Tyndall°Centre
for Climate Change Research

A bottom-up analysis of including aviation within theEU's Emissions Trading Scheme

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Abstract
European nations agree they must tackle escalating greenhouse gas emissions arising from energy consumption. In response, the EU has set an emission reduction target for 2050 chosen to correspond with stabilising the atmospheric concentration of greenhouse gases at a level likely to avoid 'dangerous climate change' or to not exceed a 2ºC rise above pre-industrial levels. By selecting a target related to *global* greenhouse gas concentrations, governments have, perhaps inadvertently, accepted such targets must include *all* greenhouse gas-producing sectors. Furthermore, aiming for a target percentage reduction by a particular date neglects the crucial importance of cumulative emissions. By addressing these two issues, this analysis quantifies the contribution of the aviation industry to future EU climate change targets. Moreover, it assesses the implications of including aviation within the EU's emissions trading scheme. Results indicate that unless the scheme adopts both an early baseline year and an overall cap designed to be in keeping with a 450ppmv cumulative emission pathway, the impact on aviation emissions will be minimal.

1. Introduction
European nations agree they must tackle escalating greenhouse gas emissions arising from energy consumption. In response, several nations have set emission reduction targets for future years. In theory at least, these targets are chosen to correspond with stabilising emissions at levels that are likely to avoid 'dangerous climate change'.

1.1 Global climate targets
Although there is no scientific consensus for what is considered to be 'dangerous' in relation to climate change, it is broadly accepted by the policy community that this relates to global mean surface temperatures not exceeding 2ºC above pre-industrial levels. The European Commission acknowledges that stabilising long-term greenhouse gas concentrations at 450ppmv CO_2eq provides around a 50% chance of ensuring global mean temperatures do not exceed the 2ºC threshold (COMM, 2007). In response it has set an aspirational target of reducing greenhouse gas emissions by 60%-80% by 2050 from 1990 levels by apportioning global emissions to EU nations.

By selecting a target related to *global* CO_2eq concentrations, governments have, perhaps inadvertently, accepted such targets must include *all* greenhouse gas-producing sectors. Furthermore, aiming for a target percentage reduction by a particular date neglects the crucial importance of cumulative emissions. By addressing these two issues, this analysis quantifies the contribution of the aviation industry to future EU climate change targets. Moreover, it assesses the implications of including aviation within the EU's emissions trading scheme. Results indicate that unless the scheme adopts both an early baseline year and an overall cap designed to be in keeping with a 450ppmv cumulative emission pathway, the impact on aviation emissions will be minimal.

1.2 Aviation trends

The air transport market within the EU25 nations continues to grow rapidly. Passenger numbers in 2005 exceeded 700 billion, with an 8.5% increase on the previous year's figures (De La Fuente Layos, 2007)[1], illustrating a resurgence of the industry following the events of September the 11th 2001. Inseparable from this resurgence is the continued high levels of growth in carbon dioxide emissions from the industry. Although nations are not required under Kyoto to publish their CO_2 emissions from international aviation within their national inventories, this data is submitted alongside as a memo. Combining the CO_2 emissions from domestic and international aviation provides an estimated CO_2 emission growth rate for the EU's aviation industry of 7% between 2003 and 2004 and 6% between 2004 and 2005. These rates of growth are similar to those produced by the industry since 1993, with the exception of the period affected by the events of September 11th 2001. This rapid growth in emissions, coupled with limited opportunities for other than incremental improvements in fuel efficiency, at least in the short- to medium-term, gives rise to the concern that as EU nations strive to reduce CO_2 emissions, aviation will be responsible for an increasing share of the EU's total.

1.3 EU emissions trading scheme

The EU's emissions trading scheme (EU ETS) began operating in 2005, with the first phase of the scheme complete by the end of 2007. The scheme initially involved some 12,000 installations covering energy activities that exceeded 20MW, as well as a number of process emission activities amounting to around 45% of the EU's CO_2 emissions. The second and expanded phase of the EU ETS began in 2008, and, in recognising the growing issue of emissions generated by the aviation industry, the EU are currently discussing including aviation within the scheme by 2012.

The proposal suggests including all departures and arrivals from EU nations with the aim of internalising some of the costs of the environmental impact of the aviation sector. To explore the implications of aviation's inclusion within the scheme, this paper presents a suite of aviation emission scenarios and compares them with the EU's overall carbon budget.

2. Carbon budgets

One of the key variables of interest to those involved in climate change mitigation and adaptation is the global mean temperature change due to the increase in atmospheric greenhouse gas concentrations. However, there is both confusion and uncertainty as to the relationship between greenhouse gases and the likely resultant temperature change. Some of this confusion stems from errors in the translation of the science into policy. For example, many UK policy documents refer to 550ppmv CO_2 'alone' being related to the 2°C threshold, when in fact the original work carried out by the UK's Royal Commission on Environmental Pollution (RCEP) linked 550ppmv CO_2 equivalent[2] (CO_2 eq) to this temperature change (RCEP, 2002). Uncertainty, on the other hand, stems from the inherent range of outputs given by climate models in assessing the impact of altering the atmospheric concentration of greenhouse gases, and the variety of model results available. The methods used in the analysis presented here are consistent with those within '*Living within a carbon budget*' (Bows et al., 2006b), and relate an atmospheric concentration of CO_2 alone and the 2°C temperature threshold, based the work of Meinshausen (Meinshausen, 2006).[3]

The EU has adopted a target of global mean surface temperatures not exceeding a 2°C rise above pre-industrial levels. To achieve this, recent studies illustrate that a 450ppmv CO_2 eq stabilisation level will provide a reasonable probability of not exceeding this 2°C threshold (Meinshausen, 2006). There are therefore a number of important issues to be addressed in

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[1] The latest figures for passenger growth are for the EU27 nations, and are therefore not comparable with the EU25 figures. However, these indicate a 5% growth compared with the previous year (De La Fuente Layos, 2008)

[2] Equivalent relates to the inclusion of the basket of six greenhouse gases

[3] The reasoning behind investigating CO_2 alone can be found in section 2.1 of (Anderson et al., 2007)

relation to the EU's climate change target and in turn how such targets relate to the aviation industry.

The first point to be considered is the ultimate aim of the target – ie for temperatures to not exceed the 2°C threshold. This threshold is associated with atmospheric CO_2 eq levels relating to different probabilities of exceeding 2°C. This type of methodology therefore assumes that all greenhouse gas-producing sectors are included, as the atmosphere does not 'see' what is or is not accounted for. In addition, it assumes that all nations globally comply with the emission reductions required. The Kyoto Protocol and the UK's climate change bill omit international aviation and shipping from their targets. For the EU, it is ambiguous as to whether or not these sectors are or are not included within current policy. If these sectors currently contribute insignificant amounts of greenhouse gases, it might be reasonable to omit them at this stage. However, the data strongly indicates that this is not the case for the aviation sector. Therefore, to institute climate policy that is both proportionate and sufficient to address the issues, there is a need to account for the emissions from international sectors that are, or may in the future represent, a significant proportion of a nation's total emissions.

Secondly, in considering how best to develop a carbon trajectory for a 2°C target, it is important not to become overly focussed on choosing a convenient percentage reduction by a future date. It is the cumulative emissions that are more influential in reaching a desired greenhouse gas concentration than the emission pathway taken (Jones et al., 2006). This is a point that, although very significant, is often overlooked by governments. Accordingly, delaying action to mitigate emissions requires more stringent measures to avoid exceeding the 2°C threshold than is generally recognised (Anderson & Bows, 2008; Bows et al., 2006b; Stern, 2006). The danger of failing to adequately account for the cumulative emissions issue in policymaking is that the resulting policies will be overly focused on the longer-term issues (and hence address energy supply), when in fact it is the short-to-medium term (and hence energy demand) that is of crucial importance [(Bows et al., 2006b): 20]. Clearly, a policy that is out of balance with the variables which it seeks to regulate will not be an efficient policy and may fail.

