedbacks). Even uplifting by the IPCC (1999) average of 2.7 shows that, by 2050, EU aviation emissions would exceed the 550ppmv contraction and convergence target for the EU by 2050.

Even more concerning is the attempt to stabilise carbon dioxide emissions at 450ppmv rather than 550ppmv. In the 450ppmv case, EU aviation emissions exceed the contraction and convergence profile by the mid- to late-2030s for an uplift factor of 3.5, and by around 2040 for the 2.7 uplift factor.

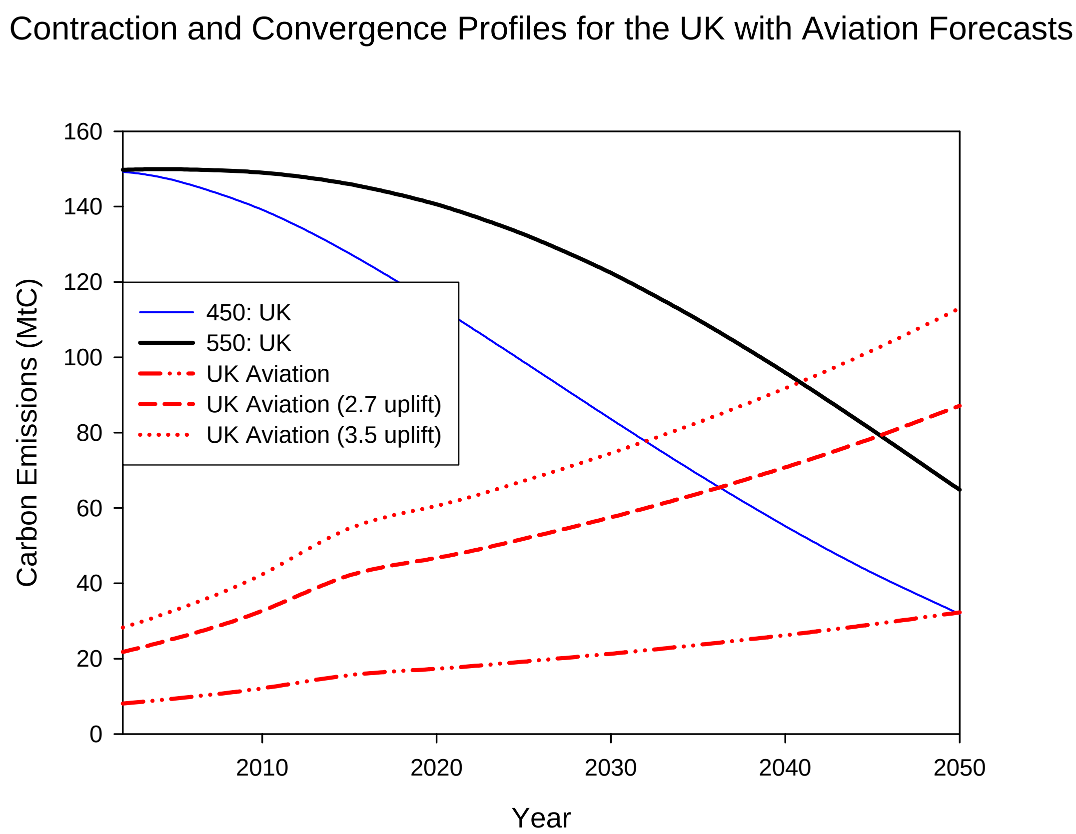

Figure 9: Contraction and convergence profiles to meet 450ppmv and 550ppmv carbon dioxide concentrations for the UK compared with the UK's projected aviation emissions with no uplift, uplifted by 2.7 and uplifted by 3.5. Emissions profile in black thick solid line for 550ppmv, blue (light) solid for the 450ppmv, dash-dot-dot for no uplift, short dash for an uplift of 2.7, and dotted for 3.5 uplift.

Figure 9 is the same set of profiles as Figure 8, but in this case for the UK alone. The industry here is growing rapidly, and therefore the proportion of emissions being taken up by the aviation industry is even higher than those seen when looking at Europe as a whole. Firstly, without any uplift, forecast unconstrained aviation emissions exceed the 450ppmv profile by 2050, and by 2050 are 50% of the 550ppmv 2050 target. If however, emissions were to stabilise at 2030 values, then they would account for 67% of the 450ppmv profile by 2050, and 33% of the 550ppmv profile by 2050. Moreover, it is clear that if policy makers choose to apply an uplift factor methodology[24], then this results in a significant difference to the proportion of emissions being taken up by the aviation industry. By 2030, uplifted emissions range between 89% and 115% of the 2050 target to stabilise emissions at 550ppmv. The range of the 2050 target consumed for 450ppmv is between 180% and 234%, again by 2030. The uplifted emissions exceed the 550ppmv profile for the UK between the early to mid 2040s, depending on which factor is used. If the UK government's aviation projections were used and uplifted by these factors, then the 2030 value of 18MtC would be equivalent to 49MtC with a factor or 2.7 or 63MtC using 3.5. Again, if these values were held constant until 2050, they would account for more than the 450ppmv profile by 2050, and between 75% and 97% of the 2050 550ppmv target.

6.6 Implications for UK aviation growth

Whether levels of aviation emissions growth relative to contraction and convergence profiles would prove to be a limitation on the development of UK and EU aviation would depend on the policy context. Key policy issues include the following:

[24] See note in italics with regard to uplift factors under section 6.5

- The level of constraints: economic (national, regional and international), fiscal policy (taxes, charges) and airport infrastructure supply.
- Will the UK maintain, reduce or strengthen its 60% target for 2050 carbon dioxide emissions?
- How would the emissions of other sectors develop in the UK and wider EU, in response to strong carbon reduction targets?
- In other terms, what carbon stabilisation level and profile will be adopted by the UK in the long run?
- Will the UK adopt an early emissions contraction profile or will it delay - and if so, for how long?
- Will the EU adopt a strong emissions contraction target at an early date, or will it delay, and if so, for how long?
- When will intra-EU aircraft emissions be brought into EU ETS?
- What, if any, radiative forcing factor will be applied to those emissions?
- Will international aircraft (and maritime) emissions be allocated to nations (or airlines) and regulated as part of a post-Kyoto policy regime? If so, when?
- When, if at all, would international aircraft (and maritime) emissions be tradable within an open, global emissions trading system?

Without knowing the answers to these and other questions, it is not possible to assess with any certainty the consequences of the present findings for UK or EU aviation. Several policy scenarios would seem possible and an open emissions trading system will likely permit the strongest aviation growth. However, for analytic purposes, this study assumes that the EU ETS is a closed system. In such a scenario, assessment of the implications of the above findings for aviation growth will be significantly influenced by the behaviour of other EU economic sectors. This is considered in some detail below for the UK only, after a brief consideration of the airport capacity implications of air passenger demand projected to 2030 in the manner described above. The values for air passenger demand can then be related to projected emissions quantities for corresponding years. That is, a UK policy user can in principle select an emission quantity from Figure 9 above that they judge should not to be exceeded, identify the corresponding date, and then interpolate from Tables 3 or 4 to identify a corresponding number of passengers that this quantity of emissions will ‘permit’. Converting this number of passengers to a number of runway-equivalents would require many assumptions, but as a very coarse rule of thumb one could say that one new standard-length runway will accommodate some 35-40,000 passengers per year. The regional location of runways raises further issues that cannot be discussed here: the purpose is only to indicate the implied level of capacity, not its geographic distribution.

6.6.1 Inferred air passenger numbers, air traffic movements and runways

Passenger numbers have been projected above as a basis for aircraft carbon emissions estimates. These passenger numbers can also be used to inform an assessment of the extent to which planned UK airport capacity can suffice to service growth to 2030, given knowledge of the level of 2030 airport capacity, air traffic movements and air passenger numbers supported by the UK aviation white paper and considered in the supporting Regional Air Services Co-ordination studies. By converting from passengers to air traffic movements, policy users can, as described above, identify a level of movements that corresponds with a level of emissions that is considered permissible.

Table 3 below estimates the quantities involved up to 2030, accounting for aircraft size and load factor, using Eurostat passenger data. Table 3 repeats this with DfT data. To clarify the calculations, the value of 105 passengers per flight is assumed to be typical of major UK airports, broadly inferred from RASCO consultation documents. In Table 2, the figure of 126 passengers per flight is based on a 20% increase in the size of aircraft, based on the knowledge that an average aircraft servicing the UK currently has 133 seats, as calculated from the current UK-relevant load factor of 79% (CAA, 2004). If an additional 20% of 105 passengers are added to each aircraft, then the number of passengers per flight increases to 126. If, in addition, aircraft become 20% larger in terms of the numbers of seats available (EADS, 2004), the new average aircraft size will be 160 seats. Whereas the application of the increased load factor to the smaller aircraft results in 126 seats being occupied, application the larger aircraft leads to 152 seats occupied.

