GREEN GROWTH AND THE FUTURE OF AVIATION

Paper prepared for the
27th Round Table on Sustainable Development
to be held at OECD Headquarters
23-24 January 2012

ACKNOWLEDGEMENTS

This paper is issued under the authority of the Chairman of the Round Table on Sustainable Development and was prepared by its staff. The Round Table would like to thank Nils Axel Braathen, Philippe Crist, Ruth Delzeit, Christina Hood, Timothy Searchinger, Anselm Eisentraut and Ron Steenblik, who provided valuable comments and input to the paper.

The Round Table on Sustainable Development gratefully acknowledges financial support provided by the World Business Council on Sustainable Development and the European Climate Foundation.

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OVERVIEW

Warren Buffet is famous for claiming that, despite a few limited success stories, commercial aviation as a sector has rarely been profitable. Sir Richard Branson joined the chorus of irony when he suggested that the fastest way to become a millionaire is to become a billionaire then purchase an airline. The airline industry is anything but normal. It is wracked by distortions that flow from governments supporting national carriers for strategic and sovereignty reasons, leading to oversupply and continuing pressure on margins. To this structural weakness must be added a series of external pressures: significant increases in the price of jet fuel and, to a lesser extent, from increasing labour costs, large volcanic eruptions, large-scale disease outbreaks, terrorist attacks, and the recent global financial crises. Although the airlines have generated poor results for decades, their key suppliers have done much better, with the major airframe manufacturers (*e.g.* Airbus and Boeing), jet engine companies (*e.g.* GE, Pratt & Whitney and Rolls Royce) and the jet fuel providers (*e.g.* BP, Total and Shell) all generally profitable.

To add fuel to the airline sector's loss-making fire, the industry is also carbon-intensive and one of the fastest growing in terms of its greenhouse gas emissions. There have been several international attempts, both from governments and the private sector, to develop global schemes to lower greenhouse gas emissions in the aviation sector. Success to date has been very limited. As a result of the lack of progress on the global level, the EU decided to add aviation to its Emissions Trading System (EU ETS) as of 1 January 2012. This has caused a storm of controversy, with opposition from at least 26 countries, including the US, Russia, India, Brazil and China.

Aviation under business-as-usual is likely to generate a sharp increase in greenhouse gas emissions and radiative forcing through 2050 because of the particularity of its emissions. The combined effect is that aviation's impact on global warming is likely to grow more swiftly than other sectors. Because of that growth, there is a strong likelihood that governments will face pressure to take action to curb radiative forcing resulting from aircraft emissions.

Although airlines have a large range of operational and technical options open to them to reduce their greenhouse gas emissions, all of these abatement opportunities will be overwhelmed if the predicted growth in airline travel eventuates. The expected growth in Asia alone will mean efforts to improve flight paths, the addition of winglets to the tips of aircraft wings, more efficient taxiing of aircraft and ongoing improvements to the fuel efficiency of jet engines will all be overtaken by the dramatic increase in flights and passenger miles. It appears that the only greenhouse gas abatement opportunities available with the potential scale to address the enormous expected growth in airline travel may be the extensive use of offsets and the large-scale production and use of aviation biofuels.

In anticipation of this, the international body that regulates the jet fuel airlines can purchase and use, certified a second process that permits biomass and plant oils to be used as feedstocks for a biofuel alternative to jet fuel (kerosene) made from fossil fuel. The new fuel, known as bio-SPK (bio-derived synthetic paraffinic kerosene), can be mixed with kerosene to create a 50-50 blend of the two fuels that requires no modifications to aircraft fuel systems or engines.

The production and use of biofuels, mostly for road transport, has had a mixed reception. With the notable exception of the sugar cane ethanol industry in Brazil, biofuel production for road transport has been associated with subsidies. The extent to which biofuels are really carbon "neutral" is also the subject of considerable on-going debate. Concerns have been raised about their neutrality over the entire life-cycle of the product, the need to take account of land use change resulting from conversion of land to biofuel production and whether or not “neutrality” requires additionality of carbon sequestration over and above that which would have taken place in any case. Another concern is the flow-on effect of increased biofuel crop cultivation on food prices.

With many governments moving to explore green growth initiatives, the question arises whether aviation biofuels represent a large potential green growth opportunity or whether the environmental, social and commercial challenges raised are too large. This is one of many technical and economic uncertainties that need to be resolved. Others include how best to deal with warming associated with tropospheric ozone and contrail-included cloud formation and the challenge of financing improvements in energy efficiency through the deployment of new aircraft.

This paper discusses the extent to which the predicted growth of aviation in a carbon-constrained world is possible given the known operational and technological options, and in particular the extent to which aviation biofuels form part of the answer. Even without a carbon constraint, aviation faces significant challenges. If capping global greenhouse gas emissions remains a serious goal, then aviation’s problems intensify. With these challenges in mind, some fundamental questions are raised, for instance:

- Given fossil-fuel resource constraints and rising costs, is it realistic to believe that growth in aviation will continue unabated?

- If there is a limited amount of additional capacity in the atmosphere to store human produced greenhouse gas emissions, should airlines be given some preferential access to this resource as a result of their limited abatement options?

- What is the potential for biofuel production to be scaled-up to the extent needed to meet future demand for aviation fuel? What would be the effect of adding aviation demand for low-carbon biofuel production to government-driven demand for biofuels by other transport sectors?

- If there is a limited capacity to produce biofuels sustainably and cost-effectively on a large scale, should most or all of it be dedicated to airline travel, as other transport sectors have a larger range of abatement options?

Standard economic analysis would argue in favour of treating aviation no differently from any other sector, in which case these questions have relatively straightforward answers. That has, however, not been the history of policy interventions in the aviation sector. While this paper does not seek to provide answers to these questions, they are unlikely to be far from the surface in the on-going debate about how to treat greenhouse gas emissions from aviation going forward.

1. GREENHOUSE GAS EMISSIONS IN THE AVIATION SECTOR

1. Understanding the key policy and commercial issues surrounding climate change and the specific impacts created by a growing aviation sector requires a general appreciation of the science of climate change and the global greenhouse gas management challenge. This section provides information on the key global climate change targets, the current status of emissions reduction efforts, the unique chemistry and physics of aviation emissions, and the global share of aviation emissions. It also reviews the scope for continuing to provide jet fuel from fossil sources (kerosene) into the foreseeable future.

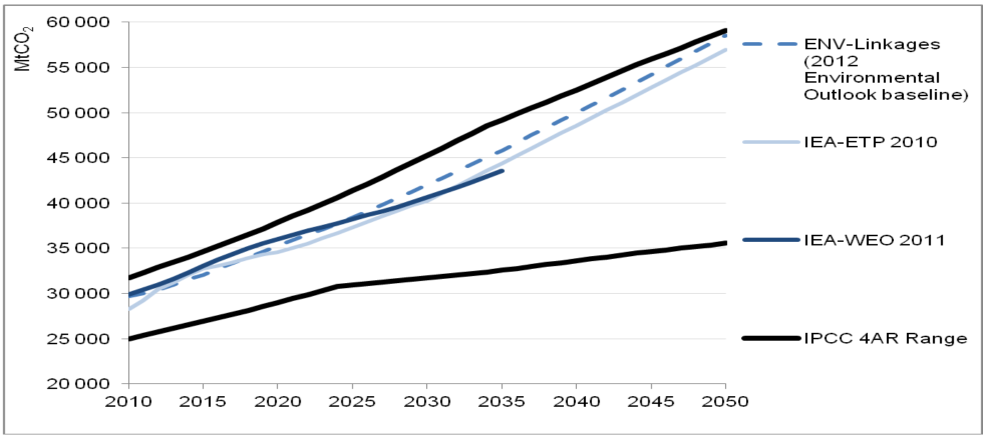
1.1 The global greenhouse gas challenge

2. The global concentration of greenhouse gases in the atmosphere resulting from human activities is growing rapidly. The total carbon dioxide component, which is the largest, has risen from 280 parts per million (ppm) before the beginning of the Industrial Revolution to more than 390 ppm in 2011. This large and rapid increase in the concentration of greenhouse gases in the atmosphere, which traps outgoing energy radiating from the surface of the planet, has led to a globally averaged increase in the surface temperature of the planet of 1.0 degrees Celsius (°C).[1]

3. The Intergovernmental Panel on Climate Change (IPCC) has strongly suggested, and the international community has agreed through the UNFCCC process, that the world should seek to limit total warming to less than 2.0°C). Staying below this threshold is necessary if we want to "prevent dangerous anthropogenic interference with the climate system".[2] Estimates suggest that this will require concentrations of greenhouse gases to be stabilised at or below 450 ppm.[3] Recent modelling by the OECD suggests that without more ambitious policies than have already been announced (including those pledged at the Copenhagen and Cancun conferences), the world will be on course for atmospheric concentrations of nearer to 685ppm CO_2-equivalents by 2050 (OECD, forthcoming). Figure 1 provides a comparison of recent emissions projections from a variety of modelling studies. They would imply global average temperatures increasing by 3 to 6 °C higher than pre-industrial levels by the end of the century. Furthermore, unless significant additional mitigation measures are undertaken prior to 2020, the costs of delayed action may be so high that achieving the 2°C goal may become unaffordable. The scale of the challenge means that no emitting sector can be exempted from mitigation measures.

Figure 1. Comparison of global emissions CO_2 from fossil fuel combustion across selected studies

$MtCO_2$



Source: Chateau, J., et. al., OECD, 2011.

1.2 Aviation's contribution to the global economy and future emissions

4. Aviation plays an essential role in global economic development[4] by connecting people for business and tourism, supporting the trade of goods, defence and a range of political and humanitarian concerns.[5] Global commerce and employment are significantly dependent on the aviation sector. In 2007, according to the World Economic Forum (WEF), the aviation industry contributed USD 426 billion to global GDP directly, an additional USD 490 billion indirectly, and another USD 620 billion through facilitating global tourism In sum, the total contribution is equal to 3.2% of global GDP. For 2007, the aviation industry accounted for 33 million jobs.[6]

5. These figures will increase significantly in the future if the demand for aviation rises by an expected 4.5% annually to 2050. By 2026, studies suggest that the contribution to global GDP from aviation could rise to USD 973 billion directly, another USD 1.1 trillion indirectly, and USD 1.5 trillion through direct support of global tourism. There is strong and growing global demand for expanding air travel and air freight shipments.

6. Although emissions from aviation currently account for approximately 3% of the total global carbon emissions, they are expected to increase significantly in the near future. The demand for aviation will be especially strong in China, India, and the Middle East. Growth in aviation is largely determined by growth in GDP. The WEF has observed that: "increased GDP is enlarging the middle class of these countries that have the disposable income to spend in travel- and tourism–related activities" (WEF, 2011).

7. Current estimates suggest that there will be 3 billion more middle class consumers by 2050, taking today's total of approximately 1.8 billion to 4.8 billion (McKinsey, 2011). The growth in global population from 7 billion today to 9-10 billion in 2050 will be accompanied by an increase in global GDP from USD 55 trillion today to USD 300 trillion by 2050. This nearly six-fold increase in global economic output over the next 40 years is twice as large as the increase that occurred between 1970 and 2010.

