Aviation and climate change: can the airline industry continue to grow in a carbon-constrained economy?

A. Macintosh and C. Downie*

The aviation industry has grown rapidly over the past 50 years. One of the downsides of this growth has been a substantial increase in aviation greenhouse gas emissions. Concerns about the growth trajectory of the industry and emissions have led to calls for measures to be introduced to restrict demand and prompt innovation. In response, the European Union has announced that both domestic and international flights will be included in its Emissions Trading Scheme from 2012. At the time of writing, no similar measures had been proposed in Australia. This article considers whether the unconstrained growth of the aviation industry in Australia is compatible with reducing the nation's greenhouse gas emissions to levels that are required to minimise the risk of dangerous climate change. To do this, the article projects Australia's aviation emissions (international and domestic) over the period 2005 to 2050 and compares the projections to likely national emission reduction targets in 2050. The results suggest that total aviation emissions could rise by more than 250 per cent over this period. With such rapid growth, aviation could account for over 30 per cent of Australia's entire emissions space by 2050 if there is a desire to reduce emissions by 60 per cent by the middle of this century.

Keywords: aviation, climate change, greenhouse gas emissions, carbon economy, emissions trading

In little more than half a century, aviation has grown from an infant industry to an integral part of the world economy. Global aviation passenger numbers are approximately 50 times larger than they were 50 years ago and the aviation sector now generates almost four trillion revenue passenger kilometres a year (ICAO 2007a). Analysts believe that the aviation sector will continue to expand into the foreseeable future, driven by

strong global economic growth and the rise of low-cost carriers (Airbus 2007; Boeing 2007; ICAO 2007b).

The ongoing expansion of the aviation sector sits uncomfortably with the policy ramifications of the available climate science. Data from the Intergovernmental Panel on Climate Change (IPCC) and other scientific organisations have clarified that the global climate is warming and that it is very likely that the main cause is the emission of greenhouse gases from human activities. The science suggests that if steps are not taken to reduce greenhouse gas emissions, the global average surface temperature could increase by between 1.1 and 6.4°C above pre-industrial levels by the end of the 21st century, leading to numerous adverse consequences, including rising sea levels, increases in extreme weather events and losses of biodiversity (National Emissions Trading Taskforce 2006; IPCC 2007; Stern 2007).

Aviation's contribution to climate change is currently relatively small. However, with the sector expected to grow rapidly in the coming decades, there is concern it will become a major cause of human-induced warming by the middle of the 21st century (Bows et al. 2005). In response to the concerns about aviation's contribution to climate change, the European Union (EU) has announced that both domestic and international flights will be included in its Emissions Trading Scheme from 2012 (EC 2005; CEU 2007).

No similar measures have been proposed in Australia. On the contrary, the object of government policy at federal and state levels is to encourage growth in the aviation sector. For example, in June 2006, former Federal Transport Minister Warren Truss stated that the 'Howard/Vaile Government is committed to doing everything that it can to ensure' continued growth in the industry (Truss 2006). The Howard Coalition Government was voted out of office in late 2007. However, the new Rudd Labor Government has given no sign that it will change the direction of Australia's aviation policy.

In this context, this article considers whether the unconstrained growth of the aviation industry in

* Andrew Macintosh and Christian Downie are with the Australian National University, Canberra. Andrew is with the Centre for Climate Law and Policy, email: macintosh@law.anu.edu.au; and Christian is with the Regulatory Institutions Network (RegNet), email: christian.downie@anu.edu.au.

Australia is compatible with reducing the nation's greenhouse gas emissions to levels that are required to minimise the risks associated with global warming. To do this, we project aviation emissions over the period 2005 to 2050 and compare the projections to likely emission reduction targets in 2050.

Greenhouse gas emissions from aviation

The science of aviation emissions

The major greenhouse gases emitted by aircraft are carbon dioxide (CO_2), nitrogen oxides (NO_x)¹, water vapour (H_2O), sulphur oxides (SO_x) (which form sulphate particles) and soot (IPCC 1999)². A summary of the atmospheric impacts of these agents and estimates of their associated radiative forcing in 2000 is provided in Table 1. Radiative forcing is a measure of the impact of an agent on the energy balance of the earth's atmosphere. It is technically defined as the change in net irradiance at the tropopause (i.e. the boundary between the troposphere and stratosphere) and is measured in watts per square metre (W/m^2). A positive number indicates that the agent

has a warming effect, whereas a negative number indicates a cooling agent.

As shown in Table 1, the three main climate agents associated with aviation are CO_2 , NO_x and H_2O . Arguably, CO_2 is the most important of the three. Unlike most other aircraft emissions, CO_2 mixes well in the atmosphere and has a relatively long atmospheric lifetime³. Due to these characteristics, the effects of CO_2 emissions from aviation are believed to be the same irrespective of altitude, and the climate impacts are not localised.

The effects of the other non- CO_2 aviation pollutants differ from CO_2 in that they generally have a shorter atmospheric lifespan and tend not to mix as well in the atmosphere. As a result, their impacts can be localised near popular flight routes. The effects of non- CO_2 aviation emissions can also differ considerably depending on the altitude at which they are released.

Emissions of NO_x have both a positive and negative effect on radiative forcing. The warming effects arise because NO_x emissions result in the production of ozone (O_3), which is a greenhouse gas. When NO_x is released in the upper troposphere, as it is by aircraft, it is more effective in producing ozone than if the gas was released at the earth's surface. Consequently, by increasing the concentration of O_3 in the troposphere, aviation NO_x emissions increase the amount of human-induced radiative forcing.

Table 1 Radiative forcing from aviation emissions in 2000

Agent	Comment	Radiative forcing (mW/m^2) [*]	Scientific understanding
CO_2	CO_2 is a well-mixed, long-lived (5-200 years) greenhouse gas and its warming effects on the climate are relatively well understood	+25	Good
NO_x	NO_x emissions have warming and cooling effects. The warming arises because aviation NO_x emissions result in the production of ozone (O_3) (a greenhouse gas) in the troposphere. The cooling effects arise because chemical reactions associated with NO_x remove methane (CH_4) (a greenhouse gas) from the atmosphere	+22	Fair
O_3		-10	Fair
CH_4			
H_2O	Aviation H_2O emissions have three main impacts. H_2O emitted from aircraft builds up in the lower stratosphere and traps infrared radiation, leading to warming. Aviation H_2O emissions create contrails, which act like clouds and trap heat. Contrails created by aircraft can lead to the creation of cirrus clouds, which also leads to warming	+2	Fair
Contrails		+10	Fair
Cirrus		+30	Poor
		(range +10 to +80)	
SO_x	SO_x emissions lead to the formation of sulphur aerosols, which reflect solar radiation and thereby cool the atmosphere. They can also have indirect effects by altering cloud formation. The radiative forcing estimates only consider the direct effects	-3.5	Fair
Soot	Soot can act as a warming agent by trapping and radiating heat. It can also have indirect warming effects by altering the albedo (reflectivity) of the earth's surface. The radiative forcing estimates only consider the direct effects	+2.5	Fair
Total (without cirrus cloud effects)		+48	

Source: Sausen et al. (2005)

* mW/m^2 means milliwatt, or 10^{-3} watts

¹ Nitrogen oxides comprise nitric oxide (NO) and nitrogen dioxide (NO_2).