Table 3: Passenger and flight forecast figures based on different load factor and aircraft size scenarios – Eurostat passenger data

	PAX/ATM (passengers per flight)	2002 (thousand)	2010 (thousand)	2020 (thousand)	2030 (thousand)
Tyndall Passenger forecast		168,742	277,176	444,596	615,133
Ratio passenger cf today		1:1	1:1.6	1:2.6	1:3.6
Number of flights if all remains the same.	**105**	1,607	2,640	4,234	5,858
Number of flights if plane size only increase by 20%	**126**	1,339	2,200	3,529	4,882
Number of flights if load factor only increased by 20%	**126**	1,339	2,200	3,529	4,882
Number of flights if both load factor and plane size increased by 20%	**152**	1,110	1,824	2,925	4,047

Table 4: Passenger and flight forecast figures based on different load factor and aircraft size scenarios – DFT passenger data (DfT, 2002b)

	PAX/ATM (passengers per flight)	2002 (thousand)	2010 (thousand)	2020 (thousand)	2030 (thousand)
DfT Low Forecast[25]		190,000	250,000	350,000	390,000
DfT Medium Forecast		190,000	275,000	400,000	490,000
DfT High Forecast		190,000	300,000	460,000	610,000
Number of flights if all remains the same – DfT Low	**105**	1,810	2,381	3,333	3,714
Number of flights if both load factor and plane size increased by 20% - DfT Low	**152**	1,250	1,645	2,303	2,566
Number of flights if all remains the same – DfT Med	**105**	1,810	2,619	3,810	4,667
Number of flights if both load factor and plane size increased by 20% - DfT Med	**152**	1,250	1,809	2,632	3,224
Number of flights if all remains the same – DfT High	**105**	1,810	2,857	4,381	5,810
Number of flights if both load factor and plane size increased by 20% - DfT High	**152**	1,250	1,974	3,026	4,013

Moving from passengers to air traffic movements and on to airport infrastructure, it is possible to make broad comments on the level of capacity required to support the level of passenger growth assumed in this study. To reiterate, those levels are based on recent historical growth rates, tempered by a maturation rate supplied by DfT, applied here after 2015. The results highlight the

[25] These figures are approximations in terms of date, and are taken from the aviation White Paper, specifically the figure on page 23 (DfT 2002b).

relatively low growth assumed in DfT modelling for the aviation white paper. To inform the White Paper, the UK Regional Air Service Consultations (RASCO) produced several scenarios for different levels and distributions of growth in the UK aviation industry up to 2030. The RASCO reference case scenario is similar to that supported by the white paper, except that two new runways are supported in the South East in the white paper, not three as in the RASCO dioxide reference case. The additional infrastructure required for the RASCO dioxide reference case scenario could accommodate 1,800,000 more flights than in the year 2000 (based on the summary in Upham, 2002).

According to our best case scenario – 20% improvement in load factor, with planes accommodating 20% more seats - there would be 4,047,000 movements in 2030. This is an increase of 2,440,000 movements relative to the current 2002 value. Without further improvements to landing rates and / or better load factors and even larger aircraft, the above infrastructure would not be able to cope. In comparison, the DfT figures show that in their best case scenario – low growth, 20% improvement in load factor, 20% increase in plane size, there will be 756,000 more flights in 2030 than currently, or for the highest growth, but with the same improvements, 2,203,000, which is again more than the listed infrastructure in the RASCO scenario can accommodate.

It should be noted that the baseline number of passengers chosen by the DfT for their forecasts is 190 million, rather than 170 million used in this analysis. As the figure of 170 million comes from the Eurostat data, and the figure of 190 million does not appear to have taken into account the drop in passenger numbers due to events on 11 September, it is considered that the figure of 170 million is more reliable.

6.7 Implications for other sectors

If the UK government is to reach its 2050 60% carbon reduction target with the aim of stabilising carbon emissions at 550ppmv, then all sectors of the economy must be taken into account in any analysis. To date, there has been little work looking at the energy system in the UK that includes sectors such as international aviation, and indeed the international marine sector. Concurrent research at the Tyndall Centre is remedying this by examining scenarios for the main economic sectors from an energy analysis perspective. These Tyndall scenarios provide an account of ways in which aviation growth may impact on other UK sectors, in terms of permissible emissions. The analysis assumes a closed system in terms of emissions trading: it is assumed that the 60% target must be met without purchase of emissions credits from Europe or elsewhere. The existence of EU ETS does not necessarily invalidate the analysis: while this would be the case if the remainder of the EU did not also commit to 550ppmv or less, we have assumed in the foregoing that the whole EU does indeed make that commitment. In fact, *CCOptions* assumes a global commitment to the target carbon dioxide concentration. As all European countries would be subject to similar reduction requirements, the options for compensating for EU aircraft emissions within Europe as a closed emissions trading system would be very limited (though not zero, particularly in the early years).

Using the Tyndall spreadsheet model of the UK's energy system (Anderson et al, 2005), scenarios have been constructed that reach the aggregate 60% carbon target by 2050 in a variety of ways. The demand-side of the model is split into fifteen sectors – household, intensive industry, other industry, commercial, public administration, construction, agriculture, the energy industry and transport, which itself is split into road passenger (public and private), road freight, rail, domestic passenger aviation, international passenger aviation, domestic marine freight and international marine freight. The other half of the model contains a variety of electricity supply-side options including conventional fossil-fuel-based power stations for electricity, as well as renewables, biomass and carbon capture and storage. In addition, direct energy and transport fuel, for example, hydrogen, biomass, renewables and conventional fossil fuels, are included. Efficiency estimates for the various supply options in 2050 have assumed current state-of-the-art levels of technology.

To estimate the impact of the growth in the UK aviation industry as outlined in the previous section (Table 1), the Tyndall Centre's spreadsheet model has been used to devise four scenarios that each meet the UK government's 60% carbon reduction target, ensuring that just 65MtC is emitted in 2050. *These scenarios do not use uplift factors for the aviation emissions.* If the DfT's revised (2004) estimate of 2030 aircraft carbon emissions were to be uplifted by the IPCC average of 2.7, the industry's 2050 emissions would be 48MtC compared to our non-uplifted value of 32MtC. In this sense, the implications of our energy scenarios need not be seen as dependent on our own carbon emissions scenarios for aviation – the implications stand if we substitute an uplifted version of DfT's emissions projections for our own figures and assume that growth in aviation emissions stops at or before the 2030 timeframe of *The Future of Air Transport*.

The scenarios below each assume a different level of economic growth and total energy consumption. Two have a total energy consumption lower than today, and two higher than today. However, they all have the same 2050 level of energy use and carbon emissions from the aviation industry as calculated in the previous section. Table 5 summarises some of the key values assumed by the scenarios.

Table 5: FOEa Scenario values

Scenario	Annual economic growth	2050 GDP compared with today	Energy consumption (Mtoe)	Primary energy demand (Mtoe)	Carbon emissions (MtC)	Aviation energy use (Mtoe)/carbon emissions(MtC)
FOE90a	2.4%	1:3.1	91	123	65	40/32
FOE130a	1.6%	1:2.1	130	184	66	40/32
FOE200a	2.7%	1:3.4	199	295	65	40/32
FOE330a	4.1%	1:6.7	331	479	65	40/32
Today	2.7%	-	170	243	162	9/8

Within Table 5, 'Mtoe' is million tonnes of oil equivalent; primary energy demand relates to the total energy used including the conversion to heat, electricity, motive power etc; the scenario labels correspond to the value of energy consumption in Mtoe – energy used not including the conversion to heat, electricity, motive power etc. Growth within the UK's aviation industry is the same for all scenarios – 6.4% per year in terms of passenger-km up to 2015, then 3.3% per year up to 2050.

As shown in Table 5, carbon emissions are the same in each scenario due to a combination of different energy supply mix and differing energy consumption across the different sectors. The additional assumption that there are no alternative fuels to kerosene for the aviation industry has been made – this differs to the Tyndall Energy scenarios (Anderson et al, 2005). Energy and emissions scenarios are often associated with particular 'storylines' or ideologies. The above scenarios are based on concurrent research to construct Tyndall Scenarios; these are essentially 'bottom-up' scenarios for achieving the 60% emission reduction target. As such they are not necessarily constrained by particular narrative descriptions of alternative UK development paths.