1.3 The unique chemistry and physics of aviation emissions

8. In addition to CO_2, aircraft emit a number of other compounds into the atmosphere that have an impact on atmospheric forcing. These emissions include Nitrogen dioxides (NOx), Volatile organic compounds (VOCs), Carbon monoxide (CO), Black carbon (BC), Organic carbon (OC) and other aerosols as well as Sulphur dioxide (SO_2). The emissions of aerosols and water vapour by aircraft engines in humid air layers also form contrails which contribute to cirrus cloud formation. This has a potentially strong climate impact, albeit one that has proven extremely difficult to quantify to-date[7]. Many of the atmospheric warming impacts from aviation result from complex photochemical reactions. The relative climate impacts of all of these different gases and particulates are compared using the concept known as "radiative forcing" (RF) (see box). Emissions components with negative radiative-forcing values lead to cooling effects and positive radiative-forcing values lead to warming effects. Whether radiative forcing from aircraft emissions is positive or negative depends on the presence of other reactants in the atmosphere, the altitude at which emissions and concentration occur and, crucially, the time scale over which the impact is measured.

Box 1. Radiative Forcing (RF) and Global Warming Potential (GWP)

The influence of a factor that can cause climate change, such as a greenhouse gas, is often evaluated in terms of its **radiative forcing**. Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative arises because these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. This radiative balance controls the Earth's surface temperature. The term forcing is used to indicate that Earth's radiative balance is being pushed away from its normal state.

Radiative forcing is usually quantified as the 'rate of energy change per unit area of the globe as measured at the top of the atmosphere', and is expressed in units of 'Watts per square metre' (see Figure 2). When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. Important challenges for climate scientists are to identify all the factors that affect climate and the mechanisms by which they exert a forcing, to quantify the radiative forcing of each factor and to evaluate the total radiative forcing from the group of factors.

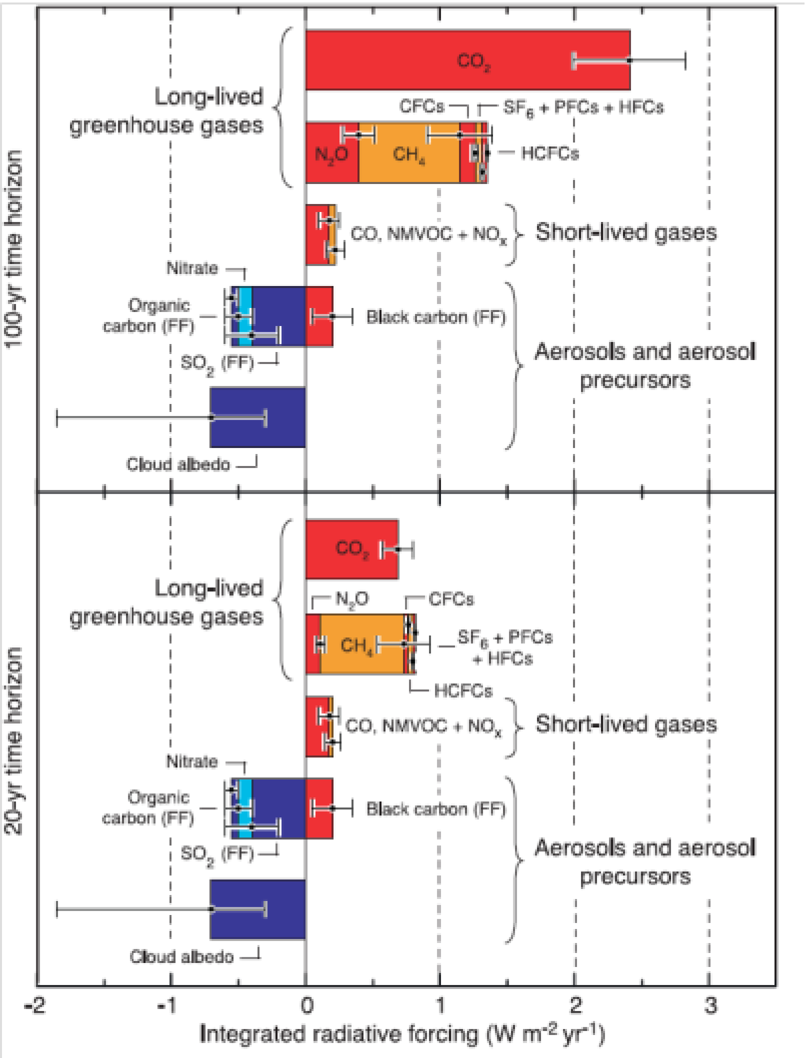
Multi-component abatement strategies to limit anthropogenic climate change need a framework and numerical values for the trade-off between emissions of different forcing agents. **Global Warming Potentials** or other emission metrics provide a tool that can be used to implement comprehensive and cost-effective policies (Article 3 of the UNFCCC) in a decentralized manner so that multi-gas emitters (nations, industries) can compose mitigation measures, according to a specified emission constraint, by allowing for substitution between different climate agents.

A physical GWP index, based on the time-integrated global mean RF of a pulse emission of 1 kg of some compound (*i*) relative to that of 1 kg of the reference gas CO2, was developed (IPCC, 1990) and adopted for use in the Kyoto Protocol. [However], by its definition, two sets of emissions that are equal in terms of their total GWP-weighted emissions will not be equivalent in terms of the temporal evolution of climate response.

Source: Adapted from IPCC FAR, WG1, CH.2 (IPCC, 2007)

9. Figure 2 shows the IPCC's best assessment of the radiative forcing of different gases and compounds in 2000 at 20-year and 100-year horizons. By contrasting the two, the relative importance of short-lived gases at short time scales becomes apparent. This is of consequence for aviation whose total radiative forcing is not dominated by CO_2 emissions alone. This figure also underscores the importance of the time-scale selected for evaluating the warming impact of aviation emissions. Ultimately, the choice of a time horizon with which to assess climate impacts is a political one and reflects the societal weighting given to short-term versus longer term impacts. Most impacts are currently assessed at a 100-year time horizon.[8] As CO_2 accumulates over time, non-CO_2 RF impacts will decrease in relative importance *at constant rates of emissions*. Given that climate impacts are the result of a near-continuous "pulse" of short-lived and long-lived compounds, reducing the short-lived component of the stream can have a real impact on short-term and cumulative longer-term forcing.[9]

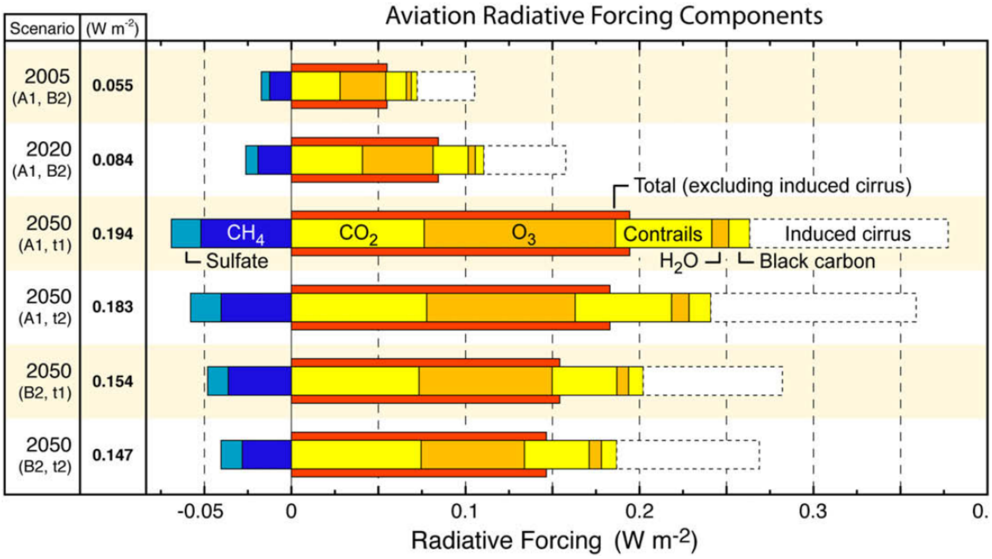
Figure 2. Integrated radiative forcing for Year 2000 emissions
(Weighted by 100-yr and 20-yr time horizons)[10]



Source: WG1, CH2, IPCC, 2007.

10. Aviation NOx emissions in the upper troposphere have both positive and negative radiative forcing impacts though the positive forcing seems to be greater than the negative forcing due to the specific photochemical reactions that take place at cruise altitudes.[11] A recent assessment of aviation's radiative forcing effect[12] confirms the importance of non-CO_2 radiative forcing from aviation over the short-term (see Figure 3). By 2050, ozone and contrail-related RF is expected to dominate CO_2 RF though at a 100-year horizon (2100) CO_2 RF is expected to grow in relative terms as more CO_2 accumulates in the atmosphere. The study finds that total aviation-induced radiative forcing (excluding contrail effects) accounted for 3.5% of the total anthropogenic radiative forcing in 2005. Including rough estimates of contrail-effects raises the total radiative forcing to 4.9% of all anthropogenic forcing, though at a much lower confidence level. Looking out to 2050, the study projects that aviation-induced radiative forcing (excluding contrail effects) could increase by a factor of 3 to 4 over 2000 values resulting in 4.0 to 4.7 of total anthropogenic radiative forcing in 2050.

Figure 3. Global radiative forcing components for aviation for 2005, 2020 forecast and 2050 scenarios



Note: Total forcing displayed by the red bars and numerically on the left account for CH4 and sulfate cooling but exclude estimates of cirrus-cloud effects.

Source: Lee, et al., 2009.

11. The discussion above highlights the importance of accounting for aviation-sector emissions of compounds and effects that are not addressed in the Kyoto protocol or in the UNFCCC process. For instance, some have pointed out that since the climate impact of these compounds is much more short-lived than CO_2, removing these from the atmosphere will affect warming trends much more rapidly and may serve to buy time for longer-acting but more challenging CO_2 reductions.[13] However, action to target non-CO_2 emissions from aviation involve tradeoffs. For instance, optimising flight stages to reduce contrail formation may entail emitting more CO_2 (via greater fuel burn) whose warming impact overwhelms any cooling impact resulting from reduced cirrus cloud formation. Likewise, strategies to optimise engine combustion for low NOx emissions may also result in greater CO_2 emissions.

1.4 Future aviation-fuel scenarios

12. Aviation accounts for approximately 10% of global transport fuel use and emits 2% of the world's carbon dioxide emissions, totalling more than 707 million tonnes.[14] The rising cost of jet fuel made from crude oil (kerosene) led airlines to spend USD 140 billion on fuel representing more than 30% of their rising operating costs in 2010 (ATAG, 2011). In 2012, the airlines' fuel costs are expected to exceed USD 200 billion and approach 35% of total operating costs.[15] This rise in kerosene prices is financially unsustainable for many airlines and now comprises the single largest operating expense for many of them.

13. With crude oil prices now sitting around USD 100 per barrel, there is considerable debate about the amount of remaining crude oil that can be recovered economically. While refinery and extraction capacity are the source of a short-term bottleneck, the long-term issue of "peak oil" continues to engage debate. The International Energy Agency (IEA) has stated that we reached an all time global peak in production of conventional oil output of around 70 million barrels per day (70 mb/d) in 2006. However, with sufficient investment, gas liquids and unconventional crude could meet rising demand for liquid fuel until 2035. What does this mean for the future of aviation fuels derived from crude oil?

14. Numerous technologies have been used under special circumstances to make liquid fuels from both natural gas and coal over the past 50 years. A leading example is the coal-to-liquids (CTL) technology used by the South African oil company, SASOL, during the apartheid period, when the country was the target of extensive restrictions on its international trade. Although currently more expensive than the technology that converts crude oil into jet fuel (kerosene), and emitting larger quantities of carbon emissions in the process, it does provide a large future pathway to continue using fossil fuels in the aviation sector. Jet fuel could be produced from coal (which remains relatively plentiful) and natural gas. There is a large and growing list of companies working to perfect these fossil-to-jet fuel conversion technologies.