² The emissions differ depending on the stage in the operating cycle. At cruising altitude and during takeoff, the main emissions are CO_2 and NO_x . While idle, the major non- CO_2 emissions are hydrocarbons (HC), but significant amounts of NO_x and carbon monoxide (CO) are also emitted. During the approach stage, there is a mixture of CO_2 , NO_x , HC and CO (BTRE 2002).

³ The atmospheric lifetime (or 'residence time') of CO_2 ranges between approximately five and 200 years, but it is often assumed to be around 100 years (IPCC 1999, 2001).

Counteracting the warming effects associated with aviation-induced increases in tropospheric O_3 are the impacts of aviation sulphur and H_2O emissions in the stratosphere, which decrease O_3 levels. The effect of sulphur and H_2O emissions on stratospheric ozone levels is thought to partially offset the impacts of NO_x emissions. However, as the IPCC stated in 1999, '[t]he degree to which this occurs is, as yet, not quantified' (IPCC 1999, p. 6).

The cooling effects associated with aviation NO_x emissions arise because they decrease the atmospheric concentration of methane (CH_4), which is another greenhouse gas. The reduction in CH_4 caused by the emission of NO_x by aircraft is far smaller than the increase in CH_4 due to other human activities. According to the IPCC's (1999) estimates, the emission of NO_x by aircraft resulted in methane concentrations in 1992 being approximately two per cent less than they otherwise would have been. To put this in perspective, other human activities have led to a 250 per cent increase in the level of methane in the atmosphere since pre-industrial times. Notwithstanding this, the reduction in CH_4 caused by aviation NO_x emissions will reduce the amount of human-induced radiative forcing.

The average radiative forcing associated with the aviation-induced changes in CH_4 and tropospheric O_3 are thought to be of similar magnitude, with the decrease in CH_4 levels having a cooling effect and the increase in O_3 levels having a warming effect. At first glance, this suggests that the effects should cancel each other out. However, CH_4 is like CO_2 in that it mixes well in the atmosphere. In contrast, the effects of NO_x emissions on tropospheric O_3 are more localised. Hence, NO_x emissions are still expected to have a net warming effect in the relevant regional areas affected by the changes in tropospheric O_3 levels.

Water emissions from aircraft are primarily associated with three atmospheric effects. Firstly, aircraft emit water vapour into the lower stratosphere, where it builds up and, as a greenhouse gas, traps infra-red radiation, leading to warming. Secondly, water vapour emitted by aircraft creates contrails that are like linear clouds that, like thin clouds, have a warming effect on the earth's surface. Thirdly, the presence of contrails can lead to the creation of cirrus clouds, which also leads to warming⁴. While a considerable amount of research has been carried out on the effects of H_2O emissions, the precise nature of

the atmosphere impacts remains uncertain, particularly in relation to cirrus clouds.

The other two major aviation emissions are sulphate and soot aerosols. The impacts of these emissions are thought to partly offset each other as soot has a warming effect and sulphate has a cooling effect (IPCC 1999). However, the impacts associated with soot and sulphate aerosols are thought to be relatively small.

Aviation's contribution to climate change

Although there is uncertainty surrounding the impacts of aviation emissions, the available evidence indicates that they are currently responsible for a relatively small proportion of human-induced climate change. The IPCC (1999, p. 8) estimated that in 1992 the radiative forcing from aviation was approximately 0.05 watts per square metre (Wm^2) (excluding cirrus cloud effects), 'or about 3.5% of the total radiative forcing by all anthropogenic activities'. Sausen et al. (2005) updated the IPCC's estimates and found that, despite a significant increase in aircraft traffic, the total radiative forcing from aviation in 2000 was still around 0.05 Wm^2 (see Table 1). The apparent stability of the estimated radiative forcing from aviation emissions was due to a downward revision of the estimated effect of contrails. Yet, like the IPCC's (1999) estimate, this approximation of the radiative forcing from aviation did not include the effects on cirrus clouds. Sausen et al. (2005) found that the impacts of cirrus clouds could be far greater than the IPCC (1999) suggested. On this basis, they concluded that the total aviation-related radiative forcing could be 0.1 Wm^2 , twice as large as the estimate without cirrus cloud effects (Sausen et al. 2005, p. 559). In a worst case scenario, it may be more than two and half times as large as the Sausen et al. (2005) estimate. Using the most recent IPCC data as a guide, these figures suggest aviation currently accounts for between three and eight per cent of total net anthropogenic radiative forcing (IPCC 2007).

While significant, the evidence suggests that the aviation industry's contribution to climate change is dwarfed by the impacts of other sectors, particularly electricity generation, land-based transport, land use change and agriculture. This is the case in Australia, where domestic and international aviation emissions were approximately 11 Mt CO_2 -e (carbon dioxide emissions) in 2004, or less than two per cent of total emissions (DEH 2006a).

⁴ Contrails and cirrus clouds reflect solar radiation, which has a cooling effect on the Earth's surface. However, they also absorb thermal radiation, which heats the Earth's surface. The heating effect associated with the absorption of thermal radiation is believed to outweigh the cooling effect associated with the reflection of solar radiation (IPCC 1999; RCEP 2002).

Similar trends are seen around the world. In the US, aviation accounts for about ten per cent of emissions from transport, or about 2.7 per cent of total emissions (CCCEF 2007). Emissions from aviation constitute approximately three per cent of total emissions in the EU (EC 2005). The Stern Review estimated that aviation emissions accounted for only 1.6 per cent of total global greenhouse gas emissions in 2005 (Stern 2007).