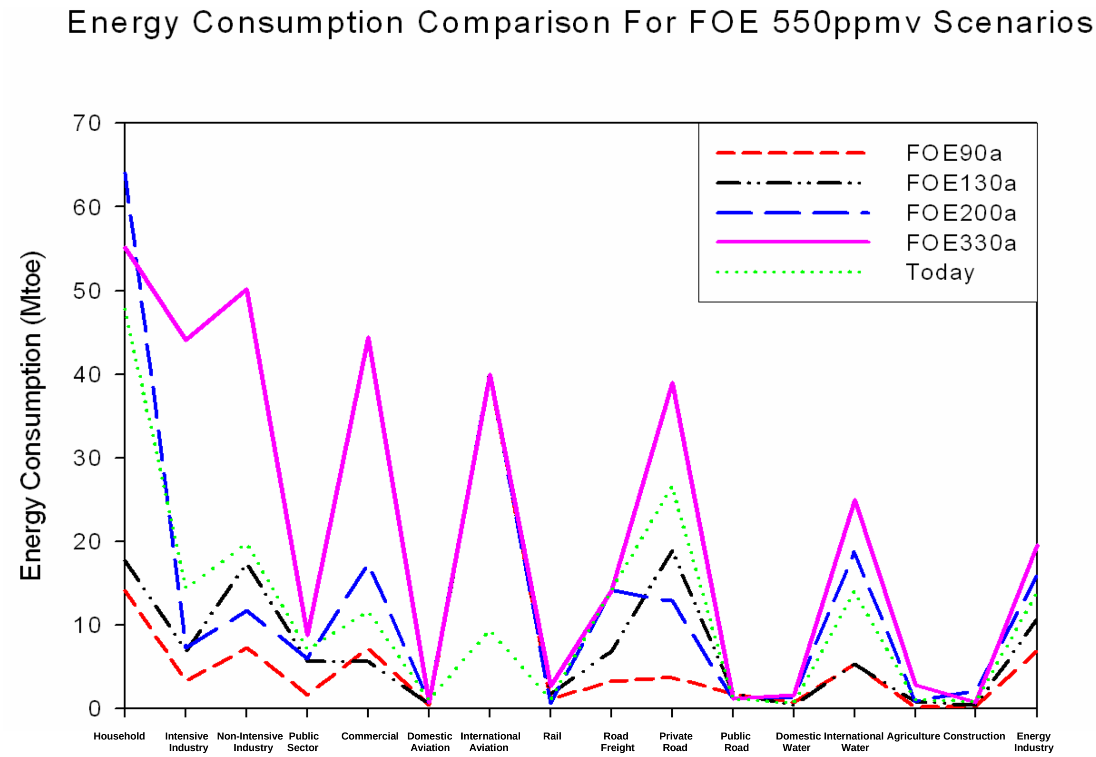

Figure 10: Energy consumption profiles for the four FOE scenarios that meet the UK government's 60% carbon reduction target. The profile for today is also shown. All the profiles show the same figures for the aviation industry, therefore their profiles are overlaid one over the other for this sector.

Figure 10 shows profiles for energy consumption for the four scenarios developed for Friends of the Earth (here labelled 'FOE scenarios' for descriptive purposes, but not necessarily sanctioned by Friends of the Earth) that each meet the UK government's 60% carbon reduction target. The energy consumption profile for today is also shown for comparison as a dotted line. In all of the FOE scenarios, energy consumption by the aviation sector remains constant.

An immediate conclusion arising from Figure 10 is that whilst in the very high energy scenario (FOE330a) the impact of high growth within the aviation industry is, to some degree, masked, in the lower energy demand scenarios (FOE90a, FOE130a and FOE200a) the aviation industry is obviously dominant (or shares dominance with the domestic sector – see FOE200a).

In terms of further detail, in scenario FOE90a, a low energy consumption scenario, aviation consumes by far the largest proportion of energy, 40 Million tonnes of Oil Equivalent (Mtoe) compared with typically less than 10Mtoe in all sectors except the household sector, which is just over 10Mtoe. Sectors such as road transport and household are required to consume significantly lower energy compared with current levels, which would require significant, though still currently feasible, improvements in energy efficiency, as well as behavioural change. In other words, if the UK chooses a low energy consumption route to reduce its carbon emissions, the aviation industry will account for a disproportionably large amount of it.

A similar conclusion can be drawn for the FOE130a scenario. Here the energy consumption is around 25% lower than current levels, with the aviation industry consuming around double the energy consumption of the next highest consuming sector – private road travel. Significant reductions have been achieved in the household sector through a mix of major improvements in the efficiency of appliances and heating, as well as behavioural change. Other sectors with significantly different energy consumption than today are the intensive industry, commercial and international marine. Within this scenario, the public sector is a relatively strong driver of the economy, with the relatively low growth of the intensive industry and commercial sectors, combined with moderate improvements in their efficiency, reducing their energy consumption.

FOE200a is a scenario with an 18% increase in energy consumption and an economic growth similar to that of today. In this scenario energy consumption from the household sector exceeds that from the aviation sector. All other sectors of the economy essentially compensate for the high fossil fuel demand of the aviation industry, through significant decarbonisation of their energy supply. The lower energy consumption within the industrial sectors is primarily due to a relative decrease in its importance within the economy, whereas the private road and freight sectors are required to make a major increase in energy efficiency through technological and behavioural changes.

FOE330a has a significantly higher energy consumption and economic growth rate than today, with increases in energy consumption occurring across all sectors. Whilst the aviation industry is the fourth largest energy consuming sector, its emissions of carbon approximate to the aggregate from all the other sectors, and consequently it has forced a very substantial decarbonisation of the energy supply system in order to meet the 65 MtC target.

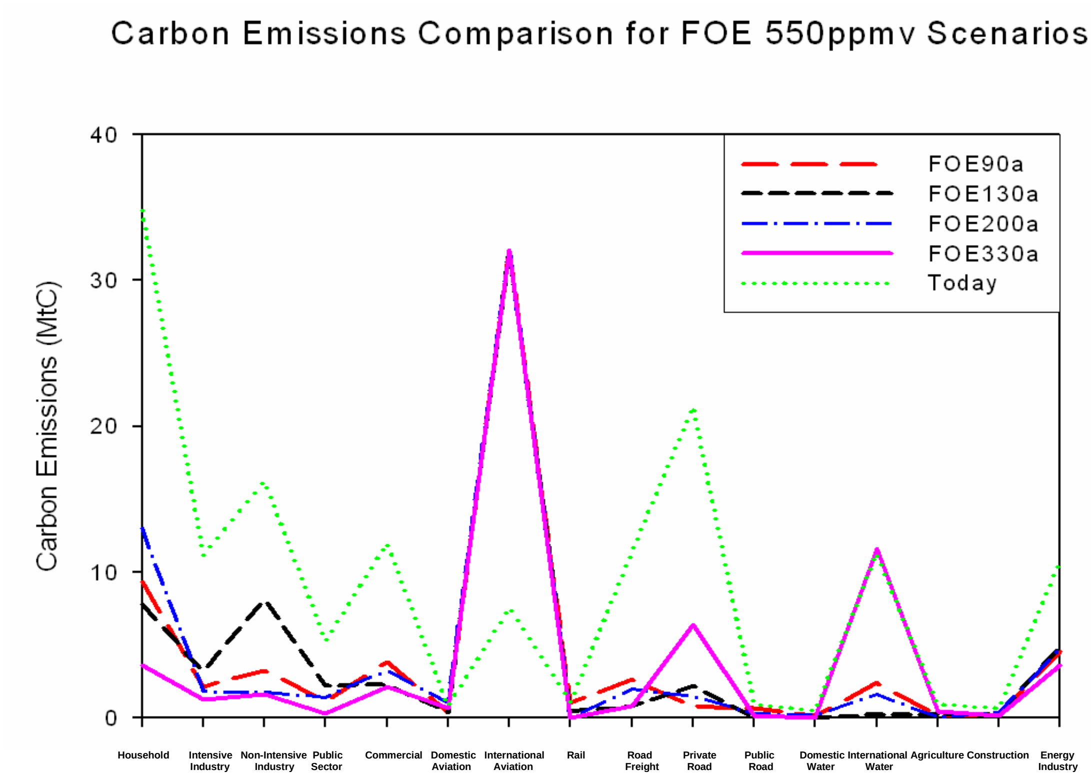

Figure 11: Carbon emission profiles for the four FOE scenarios that meet the UK government's 60% carbon reduction target. The profile for today is also shown.