A third point relates to carbon-cycle feedbacks. These feedback mechanisms have only recently, and still partially, been incorporated in climate change emission budget studies, and are shown to have a very significant effect on the carbon budgets available [(IPCC, 2007): 17]. Carbon budgets that include feedback mechanisms can be some 20% smaller than those that omit feedbacks (Matthews, 2005).

To derive a cumulative carbon budget range for the EU, it is necessary to apportion the global cumulative CO_2 emissions to nations using a modified form of the Contraction & Convergence (Meyer, 2000) approach. The global carbon budgets within Table 1 are taken directly from the IPCC's cumulative carbon budget range presented in (IPCC, 2007) and represent the outer boundaries of the range compatible with a 450ppmv stabilisation derived from a series of modelling studies employing a variety of different global climate models.

Table 1: Global and EU cumulative carbon budgets

Scenario	Global cumulative emissions[4] $GtCO_2$ (1990-2100)[5]	EU cumulative emissions $GtCO_2$ (1990-2100)
450 Low	1431	160
450 High	2257	212

[4] Not including forestry
[5] Taken from IPCC, 2007 page 17

This provides a cumulative carbon budget range for the EU, but it is also desirable to be able to understand the impact of this budget on the EU's pathway to a low-carbon future. This is achieved by firstly considering those emissions released for the years 2000-2005, incorporating current EU emission trends, and finally by constraining the pathway to remain within budget. The importance of using empirical data for the period between 2000-2005 cannot be overstated. When considering the cumulative carbon budget, nations emitting at high levels today are 'spending' their budgets very rapidly. As such, those emissions occurring between 2000 and 2005, and also for the short term future, will have a significant impact on the range of pathways available into the longer term. For example, in the case of the '450 High' scenario in Table 1, the emissions represent ~14% of the total budget in just 4 of the 50 years (i.e. 14% spent over only 8% of the timescale).

Emission pathways for the cumulative emissions for the EU from Table 1 are presented in Figure 1; the higher the cumulative target, the easier it is to manoeuvre in later years with the converse true for lower cumulative targets. Hence any policy aiming for levels at or lower than '450 Low' must both stabilise emissions urgently and maintain significant year-on-year reductions for three decades, to allow sufficient 'room for manoeuvre'.

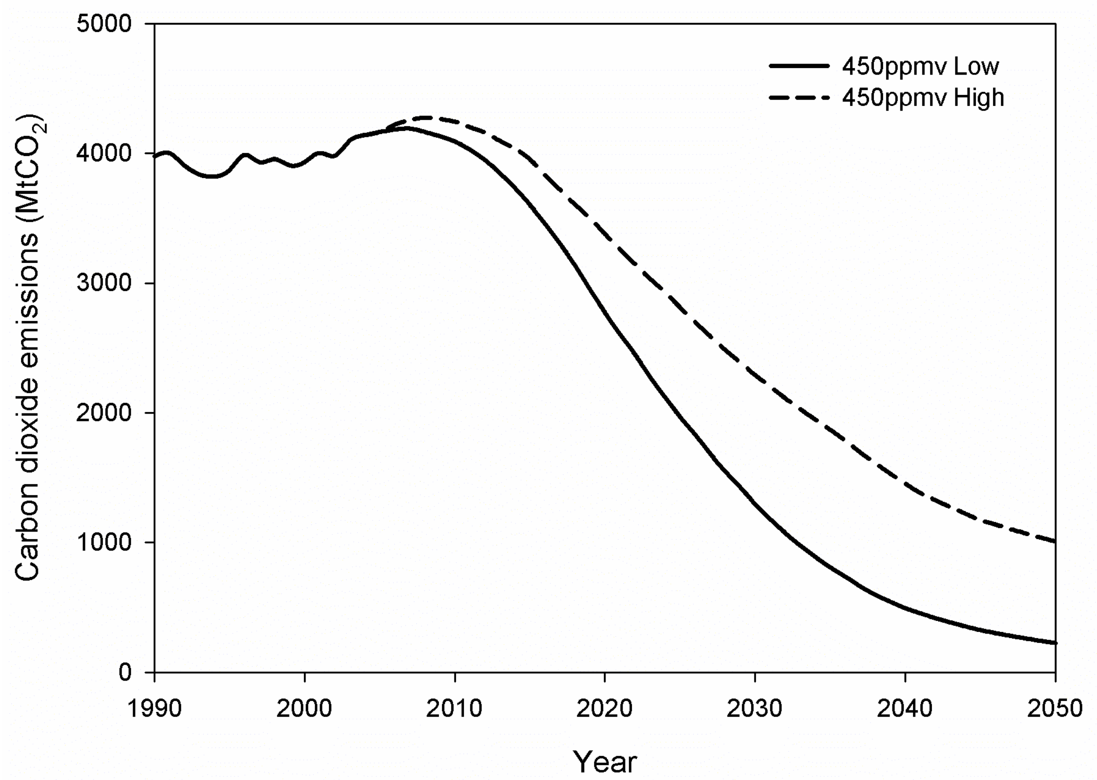

Figure 1: 450ppmv cumulative CO_2 emission profiles for the EU25

3. Aviation emission scenarios

It has been widely publicised that the aviation sector's emissions are growing more rapidly than any other sector in the UK. This is also true for the EU25. Figure 2 presents the CO_2 emissions from the aviation sector in the EU25 from 1993 to 2005.

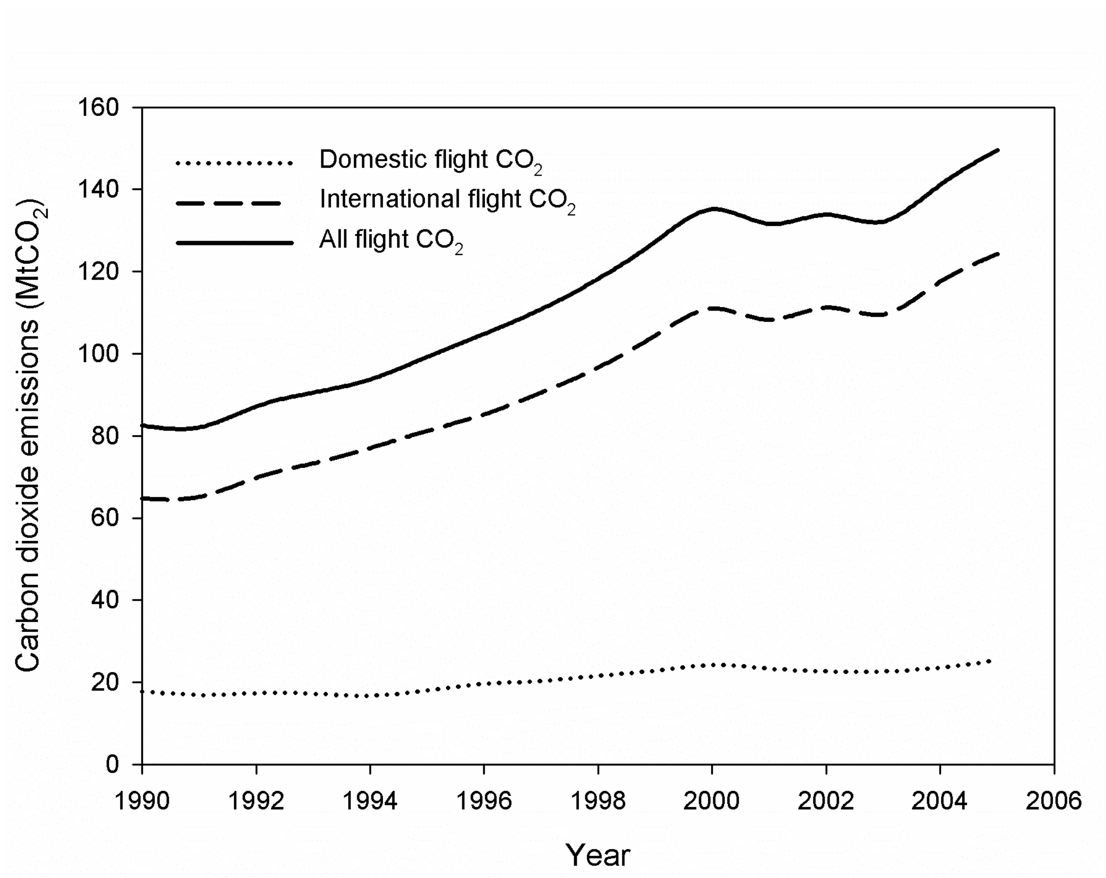

Figure 2: CO_2 emissions from the EU25's aviation sectors, from data submitted to the UNFCCC in 2007 (UNFCCC, 2007). The data incorporates estimates for Greece and Malta in 2005 due to an absence of data. Although not all of the EU25 were in the EU from 1990, all of the nations have been included in the totals from the outset.