15. The question of whether or not the world continues to produce jet fuel from oil, coal or natural gas depends on a few key factors. Cost is the single biggest driver of options for the future of fossil-derived jet fuels and the future price of crude oil is fundamental to any material changes to the status quo. With the current boom in shale gas production, it is possible that gas could become sufficiently cheap and plentiful to be converted to jet fuel. Even if gas is not converted to jet fuel, it can relax the overall energy constraint thereby lowering the prices aviation faces for traditional kerosene.

16. Against this background, decisions concerning the policies that will be used to reduce greenhouse gas emissions will play a major role in changing the cost differences between fossil-derived jet fuel options. If governments agree to put a price on carbon and other greenhouse gases, and that price is sufficiently high to change the global carbon emissions trajectory, then it is unlikely that coal-to-liquids or gas-to-liquids technologies will be viable.

2. A SHORT HISTORY OF ATTEMPTS TO LIMIT GLOBAL AVIATION EMISSIONS

17. Commercial aviation is one of the fastest growing sectors in the global economy both in terms of revenues and greenhouse gas emissions. There is a widely held view that the aviation sector requires a global framework to start the process of reducing its greenhouse gas emissions on a scale and timescale meaningful to the challenge. This section reviews attempts by both governments and the private sector to create a global framework to address the large expected increases in carbon emissions from the aviation sector.

2.1 The Kyoto Protocol and ICAO

18. During the negotiations on the 1997 Kyoto Protocol, governments decided to keep emissions from the aviation and the marine sectors outside the scope of the agreement. As the Protocol created obligations to reduce greenhouse gas emissions on national governments, and emissions from the aviation and marine sectors were largely international and outside the scope of individual nations, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) were given lead responsibility for developing global frameworks for reducing emissions from these two sectors.

19. Article 2.2 of the Kyoto Protocol states: "*The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.*"[16] Despite being given this responsibility in 1997, and the Kyoto Protocol coming into effect in 2006, ICAO has not yet managed to create a global framework for greenhouse gas emissions from the aviation sector.

20. ICAO is a specialised body of the United Nations, created by the 1944 Chicago Convention on International Civil Aviation and governed by an Assembly, in which all member countries have a seat and a vote. Its supreme rule-making body is the Council which includes representatives from 33 member countries selected on the basis of their importance to international aviation. Its Secretariat is headed by a Secretary General. In 1983, recognising the growing environmental impacts from the international aviation sector, the ICAO Council created the Committee on Aviation Environment Protection (CAEP) and gave it lead responsibility for responding to climate change-related issues. The CAEP has explored a range of options to reduce greenhouse gas emissions (including taxes and charges) from aircraft but has had difficulty in making progress.

21. In 2004, the European Parliament criticised the ICAO's decision not to pursue an emissions trading system "as unacceptable and a retrograde step for ICAO which would undermine the organisation's credibility". In 2007, ICAO established an expert group known as the Group on International Aviation and Climate Change (GIACC). In order to prepare the ICAO submission to the UNFCCC COP 15 meeting (Copenhagen, December 2009), GIACC recommended that ICAO organise a high-level meeting and, at the third GIACC meeting in February 2009, a recommendation was made to improve fuel efficiency by 2% annually through 2012. In addition, fuel taxes and emissions charges were reconsidered as voluntary measures. At ICAO's high-level meeting, which took place in September 2009, the 2% annual improvement in fuel efficiency was extended to 2020 — but only as an aspirational goal, not a mandatory measure.

22. Fifteen years after being given a mandate to do so by the Kyoto Protocol, negotiations at ICAO have not managed to create a binding regime to control greenhouse gas emissions in the aviation sector. By contrast, ICAO's marine counterpart, the International Maritime Organization (IMO), has made some real progress on controlling emissions from marine bunker fuels.[17] The key difference between the ICAO and IMO processes is that the IMO developed an instrument and a process to tighten its stringency *without* setting a target, whereas ICAO has set a target of sorts, without to date developing an instrument to achieve it.

23. On 1 December 2011, under pressure from the EU decision to include aviation within its Emissions Trading System as of 1 January 2012, ICAO announced that it would accelerate its efforts to develop a market-based emissions policy for the global aviation sector with the goal of having the scheme finalised by the end of 2012.[18]

2.2 IATA and the private sector response

24. There are numerous global, regional and national industry associations representing different sub-sectors within the global aviation sector. Two of the most important private sector organisations, in terms of creating industry responses, rules and targets for reducing carbon emissions are the International Air Transport Association (IATA), representing most of the world's airlines, and the Air Transport Action Group (ATAG) which includes key supply chain companies, *e.g.* the large airframe builders and the major jet engine companies.

25. There are also special groups created uniquely for the purpose of exploring the potential for aviation biofuels. The Sustainable Aviation Fuel Users Group (SAFUG) is a relatively new private sector organisation with numerous airlines as members and some of the major airframe builders as affiliates. SAFUG is focused exclusively on, in their own words, "... accelerating the development and commercialization of sustainable aviation biofuels". The US Government is sponsoring a public-private partnership with a similar focus. Led by the Federal Aviation Administration (FAA), the Commercial Aviation Alternative Fuels Initiative (CAAFI) brings together experts from government and industry to

explore a range of technical and commercial issues associated with the production and use of aviation biofuels.

26. IATA was created in 1947 and is the world's leading industry association for the airline sector. It represents more than 200 airlines from 150 countries. In 2007, in response to growing external pressure to address greenhouse gas emissions in the aviation sector, IATA made public its vision for addressing climate change through the following measures:

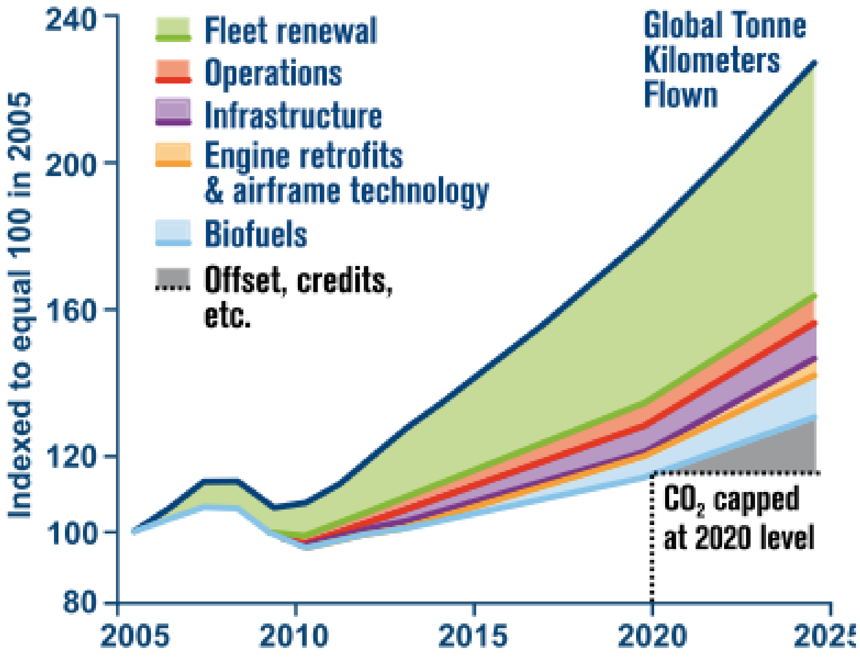
- Build a zero-emissions commercial aircraft within 50 years.
- Adopt a four-pillar strategy that includes:
  - Improved technology;
  - Effective operations;
  - Efficient infrastructure;
  - Positive economic measures.

27. In June 2009, in preparation for the UNFCCC COP15 meeting in Copenhagen, IATA launched a more detailed strategy to reduce carbon emissions through the following three targets:

- A cap on aviation CO_2 emissions from 2020 (carbon neutral growth).
- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020.
- A reduction in CO_2 emissions of 50% by 2050, relative to 2005 level.

28. Figure 4 below is an illustration of how IATA suggests various abatement possibilities could contribute to its four pillar strategy, compared with a business-as-usual projection out to the year 2025.

Figure 4. IATA's emissions abatement strategy

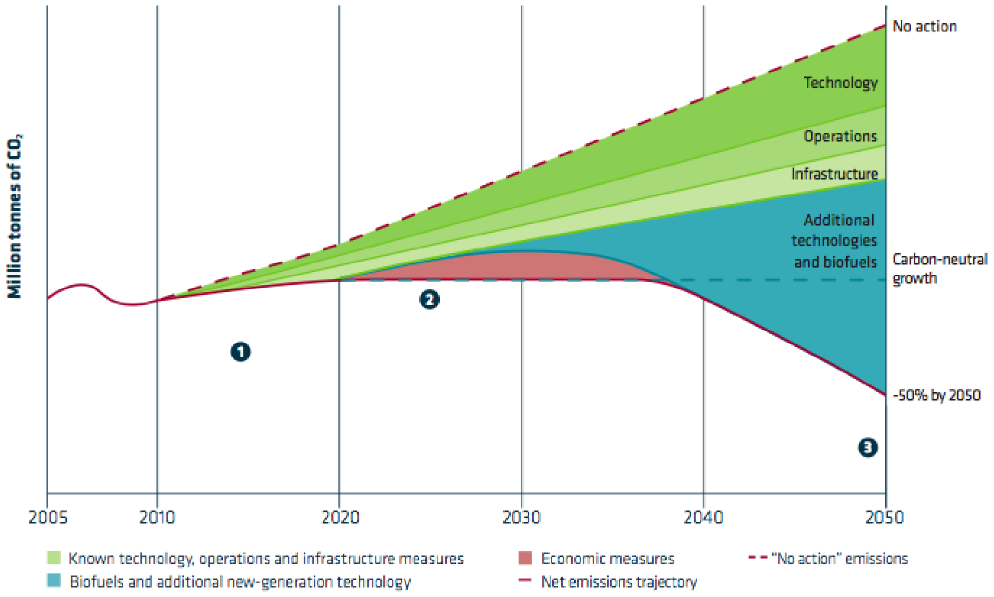


Source: IATA, 2009.

29. Figure 5 below is a similar, more general illustration from ATAG on contributions to an abatement pathway through to 2050.

30. IATA's four pillar plan is an extremely ambitious one that will be difficult to achieve – more so as its targets are voluntary. To put the scale of the financial challenge into perspective, meeting the first of the three IATA targets, a 1.5% increase in fuel efficiency from now until 2020, will require airlines to spend USD 1.3 trillion on approximately 12 000 to 15 000 new aircraft. Considering the current major challenges facing the global banking sector and the poor return on capital over decades in the airline sector, gaining access to the growing amounts of required capital will pose significant challenges (though arguably less so in China and other fast-growing Asian markets where much of the growth will take place).

Figure 5. ATAG schematic of industry commitments



Source: ATAG, 2010.

31. IATA opposes the extension of the EU ETS to the aviation sector and continues to maintain that ICAO should retain unique responsibility for implementation of an international regime to control greenhouse gas emissions emitted by the airlines. IATA remains in favour of voluntary targets to achieve reductions in the airlines' greenhouse gas emissions. In response to ICAO's proposal for agreement on a market-based policy instrument by the end of 2012, it has suggested that implementation should be deferred until after 2020.[19] IATA holds the view that the massive incentive to keep rising fuel costs down will form the basis of the required reductions in emissions well into the future.