To meet the levels of demand shown in Figure 10, the supply mix of the FOE scenarios were based on making minor adjustments to the Tyndall Scenarios (Anderson et al, 2005) to account for all the FOE scenarios using oil instead of any combination of biofuels or kerosene in 2050. Figure 11 demonstrates that if the aviation industry grows in accordance with the scenarios developed in this report, and no technological breakthroughs are made by 2050, it will dominate the economy in terms of emissions of carbon. No other sector comes close to the aviation sector's emissions, with all other sectors having to significantly decarbonise in relation to both activity and the form of energy they use. Moreover, even if emissions from the aviation industry are assumed to plateaux at 21MtC from 2030, they would still far exceed carbon emissions from all the other sectors. In those scenarios where total energy consumption has reduced, aviation dominates the energy consumption profile. Where total energy consumption has increased (FOE200a & 330a) aviation energy consumption is more in line with the other sectors, however, it still dominates the carbon emissions profile, forcing substantial decarbonisation of the energy supply system.

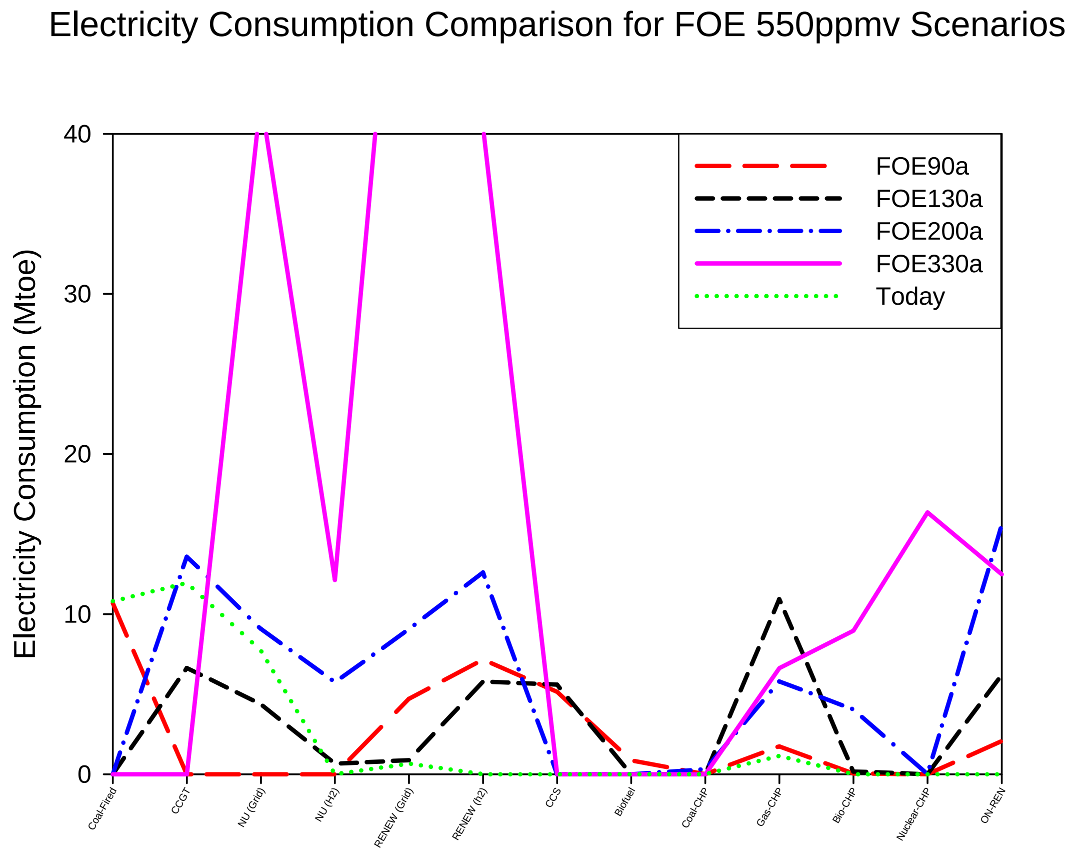

Figure 12: Electricity demand profiles for the four FOE scenarios that meet the UK government's 60% carbon reduction target, in terms of the source of the supply. The profile for today is also shown. Coal-fired, CCGT (combined-cycle gas turbines), NU (Grid) (nuclear), RENEW (Grid) (renewables), CCS (coal-fired power with carbon capture and storage) and biofuel are all sources for the national grid. NU (H2) (nuclear), RENEW (H2) (renewables) are electricity required for hydrogen production, Coal-CHP, Gas-CHP, Bio-CHP and Nuclear-CHP are the different combined heat and power sources, and ON-REN are on-site renewables.

Figure 12 illustrates the electricity generation mix for the different scenarios. The lowest energy consumption scenario – FOE90a has a high coal contribution with about 25% of it including carbon capture and storage. Nuclear power and gas have been phased out, and there is a significant increase in use of renewable energy. The low overall energy consumption has meant it has not been necessary to abandon fossil-fuels altogether, however, the reliance of the aviation industry on oil alongside the stringent carbon reduction target, has required some moderate decarbonisation of the supply system.

Scenario FOE130a demands further decarbonisation of electricity supply, although again coal-fired power with carbon capture and storage is used to supply the electricity grid. In addition Gas-CHP has also made significant inroads.

Scenario FOE200a illustrates the substantial decarbonisation necessary if total energy consumption increases and no viable alternative to using kerosene as a fuel for aviation is found. Renewable energy increases very substantially in this scenario, coal for electricity has been phased out and the use of gas and biofuel-CHP have accelerated for electricity and heat supply.

Finally, scenario FOE330a illustrates a very high total energy consumption in combination with aviation growth. Nuclear energy and renewables are assumed to dominate the supply of electricity, with the incorporation of nuclear-CHP. The scenario has substantial infrastructure implications to accommodate the very substantial increases in nuclear and renewable power, as well as hydrogen as an energy carrier.

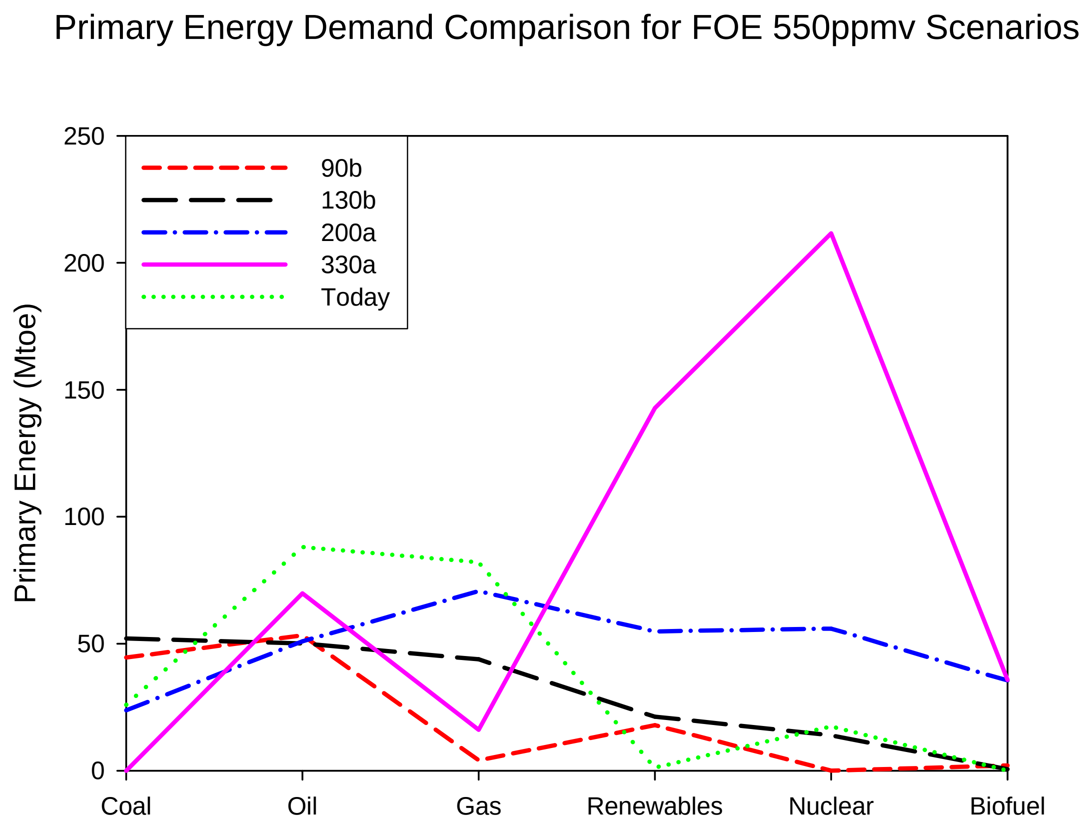

Figure 13: Primary energy demand profiles for the four FOE scenarios that meet the UK government's 60% carbon reduction target, in terms of primary fuels. The profile for today is also shown.