The emissions from international flights clearly dominate. CO_2 emissions from domestic flights have increased at an average of 2.5% per year since 1990 while the corresponding figure for international flights is 4.5%. However, the events of September 11th 2001 had a marked impact on the growth rate of aviation emissions as illustrated. If the period between 1990 and 2000 is assessed, domestic aviation's annually averaged CO_2 growth was 3.2%, with international air travel at 5.6%.[6] From 2003 to 2004, and 2004 to 2005, the total amount of CO_2 from the EU25's aviation industries increased by 7% and 6% respectively.

In addition to emitting CO_2, aircraft release soot and water vapour that lead to the formation of contrails and possibly cirrus clouds, and NO_x emissions which acts as a precursor for ozone formation and methane depletion. All of these emissions alter the radiative properties of the atmosphere either globally, in the case of well-mixed greenhouse gases (this does not include ozone), or at a local level in relation to contrails and cirrus clouds. However, there is much debate over the appropriate metric to account for these additional impacts. One metric that has been used to calculate the total impact on the climate of these emissions (in addition to CO_2) is radiative forcing. Radiative forcing is the total globally and annually averaged impact of anthropogenic emissions on the climate in terms of Watts per square metre (Wm^{-2}) in relation to an assumed zero Wm^{-2} in pre-industrial years (1750). For total global anthropogenic activities – ie from all sources, the figure stands at 1.6 Wm^{-2} (IPCC, 2007). If this metric is applied to the aviation sector, the emissions of CO_2, NO_x and contrails amount to a total radiative forcing impact in the year 2000 of around 0.048 Wm^{-2} [7](Sausen et al., 2005).

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[6] This period also incorporated the first gulf war, which understandably impacted on the industry.

[7] This figure does not include contrail-induced cirrus cloud

Whilst this metric has a clear role to play in the scientific analysis of climate change, it has limitations for developing current and future mitigation policies. Radiative forcing is often used to relate the CO_2 impact to the impact from NO_x and contrails through the use of an 'uplift factor' developed initially by the IPCC, (Penner et al., 1999) and since updated (Sausen et al., 2005). However, radiative forcing compares the impact of emissions from 1750 to date, to illustrate the historical impact of the different sectors on the overall temperature rise. When using it to look at future impacts, this measure can lead to inappropriate policy messages if it guides policy mitigation. Furthermore, the metric could lead to unhelpful policy conclusions in certain situations. For example, if applied to shipping emissions, the policy conclusion may be to increase the sulphur emissions from ships to mitigate the warming caused by their release of CO_2 emissions[8]. Consequently, the cumulative approach is more useful in the context of this research, given its importance in policy terms. Therefore, to be consistent with the cumulative carbon budget approach being taken here, the analysis of the aviation sector will address CO_2 alone, requiring no additional metric.

3.1 Aviation emission baselines

To include aviation within the EU ETS, the Commission propose a baseline above which the industry must buy emission allowances be placed at the 2004-2006 level. In other words, any CO_2 emitted above the 2004-2006 level will need to be purchased by the industry from the market. However, the UK Government has also explored the possibility of employing alternative baseline dates.

To illustrate the impact of the baseline date choice, three different baselines are explored here – one for 1990, one for 2000 and one for 2005. Aviation scenarios for the short-term period of 2006-2012 are compared with these baselines to illustrate the levels of emissions needed to be purchased if all departing and arriving flights are included within the scheme. Following on from this, a suite of aviation scenarios from 2013 to 2050 commensurate with a world striving to live within the 450ppmv carbon budget are developed. These scenarios incorporate a range of growth rates and assumptions related to fuel efficiency and, in the longer term, the inclusion of alternative low-carbon fuels. The cost implications of these different scenarios under a range of carbon allowance prices is considered for selected exemplar flights. Finally, the aviation scenarios are compared with the overall 450ppmv carbon budget for the EU25.

To develop the scenarios, the baselines must be quantified. One important distinction to make at this stage is the difference between the CO_2 baselines for emissions submitted to the UNFCCC, and the emissions that will be included in the EU ETS. For the UNFCCC, domestic aviation's CO_2 is submitted separately from the CO_2 from international aviation (where domestic aviation refers to flights within a nation, and international for flights from one nation to another). The latter broadly approximates to 50% of all flights to and from each nation within the EU to either another EU nation or an extra-EU nation. Therefore, the total domestic and international CO_2 for aviation submitted to the UNFCCC is an estimate of the CO_2 associated with all domestic flights within the EU25 and 50% of international flights to and from EU nations, giving a baseline for 2005 of 150MtCO_2; 25MtCO_2 from domestic and 125MtCO_2 from international. However, to incorporate aviation within the EU ETS, the Commission proposes CO_2 emissions from *all* departures and arrivals from and to EU nations are included. Therefore, the UNFCCC data alone is not sufficient but requires supplementary information to form the baseline. This is because it is not appropriate to simply double the CO_2 emissions submitted to the UNFCCC to account for these additional flights, as double counting for domestic and intra-EU flights will occur. The EU ETS baseline is therefore higher than the 2005 UNFCCC baseline, standing at some 225MtCO_2 in 2005. The method used to derive this alternative baseline uses empirical data for UNFCCC international and domestic flights in addition to some model data (Wit et al., 2005) to calculate those flights associated with intra-EU flights. This data is modelled because aggregated information for intra-EU flights is not currently submitted to the UNFCCC. The breakdown of EU aviation CO_2 emissions are presented in Table 2 for baselines in 1990, 2000 and 2005. For more information on the method see section 3.1 in (Anderson et al., 2007).

[8] This is a conclusion that was referred to during a Waterfront Shipping meeting with industry stakeholders.

Table 2: CO_2 emissions from all flights that either depart or arrive in the EU

UNITS: $MtCO_2$	Data type	1990	2000	2005
UNFCCC international aviation bunker CO_2[9]	Empirical	64.8	111.0	124.3
UNFCCC domestic aviation CO_2	Empirical	17.8	24.2	25.3
Intra EU flight CO_2 (EU to EU, not domestic)	Modelled	19.3	36.0	40.2
EU to EU ultra peripheral regions CO_2	Modelled	4.8	8.9	8.1
EU to EU overseas countries & territories CO_2	Modelled	0.5	0.9	0.9
Derived starting aviation CO_2 value	Empirical & model	**122.8**	**200.4**	**224.7**

3.2 Short-term

Following the baseline quantification, aviation scenario development requires quantification of the aviation CO_2 from now until the estimated commencement date of the revised scheme (2012). A number of assumptions are made leading to a range of growth rates. In addition to available passenger number and CO_2 data, factors influencing the choice of scenarios include:

** The current continued success of the low-cost air model;
** Access to a network of growing regional airports;
** The low-cost model extending in modified form to medium and longer-haul routes;
** No significant economic downturn between the 2005 data and 'today' (2007); and
** High growth routes between the EU and industrialising nations.