2.3 Government attempts to price greenhouse gas emissions

32. The failure of intergovernmental attempts to create a global framework to limit greenhouse gas emissions from the aviation sector has led to a number of bottom-up regional, national, and sub-national systems. The most prominent of these is the extension of the Emissions Trading System of the European Union (EU ETS), launched in 2005, to aviation.

33. The EU ETS as originally conceived covered approximately 40% of the total EU carbon emissions and included more than 12 000 installations within sectors including stationary energy, ferrous metal production, cement, ceramics, glass and pulp and paper. It accounts for more than 90% of the global market of the trading of carbon instruments — now estimated to exceed USD 150 billion per year. In order to manage the potentially large disruptive impact of the ETS on these carbon-intensive sectors, free allocations of emission permits were made, covering, in some cases, up to 95% of compliance obligations.

34. On 9 November 2008, the EU adopted legislation which amended the 2003 Directive which created the EU ETS. Having been agreed to by all EU member countries through the Parliament and the Council, the new Directive (Aviation Directive) made it a legal requirement that the aviation sector join the EU ETS on 1 January 2012. The Aviation Directive makes it clear that the EU will focus its compliance activities on the more than 900 aircraft operators (mostly airlines). This includes the carbon emissions from all flights within and into and out of the EU.

35. Similar to other sectors covered by the ETS, aircraft operators will need to surrender allowances equal to their total annual emissions beginning with the year 2012. In the same way that the EU allowed for a smooth transition into the ETS by other sectors, the Aviation Directive grants aircraft operators a large share of their emissions in free allowances. On 26 September 2011, the EU made public the following free-allocation schedule for aircraft operators:

- 1 January 2012 to 31 December 2012: aircraft operators will receive a free allocation of allowances to cover 85% of their emissions and 15% will be auctioned.

- 1 January 2013 to 31 December 2020: aircraft operators will receive a free allocation of allowances to cover 82% of their emissions, 15% will be auctioned and the remaining 3% will be left for new entrants and fast-growing airlines.

36. The other key variable is the cap set by the EU — that is, the total emissions that can be emitted by each sector in each year or commitment period. This sectoral cap does not directly constrain the industry’s total emissions however, as allowances can be purchased from other industrial sectors covered by the EU ETS, or offsets may be used. The Aviation Directive sets the caps as follows:

- 1 January 2012 to 31 December 2012: the total quantity of EUAs to be allocated to aircraft operators shall equal 97% of historical emissions (mean average of annual emissions in the years 2004, 2005, and 2006).

- From 1 January 2013: the total quantity of EUAs to be allocated to aircraft operators shall equal 95% of historical emissions (mean average of annual emissions in the years 2004, 2005, and 2006).

37. The Aviation Directive also includes the flights of non-EU airlines both into and out of the EU. This attempt to extend the effect of the EU ETS to aviation has attracted both political protests and a legal challenge. As of 21 December 2011, 26 nations had registered opposition to the extension of the EU ETS to their airlines.[20] These countries include China, India and the United States. Furthermore, legislation was introduced and adopted by the US House of Representatives that would make it illegal for US airlines to participate in the EU ETS.

38. In 2011, two US airlines and the Air Transport Association brought legal action in the UK High Court to stop implementation of the Aviation Directive. The UK High Court referred the case to the European Court of Justice. The claimants argued that the extension of the Aviation Directive to non-EU

airlines was a violation of international law. On 21 December 2011, the ECJ ruled against the claimants by upholding the legitimacy of the Aviation Directive and its application to non-EU airlines.

39. Only two countries outside the EU have domestic legislation covering carbon emissions from airlines. New Zealand adopted its Emissions Trading System in 2008; greenhouse gas emissions from domestic flights have been covered since 2010. In 2011, the Australian Parliament adopted legislation that creates a national emissions trading system for several sectors including domestic air travel. The Australian scheme will begin with a fixed-price period in 2012 and will evolve into a national emissions trading system in 2015.

40. The Aviation Directive includes an "equivalent measures" provision that could allow countries outside of the EU who take regulatory measures to limit carbon emissions from the aviation sector to be exempted from the application of the EU ETS to the sector. At present, the Australian and New Zealand regulations only cover domestic flights and not international traffic covered by the EU ETS, so these provisions would probably not be triggered.

41. Many Kyoto Protocol parties with obligations to reduce their carbon emissions have failed to introduce a carbon price through national legislation. One party, Canada, has announced its withdrawal from the Protocol. As energy is fundamental to the economies of all countries, and most carbon emissions flow from energy production and consumption, many governments have found it politically impossible to enact legislation creating a carbon price.

42. Nevertheless, the optimal outcome for achieving reductions in greenhouse gas emissions is to create a global regime that places a price on such emissions. Although the Kyoto Protocol was partially successful in this regard by setting emissions reductions targets for most OECD countries, the major developing country emitters (*e.g.* China, India, Brazil, Mexico and South Africa) were left without obligations to reduce their emissions. There is little prospect of a global regime to price greenhouse gas emissions being adopted any time soon. Parties to the UNFCCC committed themselves in Durban (2011) to agree on a 'legal instrument or agreed outcome with legal force' by 2015, to come into force in 2020. It remains to be seen how comprehensive or cost-effective any such outcome will be.

3. REDUCING GREENHOUSE GAS EMISSIONS IN THE AVIATION SECTOR

43. An exploration of the future of aviation in a carbon and, potentially, energy-constrained global economy requires an understanding of both the policy mechanisms that can be deployed to incentivise emissions reductions and the range of technical abatement options available to the sector. This section looks first at the use of economic instruments, including offsets. It does not explore regulatory options. It then turns to the range of operational and technical abatement opportunities available.

3.1 Incentivising the reduction of aviation emissions through the use of economic instruments

44. The most straightforward approach to limiting greenhouse gas emissions in the aviation sector is to create and implement regulations that put a price on such emissions. The two most widely canvassed instruments are a carbon tax and an emissions trading system. The advantage of a tax is that a fixed price is easy to implement and is easily incorporated by the market. If the marginal cost of abatement for a company is higher than the tax, it can cap its costs by paying the tax. The principal problem with a tax is that it is difficult to predict the exact reduction in emissions that will result.

45. An emissions trading system, as implemented by the EU, has the advantage of determining the amount of reduction in greenhouse gas emissions that will be achieved and letting the market determine the price at which this target (or cap) will be reached. Trading emission permits allows the market to find the lowest cost of abatement where companies with lower marginal abatement costs will take on a larger share of the target burden and be compensated by the companies with higher abatement costs. The disadvantage is that such a system is relatively complex and difficult to manage effectively. The operation of the EU ETS has been affected by a number of problems, ranging from the over-allocation of permits by some EU Member States to the theft of permits from electronic registries.

46. An emissions trading system that includes aviation implies that the marginal costs of reductions in the aviation sector will be no higher than the marginal costs of mitigating emissions in any other capped sector. In general, emissions trading systems allow any company facing carbon limits to buy credits from other limited sources, such as factories and power plants. For example, the EU's emissions trading system allows sources to purchase credits freely from other regulated entities. The economic value of these traded credits reached EUR 3.1 billion in 2008 (European Commission, 2009). An emissions trading system thus allows a high-cost abatement sector like aviation to purchase credits from other capped sources whose marginal abatement costs are lower. A key question for any trading system that includes aviation will be which entity will be held responsible for holding credits. The EU ETS extension to aviation includes the operators of aircraft (mostly airlines), but it would be possible to make fuel providers responsible instead. For example, the Australian and New Zealand systems are structured to make fuel providers responsible for emissions by default (and pass on costs to fuel purchasers such as airlines) while also allowing airlines to opt-in to manage their own emissions.

47. The aviation sector might also be able to meet its obligations through recourse to offsets. The purchase of "offsets" differs from the purchase of emission allowances from other regulated sources by authorising the purchase of emissions reductions from emitters who aren't otherwise regulated. An offset system allows unregulated sources of emissions to obtain credits for actions to reduce emissions that they can then sell. Offsets have played a major role in holding down cost estimates for mitigation strategies for energy use in analyses undertaken by the Stern Review of global climate mitigation costs (Stern, 2006, p. 247, Table 9.1), and by the US Environmental Protection Agency of the climate change bill that passed the US House of Representatives in 2009 (US Environmental Protection Agency, 2009).

48. Under the Kyoto Protocol, the Clean Development Mechanism provides the means of certifying credits for mitigation in developing countries that they, and by extension their companies, can purchase to meet their own required reductions. The CDM board has established extensive criteria for recognising credits. As of 2010, roughly 85% of these offsets occurred through reductions in industrial trace gases (particularly HCFCs), renewable energy projects, and methane capture projects (Vasa, 2011).

49. Much of the literature on potential offsets originally focused on land-based emissions such as reduced deforestation, planting of new forests, and agricultural practices. The Stern Report, reflecting much of the thinking at the time, projected this kind of mitigation as plentiful and cheap — a practical source of 6.5 gigatonnes of mitigation per year at USD 27 per tonne and less) (Stern, 2006, pp. 246-247). McKinsey & Company had similarly optimistic conclusions (McKinsey, 2007). More recent literature is less optimistic. For example, some have argued that carbon sequestration in soils, a big part of the earlier estimates, is both more difficult and less scientifically sure than previously believed (Powlson, 2011; McCarthy, 2011). To date, less than 1% of CDM projects have involved land use or agriculture, in part because those kinds of offsets are not allowed under EU policy, due to concerns about verification, permanence and leakage (Vasa, 2011).

50. Concerns about "additionality" have led to major doubts about offsets. For an offset to be legitimate, the payment of a credit must go toward mitigation measures that would not exist otherwise, *i.e.*

the mitigation must be "additional." Such "additionality" is inherently elusive and hard to prove. The more cost-effective and feasible a mitigation project, the more likely it is to occur anyway, *i.e.* less likely it is additional. To establish additionality, CDM requires a range of cost, and technology penetration studies to show the critical role of the offset payment. Critics have pointed to the expense and burden of preparing such studies as a barrier to offsets, but many studies have concluded that, even with these procedures, many or most CDM projects would occur anyway, and therefore are not additional (Vasa, 2011). Some researchers now view "additionality" as an impossible test on a project-by-project basis and have suggested an offset system based on improvements in the emissions from specific industries in specific countries compared to a baseline (Vasa, 2011; Haya, 2009).

51. This baseline approach is the method to be followed by "REDD," the programme accepted in the most recent climate agreement in Durban to provide funding to countries to reduce their rates of deforestation from trend levels. Exactly how the baselines will work, and how much payments will cost, remain to be determined. The role of the private offset market in paying for these reductions also remains still to be determined, but Durban did not close the door to such roles, and they could provide a source of potential credits to the aviation industry.

52. For the next several decades, despite the wide range of practical challenges, some offset system seems likely to help fund the many sources of emissions worldwide that are likely to remain unregulated and could prove an attractive option for the airline industry. Reforestation of land may also become a significant opportunity in the period post-2050. In the very long term, as global emissions must reach extremely low levels, offsets may be able to play a lesser role.

3.2 Operational and technical abatement opportunities open to the aviation sector

53. There are many ways of reducing greenhouse gas emissions through improvements in the operations of aircraft. Many of these are or could become cost-effective as, in the context of continually rising jet fuel prices, they lead to reductions in fuel use both on the ground and in the air. Reductions in fuel use lead to immediate declines in emissions of carbon. Of the many operational options identified, only two lead to significant reductions in fuel use and carbon emissions: 1) increases in load factors, and 2) improvements in air traffic management (ATM).