In terms of primary energy supply, whilst in all the scenarios there is a move away from a reliance on fossil fuels, they all have similar levels of oil use, primarily from their identical aviation related energy consumption. All scenarios use more renewable energy than today, with the two high-energy consumption scenarios requiring very substantial additional investment in renewable energy. The FOE330a scenario assumes very high levels of zero carbon energy sources (nuclear power and renewables) to meet the very high levels of energy consumption within the 65MtC constraint, with aviation absorbing most of the carbon-rich energy supply.

6.8 Scenarios for a 450ppmv target concentration

The above exercise in scenario construction has also been undertaken for scenarios that meet the cut in carbon emissions that would be required to achieve a carbon dioxide stabilisation level of 450ppmv rather than 550ppmv. Table 6 highlights the key characteristics of these scenarios.

Table 6: FOEa Scenario values for the 450ppmv scenarios

Scenario	Annual economic growth	GDP compared with today	Energy consumption (Mtoe)	Primary energy demand (Mtoe)	Carbon emissions (MtC)	Aviation energy use (Mtoe)/carbon emissions(MtC)
FOE90b	2.4%	1:3.1	90.7	124.7	34.72	40/32.1
FOE130b	1.6%	1:2.1	130.4	184.9	35.22	40/32.1
FOE200b	2.7%	1:3.4	199.4	305.9	35.4	40/32.1
FOE330b	4.1%	1:6.7	330.7	495.5	34.6	40/32.1
Today	2.7%	-	170.3	243.3	162.1	9.4/7.8

Again, the same level of energy consumption in the aviation sector is applied across all of the scenarios. For this set of scenarios the necessary further reductions in carbon, to 32MtC, have been achieved though additional decarbonisation of the supply system rather than reductions in the energy consumption of the other sectors. Consequently, the energy demand pattern for these scenarios is identical to those for 550ppmv illustrated in Figure 10. As the aviation scenario used in this analysis (ie UK aviation growing at 6.4% until 2015, then 3.3% from 2015-2050) has the aviation industry itself releasing 32MtC by 2050, the implications for the supply system and associated infrastructure are very demanding. It is important to note that the same situation arises if the FOE aviation scenario is substituted by the DfT's figure of 17.7MtC (Table 10a) but uplifted by 2.7. Figure 14 demonstrates the implications of a 450ppmv target with the either the FOE or DfT uplifted (2030) scenarios.

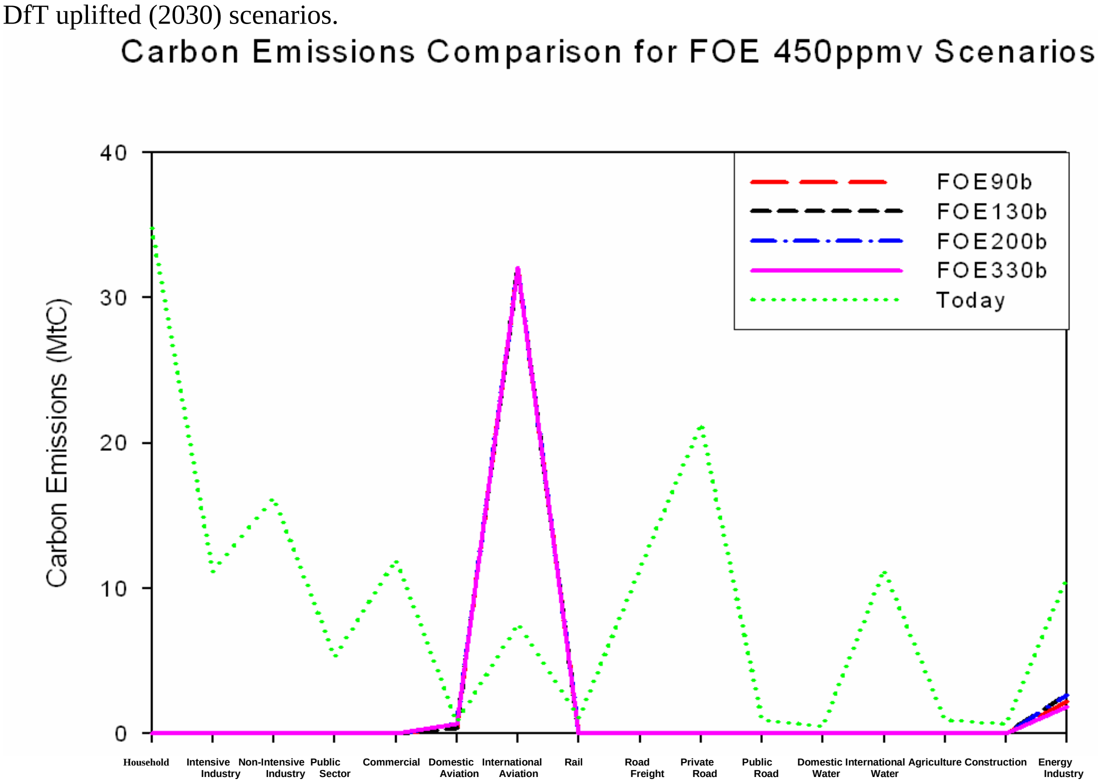

Figure 14: Carbon emission profiles for the four FOE scenarios that try to achieve a carbon dioxide concentration that stabilises at 450ppmv. The profile for today is also shown.

Under a 450ppmv stabilisation profile the 2050 target of 32MtC can only be achieved with zero carbon emissions from all other sectors. That said, Figure 14 does assume the energy industry emits a small amount of carbon, bringing the total emitted to around 35MtC. This is because the energy sector is treated differently to the other sectors within the spreadsheet model, taking a proportion of the fuel sources from across the sectors to estimate the likely mix of its own energy use. However, this is relatively unimportant, as the conclusion remains that to reach 450ppmv with either the FOE aviation or DfT uplifted scenarios, no carbon emissions can be emitted by any sector other than the aviation sector. Figures 15 and 16 illustrate the implications for the supply of electricity and primary fuel sources – extrapolated from the Tyndall scenarios.

Electricity Consumption Comparision for FOE 450ppmv Scenarios

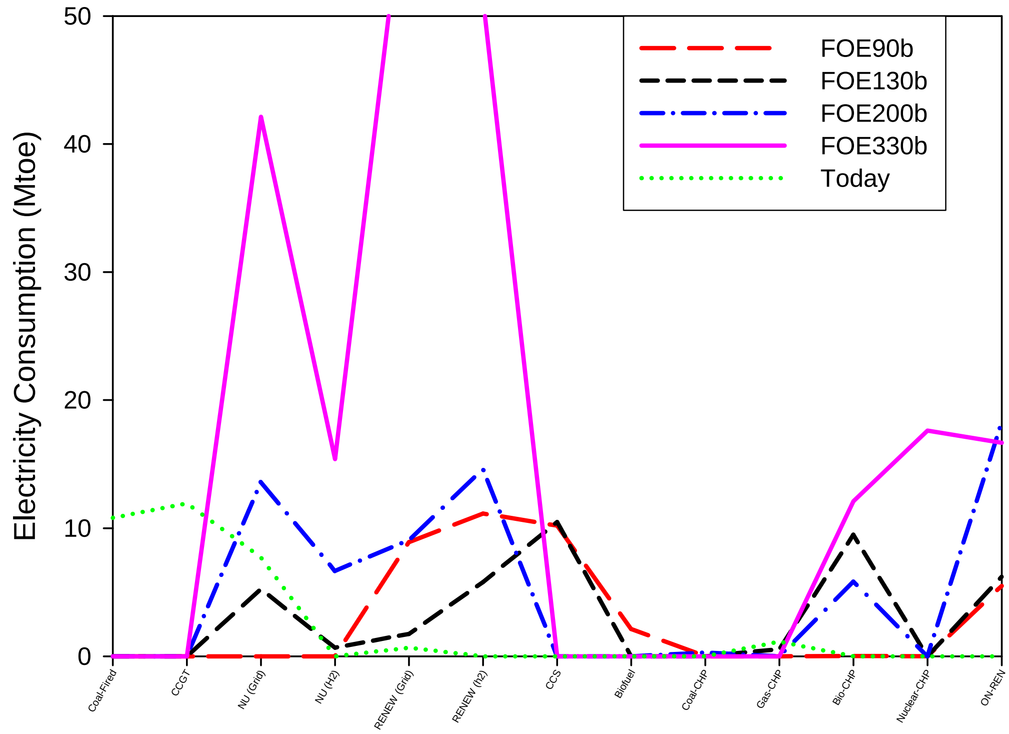

Figure 15: Electricity demand profiles for the four FOE scenarios that reach a level that attains a carbon dioxide stabilisation of 450ppmv, in terms of the source of the supply. The profile for today is also shown. Coal-fired, CCGT (combined-cycle gas turbines), NU (Grid) (nuclear), RENEW (Grid) (renewables), CCS (coal-fired power with carbon capture and storage) and biofuel are all sources for the national grid. NU (H2) (nuclear), RENEW (H2) (renewables) are electricity required for hydrogen production, Coal-CHP, Gas-CHP, Bio-CHP and Nuclear-CHP are the different combined heat and power sources, and ON-REN are on-site renewables.