These estimates of aviation emissions are slightly misleading because they do not account for the effects of most non-CO₂ aviation emissions, which are not required in the greenhouse accounting rules under the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto framework. The IPCC guidelines that govern the preparation of national inventory reports under the UNFCCC stipulate that only a select group of direct greenhouse gases should be counted towards national totals: CO₂, CH₄, nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). If other gases are reported, they are a separate item and are not included in the national totals. The targets under the Kyoto Protocol apply to the same group of direct greenhouse gases.

Most estimates of aviation emissions are based only on the emissions of the direct greenhouse gases included in national totals, of which CO₂ is the most important. However, as discussed, aircraft emit a number of other direct (e.g. H₂O) and indirect greenhouse gases (e.g. NO_x) that contribute to climate change (often called non-CO₂ aviation emissions).

To account for the impacts associated with non-CO₂ aviation emissions, a number of studies have applied an 'uplift factor' to aviation CO₂ emissions to approximate the total impacts of all aviation emissions⁵. The uplift factor is calculated using a radiative forcing index (RFI), which is defined as:

... a ratio between the total radiative forcing from aviation at some given time to the radiative forcing from aviation emissions of carbon dioxide at the same time (Forster et al. 2006, p. 1118).

The 1999 IPCC special report on aviation concluded that the radiative forcing associated with aviation was approximately two to four times larger (with a best estimate of 2.7 times larger) than the effects related to

aviation CO₂ emissions alone⁶. On this basis, several studies have applied uplift factors of between 2.5 and 2.7 in estimating aviation emissions and their contribution to climate change⁷. More recent data from Sausen et al. (2005) indicate that the radiative forcing associated with aviation could range between 1.9 and 5.1 (midpoint of 3.5) times aviation CO₂ emissions, depending on whether cirrus cloud effects are included.

Although uplift factors can be used to provide an approximation of aviation's contribution to climate change, they are controversial⁸. The science concerning the impacts of non-CO₂ emissions is uncertain and it is difficult to devise a single metric that accurately accounts for the different atmospheric impacts of the various aviation emissions. This contrasts with the situation for most direct greenhouse gases, where it is relatively easy to convert emissions into carbon dioxide equivalents using global warming potentials (GWPs).

GWPs are a measure of the cumulative radiative forcing associated with a unit mass of the relevant direct greenhouse gas when compared to the same mass of CO₂ over a specified period (typically 100 years) (IPCC 2001; DEH 2006b). Hence, for example, GWPs allow a comparison to be made between the impact of one tonne of CH₄ over 100 years versus one tonne of CO₂ over the same period.

Difficulties arise with aviation because GWPs are not calculated for H₂O and indirect greenhouse gases like CO and NO_x⁹. This is because the atmospheric lifetime of these gases is generally short and their impacts and lifespan vary depending on when and where they are released (IPCC 2001; Forster et al. 2006). The absence of GWPs for these non-CO₂ aviation emissions means that it is very difficult to compare the impacts of a unit mass of these gases to those associated with a unit mass of direct greenhouse gases like CO₂.

Uplift factors provide a basis for estimating the combined impact of CO₂ and non-CO₂ aviation emissions in CO₂-e. However, as discussed, they are calculated on the basis of the radiative forcing associated with aviation, which provides a measure of the cumulative impact of past aviation emissions on the Earth's heat balance at a particular point in time. This is effectively a measure of the historic impact of aviation. As a result, it may not

⁵ See, for example, Bows et al. (2005), DFT (2004) and SCEA (2004). To calculate aviation emissions using an uplift factor, unadjusted aviation CO₂ emissions are multiplied by the relevant metric (i.e. 2.7).

⁶ See IPCC (1999), Table 6.1.

⁷ See, for example, Bows et al. (2005), DFT (2004) and SCEA (2004). For discussion, see also GAO (2000), RCEP (2002), SCEA (2006) and Forster et al. (2006).

⁸ See, for example, Bows et al. (2005), Tyndall Centre for Climate Change Research (2006) and Forster et al. (2006).

⁹ Indirect greenhouse gases contribute to global warming by triggering the build up of direct greenhouse gases (for example, ozone).

Figure 1 Growth in air passenger numbers in Australia, in millions

provide an appropriate basis from which to estimate the impact of current emissions for the purposes of devising policy responses to global warming.

In addition, uplift factors are often applied as if they were GWPs without reference to the time horizon of the analysis or the atmospheric lifetime of the gases involved. The atmospheric lifetime of most non- CO_2 aviation emissions is around ten days, sometimes less (contrails caused by aviation H_2O emissions can last for only a few hours) (Forster et al. 2006)¹⁰. In contrast, CO_2 can remain in the atmosphere for hundreds of years. CO_2 may have a lower initial radiative forcing than some non- CO_2 emissions but, because it remains in the atmosphere longer, its cumulative impact on the climate is likely to be greater. Consequently, the time horizon of the analysis is a crucial determinant of the size of the uplift factor. If the object is to determine the impact of aviation over 100 years (consistent with the approach adopted under the UNFCCC and Kyoto Protocol), research by Forster et al. (2006) suggested that the appropriate uplift factor is likely to be in the order of 1.7, with uncertainties that could be greater than 50 per cent. If the focus is on short-term effects (20 years or less), an uplift factor substantially higher than 2.5 may be appropriate.

Using uplift factors of 1.7 and 2.7 suggests that aviation emissions accounted for between 2.5 to 4.0 per cent of global greenhouse gas emissions in 2005. The application of the same uplift factors to Australia's aviation emissions suggest that they were 18 or 29 Mt $\text{CO}_2\text{-e}$ in

2004, or between three and five per cent of total emissions.

Growth in aviation emissions

While aviation emissions constitute only a relatively small proportion of total emissions, they have increased rapidly in recent times. Since 1990, world aviation emissions have risen sharply, in some regions by as much as 70 per cent. This growth is a reflection of the growth in air transport, which has been fuelled by the expansion of the world economy, the proliferation of low-cost carriers and the industry's success in new markets (Airbus 2006; IATA 2007).

Australia has witnessed a similar trend. Between 1990 and 2004, domestic aviation emissions rose from 2.9 to 4.8 Mt $\text{CO}_2\text{-e}$; a 65 per cent increase¹¹. Over the same period, Australia's international aviation emissions increased by 38 per cent, rising from 4.4 to 6 Mt $\text{CO}_2\text{-e}$. In comparison, since 1990, emissions from road vehicles rose by 25 per cent while emissions from rail and domestic shipping fell (DEH 2006a).