For the years from 2006 to 2012, recent and longer-term trend data significantly influences the choice of scenarios. According to the submissions to the UNFCCC, there has been a long-term trend of increasing CO_2 emissions from EU25 nations of the order of 6% per year. More recent emissions have also increased at 6% per year, once allowance is made for the period affected by the events of 11th September 2001. Reinforcing this 6% figure is Eurocontrol's forecast of strong growth for 2007-2008 (EUROCONTROL, 2007). The range of scenarios considered for the period from 2006 to 2012 therefore uses 6% annual emission growth as a mid-range value, with 4% for the lower-range and 8% for the higher-range. Assuming no radical step changes in the short-term, the scenarios all use a 1% per year improvement in fuel efficiency across the fleet for this short-term period.

[9] 2007 submission (UNFCCC, 2007)

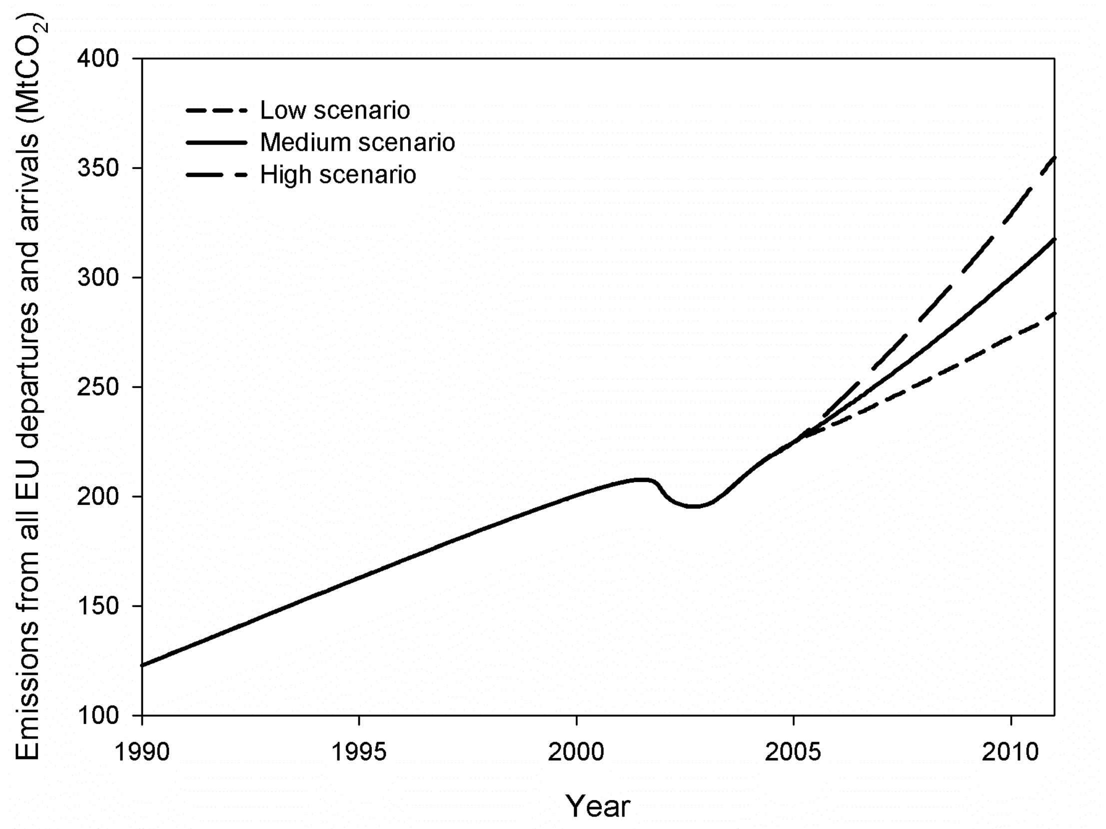

Figure 3: Aviation CO_2 emissions for all departures and arrivals under a range of growth rates. This range is the same as that applied to the UNFCCC data presented in

Based on these scenarios, by the end of 2011, the aviation sectors emissions range between around 284 and 355 $MtCO_2$, (Figure 3). Of the three initial baselines of 1990, 2000 and 2005 for aviation emissions considered here (Table 2), Table 3 presents the allowances that need to be purchased in 2012.

Table 3: Emissions allowances to be purchased in 2012 under the range of Tyndall scenarios

Baseline year	Emissions in baseline year ($MtCO_2$)	Emissions in 2012 ($MtCO_2$)	Emissions to be purchased ($MtCO_2$)
1990	123	284 - 355	161-232
2000	200	284 - 355	84-155
2005	225	284 - 355	59-130

The earlier the baseline year, the more allowances must be purchased by the industry. In fact, the aviation sector has grown so significantly since 1990 that the emissions allowances required by 2005 under the 1990 baseline are in excess of the total amount of emissions released in 1990. The range is somewhat lower for the 2005 baseline, where between 59 and 130 million allowances must be purchased by the industry. The cost to the industry will depend on the price of carbon on the market and will be discussed in the next section.

3.3 Medium to long-term

In considering aviation emission scenarios for the medium (2017-2030) to long-term (2031-2050), not only must a range of assumptions be made in relation to the aviation industry, but attention must also be paid to the overarching EU policy climate.

In aiming for a 450ppmv stabilisation level, it is assumed that:

** The EU adopts a comprehensive and scientifically literate basis for its climate policy derived from a cumulative carbon budget approach;
** It has a complete account of all sectors; and
** It uses a Contraction and Convergence regime for emission apportionment.

From 2011 onwards, three suites scenarios commensurate with 450ppmv are considered alongside one illustrative suite outside of the 450ppmv regime. Given that the core scenarios are required to be commensurate with the cumulative emissions budget for 450ppmv, the sooner the EU responds, the less demanding will be the emissions pathway from that point onwards.

Future aviation emissions are subject to a number of factors including the rate of growth in the short, medium to long-term (i.e. after 2012) and the rate of introduction of new technologies and operational measures that may improve the efficiency and carbon intensity of the industry. Accordingly, building on the three near-term scenarios to 2012 (Figure 3) a series of scenarios that reflect the range of reasonable and optimistic possibilities for the short, medium and long-term are developed. These scenarios are called *Indigo, Aqua, Violet* & *Emerald*.

In each case, the four scenarios are divided into three time periods after 2012:

Short-term	Start of 2012 to the start of 2017
Medium-term	Start of 2017 to the start of 2031
Long-term	Start of 2031 to the start of 2051

All but the *Emerald* scenario are based on an assumption that the EU is committed to meaningful 450ppmv carbon budget, and that aviation will play its part in that process, including a modification to the growth rate. Consequently, all these scenarios assume the significant reductions in the CO_2 emitted per passenger-km flown (CO_2/pax), as presented in Table 4; these combine to give a reduction in CO_2/pax for 2012-2050 of 68.5%. The overarching context of this reduction in carbon intensity is society's explicit and genuine commitment to a 450ppmv pathway.

Table 4: CO_2/pax improvement per period

	Short	**Medium**	**Long**
Mean annual improvement in CO_2/pax	1.5%	2%	4%
Total improvement of the period	7% in 5 yrs	23% in 14yrs	56% in 20 yrs

The *Greener by Design* (Greener by Design, 2005) study highlights a number of areas that could offer substantial improvements in terms of the fuel burn saved per seat km. For example, in the short to medium-term, air traffic management improvements could offer an 8% reduction in fuel burn, open rotor engines could improve fuel efficiency by some 12% and the use of lighter materials such as carbon-fibre could offer an additional 15-65% improvement. In the longer term, laminar flow-type aircraft designs could reduce fuel burn by over 50% and alternative fuels, although generally believed unlikely to be used across the fleet prior to 2030 perhaps even 2050, could play a role to reduce aviation's CO_2 emissions, if the drive towards a low-carbon economy was strong enough. It is the timescale over which the gains in fuel efficiency and the incorporation of low-carbon fuels into the mix can be achieved that is of key importance.