All of the electricity supply required to meet the 450ppmv stabilisation level is from non-carbon emitting sources, as shown in Figure 15. This means that traditional coal-fired power stations, CCGT, as well as gas- and coal-CHP either cannot exist, or there emissions must be captured and stored.

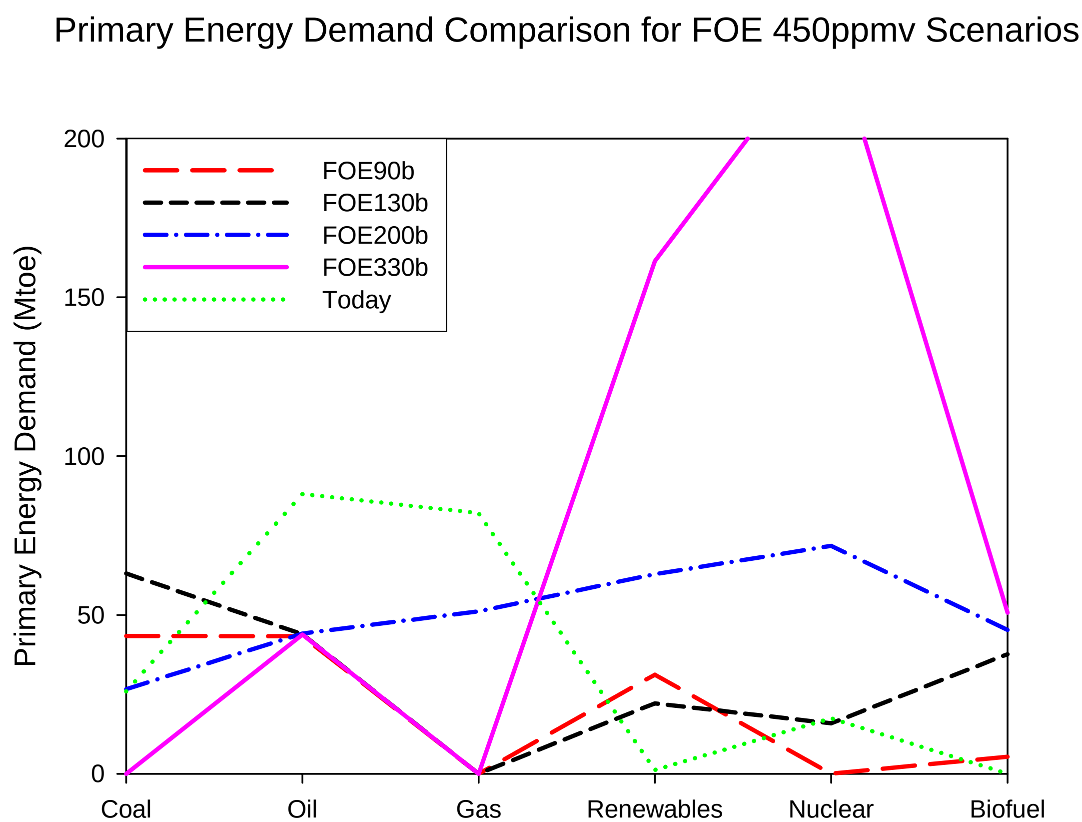

Figure 16: Primary energy demand profiles for the four FOE scenarios that attain a carbon dioxide stabilisation level of 450ppmv, in terms of primary fuels. The profile for today is also shown.

Focussing now on primary energy, Figure 16 clearly shows the same level of oil for each of the scenarios, this being the level required by the aviation industry. The primary supply can continue to use coal and gas provided all the carbon emitted is captured and stored. Renewables, nuclear power and biofuels become increasingly important as primary sources of fuel.

The original Tyndall scenarios (Anderson et al, 2005), on which the FOE scenarios were based, although not presented here, do allow some additional conclusions to be drawn. Within those scenarios, the aviation sector is allowed to grow at both lower and higher levels than presented here (between 1.4% per year and 5% per year). The consequence of this is that very significant or even step changes in technological development are required in terms of aircraft design and operation; for the Tyndall scenarios these changes relate to the introduction of alternative fuels such as biofuel (in the medium terms) and hydrogen (in the longer term). See Anderson et al, 2005 for more details.

7. Conclusions

7.1.1 Implications of aviation growth in the EU

Using historical and maturing passenger growth rates, a scenario for the number of passenger kilometres travelled by air, both international and domestic, for all 25 nations within the EU up to 2050 has been developed. The original EU15 nations and the 10 new EU nations have been separated to show the relative significance of their projected aircraft emissions. In addition, the scenario work focuses on the UK, with its particularly large and expanding aviation industry. No assumptions are made regarding any additional constraints on passenger demand, beyond those that have pertained to the last decade, and hence are implicit in passenger growth rates over that period. The scenario could thus be described as 'business as usual', with continued incremental improvements in fuel efficiency and other operational factors. Extrapolation of recent trends allows a transparent examination of the consequences of such trends continuing.

While the DfT (2004) and EUROCONTROL (2004) have projected slightly lower passenger and air traffic movement trends up to 2030 than are used in this report, our 2030 UK passenger scenario is similar to that of the DfT's high growth forecast for 2030 (i.e. three new runways in SE England). Moreover, the DfT's revised 2030 carbon emissions estimate for UK aviation, if uplifted by the IPCC average of 2.7, exceeds our non-uplifted scenario of UK aviation emissions for 2050. Thus, in our analysis of the impact of aviation emissions on the emission allowance for other UK sectors in 2050, our non-uplifted value is *effectively* lower than DfT's 2030 projection. Consequently, our scenarios of patterns of energy consumption and supply in 2050 are instructive in terms of the implications of the UK Energy White Paper and the UK White Paper on aviation, for both the 2030 and 2050 timeframes.

As passenger kilometres travelled within the EU continue to grow, then, if all other factors remain unchanged, carbon emissions will grow proportionally. However, it is highly unlikely that all of the other factors affecting the carbon intensity of aviation will remain unchanged until 2050. Therefore, a factor reflecting the combination of aircraft design, aircraft size, air transport management and engine efficiency is subsequently applied to the growth figures to produce a carbon emission scenario for the EU up to 2050. This factor is taken from IPCC (1999) and is slightly greater than that assumed by the DfT for the UK fleet up to 2030. (The factor used is a 1.2% per annum reduction in emissions per passenger-km travelled, compared with 1% used by the DfT).

Extrapolating from recent trends, all EU member states show strong growth in aircraft carbon emissions. While aircraft emissions continue to grow, we have assumed that EU nations as a whole will strive to reduce their aggregate greenhouse gases emissions year-on-year to meet, in the first instance, the Kyoto protocol constraints. No post-Kyoto agreement has been formalised to date, however for this analysis, the contraction and convergence regime has been used to illustrate the significance of on-going aviation growth under a contracting carbon target.

At the most general level, the results show that both the EU15 and New EU nations are required to cut emissions by 60% by 2050 if they are to make their 'fair' contribution to stabilising global carbon dioxide concentrations at 550ppmv. It should be noted that this result is obtained with the older version of the GCI contraction and convergence model *CCOptions*; the newer version takes account of carbon-cycle feedbacks and would show a requirement for a larger cut in emissions. We have used the older version for consistency with the UK Government's 60% target. Although some of the New EU nations are slightly less industrialised than those EU15 nations, this makes little difference to the *percentage* carbon reduction targets required of them under a contraction and convergence regime. Consequently all of the EU, not just the EU15, will need to make significant changes to their carbon-based energy usage if 550ppmv is adopted as the carbon dioxide stabilisation target. Stabilising carbon dioxide concentrations at the lower level of 450ppmv, rather than at 550ppmv is considered both by IPCC (IPCC, 1999) and the RCEP (RCEP, 2000). Current research also indicates that lower stabilisation levels than 550ppmv may have to be reached to avoid any major disruption to the climate (Elzen & Meinshausen, 2005). Moreover, the

Department for the Environment, Food and Rural Affairs (DEFRA) acknowledge that the latest science tends to suggest a carbon dioxide concentration of 450ppmv rather than 550ppmv relates to a temperature increase of 2°C (DEFRA, 2004). Use of the GCI model in this study shows that the cuts to carbon emissions necessary for the EU15 and the New EU nations are nearer to 80% under this more demanding carbon constraint.