The growth in emissions in Australia is underpinned by the increase in demand for air travel. As Figure 1 shows, aside from a fall in demand for air travel as a result of September 11 and SARS in 2001 and 2002, the domestic and international airline industry has experienced sustained growth over the last decade. Between 1996 and 2005, domestic passenger numbers increased by 46 per cent and international passenger numbers by 62 per cent. Annual domestic passenger numbers are now in excess of 40 million and international passenger numbers are greater than 20 million.

The growth in the demand for aviation services is projected to continue. Global flight numbers are forecast to double by 2020 and triple by 2030 (Lucas 2006). Airbus has predicted that global revenue passenger-kilometres will grow by an average of 4.8 per cent a year between 2006 and 2025 (5.3 per cent a year between 2006 and 2015, falling to 4.4 per cent a year between 2016 and 2025 as markets mature) (Airbus 2006). The strongest growth is expected in the Middle East and Asia, where revenue passenger-kilometres are expected

¹⁰ See also IPCC (2001).

¹¹ Unless otherwise stated, aviation emissions do not include an uplift factor.

Figure 2 Projected growth in air passenger numbers, in millions

to grow at an average annual rate in excess of six per cent between 2006 and 2025.¹²

Consistent with these trends, domestic and international air travel in Australia is expected to continue to grow rapidly in the short- to medium-term. Estimates based on data from the Bureau of Transport and Regional Economics (BTRE) suggest that domestic and international air passenger numbers will double between now and 2020. As Figure 2 shows, domestic passenger numbers are expected to jump from 40.8 million in 2005 to 80 million in 2020, an average growth rate of 4.6 per cent per annum. Similarly, international passenger numbers are expected to rise from 20.9 to 44.1 million between 2005 and 2020, an average annual growth rate of 5.1 per cent.

Projected Australian aviation emissions, 2005 to 2050

Method

The Tyndall Centre for Climate Change Research in the UK has estimated likely emissions from aviation in the European Union to 2050 using a method based on the projected growth in passenger numbers (Bows et al. 2005). An adjusted passenger growth rate figure was

applied to the latest actual aviation emission figures and projected up to 2050.

To determine the passenger growth rate to 2050, the Tyndall Centre extrapolated from recent growth rate trends up until 2015 for older EU countries and to 2025 for newer EU countries. The distinction was made between the countries on the basis that the aviation market in the older EU countries was likely to reach maturity in 2015, while maturity in the aviation market in the newer EU countries would take at least until 2025. Beyond the maturity date, the Tyndall Centre assumed that the passenger growth rate across all EU countries would be equal to the rate adopted in the UK Government's Aviation White Paper for the period 2000–2030 (i.e. 3.3 per cent).

The passenger growth rate was adjusted by subtracting a figure to account for 'a combination of load factor improvement, aircraft design, aircraft size, air transport management and engine efficiency' (Bows et al. 2005, p. 51). The figure used for this purpose was 1.2 per cent, which is the average of the efficiency improvements estimated by the IPCC in its 1999 aviation report (IPCC 1999). Consequently, the Tyndall Centre's estimate of emissions for a given year were calculated by subtracting 1.2 per cent from the relevant passenger growth rate, then applying the adjusted growth rate to the emissions for the previous year.

There are several other methods for estimating aviation emissions, the most common of which are based on projected rates of fuel consumption¹³. However, in this article, we have chosen to use the Tyndall Centre's adjusted passenger growth rate method. This is justified on the following grounds.

- Like the Tyndall Centre's report, the purpose of this article is to estimate the possible level of aviation emissions in 2050 to evaluate the compatibility between the current rate of growth in the aviation industry and the objectives of emerging greenhouse policies.

¹² These projections are similar to those published by the International Air Transport Association (IATA), which suggested that international air passenger traffic in the Middle East will grow by almost seven per cent per annum between 2006 and 2010 and by 5.7 per cent per annum in the Asia-Pacific region over the same period (IATA 2007).

¹³ See, for example, Newton and Falk (1997) and BTRE (2002, 2005).

- Given the long-term nature of the projections, any model is likely to suffer from considerable uncertainties. The adjusted passenger growth rate approach is simple, easy to understand and is based on one of the major drivers of aviation emissions (i.e. demand for aviation services).
- Although aviation emissions are primarily a function of aircraft movements, passenger numbers are a major determinant of aircraft traffic. Passenger load factors have been very stable over the past 30 years at around 70-75 per cent (BTRE 2002). As a result, increases in passenger numbers are likely to result in more flights rather than merely an increase in the numbers of passengers per flight. Further, increases in load factors are likely to result in greater fuel use because of increases in weight.
- The major source of data on aviation fuel use in Australia is the Australian Petroleum Statistics series published by the Department of Industry, Tourism and Resources (DITR 2007). However, there are problems with this database that prevent the accurate attribution of fuel use between the domestic and international markets. In addition, there is a lack of publicly available information on several important variables that are necessary to extend the BTRE estimates beyond 2020 (for example, income and price elasticities for all relevant segments of the aviation market). As a result, there is a risk that the adoption of an alternative fuel consumption-based model may be no more accurate than an adjusted passenger growth rate approach.
- There are differences in the historic aviation emission estimates published by the BTRE (2005) and the Commonwealth Department of the Environment and Water Resources (DEWR 2007)¹⁴. As the BTRE (2005) paper compares aviation emission estimates to emission reduction targets based on DEWR (2007) data, reliance on the BTRE (2005) data could lead to inconsistencies.
- To minimise the risk of overestimating possible emission levels, relatively conservative assumptions have been adopted in relation to uplift factors, passenger growth rates and the fuel efficiency improvements of the domestic and international aircraft fleets.

Following the approach adopted by the Tyndall Centre, the formula below was used to project domestic emissions in Australia from 2005 to 2050.

$$DE \text{ for year}_1 = [DE \text{ for year}_0 \times [1 + (PGR - FEF)]] \times UF$$

Where: DE = domestic emissions CO₂-e (or CO₂ for scenarios with uplifts factors)

PGR = passenger growth rate

FEF = fuel efficiency factor

UF = uplift factor

International aviation emissions were projected over the same period using the following formula.

$$IE \text{ for year}_1 = [IE \text{ for year}_0 \times [1 + (PGR - FEF)]] \times UF$$

Where: IE = international emissions CO₂-e (or CO₂ for scenarios with uplifts factors)

The Australian Greenhouse Emissions Information System (AGEIS) was used to obtain the CO₂ and CO₂-e emissions for domestic and international aviation in the base year (i.e. 2004) (DEWR 2007). The estimates of aviation emissions prepared by DEWR were based on fuel acquired or uplifted in Australia¹⁵. Like the estimates prepared by the BTRE, they also excluded emissions from military operations. The BTRE (2005) has estimated that approximately 10-20 per cent of domestic aviation fuel sales are for military purposes. Hence, by excluding emissions from military operations, the base year emission estimates of both CO₂ and CO₂-e are an underestimate of the total emissions from all aircraft¹⁶.