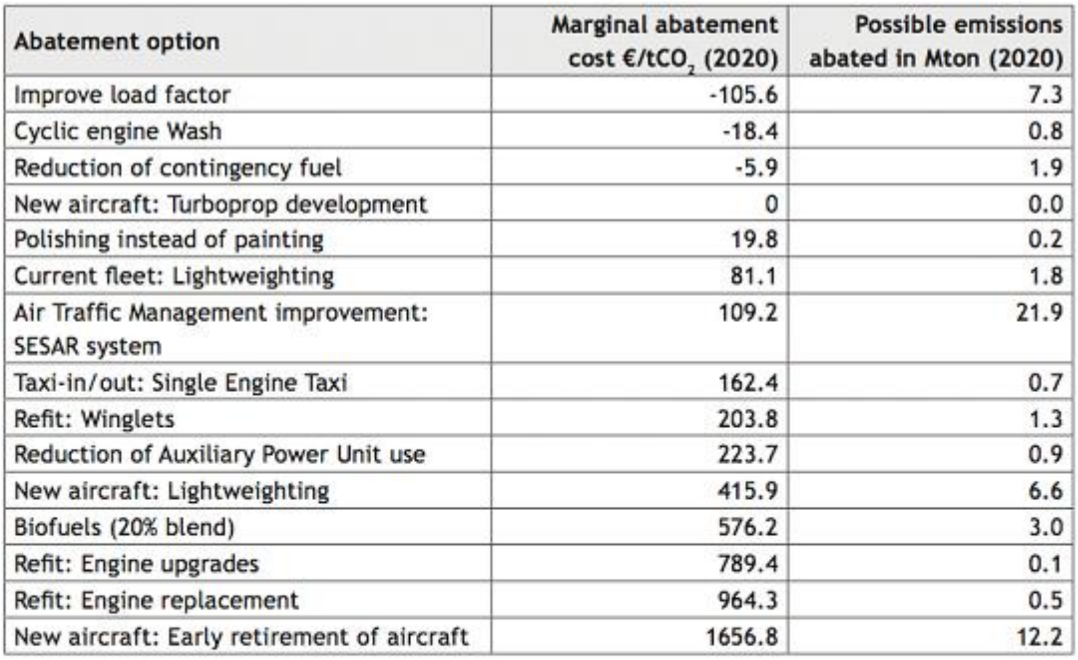
54. Increasing load factors can contribute to lower emissions if the effect is to remove flights from schedules. The International Centre for Trade and Sustainable Development (ICTSD) estimates that the marginal carbon abatement cost of increasing load factors could reach minus EUR 105.6 per tonne CO_2eq by 2020 — that is, after subtracting the cost of implementing the load factor improvements, these reductions yield a return of almost EUR 106 per tonne CO_2eq abated by 2020.

55. Although it represents an excellent return on investment, the total abatement that can be achieved by improving load factors is estimated at 7.3 million tCO_2eq in 2020. This is in comparison with the approximately 750 million tCO_2eq emitted by the global airline sector in 2010 and an expected increase to over 1 billion tCO_2eq in 2020 (Köhler, 2010). More importantly, hanging onto these gains is only possible if there is no "rebound effect" in response to increased demand.

56. Aircraft use a very large amount of fuel taking off, landing, on landing approaches and flight paths including changes in direction and altitude. There are large potential reductions in fuel use and, consequently, greenhouse gas emissions from improvements in air traffic management (ATM). In European airspace alone there are thousands of daily flights. Airlines and air traffic controllers are not currently in a position to optimise flight paths to drive reductions in fuel use and greenhouse gas emissions.

57. Sophisticated computer systems managing large amounts of flight data can correct this problem through next generation ATM programmes. Two such advanced ATM programmes are under development in the United States (the Next Generation Air Transportation System or NextGen) and in Europe (the Single European Sky ATM Research initiative or SESAR). NextGen is expected to be fully operational between 2012 and 2025, and SESAR is planned for deployment between 2014 and 2020. The ICTSD estimates the marginal cost of carbon abatement from next generation ATM systems to be EUR109.2 per tonne CO_2eq in 2020 and total abatement to equal 21.9 million tonne CO_2eq in 2020 (Table 1).

Table 1. Marginal abatement costs and emission reduction potential for aviation in 2020



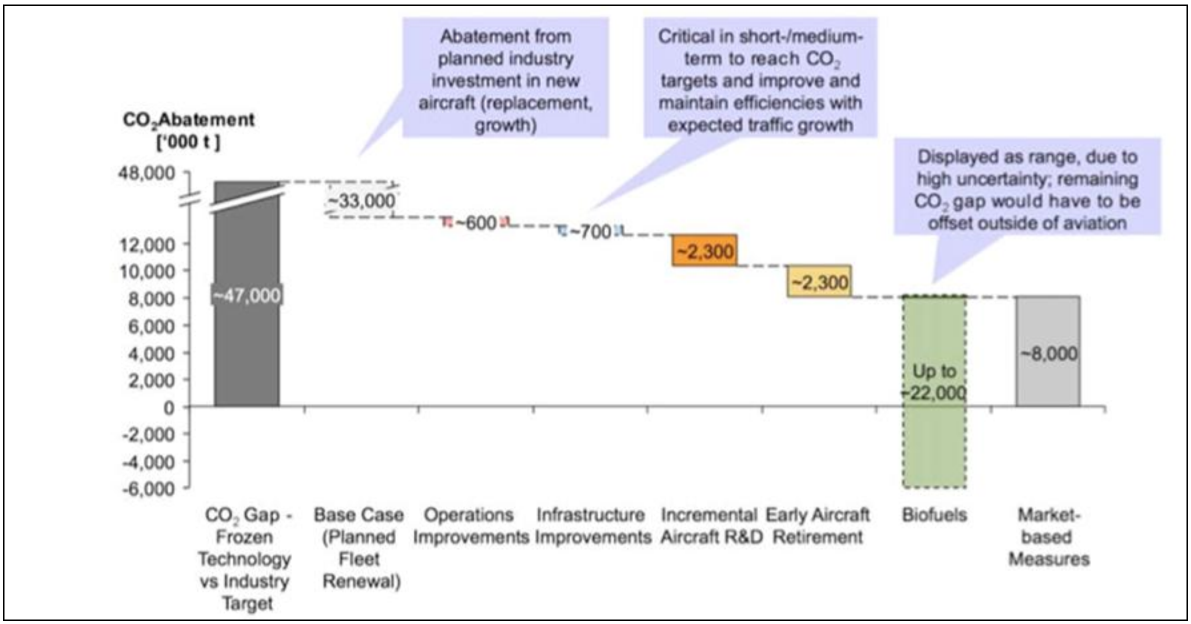
Abatement option	Marginal abatement cost €/tCO_2 (2020)	Possible emissions abated in Mton (2020)
Improve load factor	-105.6	7.3
Cyclic engine Wash	-18.4	0.8
Reduction of contingency fuel	-5.9	1.9
New aircraft: Turboprop development	0	0.0
Polishing instead of painting	19.8	0.2
Current fleet: Lightweighting	81.1	1.8
Air Traffic Management improvement: SESAR system	109.2	21.9
Taxi-in/out: Single Engine Taxi	162.4	0.7
Refit: Winglets	203.8	1.3
Reduction of Auxiliary Power Unit use	223.7	0.9
New aircraft: Lightweighting	415.9	6.6
Biofuels (20% blend)	576.2	3.0
Refit: Engine upgrades	789.4	0.1
Refit: Engine replacement	964.3	0.5
New aircraft: Early retirement of aircraft	1656.8	12.2

Source: Köhler, 2010.

58. Although there is no question that the sector should pursue all of the reductions in both fuel use and greenhouse gas emissions that result from improvements in aircraft operations, it is important to note that the large predicted growth in airline travel will far outrun the emissions gains achieved through these activities. Airlines will not solve their greenhouse gas challenges through improvements in aircraft operations alone — this entire category of abatement options leads to less than a 1% reduction in aviation carbon emissions by 2020 and much less in 2050.

59. Airlines have another category of carbon abatement options that result from technical improvements to their aircraft. These include, for example, using lighter-weight materials in everything from the airframe to seats, adding winglets to the tips of wings, and improving the fuel efficiency of engines. With the rising price of jet fuel, all of the major suppliers in the aviation sector are exploring every technical option to improve aircraft performance. They have a large incentive to do so, as these technical improvements lead to lower costs for their customers and provide them with a real advantage in an extremely competitive market. Figure 6 illustrates estimates of possible CO_2 abatement options in relation to aviation in the period up to 2050, as presented by the WEF.

Figure 6. Cumulative CO_2 abatement potential until 2050



Source*:* World Economic Forum / Booz & Company analysis, 2011.

60. Again, most of the significant abatement opportunities resulting from technical improvements include just two options: 1) incorporating more lightweight materials, and 2) improving the fuel efficiency of jet engines. Opportunities to use lighter-weight materials in aircraft can be divided into two categories: a) retrofitting of existing aircraft, and b) building new aircraft with, for example, lightweight composite materials. As there are relatively high costs associated with lightweight retrofits, and limited places where the lighter materials can be applied, this is a high-cost abatement option with a low total greenhouse gas abatement potential.

61. Building new aircraft with advanced composites is a more promising emission abatement option than retrofitting existing aircraft. Aircraft frames were originally built from wood until aluminium became available. Aluminium airframes form the structural basis of the vast majority of planes flying today. In the 1970s, engineers began developing new lightweight materials designed to be strong enough to form part of the primary structure of aircraft. The resulting advanced materials and carbon composites have delivered significantly lighter materials that yield fuel savings and emissions reductions. Estimates of the marginal carbon abatement cost of employing lightweight composite materials in new aircraft suggest relatively high costs and modest total abatement potential.

62. Jet engine manufacturers have been steadily improving the fuel efficiency of their main product for decades. They expect continuous improvements well into the future. Carbon emissions from aircraft engines are directly related to the fuel consumed with a ratio of approximately 3:1– that is, each kilogram of kerosene consumed produces about 3 kilograms of carbon emissions. There remain several areas where jet engine manufacturers expect to continue generating fuel efficiency improvements — some of these include advanced turbofan designs and new lightweight ceramics. One needs to keep in mind, however, the possibility that some measures to improve fuel efficiency of aircraft engines *could* cause increased emissions of non-carbon greenhouse gases from the sector.

63. Again, as is the case with the vast majority of aviation carbon abatement options, the emissions savings generated through technical improvements will, given projected growth in air travel and air freight, have only a very modest impact in reducing overall greenhouse gas emissions. However, these

improvements reduce fuel use, leading to real reductions in costs with short to medium payback periods. As a result, the airline sector is pursuing all of these technical options in the absence of any specific policy to capture the additional emissions savings. Table 1 (previous) gives an idea of the relative marginal abatement costs and emission reduction potentials of the available abatement options through to 2020.

3.3 Hypersonic air travel

64. When reviewing the full range of carbon abatement options available to the aviation sector it is important to remember that the required reductions in emissions will need to take place over decades, through at least to the end of this century. On these longer timescales it is useful to consider some of the more exotic options that are being advanced short of pure science fiction. Technological advances that can be expected in the next few decades include entirely new classes of aircraft with new engines that fly many times faster than the speed of sound.

65. Recent tests with unmanned hypersonic aircraft were sufficiently successful to prove the concept. Some of these prototypes are designed to fly at and above Mach 20 — *i.e.* 20 times the speed of sound (20 000 kms per hour). By comparison, the supersonic Concorde flew at speeds just above Mach 2. The Defense Advanced Research Projects Agency (DARPA), part of the US Department of Defense, has been exploring the merits of a hypersonic aircraft through its Falcon Hypersonic Technology Vehicle 2 (HTV-2) program. HTV-2 flew its maiden flight on 22 April 2010 when it flew between Mach 17 and Mach 22 for more than 2 minutes.