Stabilising emissions at either 550ppmv or at 450ppmv will have significant implications for any high-growth, carbon-emitting industry. Our extrapolation shows 2050 aircraft emissions of almost 160MtC for the EU15 nations and about 16MtC for the New EU nations, (excluding uplift). Comparing these results with contraction and convergence profiles, it is clear that the large proportion of 'emissions space' taken up by the aviation industry would require other sectors to compensate through either cuts in energy demand or the use of low carbon energy sources.

A summary of the proportion of carbon emissions taken up by the aviation industry under contraction and convergence regimes that lead to 450ppmv and 550ppmv are presented in Table 7. It can be seen, for example, that by 2030, 26% of an EU 550ppmv 2050 target would be consumed by flights to and from the EU (excluding uplift). The corresponding value with an uplift factor of 2.7 would be 69%[26].

Table 7: Proportion of EU25 emissions from aviation relative to 2030 and 2050 contraction and convergence targets for 550ppmv and 450ppmv (Tyndall Calculations).

Stabilisation target (ppmv)	Relative year	Uplift	2002	2010	2020	2030	2040	2050
550	2030	None	4%	6%	10%	13%	-	-
550	2050	None	8%	13%	20%	26%	32%	39%
550	2030	2.7	11%	17%	27%	34%	-	-
550	2050	2.7	21%	35%	55%	69%	85%	105%
450	2030	None	6%	9%	15%	19%	-	-
450	2050	None	16%	26%	41%	52%	64%	79%
450	2030	2.7	15%	25%	40%	50%	-	-
450	2050	2.7	43%	71%	111%	141%	174%	214%

Within this report, we have posited four scenarios for the UK illustrating possible sectoral responses to the high carbon emissions assumed with our aviation scenario. The analysis has assumed that all nations take responsibility for half of the aircraft emissions of flights arriving in or departing from their airports. It has also been assumed that the 60% target is a commitment to reduce UK emissions absolutely (i.e. without purchase of emissions credits or allowances from elsewhere). With all European nations assumed to be subject to similar carbon reduction requirements as the UK, the options for them to compensate for their growing aviation emissions using internal emissions trading would be severely limited. What would affect the validity of the analysis more substantially would be the existence of a global emissions trading system that could accommodate the short-term scale of increase in the aircraft emissions in both our scenario and the government's forecast. While such analysis is beyond the scope of this study, the potential for reconciling medium to long-term aviation emissions growth, a global economic growth of over 4%

[26] See note in italics with regard to uplift factors under section 6.5

per year and climate change targets at 550ppmv or below must be in doubt. Clearly this is a matter that even within a global emissions trading system, requires urgent investigation.

The application of the IPCC average uplift factor of 2.7[27] significantly increases the aviation industry's proportion of human-induced climate change. Uplifted EU aviation emissions alone would exceed the 550ppmv contraction and convergence target for the EU by 2050, leaving no emissions space for any other sectors. Even by 2030, application of the 2.7 uplift factor shows aircraft taking 34% of the EU carbon allowance under the 550ppmv regime and 50% for the 450ppmv regime. As it appears unlikely that any alternative to kerosene as an aviation fuel will be in widespread use by 2030, permitting these emissions would require either major changes to EU energy supply and consumption or a commensurate purchase of emissions credits from elsewhere in the world. As the latter is likely to be an attractive option to the aviation industry (given ICAO's support for an open emissions trading system), due consideration must be given to the potential disadvantages to those sellers of emissions credits in a relatively low state of economic development. These disadvantages would particularly pertain if a government were attracted by the prospect of immediate foreign revenue as apposed to longer term economic development. If aviation emissions were to be offset through the use of the Clean Development Mechanism, and/or Joint Implementation, then partners of lower economic development would need to ensure that all investments supported key development priorities, as such, trade would effectively forgo their future ability to emit.

7.1.2 Implications of aviation growth in the UK

Turning to the situation within the UK, Figure 2 shows emissions under the aviation growth scenario developed here as 21MtC by 2030 and 32MtC by 2050. As Figure 3 illustrates, under a contraction and convergence regime oriented to 550ppmv – equivalent to the government's 60% target – the UK is required to reduce its emissions from around 155MtC today to around 65MtC by 2050.

Our scenario, based on historical and then maturing passenger growth trends, shows aviation emissions exceeding the 450ppmv target by 2050, and representing 50% of the 550ppmv target by 2050 (Figure 9 and Table 8).

[27] Please see preceding caveats on uplift methodology.

Table 8: Proportion of UK emissions from aviation relative to 2030 and 2050 contraction and convergence targets for 550ppmv and 450ppmv (Tyndall Calculations)

Stabilisation target (ppmv)	Relative year	Uplift	2002	2010	2020	2030	2040	2050
550	2030	None	7%	10%	14%	17%	-	-
550	2050	None	12%	18%	27%	33%	40%	50%
550	2030	2.7	18%	27%	38%	47%	-	-
550	2050	2.7	34%	50%	72%	88%	109%	134%
450	2030	None	10%	14%	21%	25%	-	-
450	2050	None	25%	38%	54%	67%	82%	101%
450	2030	2.7	26%	39%	56%	68%	-	-
450	2050	2.7	69%	102%	146%	180%	221%	272%

If however, emissions were to stabilise at 2030 values, as assumed in the UK government forecasts, then the aviation industry would account for 67% of the 450ppmv target by 2050, and 33% of the 550ppmv target by 2050. Moreover, it is clear that if an uplift factor is used[28], this significantly affects the proportion of 'permissible' emissions taken up by the UK aviation industry. For example, by 2030, uplifted emissions account for 88% of the 550ppmv target for 2050. According to our scenarios, the uplifted emissions (at 2.7) exceed the 550ppmv profile for the UK by 2046. If this growth continued at our assumed rate for a mature aviation sector of 3.3% per annum to 2050, the UK would not be able to reach its 60% target within a closed UK system if the IPCC's (1999) average uplift factor were applied.

Table 9 summarises the implications of the DfT's own emissions projections for UK aviation. Relative to a 550ppmv (carbon only) contraction and convergence profile, the non-uplifted 2030 value of 18MtC would take up 14% of the permissible emissions quota in that year. By 2050, the UK government's figures show that an equivalent of 27% of the contraction and convergence target for 550ppmv would be used by the aviation industry. If the lower stabilisation target of 450ppmv is chosen, then this figure would be 54%. If these figures were then uplifted by a factor of 2.7[30], by 2050 the aviation industry would take an equivalent of 72% of the 2050 target for 550ppmv, or exceed the 450ppmv target prior to 2020.

[28] Please see preceding caveats on uplift methodology.

Table 9: Proportion of UK emissions from aviation relative to 2030 and 2050 contraction and convergence targets for 550ppmv and 450ppmv (DfT projections, central case)

Stabilisation target (ppmv)	Relative year	Uplift	2000	2010	2020	2030	2040	2050
550	2030	None	7%	9%	12%	14%	-	-
550	2050	None	14%	17%	23%	27%	28%	27%
550	2030	2.7	19%	24%	33%	39%	-	-
550	2050	2.7	37%	45%	62%	74%	76%	72%
450	2030	None	10%	13%	18%	21%	-	-
450	2050	None	28%	34%	47%	55%	57%	54%
450	2030	2.7	28%	35%	48%	57%	-	-
450	2050	2.7	74%	91%	126%	149%	155%	147%

7.1.3 Inferences from the multi-sector UK scenarios

With the aviation industry expanding throughout Europe, in conjunction with a contraction limit on the emissions space available for all the sectors of the economy, there would need to be substantial trade-offs with other sectors within and/or outside Europe. The multi-sector scenarios developed within this report assume that the UK is required to achieve a 60% reduction in its absolute[29] emissions. Consequently, all of the other sectors of the economy must significantly decarbonise to allow the aviation industry to grow and to continue to use kerosene up to 2050. As the scenarios demonstrate, this decarbonisation of the sectors may be through either a reduction in energy consumption or the adoption of a lower carbon energy supply. An immediate and dramatic increase in investment in renewable energy, carbon capture and storage, nuclear power, hydrogen and energy efficiency is required for all of the scenarios if aviation emissions are to be both permitted and accommodated; this being greater for those scenarios with higher energy consumption. Similarly, all of the scenarios require very significant improvements in energy efficiency, with this being greater for the low demand than high demand scenarios.