The estimates of CO₂-e emissions included in the AGEIS were drawn from the National Inventory Report that was submitted by the Federal Government under the UNFCCC (DEWR 2007). The estimates of Australia's total CO₂-e emissions in the National Inventory Report were based on the major greenhouse gases (i.e. CO₂, CH₄, N₂O, PFCs, HFCs and SF₆). Details of indirect greenhouse gas emissions, including CO and NO_x, were also included in the National Inventory Report. However, because there were no GWPs for these indirect greenhouse gases, they were not included in the national totals of CO₂-e emissions. As a result, the base year unadjusted CO₂-e estimates underestimated aviation emissions by excluding relevant gases, particularly NO_x.

Data on the passenger growth rate were obtained from the BTRE for the period 2005 to 2020 (BTRE 2005)¹⁷. In

¹⁴ The differences are primarily due to a change in the average emission factors of the aviation fleet that occurred after the publication of BTRE (2005).

¹⁵ The international emissions data used in the Tyndall Centre report were calculated using an assumption that emissions from international bunker fuels would be divided equally between the countries of departure and arrival.

¹⁶ The base year estimates are also significantly less than the BTRE estimates for 2004.

¹⁷ BTRE (2005) uses a constrained growth approach that assumes air travel never exceeds a 40 per cent mode share of non-urban passenger-kilometres.

contrast to the Tyndall Centre report, which relies solely on the growth in passenger numbers, we used the growth in passenger-kilometres to determine the domestic passenger growth rate between 2005 and 2020. For international emissions, the passenger growth rate between 2005 and 2020 was determined using the growth in international passenger numbers. This approach was adopted because the 2005 BTRE report only provided data on growth in passenger-kilometres for domestic aviation and the growth in passenger numbers for international aviation. In adopting this approach for international emissions, we assumed that there will be no growth in the average length of international flights (i.e. no increase in the average kilometres travelled per passenger). However, this assumption is unrealistic, as the average length of flights is expected to increase due to falling airfares, rising incomes and improvements in fuels and aircraft design (BTRE 2002)¹⁸. By excluding increases in the average length of international flights, our adjusted passenger growth rate approach underestimates likely increases in international aviation emissions.

As the BTRE projections do not extend beyond 2020, an estimate of the passenger growth rate over the period 2021–2050 had to be devised. Based on estimates from the Australian Bureau of Agricultural and Resource Economics (ABARE) and the most recent Intergenerational Report, released by Treasury in April 2007, we estimated that annual GDP growth is likely to be approximately 2–2.2 per cent from 2021 to 2050 (Cuevas-Cubria & Riwoe 2006; Department of the Treasury 2007).

Research on the aviation industry also indicates that income elasticities of demand for aviation services are high, but that they will gradually decline over time as the market matures, particularly in relation to domestic services (BTCE 1995; Scottish Executive 2006). Analysts have projected also that revenue passenger-kilometres will grow by five per cent per annum in the Asian market between 2016 and 2025, down from 7.4 per cent per annum over the period 2006–2015 (Airbus 2006). On this basis, and following discussions with the BTRE, we assumed an annual passenger growth rate for domestic aviation of 3.5 per cent from 2021 to 2035, falling to 3.0 per cent from 2036 to 2050. For international aviation, we assumed an annual passenger growth rate of 4.2 per cent from 2021 to 2035 and 4.0 per cent from 2036 to 2050¹⁹.

The use of a passenger growth rate method assumes that cargo (i.e. freight and mail) emissions will increase in line with those associated with the passenger task. Globally, cargo traffic constitutes approximately 30 per cent of the total scheduled aviation task (measured in revenue tonne kilometres), with the majority of this carried on international flights (ICAO 2007a). Global cargo traffic is growing faster than passenger traffic and most research suggests that this trend will continue over the coming decades (Airbus 2007; Boeing 2007; ICAO 2007b). International cargo in Australia has followed the global trend (BTRE 2006). The situation in the domestic market in Australia is less clear due to problems associated with national aviation databases (BTRE 2006). However, there is some evidence that suggests that there has been strong growth in domestic cargo markets in recent times (Apelbaum Consulting 2007). Noting these data problems, the assumption that cargo emissions will increase in line with passenger-related emissions is considered to be conservative given the trends in cargo traffic.

The fuel efficiency factor represents the annual rate of improvement in fuel efficiency that is expected to arise as a result of improvements in aircraft and engine design, advancements in fuel technology and air traffic management. As discussed, based on the 1999 IPCC report, the Tyndall Centre assumed an average fuel efficiency improvement of 1.2 per cent per year to 2050. The BTRE has suggested that the rate of fuel efficiency improvement of the Australian domestic aircraft fleet to 2020 is likely to be higher, at approximately 1.6 per cent per year. Its projections for the rate of fuel efficiency improvement of the international aircraft fleet to 2020 are very similar to the rate adopted by the Tyndall Centre (i.e. approximately 1.2 per cent per year).

On the basis of the data in the 1999 IPCC report, and to ensure consistency with the method employed by the Tyndall Centre, we used a constant fuel efficiency factor of 1.2 per cent per year for the period 2005 to 2050 for both domestic and international emissions²⁰. This is a relatively high figure, as research suggests that the IPCC's (1999) estimate may have been overly optimistic and that fuel efficiency improvements are decreasing and will continue to decline over time (Peeters et al. 2005).

We have developed three emission scenarios to account for the impacts of non-CO₂ emissions released at

¹⁸ The BTRE assumed that average kilometres per passenger would increase by 1.5 per cent per annum from 2000 to 2020.

¹⁹ BTRE suggested 3.5 per cent for domestic aviation and 4.2 per cent for international aviation for the entire period 2020–2050. We revised these estimates down for the period after 2035 to ensure that our outputs were conservative and to account for uncertainties, growth constraints and the expected gradual decline in GDP growth.

²⁰ If the BTRE's higher fuel efficiency improvement estimates are adopted, the projected emission outcomes vary only marginally, see Macintosh and Downie (2007).

Figure 3 Projected growth in domestic aviation emissions to 2050, in Mt CO₂-e

altitude and the different fuel efficiency improvement assumptions.