In terms of these Tyndall scenarios, technological improvements in efficiency coupled with a variety of air traffic management and operational changes provide the principal components of the reducing CO_2/pax during the first two periods (2012-2017 and 2018-2030). Typical changes include continued incremental jet-engine improvements and the incorporation of rear-mounted open rotor engines particularly for shorter-haul flights. In addition, improvements are made through airframe modifications to wing design to improve air flow and reduce fuel burn and increasing amounts of lighter materials. It is assumed there will be additional load-factor increases, and a series of efficiency gains across the air traffic management system through more direct routing, reduced taxiing, waiting and circling, and reduced use of the auxiliary power unit.

Fuel switching is considered to be a minor component within the two earlier periods. In the long-term period, fuel efficiency improvements across the fleet continue to be of the order of 2% per year, with the remaining 2% being derived from fuel switching to a low carbon fuel such as biofuel or hydrogen for example. In considering these assumed efficiency savings and the introduction of low-carbon fuels, it must be noted that these reflect a situation where the aviation industry goes well beyond its achievements over the previous two decades. However, such significant improvements to the technical, operational and managerial efficiency of aviation are only considered possible when driven by a concerted effort on the part of the industry (and society) to deliver them.

In terms of drivers for such a change, the three scenarios reflect a society whose focus is very different from that of today. Within this society, low-carbon innovation, not only on aircraft themselves, but in addition in relation to video-conference etc. receives very significant funding and policies would be in place to regulate low-carbon behaviour and operation within companies. The difference in emphasis of this world from ours is central to these scenarios. Therefore it is worth reiterating that the carbon intensity improvements envisaged are well in excess of what has occurred within most fleets in recent times yet in keeping with what is possible (Green, 2005) if the right suite of incentives were in place.

In terms of the other variables reflected in the scenarios, while three of the scenarios all have the same level of carbon intensity improvement, each differs in the rate of passenger growth. These factors combine to produce different emission changes between 2012 and 2050 which, in combination with the range of short-term scenarios, produce a range of possible net CO_2 emissions from aviation.

A fourth scenario (*Emerald*) differs from the others in terms of both passenger growth and technological efficiency improvements. This scenario reflects only partial commitment to both curbing passenger growth rates and instigating the technological efficiency improvements described above, and is highly unlikely to be compatible with a 450ppmv pathway.

Table 5: Scenario passenger-km growth and carbon intensity improvements

Parameter	Scenario	Short	Medium	Long
Annual pass-km growth	*INDIGO*	3%	1.5%	1%
	AQUA	4%	3%	2%
	VIOLET	5%	4%	3%
	EMERALD	6%	5%	3%
Annual CO_2/pax improvement	*INDIGO/AQUA/VIOLET*	1.5%	2%	4%
	EMERALD	1%	1.5%	2%
Annual emissions change	*INDIGO*	1.5%	-0.5%	-3%

AQUA	2%	1%	-2%
VIOLET	3.5%	2%	-1%
EMERALD	5%	3.5%	1%

The scenario emission growth rates are presented in Table 5. *Indigo* is the most responsive to the climate change issue and the EU ETS and shows a significant, comprehensive and early drive towards a low-carbon aviation industry within the EU. The net aviation emission change between 2012 & 2050 equates to a *45% reduction,* though compared with 1990, it still represents a 24%- 55% increase.

In *Aqua*, aviation responds more slowly to the EU ETS scheme, compensated by slightly larger reductions by other sectors. Net aviation emission change between 2012 & 2050 equates to a *16% reduction,* though compared with 1990, it represents a 95% to 144% increase.

In *Violet*, the aviation industry continues to grow its emissions at a higher rate than in the *Indigo* and *Aqua* scenarios at the expense of the other sectors in the EU ETS. The net aviation emission change between 2012 & 2050 equates to a *26% increase,* and compared with 1990, a 184% to 256% increase.

Emerald is an additional scenario used to illustrate a future where the current rhetoric on climate change is only partially converted into meaningful action. Such a future would be more attuned to cumulative emissions associated with much higher CO_2 concentrations and a failure to respond to the 2°C commitment. In this case, the net aviation emission change between 2012 & 2050 equates to a *146%* increase, and compared with 1990, a 278% to 373% increase. Assumptions behind these growth rates include new EU nations expanding their aviation industries towards per capita rates of old EU nations, and a modified version of the low-cost model assumed to extend to medium and long-haul flights. Point-to-point aircraft, in combination with the expansion of regional airports are assumed to provide much quicker and convenient air travel for all. Security becomes less of an obstacle to flying and big improvements in check-in improve the quality of experience for the traveller. Increasing globalisation stimulates more migration and consequently international travel to maintain family ties. In economic terms, world GDP growth continues and the EU's economy grows at 2.5 – 3% p.a. Although it is impossible to paint an accurate picture of a business as usual future for aviation emissions, the *Emerald* scenario represents the closest to an extrapolation of current trends of all the scenarios.

When combined with the three near term growth scenarios (Figure 3), the full scenarios result in nine core scenarios, with a further three for the *Emerald* set. The resulting net CO_2 emissions for all twelve scenarios are provided in Figure 4.

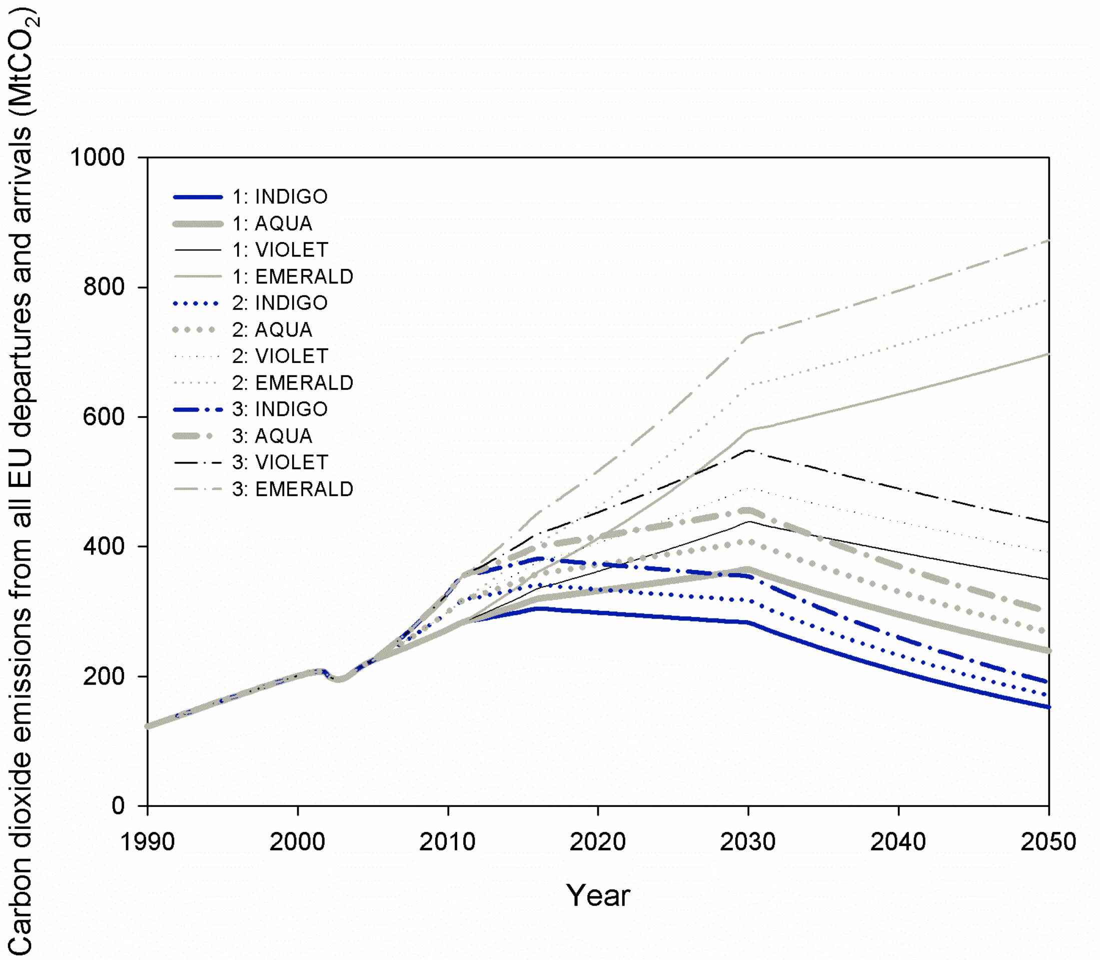

Figure 4: CO_2 emissions from the nine core scenarios (Indigo, Aqua and Violet for pre-2012 near term growth scenarios low-1, medium-2 and high-3) in blues and purples, and the three illustrative higher growth scenarios (Emerald for pre-2012 near term growth scenarios low-1, medium-2 and high-3).