[29] The latest scientific date combined with full consideration of the basket of six gases suggests the more appropriate target associated with the 2 degree centigrade temperature rise is nearer to 450ppmv than 550ppmv. That is an 80%+ reduction in carbon emissions for the UK. Consequently the 60% target used here could also be assumed to permit a 20% 'reduction through trading' if the 450ppmv carbon dioxide concentration is assumed to relate to 2 degrees centigrade.

Appendix

Appended below is supplementary and summary information relevant to the study.

(A) Summary of 2030 UK Aviation Emissions Forecasts and Scenarios

Table 10 shows the sensitivity of the emissions forecasts and scenarios to assumptions regarding efficiency improvement, passenger demand growth and radiative forcing uplift factor. Over an approximately fifty-year period, relatively small fractions compound to give substantially different results. Mid-range or base-case values are given in Table 10; in some cases authors provide a range of values. Comments are overleaf.

Table 10a: 2030 UK aviation emissions forecast by DfT (aviation White Paper and DfT, 2004 central case)

Source	UK total carbon emissions 2030 (MtC)	Passenger numbers, 2030 (mppa)	Annual fuel efficiency assumptions up to 2050	UK aviation carbon emissions 2030 (MtC)	UK aviation carbon emissions as % of total UK 2030	Radiative forcing (uplift) factor	Uplifted UK aviation emissions 2030 (MtC)	Uplifted UK aviation emissions as a % of total UK 2030
Aviation White Paper, 2003	99 *(60% contraction)*	480	1%	17.7	18%	0	-	-

Table 10b: Summary of Tyndall 2030 UK aviation emissions scenarios

Source	UK total carbon emissions 2030 (MtC)	Passenger numbers, 2030 (mppa)	Annual fuel efficiency assumptions up to 2050	UK aviation carbon emissions 2030 (MtC)	UK aviation carbon emissions as % of total UK 2030	Radiative forcing (uplift) factor	Uplifted UK aviation emissions 2030 (MtC)	Uplifted UK aviation emissions as a % of total UK 2030
Tyndall, 2005 (550ppmv)	122	475	1.2%	21.3	17%	2.7	57.6	47%
Tyndall, 2005 (550ppmv)	122	475	1.2%	21.3	17%	3.5	74.6	61%
Tyndall, 2005 (450ppmv)	83.6	475	1.2%	21.3	25%	2.7	57.6	69%
Tyndall, 2005 (450ppmv)	83.6	475	1.2%	21.3	25%	3.5	74.6	89%

Table 10c: Summary of 2030 UK aviation emissions scenarios/forecasts: associated research

Source	Total carbon emissions for UK in 2030 (MtC)	Passenger numbers in 2030 (million pass per annum)	Annual fuel efficiency assumptions up to 2050	Aviation carbon emissions for UK in 2030 (MtC)	Aviation carbon emissions as % of total UK in 2030	Radiative forcing (uplift) factor	Uplifted aviation emissions for UK in 2030 (MtC)	Uplifted aviation emissions as a % of total UK in 2030
Halcrow, 2002	-	478	0.2% *(implicit, operational)*	21	-	-	-	-
Treasury/DfT, 2003 (*Aviation & the Environment)*	135 *(2020; no contraction)*	480	0.2% *(implicit, operational)*	19	14%	2.5	47.0	35%
Upham, 2003	100 *(60% contraction)*	480	0.2% *(implicit, operational)*	21	21%	2.7	56.2	56%
Köhler et al., 2004	100 *(60% contraction)*	480	0.2% (implicit, operational)	21	21%	2.7	56.2	56%
DfT, 2004 (*Aviation and global warming)*	99 *(60% contraction)*	480	1%	17.7	18%	2.5	43.8	Premises queried
EAC, 2004 (3rd report, 2003-4 session)	99 *(60% contraction)*	475	1%	17.7	18%	2.5	44.6	45%

Notes for Table 10c

1. Somewhat belatedly with respect to the timescale of the aviation White Paper, Halcrow (2002, sec.8.1.3, p.93) were commissioned by Department of the Environment Food and Rural Affairs (DEFRA) to estimate the emissions implications of two cases of carbon dioxide emissions for the whole UK air transport system: (i) a base or constrained case of no new runways anywhere in the UK, and (ii) three new runways in the SE, and unconstrained capacity in the regions (Halcrow, 2002, Table 8.3, p.103). Their emissions projections are summarised in Table 8.9 of Halcrow (2002). The implicit operational efficiency is a result of assuming use of great circle routes (DfT, 2004, 3.10).

2. The Treasury and DfT (2003, paragraph 3.11, p. 12 and Table C.1, p. 21) used Halcrow's estimates for the high capacity case (which, at 480mppa, actually approximates to the level of growth supported in the aviation white paper).

3. Upham (2003) derived the same emission values for 2000 and 2020 from the same Halcrow estimates, but used the high capacity case (480mppa, circa the level of demand supported by the aviation white paper) for 2030 (DfT, 2003, Table D.6), not the average of the two cases apparently used by the Treasury/DfT. The value for non-contracting UK total 2030 carbon dioxide was assumed to be equal to the 2020 central low estimate of aggregate UK emissions given in Table 7.1 of DTI (2002).

4/5. *Aviation and Global Warming* by DfT was not publicly available prior to issue of the *Future of Air Transport* White Paper, but nevertheless informs the white paper estimates of aviation carbon dioxide emissions. DfT's revision states that it takes account of the upper range of technological improvement forecasts by IPCC (1999) and ACARE (Advisory Council for Aeronautical Research in Europe – see RCEP, 2002, for a comparison of IPCC and ACARE estimates for technological improvement). These envisage up to a 50% improvement in fleet fuel efficiency between 2000 and 2050. DfT views the Energy White Paper target as relating to domestic emissions only and queries the legitimacy of excluding international aviation emissions from that baseline prior to calculation of a contraction profile. It also states that the emissions allocation method used elsewhere in the Table (50:50 to origin and destination) is an analytical convenience not an international agreement.

6. The House of Commons Environmental Audit Committee (2004a, p.23-4) used DfT's (2004) revised aircraft carbon emissions estimates for consistency, while stating that it does not necessarily share its assumptions of improved engine technologies being in use up to 2030.

(B) Maximum numbers of 2030 UK flights
Table 11 provides an indication of the 'maximum' number of flights that might be associated with UK aircraft emissions in 2030, assuming no infrastructure constraints. Section (1) shows how the number of 2030 air traffic movements in the Tyndall scenario for the UK might be reduced with an increase in aircraft size and load factor (1). Parts (2) and (3) of Table 11 repeat this, showing the maximum number of UK 2030 flights possible under 550 and 450ppmv if all UK 'emission space' were made available for aircraft, again with and without an increase in aircraft size and load factor. The maximum numbers of flights in sections (2) and (3) have been calculated by scaling up the number of historically-based flights in section (1) of the Table by the relationship of total permissible 2030 emissions to the emissions anticipated in the historically-based Tyndall scenario. Thus the number of 2030 flights in each row of section (1) of the Table is multiplied by the ratio of 2030 aircraft emissions in the main Tyndall scenario (based on historical and then mature growth rates) to total UK 2030 emissions permissible under 550 and then 450ppmv.

For example:

Number of 2030 UK flights possible under 550ppmv, when the number passengers per flight is 105 = 5,858 x 122/21.3 = 33,553

Table 11: Air traffic movement scenarios

Aviation scenario (passengers/flight)	**Projected UK 2030 flights**
1. Other sectors also emitting	
Passengers/flight remains at today's levels (105)	5,858
Plane size increased by 20% (126)	4,882
Load factor increased by 20% (126)	4,882
Both plane size and load factor increased by 20% (152)	4,047
2. Aviation taking all emissions space under the 550ppmv scenario	
Passengers/flight remains at today's levels (105)	33,553
Plane size increased by 20% (126)	27,963
Load factor increased by 20% (126)	27,963
Both plane size and load factor increased by 20% (152)	23,180
3. Aviation taking all the emissions space under the 450ppmv scenario	
Passengers/flight remains at today's levels (105)	22,992
Plane size increased by 20% (126)	19,162
Load factor increased by 20% (126)	19,162
Both plane size and load factor increased by 20% (152)	15,884

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