- **No Uplift Scenario (NU1).** This scenario assumed that there is no uplift factor. It was based on estimates of CO₂-e obtained from AGEIS for 2004 (DEWR 2007). As noted, the estimates of CO₂-e in AGEIS did not include all greenhouse gas emissions from aviation (for example, NO_x is excluded). The use of the official CO₂-e emission data for 2004 and the absence of an uplift factor in this scenario mean that it provides a conservative estimate of aviation emissions and their contribution to climate change.
- **Uplift Scenario One (US1).** This scenario applied an uplift factor of 1.7 to CO₂ estimates. The base year CO₂ estimates were obtained from the AGEIS (DEWR 2007). A constant fuel efficiency factor of 1.2 per cent per year for the period 2005 to 2050 was assumed. The uplift factor of 1.7 was chosen on the basis of the estimates in Forster et al. (2006) using a 100 year time horizon. The 100 year time horizon was consistent with the method applied under the UNFCCC and Kyoto Protocol.
- **Uplift Scenario Two (US2).** This scenario used an uplift factor of 2.7, as adopted in the Tyndall Centre report. Forster et al. (2006) also suggested that their estimate of an uplift factor of 1.7 over a 100 year time

horizon could be subject to uncertainties over 50 per cent. If the actual GWPs of non-CO₂ emissions are 50 per cent higher than Forster et al. (2006) estimated, then the uplift factor would be almost 2.7. Like US1, the uplift factor of 2.7 was applied to CO₂ estimates and a constant fuel efficiency factor of 1.2 per cent per year was assumed.

It is important to emphasise the uncertainties associated with the use of uplift factors. As discussed, there is no accurate metric to convert non-CO₂ aviation emissions into CO₂-e. US1 and US2 were merely intended to provide a guide as to the potential magnitude of effects of aviation emissions over a 100 year time horizon. They should be viewed as indicative only.

Results

Projected domestic aviation emissions

Figure 3 plots the projected emission scenarios for domestic aviation from 2005 to 2050. Under US1, domestic aviation emissions rise from 8.7 to 26.3 Mt CO₂-e over this period, a 203 per cent increase. US2 suggested that domestic aviation emissions will rise from 13.8 to 41.8 Mt CO₂-e between 2005 and 2050. Under the NU1 Scenario, aviation emissions increase from 5.2 to 15.6 Mt CO₂-e between 2005 and 2050²¹.

Projected international aviation emissions

Figure 4 plots projected emission scenarios for international aviation to 2050. US1 suggested that international aviation emissions will rise from 10.8 to 45.3 Mt CO₂-e between 2005 and 2050, a 318 per cent increase. Under US2, international aviation emissions rise from 17.2 to 72 Mt CO₂-e over this period. Under the NU1 Scenario, emissions from international aviation were projected to increase by 320 per cent between 2005 and 2050, rising from 6.4 to 26.9 Mt CO₂-e²².

Total projected aviation emissions

Figure 5 shows the growth in Australia's total aviation emissions over the period 2005 to 2050. Under US1, aviation emissions rise from 19.5 to 71.6 Mt CO₂-e, a 267

²¹ Immediately prior to acceptance of this article, the Federal Government published the 2005 *National Greenhouse Accounts*, which stated that domestic aviation emissions in 2005 were 5.1 Mt CO₂-e, slightly below the NU1 estimate (DEWR 2007).

²² The 2005 *National Greenhouse Accounts* stated that international aviation emissions in 2005 were 6.8 Mt CO₂-e (DEWR 2007).

Figure 4 Projected growth in international aviation emissions to 2050, in Mt CO₂-e

per cent increase. US2 suggested that aviation emissions will rise from 31 to 113.8 Mt CO₂-e. Under the NU1 Scenario, total emissions increase from 11.6 to 42.5 Mt CO₂-e between 2005 and 2050.

Projected aviation emissions versus desired emission reduction targets

There is a significant risk that if the aviation sector is allowed to continue on its current growth trajectory it could undermine efforts to reduce emissions. In Europe,

the atmospheric greenhouse gas concentration at 550 ppm CO₂-e²⁴. This target was consistent with the strategy recommended in the Stern Review (Stern 2007). If national emission allocations are determined on a per capita basis, Australia will be required to reduce its emissions by at least 80 per cent between 2000 and 2050.

The 60 per cent target represented a political compromise that assumed that a higher stabilisation goal will be adopted or that the developed nations abandon or postpone convergence. In this article, we chose the 60 per cent target as the preferred goal because it was consistent with the position adopted by

Figure 5 Projected growth in total aviation emissions to 2050, in Mt CO₂-e

several studies have warned that the limitless growth in aviation emissions could derail attempts by the EU to meet emission reduction targets (RCEP 2002; Bishop & Grayling 2003; Bows et al. 2005; Wit et al. 2005; Bows & Anderson 2007; Stern 2007). To determine whether this could happen in Australia, two emission reduction targets for 2050 were adopted: 80 per cent below 2000 levels (i.e. 113 Mt CO₂-e) and 60 per cent below 2000 levels (i.e. 227 Mt CO₂-e)²³.

The 80 per cent target was based on the assumption that the international community agrees to reduce global greenhouse gas emissions by 25 per cent between 2005 and 2050 (i.e. from approximately 45 GtCO₂-e in 2005 to 34 GtCO₂-e in 2050) so as to stabilise

²³ These estimates were based on the Department of the Environment and Water Resources (DEWR 2007) estimate of national emissions in 2000 (i.e. 551.5 Mt CO₂-e), which was adjusted using a 1.7 uplift factor for domestic and international aviation CO₂ emissions. After adjustment, the national emissions in 2000 were approximately 567.4 Mt CO₂-e. The same targets were applied in relation to each emission scenario. Technically, the targets should be adjusted to account for the uplift factor assumptions. However, to avoid unnecessary complexity, only a 1.7 uplift target scenario was used.

²⁴ The precise nature of the emission target will ultimately depend on the trajectory of emissions. If emissions are allowed to continue to increase in the short- to medium-term, larger reductions will be required in later years to keep the atmospheric concentration of greenhouse gases below 550 ppm CO₂-e.

Figure 6 Projected aviation emissions versus emission reduction targets, to 2050, in Mt CO₂-e

the Rudd Labor Government and governments in other developed nations, particularly in the EU. In the longer-term, it is likely that the 80 per cent target (or a higher target) will be necessary if the object of government policy is to avoid dangerous climate change, or at least to minimise the risks associated with global warming.