66. Where the DARPA HTV-2 project is designed to produce new hypersonic aircraft for military use, EADS, the parent company of Airbus, has revealed a concept near-hypersonic aircraft for civilian use. The Zero Emission High Supersonic Transport (ZEHST) concept design would employ three engine types: 1) a jet engine using 100% biofuels made from seaweed or algae for take-offs, 2) a rocket engine to accelerate to Mach 2.5 and 3) a ramjet to reach Mach 4. The development time is expected to be at least 25 years with these types of aircraft reaching commercial service in the second half of the century.

67. These hypersonic aircraft reach altitudes just above the Earth's atmosphere and are classified as "suborbital flights". Their proponents suggest that these flights will offer more direct routes with substantially shorter flight times resulting in significantly lower carbon emissions. However, according to published scientific studies, radiative forcing from black carbon, or soot, emitted by rocket engines would be very significant and would outweigh any reductions in warming from reduced carbon emissions. Radical reductions in flight times could also, by itself, stimulate increased transport activity, with resulting increases in greenhouse gas emissions (Ross, 2010).

4. EXPLORING THE POTENTIAL OF AVIATION BIOFUELS

68. Because of strong current interest, aviation biofuels receive an entire section of this paper. That interest reflects in part the limits of the other options for reducing carbon emissions. This section assesses the technical and economic potentials of biofuels, and whether and under what conditions they actually reduce greenhouse gas emissions.

4.1 Recent interest in aviation biofuels

69. Government interest in aviation biofuels has led to a recent proliferation of programmes in several countries and regions. Most of these are public-private partnerships involving some combination of government agencies, universities, research institutes and private companies. Some examples include the

Commercial Aviation Alternative Fuel Initiative (CAAFI) led by the Federal Aviation Administration (FAA) in the United States, the *Sustainable Aviation Fuel Users Group* (SAFUG) based in Europe, the *European Advanced Biofuels Flight Path* led by the EU Commission, the *Aviation Initiative for Renewable Energy* in Germany, and the *Queensland Sustainable Aviation Fuel Initiative* in Australia.

70. Commercial interest in aviation biofuels is moving so quickly that it is difficult to stay abreast of the pace of new developments and new data and research on their potential merits. Consortia and other collections of private companies and research institutes are now active in, for example, China, Brazil, Singapore, Japan, Abu Dhabi, Qatar, Australia, Mexico, Canada and the United States. The United States currently dominates this space with considerably more than half of all of these collective private sector activities. These groups are working to advance every aspect of the aviation biofuels value chain, including the selection and growing of the biological feedstocks, the many different conversion technologies and resulting fuel types, and the infrastructure required for full-scale commercial production.

71. Although none of the major international oil and gas companies are directly explorating aviation biofuels, the list of smaller companies is growing and includes Neste Oil (Finland), Altair Fuels (US), Amyris (US), UOP (US), Dynamic Fuels (US), GEVO (US), SkyNRG (Netherlands), Rentech (US), Solazyme (US), Solena (US) and Virent (US). Although this is not a comprehensive listing of all the companies involved, it does demonstrate that many of them are based in the United States.

72. Airlines are also direct participants in the development of aviation biofuels with some companies having made direct investments in commercialisation projects. These include British Airways, Qantas, Air New Zealand, Lufthansa, Virgin Australia and Iberia. Airlines which have used biofuels on regularly scheduled passenger flights and, in some cases, are now doing so continuously, include Air France, Lufthansa, KLM, Finnair, Aeromexico, Interjet and Thomson Airways. Jet engine manufacturers (*e.g.* GE and Rolls Royce) and airframe producers (*e.g.* Boeing, Airbus, Bombardier and Embraer) are involved in the testing and approval of aviation biofuels by the certification entities, including ASTM International.

Box 2. What are aviation biofuels?

The majority of fuel used by aircraft since the beginning of powered flight has been derived from petroleum with very limited amounts produced from coal and natural gas. Jet fuel refined from oil (kerosene) is the most widely used by commercial aviation and is also known by its technical designations for civilian (Jet A and Jet A-1) uses. Jet fuel must meet very strict certification standards for a range of key operating parameters including composition, volatility, fluidity, combustion, corrosion, thermal stability, and contaminants. Jet fuel used by airlines (civil aviation) is certified by the American Society for Testing and Materials (ASTM International).

Biofuels used by civilian aircraft (also known collectively as “biojet”) are produced from biological feedstocks and must also meet the strict qualification standards implemented by ASTM International and other associated organisations globally. There are currently three approaches for using biological feedstocks as a substitute for oil in the production of aviation fuels – two of these have already been certified for use in civilian aviation and airlines are using both of them now in regularly scheduled flights.

Current approaches to converting biomass and plant oils into aviation biofuels produce what is known as synthetic paraffinic kerosene (SPK). The first approach uses the well-established Fischer-Tropsch process to convert biomass into liquid fuels (BTL). The resulting fuel category, regardless of the actual biomass feedstock used, is known as FT-SPK. This capital intensive process involves gasification of biomass, wood and solid waste. ASTM International certified FT-SPK for use in civilian aircraft in September 2009 under the designation D-7566 for use up to a 50:50 blend with kerosene. Shell and Sasol are the current leading producers of FT-SPK. The FT process has also used municipal solid waste as a feedstock. Hybrid processes are under development that would use natural gas (GBTL) or coal, or both, with biomass and carbon sequestration. Companies advancing the BTL and GBTL process include Solena and Rentech.

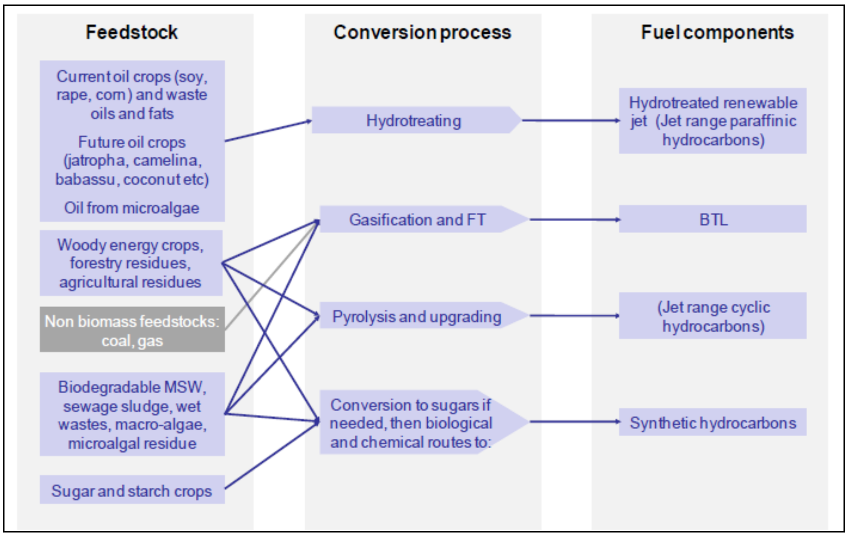
Hydrotreated Esters and Fatty Acids (HEFA), also known as Hydrotreated Renewable Jet (HRJ), uses plant oils and animal fats to produce an aviation fuel category known as bio-SPK. Bio-SPK represents the second approach for producing biojet and was certified by the ASTM for use in civilian aircraft up to a 50:50 blend with kerosene in July 2011. Feedstocks for bio-SPK can be virtually any plant oil but the aviation sector is focussing on oils from jatropha, camelina, some halophytes, and algae. Several airlines were involved in flight tests of bio-SPK from different feedstocks including Air New Zealand in 2008 (jatropha), Continental Airlines in 2009 (jatropha and algae) and Japan Airlines in 2009 (jatropha, camelina and algae). Neste Oil (Finland) and Dynamic Fuels (US) are leading producers of Bio-SPK and have produced fuel currently used in commercial service at Lufthansa (Neste) and KLM, Finnair, and Thomson (Dynamic).

Fermented Renewable Jet (FRJ), Pyrolitic Renewable Jet (PRJ), and Catalytic Renewable Jet (CRJ) fuels, and the broad category of alcohol-to-jet (ATJ), are all produced by different process technologies. All three are in the early process of testing but show promise as new technologies which could be scaled up to full commercial production. ASTM International has initiated a task force approach to move these technologies forward using the ASTM and ICAO endorsed *Fuel Readiness Level* (gated risk management processes). ASTM qualification of alcohol-to-jet (ATJ) fuels is expected in 2 to 4 years based on the experience with the FT and HEFA fuels.

FRJ uses plant sugars (including, potentially, cellulosic non-food material) as a feedstock to ferment alcohols using biological agents or microbes to produce biojet. Amyris, a U.S company with projects in Brazil and Australia, is scheduled to fly a FRJ 50/50 blend made from cane sugar in Brazil on Azul Airlines in 2012. CRJ is similar to FRJ but, unlike FRJ that uses biological agents or microbes, CRJ use catalysts to break down the biomass. Virent (US) is one of the companies working on the commercialisation of CRJ technology.

PRJ uses a pyrolysis process (operating at high temperatures and pressures) to break down the structural components of plants (lignocellulose) to produce a bio-crude oil. The bio-crude oil is then sent through a conventional refining process to produce biojet. One advantage of PRJ is that it is high in aromatic content enabling it to act as a blend stock with other fuel types (*e.g*. HEFA). The principal reason why ASTM International has only approved 50:50 blends of FT and HEFA produced biojet with kerosene is that these fuels are low in aromatics. Aromatics are important because they swell when in use and act to seal fuel systems — they are also important in maintaining the lubricity of aviation fuels. The feedstocks for PRJ could include, for example, switchgrass, corn stover and forest waste. One of the first commercial PRJ production facilities, being built in Western Australia, will use wood chipped from eucalyptus trees.

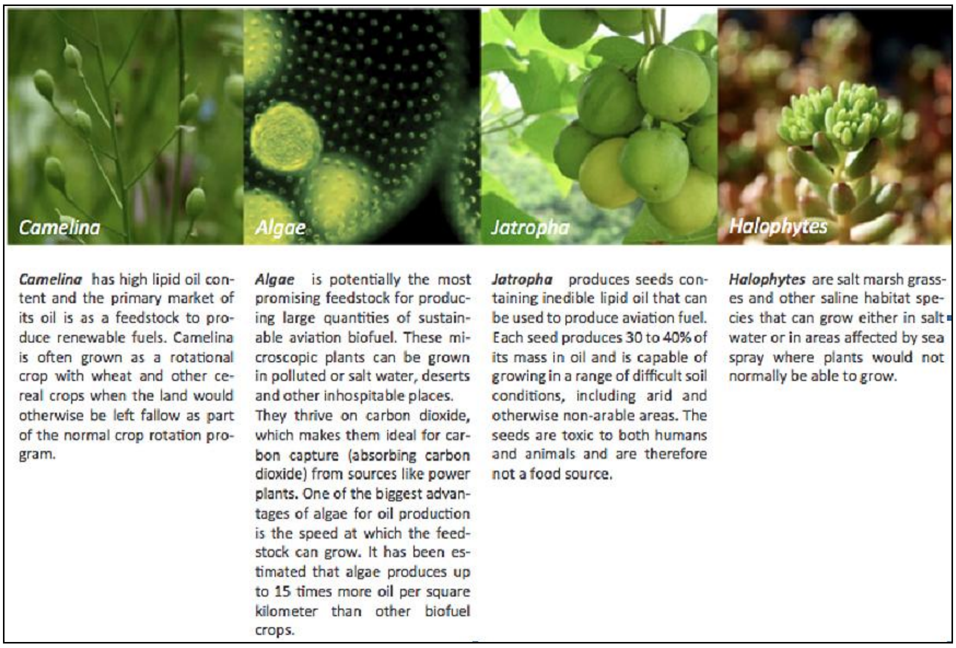
Figure 7. Feedstock/conversion pathways



Source: OECD, 2011.