To compare the scenarios with total emissions consistent with a 450ppmv budget, the scenario assumptions are applied to the UNFCCC baseline figure of 150MtCO_2 (Figure 5).

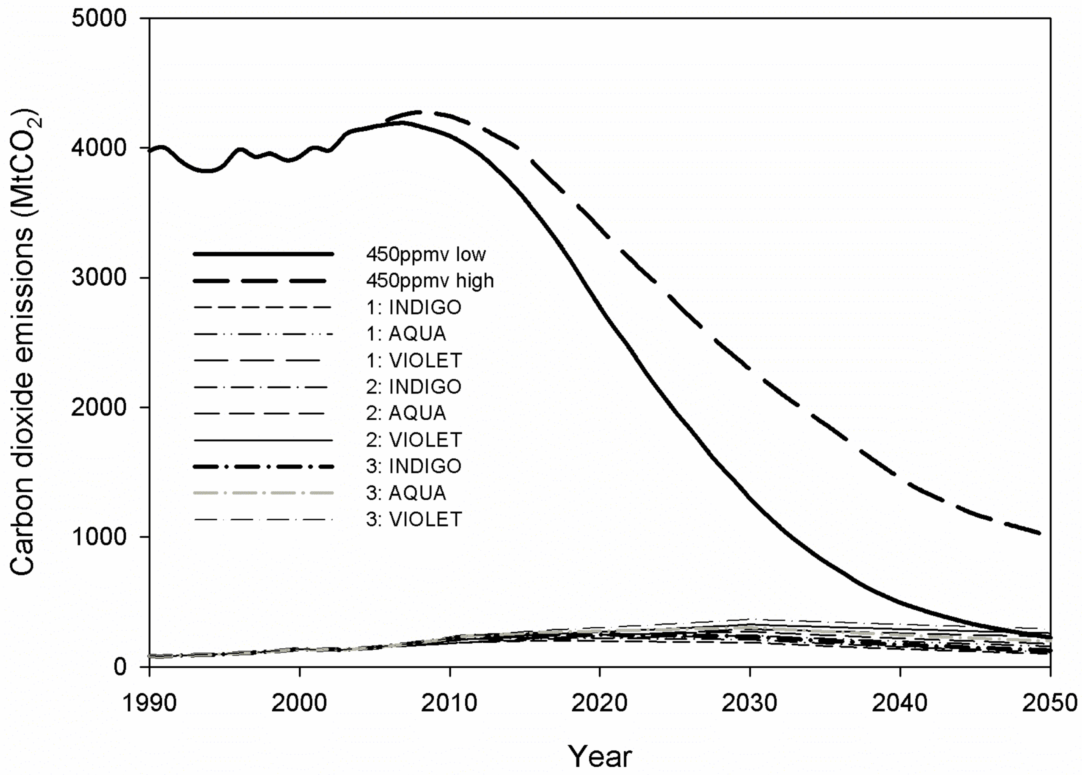

Figure 5: CO_2 emission budgets for 450ppmv compared with aviation emissions scenarios based on the UNFCCC data to account for 50% of international flights and all domestic and intra-EU flights.

Unless very low growth rates and substantial improvements to carbon efficiency are achieved, aviation emissions could exceed the 450ppmv 'low' pathway by the late 2040s. For the 450ppmv 'high' pathway, the emissions from aviation account for at best 10% and at worst 29% of the total budget for all sectors and all emissions.

All of the aviation industry scenarios, within a world striving to achieve a 450ppmv future, reflect an increase in CO_2 levels in 2050 compared with 1990. This is in sharp contrast to the other sectors of the economy, where 75 to 90% reductions from 1990 levels have been required to remain within budget.

4. Economic analysis

To investigate the likely scale of carbon price necessary to bring about the growth and efficiency changes embedded in the scenarios, a basic and illustrative analysis is presented in relation to three different emission baseline levels, for three typical flight lengths. Note that price elasticities are not presented here given the changes being investigated are step changes in prices, whereas price elasticities are useful only in investigating the impact of increment price changes. The price of carbon is varied to provide a range of possible impacts on flight price.

The first stage compares the emissions over different time periods with the baseline results for 1990, 2000 and 2005. The choice of baseline significantly impacts the amounts of carbon permits required. For example, by the end of 2011, between 57% and 65% of emissions must be purchased if 1990 is to be the chosen baseline. Whereas, 21% to 37% would need to purchased if 2005 were the baseline (Table 6). The carbon intensity improvements are assumed to be the same across all types of flight.[10]

Table 6: Percentage of permits that would need to be purchased for the lowest Indigo and highest Violet scenarios.

	INDIGO		
Baseline dates	**Percentage of the carbon on a flights that needs to be purchased**		
	End 2011	**End 2016**	**End 2050**
1990	57%	60%	20%
2000	29%	34%	-31%
2005	21%	26%	-47%
	VIOLET		
Baseline dates	**Percentage of the carbon on a flights that needs to be purchased**		
	End 2011	**End 2016**	**End 2050**
1990	65%	71%	72%
2000	44%	52%	54%
2005	37%	46%	49%

To estimate the additional cost of a typical flight (assuming that *all* costs are passed on to the passenger) a range of carbon prices for these permits is considered. Although carbon prices above €50 have yet to materialise, the premise of this report is that the EU is genuinely committed to 450ppmv. Within this in mind, it is assumed that between 2012-2017 carbon prices are €50-€100, increasing in the longer term to €100 to €300. These prices broadly reflect the higher ranges of values discussed within the literature [p.323 (Stern, 2006)];(Uyterlinkde et al., 2006).

Typical emissions per passenger data is used to provide indicative costs per passenger for flights. As carbon intensity improves over time in line with the figures presented in Table 5, so the carbon emissions per passenger will fall for the same flight. For three exemplar flights, Table 7 presents the carbon emissions over time relating to the carbon efficiency improvements.

Table 7: Tonnes of CO_2 per passenger for 3 example flights in 2005, 2011 and 2050 with carbon efficiencies taken from Table 5

One way flight[11]	2005	End 2011	End 2050
Short-haul (e.g. London – Barcelona)	0.25	0.235	0.073
Medium-haul (e.g. London – Washington)	1	0.941	0.291
Long-haul (e.g. London – Sydney)	2	1.883	0.582

[10] Tables 12 and 14 in (Anderson et al., 2007) give more details.

[11] These figures do not reflect actual flights but are typical values associated with 'short, medium and long-haul' flights within an appropriate range.

To estimate the typical indicative cost per passenger, the percentage of a flight's carbon emissions for which permits are required to be purchased can be applied to the data in Table 7 for the lowest growth scenario, *Indigo*, and the highest growth scenario, *Violet*. Using the percentages, the typical costs per flight are presented in Table 8 for *Indigo* and *Violet*.[12]

Table 8: Typical prices for exemplar flights over different periods and baselines for the lowest Indigo scenario and Highest Violet scenario. The '--'s in the table below illustrate that, within a 450ppmv budget, a value of € 50 per tonne is unrealistic post-2030. Similarly, much higher carbon prices of € 300 are unlikely in the period prior to 2012.