Figure 6 plots the projected NU1, US1 and US2 Scenarios alongside the two emission target scenarios. Both emission target scenarios assumed that emissions will increase to a maximum of 600 Mt CO₂-e in 2010, in line with Federal Government forecasts (DEH 2006b). Beyond 2010, we assumed that emissions will be reduced by a constant amount each year to 2050. For the 60 per cent target, this assumption resulted in a reduction of 9.33 Mt CO₂-e per year from 2010. For the 80 per cent target, emissions would have to be reduced by 12.18 Mt CO₂-e per year after 2010²⁵.

As shown in Figure 6, under US1, aviation emissions accounted for almost one-third (32 per cent) of Australia's total emissions in 2050 if there is a 60 per cent emission reduction target. US1 suggested that aviation emissions will consume 63 per cent of Australia's total emissions in 2050 if there is an 80 per cent reduction target.

Under US2, aviation emissions accounted for approximately half (50 per cent) of Australia's total emissions in 2050 if there is a 60 per cent reduction target. With an 80 per cent target, US2 suggested that aviation emissions will consume more than Australia's entire emissions space (101 per cent) by 2050.

Under the NU1 Scenario, aviation emissions were expected to account for 19 per cent of Australia's emission space in 2050 with a 60 per cent target. With an 80 per cent target, aviation emissions accounted for approximately 38 per cent of Australia's emissions in 2050.

In summary, if the Australian aviation sector is allowed to continue to operate under business-as-usual conditions and the Federal Government adopts a target of reducing emissions to 60 per cent below 2000 levels by the middle of this century, aviation could account

for between 32 and 50 per cent of the total greenhouse gas allowance by 2050. If the reduction target is set at only 80 per cent below 2000 levels by 2050, aviation could account for more than Australia's entire emission allowance at 2050.

Conclusion

To date, very little action has been taken at either a domestic or international level to address the growing contribution of the aviation sector to climate change. The measures that have been implemented domestically are unlikely to have a significant impact on aviation emissions and have been driven primarily by commercial concerns. The best example of these measures is the designation of 'fuel friendly' flight routes and improvements in air traffic management that have occurred over the last five years. While beneficial, the emission reductions associated with these changes are certain to be overwhelmed by growth in the industry. Similarly, voluntary programs like carbon offset schemes are unlikely to reduce the sector's contribution to global warming.

Part of the reason for the absence of greenhouse measures that target aviation is that the industry is responsible for

²⁵ In reality, emissions are unlikely to be reduced at a constant rate because of different abatement costs, political factors and the need to limit the total amount of emissions between 2005–2050 if the objective is to keep the atmospheric concentration of greenhouse gases below 550 ppm CO₂

less than five per cent of global and domestic greenhouse gas emissions (IATA 2006; Stern 2007). However, this is likely to change over the coming decades.

In Australia, aviation emissions are projected to rise dramatically. Between 2005 and 2050, total unadjusted aviation emissions are expected to rise from 11.6 to 42.5 Mt CO₂-e, an increase of 267 per cent. When an uplift factor is applied to account for the impact of non-CO₂ emissions, aviation emissions could rise from between 19.5 and 31 Mt CO₂-e in 2005 to between 71.6 and 113.8 Mt CO₂-e in 2050.

The available evidence indicates that, to minimise the risks associated with human-induced climate change, it will be necessary to cut global emissions by a minimum of 25 to 30 per cent between 2005 and 2050. If this target is adopted by the international community, it will require developed nations that currently have high emissions per capita to make larger cuts, typically in the order of at least 60 per cent below current levels. The available scientific evidence suggests that Australia may have to cut its emissions by 90 per cent by 2050, based on 2005 levels, if it is going to make an equitable contribution to minimising climate-risks. These types of emission cuts are incompatible with the current trajectory of emission increases from the aviation sector.

Under the US1 Scenario adopted here, and assuming a 60 per cent emission reduction target, aviation emissions may account for 32 per cent of Australia's entire emissions space by 2050. With an 80 per cent target, US1 suggested that aviation emissions may account for 63 per cent of Australia's total emissions in 2050. However, these estimates were based on a number of conservative assumptions. The true figure could be higher, particularly if the impact of non-CO₂ emissions is greater than expected. For example, under the US2 Scenario that used a higher uplift factor, aviation emissions accounted for 50 per cent of Australia's total emissions in 2050 if there is a 60 per cent reduction target and 101 per cent of total emissions in 2050 with an 80 per cent target. Despite the uncertainties associated with these projections, it is clear that if the aviation sector continues to grow under business-as-usual conditions, it will be a major contributor to Australia's emissions by the middle of this century.

References

Airbus 2006, *Global market forecast: the Airbus market outlook for 2006–2025*, Airbus, Toulouse, France, viewed 5 May 2007, <http://www.airbus.com/en/corporate/gmf/index.html>.

Airbus 2007, *Flying by nature: global market forecast 2007–2026*, Airbus, Toulouse, France.

Apelbaum Consulting 2007, *Australian transport facts 2007*, Apelbaum Consulting Group Pty Ltd, Mulgrave, Victoria.

Bishop, S & Grayling, T 2003, *The sky's the limit: policies for sustainable aviation*, Institute for Public Policy Research, London.

Boeing 2007, *Current market outlook 2007*, Boeing, Chicago.

Bows, A & Anderson, K 2007, 'Policy clash: can projected aviation growth be reconciled with the UK Government's 60% carbon-reduction target?', *Transport Policy*, vol. 14, pp. 103–110.

Bows, A, Upham, P & Anderson, K 2005, *Growth scenarios for EU & UK aviation: contradictions with climate policy*, Report for the Friends of the Earth Trust Ltd, Tyndall Centre for Climate Change, Manchester, UK.

BTCE (Bureau of Transport and Communications Economics) 1995, *Demand elasticities for air travel to and from Australia*, Working paper no. 20, Commonwealth of Australia, Canberra.

BTRE (Bureau of Transport and Regional Economics) 2002, *Greenhouse gas emissions from transport: Australian trends to 2020*, Report 107, Commonwealth of Australia, Canberra.

BTRE (Bureau of Transport and Regional Economics) 2005, *Greenhouse gas emissions from Australian transport: base case projections to 2020*, report for the Australian Greenhouse Office, Commonwealth of Australia, Canberra.

BTRE (Bureau of Transport and Regional Economics) 2006, *Airline industry monthly summaries, by industry sector*, Commonwealth of Australia, Canberra, viewed 15 March 2007, <http://www.btre.gov.au/statistics/xls/Monthly_airline_performance.xls>.