73. Present aviation biofuels can be derived from a variety of feedstocks.

Figure 8. Most promising feedstock for "second generation" biofuels



Camelina has high lipid oil content and the primary market of its oil is as a feedstock to produce renewable fuels. Camelina is often grown as a rotational crop with wheat and other cereal crops when the land would otherwise be left fallow as part of the normal crop rotation program.

Algae is potentially the most promising feedstock for producing large quantities of sustainable aviation biofuel. These microscopic plants can be grown in polluted or salt water, deserts and other inhospitable places. They thrive on carbon dioxide, which makes them ideal for carbon capture (absorbing carbon dioxide) from sources like power plants. One of the biggest advantages of algae for oil production is the speed at which the feedstock can grow. It has been estimated that algae produces up to 15 times more oil per square kilometer than other biofuel crops.

Jatropha produces seeds containing inedible lipid oil that can be used to produce aviation fuel. Each seed produces 30 to 40% of its mass in oil and is capable of growing in a range of difficult soil conditions, including arid and otherwise non-arable areas. The seeds are toxic to both humans and animals and are therefore not a food source.

Halophytes are salt marsh grasses and other saline habitat species that can grow either in salt water or in areas affected by sea spray where plants would not normally be able to grow.

Source: EQ^2, 2010.

4.2 Debate on greenhouse gas reductions from biofuels

74. As aviation biofuels are unlikely to be cost-competitive with the production of kerosene for some time, expected climate benefits is the key driver of market interest in aviation biofuels. The potential greenhouse gas benefits are the subject of on-going debate and almost certainly depend heavily on the types of biomass used.

75. Any understanding of the greenhouse gas debate must start with the question of why biofuels might be able to reduce emissions. Typically, greenhouse gas comparisons of biofuels and fossil fuels use lifecycle assessments (LCAs) that calculate the emissions from both the production process for the fuels (such as the emissions from mining and refining crude oil and the emissions from growing and refining crops into biofuels) as well as emissions from burning the fuel. There is broad agreement that production emissions for crop-based biofuels exceed those for fossil fuels, and the combustion of both emits carbon dioxide from the vehicle or jet. Why then can biofuels reduce greenhouse gas emissions? The answer is an accounting convention that LCAs should not count emissions from the combustion of biofuel while they should count emissions from fossil fuel combustion. This is based on the premise that while fossil fuels introduce new carbon into the atmosphere, biofuels are only recycling into the atmosphere carbon that was absorbed from it in growing the biofuel crop. In this way, the combustion of biofuel has come to be regarded as "carbon neutral".

76. This approach has been broadly followed over the last decade by researchers, government agencies, and international organisations such as the International Energy Agency and the IPCC. It has similarly been adopted by the Roundtable on Sustainable Biofuels (RSB), a co-operative effort of 130 organisations representing farmers, biofuel producers, environmental groups and many other stakeholders, including aviation interests. In effect, under this approach, unless the emissions involved in producing a

biofuel exceed the combined emissions from both producing and burning a fossil fuel, the biofuel is deemed to reduce greenhouse gas emissions.

77. Despite this long pedigree, the assumption that biomass combustion is “carbon neutral” is the subject of serious debate. In 2008, two well-publicised papers in the journal *Science* pointed out that this characterisation of “neutrality” overlooks the effects of land use change (Fargione, 2008; Searchinger, 2008). For example, if biofuels replace forest or grassland, they release large quantities of carbon from their vegetation and soils, and if biofuels use existing cropland, they are likely to trigger clearing of forest and grassland to replace the food. Although some debate remains, a very large body of researchers and international organisations, including the IEA (IEA, 2008), the FAO (FAO, 2008), the US National Academy of Sciences (National Research Council, 2011), and the Netherlands Environmental Assessment Agency (NEAA, 2008) agreed that life-cycle analyses should reflect the emissions from land use change, both direct and indirect. Modelling studies undertaken to estimate these land use change emissions vary significantly, but nearly all find the emissions to be substantial for nearly all crop-based biofuels, with biodiesel having the largest emissions (Marelli, 2011). The RSB standards do not incorporate estimates of indirect land use change as the stakeholders have not been able to agree on how to do so.

78. Recently, the European Environmental Agency’s Scientific Committee challenged the assumption that biofuel combustion is carbon neutral even more directly by claiming it is based on a fundamental accounting or “baseline” error (EEA Science Committee, 2011). The Committee proposes that emissions from the combustion of bioenergy will only be “neutral” if the offsetting plant growth is “additional” to any plant growth that would otherwise have occurred. The assumption of carbon neutrality in effect assumes that land would not grow plants except for biofuels, but because nearly all land grows plants that absorb carbon anyway, biofuels can only reduce greenhouse gases if they lead to *additional* plant growth. Biofuels can also reduce emissions by taking plants that people would otherwise consume for food or fibre, but that comes at a human cost. Nearly all studies project a need for some additional agricultural land between now and 2050, when the global population is likely to be over 9 billion people. How much depends heavily on productivity gains. Demographic changes and improvements in the yield of key food crops may make more land available in the middle decades of the century. Recent OECD modelling suggests that the demand for agricultural land will stabilise at current levels by 2050 (OECD, forthcoming).

79. If biofuels production is to reduce greenhouse gas emissions by large amounts without competing with food crops *and* meet the EEA Scientific Committee’s requirement of additionality, the additional biomass would need either to come from waste (such as garbage or unused and unneeded crop or timber residues) or be grown on marginal degraded land that is capable of producing biomass abundantly but is not presently so used. The Committee stresses that this way of focusing on the issue is mathematically the same as incorporating emissions from land use change, but also calls attention to the extent to which greenhouse gas reductions result from reduced human consumption of food or fibre. The Committee also argues that the search for “additional biomass” makes it intuitively easier to understand why biofuels may or may not reduce emissions.

80. From this perspective, the bioenergy potential of abandoned agricultural land becomes particularly interesting. Farmers abandon some farmland each year even as they expand farming into new areas, including forests. Some estimates of bioenergy potential see large potential for carbon-neutral biomass using abandoned land. But critics argue that most abandoned farmland reverts to forest or grassland and absorbs carbon that is part of the “terrestrial carbon sink” that holds down global warming, so using this land for biofuels sacrifices this important carbon sequestration. They argue that using abandoned land to produce biofuels only reduces global warming if and to the extent the savings from reduced use of fossil fuels exceeds the sequestration that would occur on this land from natural reversion.

81. There is some agreement that "second-generation" biofuels from cellulose have the potential to be low-carbon fuels although there are significant differences in emphasis. Some researchers believe cellulosic material has the potential to be low-carbon because it takes little energy (and emissions) to grow and will potentially have high yields. To others, the issues of land and "additionality" remain the same, but this process not only increases the potential to use wastes but also to grow biomass on otherwise unproductive land.

82. Although differences over carbon accounting have led to substantial disagreements on global bioenergy potential, most global assessments of bioenergy potential have grown more cautious. For example, although the IEA continues to identify a fairly large potential, in part by hoping to use abandoned farmland, it has emphasised that realising this potential requires much larger increases in agricultural productivity than currently expected in order to free up this land, and an effective global system for land-use controls (IEA, 2008; IEA, 2010). An IEA study that focuses on timber and agricultural residues suggests more modest goals to produce 5% to 15% of transportation fuel demands by 2030, which would require that 10-25% of all such residues worldwide be harvested for energy (Eisentraut, 2010). Achieving even those figures will be a substantial challenge because residues are already heavily used worldwide for feed, bedding or fuel, because residues play a critical role in replenishing soil carbon and nutrients, and because economical production of biofuels requires a large and consistent supply of residues from a reasonably modest radius of the plant.

83. World bioenergy use and goals potentially extend far beyond aviation biofuels. For example, the EU is requiring that member countries obtain 20% of their entire energy supplies, not merely transportation fuels, from renewable fuels by 2020, and a recent review indicated that country plans indicated that bioenergy should supply more than half of this target (Atanasiu, 2011). If low-carbon biomass potential is limited, one question is whether policies should focus that biomass on energy uses, such as aviation, that have the fewest potential alternatives.

84. Algae, which can directly produce oil, provide one potential opportunity for producing aviation biofuels in ways that do not occupy otherwise productive, vegetated lands, do not displace carbon sequestration or food or fibre for human use, and therefore have the potential to be low-carbon. Algae faces a number of key challenges.

- First, standard existing tools for removing oil from algae require large quantities of energy to dry them. That energy is both expensive and likely to lead to large carbon emissions (Shirvani, 2011; Sheehan, 2011). However, experimental technologies that extract the oils while the material is still wet have the potential to address these concerns substantially (Sheehan, 2011).

- Second, at this time many experts argue both that the only potentially economical and energy-generating form of algal production requires production in open ponds (Sheehan, 2011; Huesemann *et al.*, 2010). Several analyses have found that the construction and use of constructed "bioreactors" requires so much energy that algae become net energy consumers (Huesemann *et al*., 2010). However, open ponds, particularly in dry, hot areas that would maximise production and avoid displacing good land, results in enormous levels of evaporation, over 1000 litres of water for each litre of biofuel (Sheehan, 2011). Given the demand for water that is implied it might be necessary to use saltwater and focus production in dry hot areas in proximity to coastlines.

- Third, algae is presently extremely expensive – as of 2006, costs were estimated at over USD 1 000 per barrel (Sheehan, 2011). Reducing costs to any reasonable levels require a series of technological breakthroughs, including extremely high rates of reproduction and simple oil extraction.

85. Finally, it should be noted that increased biofuel production could also lead to large increases in use of nitrogen and phosphorus — even algae need large quantities of nitrogen. Nitrogen is a major source of greenhouse gas emissions and water pollution, and there are concerns that phosphorus supplies are limited and so should be husbanded for food production.