Carbon prices for different types of typical flights

INDIGO

Carbon price		End 2011		End 2016		End 2050	
	Baseline years	1990	2005	1990	2005	1990	2005
	Short-haul	€ 7	€ 2	€ 7	€ 3	--	--
€ 50	Medium-haul	€ 27	€ 10	€ 26	€ 11	--	--
	Long-haul	€ 53	€ 20	€ 52	€ 23	--	--
	Short-haul	€ 13	€ 5	€ 13	€ 6	€ 1	-€ 3
€ 100	Medium-haul	€ 53	€ 20	€ 52	€ 23	€ 6	-€ 14
	Long-haul	€ 107	€ 39	€ 104	€ 46	€ 11	-€ 27
	Short-haul	--	--	€ 39	€ 17	€ 4	-€ 10
€ 300	Medium-haul	--	--	€ 156	€ 69	€ 17	-€ 41
	Long-haul	--	--	€ 313	€ 138	€ 34	-€ 82

VIOLET

		End 2011		End 2016		End 2050	
	Baseline years	1990	2005	1990	2005	1990	2005
	Short-haul	€ 8	€ 4	€ 8	€ 5	--	--
€ 50	Medium-haul	€ 31	€ 17	€ 31	€ 20	--	--
	Long-haul	€ 62	€ 35	€ 62	€ 41	--	--
	Short-haul	€ 15	€ 9	€ 15	€ 10	€ 5	€ 4
€ 100	Medium-haul	€ 62	€ 35	€ 62	€ 41	€ 21	€ 14
	Long-haul	€ 123	€ 69	€ 124	€ 81	€ 42	€ 28
	Short-haul	--	--	€ 46	€ 30	€ 16	€ 11
€ 300	Medium-haul	--	--	€ 185	€ 122	€ 63	€ 42
	Long-haul	--	--	€ 371	€ 243	€ 125	€ 85

[12] These figures do not reflect actual flights but are typical values associated with 'short, medium and long-haul' flights within an appropriate range.

Table 8 illustrates the typical additional costs per passenger for a one-way flight under the *Indigo* and *Violet* Scenarios. Again, the earlier the baseline, the higher the additional cost.

Even in the case of the higher growth scenario (*Violet*) and even assuming that *all* costs were passed on to the passenger, the additional €8 to €15 for a short-haul flight is unlikely to significantly influence passenger growth rates (the €15 figure, equates to a carbon price of €100 per tonne).

For the longer-haul flights, the maximum additional premium would be €371 if 1990 were to be the baseline. The permit price in this case is €300 – an order of magnitude higher than other studies typically expect in the future. Only at such a level, and with an early baseline, is there likely to be a sufficient price signal to significantly curb the growth in emissions from the aviation sector. When considering the 2005 emission baseline, it is probable that carbon prices would have to rise well above €300 per tonne to have a significant influence on growth.

The *Violet* scenario adds an additional €30 to a short-haul flight by the end of 2016, €122 to a medium-haul flight and €243 to a long-haul flight (all at €300 per tonne). The respective figures are €5, €20 and €41 at the lower carbon price of €50 per tonne. Here, again, price signals from even high estimates of carbon prices would not seem to be sufficient to produce the required effect.

5. Discussion & conclusions

In March of this year the EU reaffirmed its commitment to not exceeding the 2°C target. Drawing on this commitment, this paper illustrates the EU's associated emission-reduction pathway over the next fifty years, with particular focus on what this means for the aviation sector. Three of the scenario suites presented reflect emission pathways for the aviation sector that, although representing a growing share of the EU's emissions, could nevertheless be reconciled with a 450ppmv CO_2 pathway. However, in all cases, these scenarios reflect the situation where there is a concerted effort to produce not only very significant increases in the carbon efficiency of aviation, but a curbing of passenger-km growth rates. Furthermore, even though the aviation emissions pathways implied by the scenarios can be reconciled with the 450ppmv CO_2 pathway, the other sectors would have to significantly compensate for aviation to remain within the carbon budget available. Whilst these scenarios are, in principle, achievable, they also represent an urgent and radical departure from the current level of aviation's emission growth and the majority of analyses and passenger growth forecasts for the future of aviation.

5.1 Current aviation emissions *are* significant

In 2005 aviation emissions were approximately 150MtCO_2, representing 4% of the EU's total CO_2 emissions. It is such percentages that give rise to the repeated and dangerously misleading claim that "aviation is not a major greenhouse gas polluter" (IATA, 2007). Making simplistic comparisons with other emissions sources conveniently chosen to underplay aviations' contribution to total emissions only serves to confuse an already confusing issue [see (IATA, 2007) p.12]. The same basis of analysis would suggest that the UK's total transport and power station emissions are not major sources when compared with global totals; similarly the emissions from nations such as Belgium, Portugal and the Netherlands are too small to be the focus of concerted low-carbon action. Unfortunately, this view is all too prevalent in discussions over climate change. The UK's proportion of world emissions is often cited as only 2% of the global total and, so the argument goes, whatever the UK does in terms of carbon emissions is of little relevance. Similarly, Beijing, New York, Delhi, Paris, and all the other major cities of the world are respectively less than 2% of total emissions. This apparent logic would suggest there is little benefit in their implementing stringent carbon-reduction strategies. *All* emissions are inevitably the aggregate of smaller percentages; using this as an excuse for relative inaction will collectively lead to individual, sectoral, national and, ultimately, global apathy. The aviation sector's 4% of EU emissions is therefore already a significant proportion of total EU emissions, and it is essential this is recognised.

5.2 EU Aviation scenarios within a 450ppmv budget

Most of the scenarios presented within this paper, unlike many existing aviation scenarios, are expressly designed to be compatible with a 450ppmv CO_2 pathway. Understanding the importance of this emphasis is essential if the scenarios are to provide a useful heuristic for policy makers and other stakeholders. Seriously exacerbating the aviation sector's already significant level of emissions is the sector's rate of growth. Whilst emissions from most sectors are broadly stable,[13] the latest EU aviation data show increases in emission of between 6% and 7% per annum, consistent with long-run trends. Such growth rates are often ignored or underestimated by those with a vested interest in the sector's continued prosperity. Currently, the limited constraints on the expansion of the EU's aviation sector are being dwarfed by the drivers for expansion. In the absence of explicit and coordinated action to both constrain growth and increase efficiency it is difficult to envisage the current situation changing appreciably. Previous Tyndall scenarios demonstrated the dangers of relative inaction in relation to emissions growth (Anderson et al., 2005; Bows et al., 2006a); by contrast these scenarios illustrate what viable aviation emission-pathways may look like, provided radical policies are implemented to constrain emissions growth as a matter of urgency.

These latest scenarios contain reductions in carbon intensity per passenger-km well above those assumed within all but the industry's more optimistic predictions. This is a consequence of the latest scenarios being developed for an explicit 450ppmv CO_2 future. There is a raft of opportunities for reducing the carbon intensity at levels not dissimilar to those used within this report. However, the scope and scale of policies necessary to bring about such changes and the more immediate and short-term benefits of behavioural and operational adjustments are often ignored.