CCCEF (Centre for Climate Change and Environmental Forecasting) 2007, *Aviation and emission reductions*, CCCEF, Washington, DC, viewed 3 April 2007, <<http://climate.dot.gov/aviation.html>>.

CEU (Council of the European Union) 2007, *Proposal for a directive of the European Parliament and of the council amending directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community*, Inter-institutional file 2006/0304 (COD), doc. no. 16855/07, CEU, Brussels.

Cuevas-Cubria, C & Riwoe, D 2006, *Australian energy: national and state projections to 2029–30*, ABARE research report no. 06.26, Commonwealth of Australia, Canberra.

DEH (Department of the Environment and Heritage) 2006a, *National greenhouse gas inventory 2004 – accounting for the 108% target*, Commonwealth of Australia, Canberra.

DEH (Department of the Environment and Heritage) 2006b, *National inventory report 2004 (revised) – volume 1*, Commonwealth of Australia, Canberra.

Department of the Treasury 2007, *Intergenerational report 2007*, Commonwealth of Australia, Canberra.

DEWR (Department of the Environment and Water Resources) 2007, *Australia's national greenhouse accounts*, Commonwealth of Australia, Canberra, viewed 3 April 2007, <<http://www.greenhouse.gov.au/inventory/index.html>>.

DFT (Department for Transport, UK) 2004, *Aviation and global warming*, UK Government, London.

DITR (Department of Industry, Tourism and Resources) 2007, *Australian petroleum statistics*, DITR, Canberra, viewed 2 April 2007, <<http://www.industry.gov.au/content/itrinternet/cmscontent.cfm?objectid=1B4E9FA4-F1E6-4A46-A74A8835D990B633&searchID=279369>>.

EC (European Commission) 2005, *Questions and answers on aviation and climate change*, Memo, 27 September 2005, EC, Brussels, viewed 2 March 2007, <<http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/05/341&format=HTML&aged=0&language=EN&guiLanguage=en>>.

Forster, P, Shine, K & Stuber, N 2006, 'It is premature to include non-CO₂ effects of aviation in emission trading schemes', *Atmospheric Environment*, vol. 40, pp. 1117-1121.

GAO (General Accounting Office) 2000, *Aviation and the environment: aviation's effects on the global atmosphere are potentially significant and expected to grow*, Report to the Honorable James L. Oberstar, Ranking Democratic Member, Committee on Transportation and Infrastructure, House of Representatives, United States Government, Washington, DC.

IATA (International Air Transport Association) 2006, *Aviation and the environment - killing myths and setting the agenda*, media release, IATA, Montreal, viewed 2 April 2007, <<http://www.iata.org/pressroom/pr/2006-04-25-02.htm>>.

IATA (International Air Transport Association) 2007, *Factsheets, industry statistics*, IATA, Montreal, viewed 3 March 2007, <<http://www.iata.org/NR/rdonlyres/6B5FE6C7-7346-4728-8C16-E038D5E29676/0/IndustryStatisticsFEB07.pdf>>.

ICAO (International Civil Aviation Organization) 2007a, *Annual report of the council 2006*, ICAO, Montreal.

ICAO (International Civil Aviation Organization) 2007b, *Outlook for air transport to the year 2025*, ICAO, Montreal.

IPCC (Intergovernmental Panel on Climate Change) 1999, *Aviation and the global atmosphere*, special report, Cambridge University Press, Cambridge.

IPCC (Intergovernmental Panel on Climate Change) 2001, *Climate change 2001: the scientific basis*, Cambridge University Press, Cambridge.

IPCC (Intergovernmental Panel on Climate Change) 2007, *Climate change 2007: the physical science basis, summary for policymakers*, Contribution of Working Group I to the Fourth Assessment Report, IPCC, Paris.

Lucas, C 2006, 'Aviation the worst greenhouse polluter', *The Canberra Times*, 23 June 2006, p. 13.

Macintosh, A & Downie, C 2007, *A flight risk? Aviation and climate change in Australia*, Discussion paper no. 94, The Australia Institute, Canberra.

National Emissions Trading Taskforce 2006, *Possible design for a national greenhouse gas emissions trading scheme*, NETF, Melbourne, viewed 2 April 2007, <http://www.emissionstrading.nsw.gov.au/_data/assets/pdf_file/2017/Discussion_Paper_-_Full_document.pdf>.

Newton, P & Falk, R 1997, *DTI forecast of fuel consumption and emissions from civil aircraft in 2050 based on ANCAT/EC2 1992 data*, Department of Trade and Industry (UK), London.

Peeters, P, Middel, J & Hoolhorst, A 2005, *Fuel efficiency of commercial aircraft: an overview of historical and future trends*, National Aerospace Laboratory NLR, Amsterdam.

RCEP (Royal Commission on Environmental Pollution) 2002, *The environmental effects of civil aircraft in flight*, Government of the United Kingdom, London.

Sausen, R, Isaken, I, Grewe, V, Hauglustaine, D, Lee, D, Myhre, G, Kohler, M, Pitari, G, Schumann, U, Stordal, F & Zerefos, C 2005, 'Aviation radiative forcing in 2000: an update on IPCC (1999)', *Meteorologische Zeitschrift*, vol. 14, no. 4, pp. 555-561.

Scottish Executive 2006, *Scottish economic report*, 14th edition, Scottish Executive, Edinburgh.

SCEA (Select Committee on Environmental Audit) 2004, *Third report of session 2003-04: pre-budget report 2003 - aviation follow-up*, House of Commons, Government of the United Kingdom, London.

SCEA (Select Committee on Environmental Audit) 2006, *Reducing carbon emissions from transport*, Ninth report of the session 2005-06, vol. 1, House of Commons, Government of the United Kingdom, London.

Stern, N 2007, *The economics of climate change: the Stern review*, Cambridge University Press, Cambridge.

Truss, W 2006, *Address to the BTRE Transport Colloquium*, 14 June 2006, Commonwealth of Australia, Canberra.

Tyndall Centre for Climate Change Research 2006, *Memorandum submitted by Tyndall Centre for Climate Change Research, Manchester*, House of Commons Select Committee on Environmental Audit, United Kingdom, viewed 21 March 2007, <<http://www.parliament.the-stationery-office.com/pa/cm200506/cmselect/cmenvaud/981/981we67.htm#note105>>.

Wit, R, Boon, B, Velzen, A, Cames, M, Deuber, O & Lee, D 2005, *Giving wings to emission trading: inclusion of aviation into the European emissions trading system - design and impacts*, Report for the European Commission, CE Delft, The Netherlands.