4.3 Production costs, scaling and timing

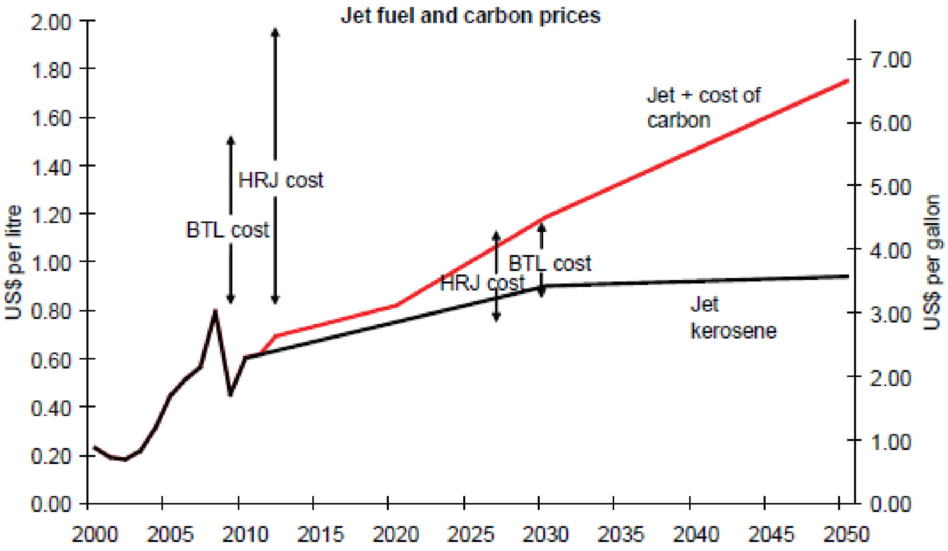
86. Apart from environmental concerns, production will have to scale up rapidly and come at reasonable costs if aviation biofuels are to help the aviation industry substantially address climate change. Because little commercial production of aviation biofuels exists today, it is difficult to predict what the future production costs might be. Experience with the global large-scale production of road transport biofuels provides some guidance. IATA has released cost figures (Figure 9 below) for the two currently approved aviation biofuel technologies: 1) biomass-to-liquids (BTL) using the Fischer-Tropsch (FT) process (the resulting fuel is FT-SPK) and 2) hydroprocessed esters and fatty acids (HEFA), also known as hydrotreated renewable jet (HRJ), where the resulting fuel is bio-SPK.

87. Figure 9 suggests that costs for aviation biofuels from the BTL and HRJ processes could come down by 2030 to a level similar to that of kerosene — and below that level if there is a robust global carbon price in place. In the absence of a strong carbon price, or dramatic increases in the cost of crude oil, it is unlikely that biojet will be competitive with kerosene before 2050.

88. Of the three key risks facing airlines (fuel price, interest rates and exchange rates), the rising fuel (kerosene) price is having the biggest downward impact on profitability and is expected to continue indefinitely. If the aviation biofuels sector is unable to bring biojet production costs down significantly, it will be very difficult for airlines to meet the aggressive carbon reduction targets proposed by IATA as well as the IATA target of replacing 6% of global kerosene use with biojet by 2020. Potential price volatility also complicates the significant investment decisions that will be needed if biofuel production is to be increased by rendering future returns uncertain.

89. Most of the companies attempting to produce biojet at large scale have indicated they will use either non-food crops grown specifically as feedstocks or will attempt to gain access to plant and animal wastes. The key cost factor will be the cost of the feedstock. Estimates of the costs of producing the biological feedstocks include the price of agricultural land, the cost of water, labour, pesticides and fertilisers, and infrastructure (vehicles to plant and harvest, including fuel costs). Merely relying on non-food crops does not avoid competition with food for the use of this land so long as the feedstocks would use cropland.

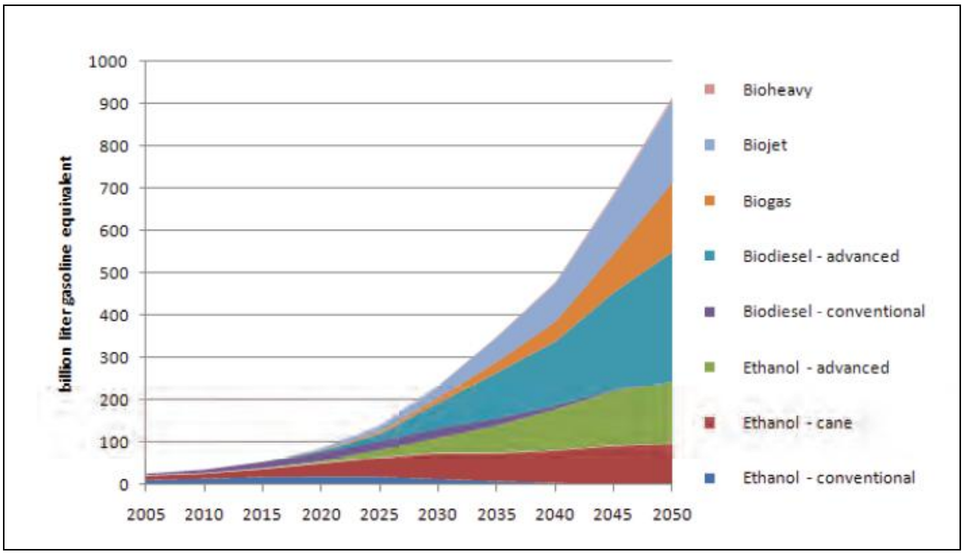
Figure 9. Jet fuel and carbon prices



Source: IATA, 2010.

90. Figure 10 below outlines the International Energy Agency's optimistic scenario for the future production of all biofuels. The IEA's best case projections are in line with the expectations for future biojet production made public by IATA in 2009. The graph suggests that biojet production could reach global production of approximately 100 billion litres of gasoline equivalent by 2050. One hundred billion litres is equal to 40% of current global kerosene consumption and less than one tenth of the projected demand for jet fuel in 2050. This suggests that biofuel will not be able, by itself, to help the aviation sector meet IATA's goal of a 50% reduction in emissions over 2005 levels by 2050.

Figure 10. IEA BLUE Map scenario for biofuels



Source: IEA, 2011.

CONCLUSION

The foregoing discussion suggests that aviation under business-as-usual is likely to generate a sharp increase in greenhouse-gas emissions and radiative forcing through 2050 because of the particularity of the emissions. The combined effect is that aviation's impact on global warming is likely to grow more swiftly than other sectors. Because of that growth, there is a strong likelihood that governments will face pressure to take action to curb radiative forcing resulting from aircraft emissions. Much of the immediate interest in abatement strategies focuses on rapid commercialisation of aviation biofuels, but there has so far been limited attention to the environmental questions raised about such fuels, especially in the context of government policies to promote the production and use of biofuels for ground transport and household heating, which are much bigger consumers of liquid fuels.

An ideal aviation future would 1) meet the rising demand for air travel and air cargo; 2) maintain the long-term precedent of lowering relative costs for aviation travel; and 3) dramatically constrain carbon emissions and other radiative forcing from aviation. But it is not clear that all these goals can be met. As with most policy debates, trade-offs will be inevitable.

This paper has described many important technical and economic uncertainties surrounding direct mitigation strategies for the aviation sector. Foremost among these are: 1) the potential for strategies to abate the increases in radiative forcing associated with the sheer movement of airlines through the sky in the form of tropospheric ozone and contrail-induced cloud formation ; 2) the challenge of financing improvements in energy efficiency through the deployment of new aircraft; and 3) ascertaining which biofuels can be genuinely characterised as low-carbon and the practicability of producing them on a sufficiently large scale (not only for aviation but also for other transport sectors) to make a significant impact on greenhouse gas emissions, while at the same time not competing with land needed for food production.

Policy approaches to abate aviation's global warming impact will need to consider the possibilities for direct mitigation, the extent to which off-setting emissions can be relied upon and the extent to which aviation presents a special case. Even without the constraint of abating greenhouse-gas emissions, aviation faces significant challenges. If capping global greenhouse-gas emissions remains a serious goal, then aviation's problems intensify. With these challenges in mind, some fundamental questions are raised, for instance:

- Given fossil-fuel resource constraints and rising costs, is it realistic to believe that growth in aviation will continue unabated?

- If there is a limited amount of additional capacity in the atmosphere to store human produced greenhouse-gases, should airlines be given some preferential access to this resource, as a result of their limited abatement options?

- What is the potential for low-carbon biofuel production to be scaled-up to the extent needed to meet future demand for aviation fuel? What would be the effect of adding aviation demand for low-carbon biofuel production to government-driven demand for biofuels by other transport sectors?

- If there is a limited capacity to produce biofuels sustainably and cost-effectively on a large scale, should most or all of it be dedicated to airline travel, as other transport sectors have a larger range of abatement options? If so, how might that prioritisation be ensured?

Standard economic analysis would argue in favour of treating aviation no differently from any other sector, in which case these questions have relatively straightforward answers. That has, however, not been the history of policy interventions in the aviation sector. While this paper does not seek to provide answers to these questions, they are unlikely to be far from the surface in the on-going debate about how to treat greenhouse gas emissions from aviation going forward.

END NOTES

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[1] For the most recent and comprehensive overview of climate change science see: *The Copenhagen Diagnosis* (2009) at www.copenhagendiagnosis.org/.

[2] This phrase (in italics) is taken directly from Article 2 of the *United Nations Framework Convention on Climate Change* (UNFCCC); see: http://unfccc.int/resource/docs/convkp/conveng.pdf.

[3] Dr. James Hansen, the Director of the NASA Goddard Institute for Space Studies in New York, and others have suggested that the atmospheric stabilization target to stay below 2.0 degrees C must be lowered to 350ppm CO2; see: J. Hansen *et al*., "Target atmospheric CO_2; Where should humanity aim?" *Open Atmos. Sci. J.* (2008), vol. 2, pp. 217-231.

[4] Approximately 2 billion people and more than 43 million tons of freight (35% of exported goods by value) are transported by aviation, see: WEF *Policies and Collaborative Partnership for Sustainable Development:* http://www3.weforum.org/docs/WEF_ATT_SustainableAviation_Report_2011.pdf.

[5] For a further discussion of the aviation sector, see OECD (2010).

[6] According to the WEF, "aviation's contribution to employment equalled 5.6 million jobs directly and 33 million jobs in total, including direct, indirect, induced and catalytic jobs".

[7] Reduced contrail formation could result from optimised engine combustion (e.g. reducing water vapour and aerosols) or from flying in less humid air layers. Both are problematic, the former from the point of view of combustion optimisation and the second from the fuel use required to avoid contrail-formation layers (see www.omega.mmu.ac.uk/jet-engine-exhaust-and-climate-change-influencing-engine-design-and-operations.htm). Additional scientific study is required to better understand the role of contrails and cirrus clouds.

[8] However, *RF impact should not be interpreted as a "multiplier" to derive climate impacts in CO_2-equivalent terms for future emission scenarios*. Rather, RF provides a numerical indicator of the magnitude of non-CO_2 RF evaluated for *a specific date* (Lee, et al., 2009).

[9] Molina, et al, (2009).

[10] Integrated RF of year 2000 emissions over two time horizons (20 and 100 years). The figure gives an indication of the future climate impact of current emissions. The values for aerosols and aerosol precursors are essentially equal for the two time horizons. It should be noted that the RFs of short-lived gases and aerosol depend critically on both when and where they are emitted; the values given in the figure apply only to total global annual emissions. For organic carbon and BC, both fossil fuel (FF) and biomass burning emissions are included. The uncertainty estimates are based on the uncertainties in emission sources, lifetime and radiative efficiency estimates.

[11] Penner, et al., (1999) and Sausen, et al. (2005)

[12] Lee, et al., (2009)

[13] Molina, et al., (2009) and Wallack & Ramanathan (2009).

[14] www.iea.org/co2highlights/co2highlights.pdf

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[15] IATA Director General and CEO Tony Tyler announced expected future fuels costs: www.iata.org/pressroom/Documents/iata-letter-south-china-morning-sept2011.pdf

[16] http://unfccc.int/resource/docs/tp/tp0200.pdf

[17] Mandatory measures to reduce emissions of GHGs from international shipping were adopted by the Marine Environment Protection Committee (MEPC) of the IMO, when it met for its 62nd session from July 11-15 2011 in London. This was the first mandatory GHG reduction regime for an international industry sector. Measures include the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

[18] www.reuters.com/article/2011/12/02/uk-airlines-emissions-idUSLNE7B001820111202.

[19] www.pointcarbon.com/news/1.1696228?date=20111203&sdtc=1&ref=search

[20] www.greenaironline.com/news.php?viewStory=1366

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