The analysis presented within this paper begins to sketch out the necessary scope and scale of policies; with an inevitably conditional conclusion, being that if price is to be the principal driver, the € per tonne carbon prices currently being discussed are an order of magnitude too low. Carbon prices of €50 to €100 per tonne in 2012 equate to a typical short-haul flight price increase of €2-€15 per passenger, medium-haul €10-€60, and flights from, for example, the UK to Australia, €40-€120. It is difficult to envisage such small price signals having other than marginal impacts on the rate of growth of aviation emissions. In relation to the more demanding of the report's scenarios (*Indigo*), the €300 carbon price in 2017 equates to a per passenger supplement for typical short, medium and long-haul flights of €15-€40, €70-€155 and €140-€310 respectively. Given the radical departure from aviation's current high emission growth represented by the *Indigo* scenario, these additional costs are still likely to be insufficient. Current discussions often refer to carbon prices well below €50/tonne, with the latest IATA report [(IATA, 2007) p.3] focussing on values per tonne of CO_2 of between €15 and €33. Such low prices are considered inconsistent with a genuine drive towards an EU 450ppmv CO_2 pathway, and consequently the prices are revised upwards significantly. Only with carbon prices an order of magnitude higher than those currently being considered by the industry (i.e. €100 to €300 per tonne as opposed to €15 to €33 per tonne), and with an early baseline year, can the scheme have sufficient impact on reducing current levels of emission growth.

5.3 Aviation remains privileged

On first reading of this paper, the scenarios may appear to place undue constraints on the aviation sector. However, even under the most demanding scenario (*Indigo*), aviation remains highly privileged in relation to emissions. The 450ppmv CO_2 pathway demands aggregate emission reductions from all sectors, compared with 1990, of approximately between 75% and 90% by 2050. By contrast, even the *Indigo* scenario has an emissions increase from the aviation sector in 2050 of between 23% and 53%, compared with 1990. This growth is despite the exceptionally high levels of efficiency and unprecedented reduction in passenger-km growth assumed within the scenario. Such findings illustrate the scale of the challenge facing the EU and its member states and reveal the failure of existing policy instruments to address the rapid growth in aviation emissions. Moreover, it exposes the

[13] Seldom increasing or decreasing at more than 1-2% per annum.

politically-expedient rather than scientifically-literate basis of discussions informing and framing the scale of forthcoming policy instruments. It is imperative this reluctance to actively engage in evidence-based analysis of current and future emissions be reversed if the EU is to meet even the higher 450ppmv emission pathway, let alone the EU's own 2°C commitment.

5.4 Conclusion

From the relatively simple 'what-if' economic analysis presented in this paper, a series of options for reconciling aviation with a 450ppmv CO_2 pathway are evident. Firstly, the EU ETS cap must be designed in keeping with a cumulative 450ppmv pathway. A reconsideration of an early baseline year should be a prerequisite for aviation's inclusion in the EU ETS and early inclusion in the scheme is highly desirable, with stringent constraints on the sector's emission growth implemented in the interim. In relation to the carbon price, the overall EU ETS cap needs to be sufficiently tight that carbon prices well in excess of €300/tonne are achieved. Finally, in relation to non-CO_2 climate change impacts, additional and substantial flanking instruments must be implemented. Constrained and responsible growth of the aviation sector can be reconciled with a 450ppmv CO_2 future, but the carbon price currently being discussed is an order of magnitude too low to stimulate the necessary changes.

For the EU to achieve its climate targets, all sectors require mitigation policies. If a realistically high carbon price is considered unachievable, there are a number of alternative mechanisms available for consideration. For example, the aviation sector could operate within a sector-specific cap; either for aviation only, or for all transport modes, based on the sector making its fair contribution to a 450ppmv cumulative CO_2 pathway. Or, a very high carbon-related price could be placed on the industry in the form of a fuel tax, air passenger duty, or some other innovative charging instrument. One other mechanism is for a stringent carbon rationing regime to be introduced, such as personal carbon allowances, with the quantity of allowances in line with a cumulative 450ppmv CO_2 pathway. If a stringent policy mechanism is not chosen, the EU must prepare to adapt to climate change impacts in excess of a +2°C future. The transition from the EU's rhetoric on climate change to a scientifically-literate policy agenda demands a reframing of the debate in terms of cumulative carbon budgets and accompanying carbon-reduction pathways. Within such a framing, addressing urgently aviation's rapidly escalating emissions becomes a prerequisite of any meaningful carbon-reduction strategy.

Anderson,, K., and Bows, A., 2008 Reframing the climate change debate in light of post-2000 emission trends, *Philosophical Transactions of the Royal Society A*, 366, 3863-3882.

Anderson, K., A. Bows and A. Foottit, 2007. Aviation in a low-carbon EU. Report for Friends of the Earth, Tyndall Centre Manchester.

Anderson, K., S. Shackley, S. Mander and A. Bows, 2005. Decarbonising the UK: Energy for a climate conscious future, The Tyndall Centre for Climate Change Research, Manchester.

Bows, A., K. Anderson and P. Upham, 2006a. Contraction & Convergence: UK carbon emissions and the implications for UK air traffic. Tyndall Centre Technical Report. Norwich, Tyndall Centre for Climate Change Research.

Bows, A., S. Mander, R. Starkey, M. Bleda and K. Anderson, 2006b. Living within a carbon budget. Report commissioned by Friends of the Earth and the Co-operative Bank. Tyndall Centre. Tyndall Centre, Manchester.

De La Fuente Layos, L., 2007. Air transport in Europe in 2005. Statistics in focus. European Communities, EU.

De La Fuente Layos, L., 2008. Air transport in Europe in 2006. Statistics in focus. European Communities, EU.

EUROCONTROL, 2007. Flight Movements 2007-2008. Short-Term Forecast. EUROCONTROL, STATFOR.

Green, J. E., 2005. Future aircraft - greener by design? Meteorologische Zeitschrift. 583-590.

Greener by Design, 2005. Mitigating the environmental impact of aviation: opportunities and priorities. Air Travel - Greener by Design, Royal Aeronautical Society.

IATA, 2007. Financial impact of extending the EU ETS to airlines, from www.iata.org/economics.

IPCC, 2007. Climate Change 2007: the physical science basis. Report of Working Group 1 to the Fourth Assessment report of the Intergovernmental Panel on Climate Change.

Jones, C. D., P. M. Cox and C. Huntingford, 2006. Impact of climate-carbon cycle feedbacks on emissions scenarios to achieve stabilisation, in: Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. and Yohe, G. (Eds.), Avoiding dangerous climate change. Cambridge University Press, Cambridge, pp. 323-331.

Matthews, H. D., 2005. Decrease of emissions required to stabilise atmospheric CO2 due to positive carbon cycle-climate feedbacks. Geophysical Research Letters. 32,(L21707), DOI:10.1029/2005GL023435.

Meinshausen, M., 2006. What does a 2C target mean for greenhouse gas concentrations? a brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates, in: Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. and Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, pp. 253-279.

Meyer, A., 2000. Contraction & Convergence - the global solution to climate change, Green books, Devon.

Penner, J. E., D. G. Lister, D. J. Griggs, D. J. Dokken and M. McFarland, Eds., 1999. Aviation and the global atmosphere; a special report of IPCC working groups I and III Cambridge University Press, Cambridge.

RCEP, 2002. The environmental effects of civil aircraft in flight. Special report of the Royal Commission on Environmental Pollution, Royal Commission on Environmental Pollution.

Sausen, R., I. Isaksen, V. Grewe, D. Hauglustaine, D. S. Lee, G. Myhre, M. O. Kohler, G. Pitari, U. Schumann, F. Stordal and C. Zerefos, 2005. Aviation radiative forcing in 2000: An update on IPCC (1999). Meteorologische Zeitschrift. 14,(4), 555-561.

Stern, N., 2006. Stern Review on the Economics of Climate Change. Her Majesty's Treasury. Cambridge, Cambridge University Press.

Uyterlinkde, M. A., G. H. Martinus, H. Rosler, B. C. C. Van der Zwaan and et al, 2006. The contribution of nuclear energy to a sustainable energy system. CASCADE MINTS.

Wit, R. C. N., B. H. Boon, A. van Velzen, A. Cames, O. Deuber and D. S. Lee, 2005. Giving wings to Emissions Trading - Inclusion of Aviation under the European Trading System (ETS): Design and Impacts, CE, Delft.

UNFCCC, 2007. Greenhouse Gas Submissions to the United Nations Framework Convention on Climate Change, http://unfccc.int

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