THE GLOBAL POTENTIAL FOR CO_2 EMISSIONS REDUCTION FROM JET ENGINE PASSENGER AIRCRAFT

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ABSTRACT

We analyse the costs of CO_2 emissions mitigation measures available to aviation using a global aviation systems model. In that context, we discuss the relationship between mitigation potential and scenario characteristics, and how these interact with policy measures that increase the effective price of fuel, for example ICAO's CORSIA emissions offset scheme. We find that global fuel lifecycle CO_2 emissions per revenue passenger-km could be reduced by 1.9 – 3.0 % per year on average by the use of a combination of cost-effective measures, for oil prices which reach \$75–185/bbl by 2050. Smaller additional emissions reductions, of order 0.1%/year, are possible if carbon prices of \$50-150/tCO_2 are assumed by 2050. These outcomes strongly depend on assumptions about biofuels, which account for about half of the reduction potential by 2050. Absolute emissions reductions are limited by the relative lack of mitigation options for long-haul flights, coupled with strong demand growth.

Keywords: Aviation emissions, Aviation technology, Emissions mitigation, Carbon trading

1. INTRODUCTION

Currently, aviation contributes around 2.5% of global fuel combustion-related CO_2 (*1,2*). Aviation emissions have risen by 3.6 % per year since 1980 (*2*). This increase is expected to continue, even with ongoing reductions in emissions per revenue passenger-kilometre (RPK), due to the sector's rapid growth. 4 – 5 % per year increases in RPK are projected over the next twenty years (*3,4*). Consequently, the sector is a target for local, regional and global emission-reduction policy efforts - most notably, ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA, *5*), which aims to offset aviation CO_2 growth after 2020 via the purchase of emissions allowances from other sectors. This approach does not require emissions reductions within the aviation sector, although airlines may choose to reduce emissions if allowance costs become sufficiently high. This is a cause for concern because aviation also has substantial non-CO_2 climate impacts (*6*), which are not covered by CORSIA. It may also represent an over-pessimistic approach to cost-effective within-sector reductions. Recent research has shown that a combination of technological and operational measures which are cost-effective at oil prices of $50-100 per barrel could reduce CO_2 per RPK for North American narrowbody aircraft by 2% per year to 2050 (*7*). Given projected regional RPK growth rates of around 3%/year (e.g. *4*) these strategies could make a significant contribution towards carbon-neutral growth at zero marginal cost. More generally, reductions in aviation fuel use will also help address the sector's non-CO_2 climate and health impacts.

Many of the measures outlined in (*7*) are replicable on a global scale. New aircraft technologies and retrofits may be applied anywhere, although different regional operating costs may affect their cost-effectiveness. The main obstacle in achieving carbon-neutral growth in other world regions is that their projected RPK growth rates are typically higher than in North America (e.g. *4,5*). Other studies have also investigated the cost-effectiveness of mitigation measures applied to other aircraft size classes, albeit with limited geographic scope and/or limited communication of the underlying assumptions (e.g. *8-14*). However, there remains limited research assessing cost-effective mitigation potential at a global level.

A further challenge in assessing the potential of within-sector mitigation measures is the complexity of interactions between passengers, airlines, airports, regulators and other stakeholders. For example, airlines may respond to the introduction of fuel-saving technologies by lowering ticket prices, leading to demand increases and lower-than-expected reductions on overall emissions (e.g. *15, 16*). The mitigation potential of new technologies at any given time is determined by the rate of fleet turnover (*17*). The potential of new aircraft models may also be limited by existing infrastructure. These issues are typically neglected in the literature on marginal abatement costs.

In this paper, we address these gaps by extending the analysis of (*7*) to also cover passenger transport by regional jets and widebody aircraft on a global scale. We use this analysis as input to an aviation systems model (AIM2015; *18*) to assess how system-level interactions and carbon pricing affect outcomes. Section 2 discusses our assumptions on technology characteristics, systems modelling and uncertainty. Sections 3 and 4 discuss modelling outcomes and conclusions.

2. METHODOLOGY

2.1. Mitigation Options

CO_2 emissions per RPK can be reduced by reducing fuel life cycle carbon content, by increasing engine and/or aerodynamic efficiency, by decreasing structural weight, or by adding passengers (e.g. *7*). In addition, overall emissions can be lowered by reducing inefficiencies that lead to longer flight or taxi distances. Because relatively small benefits are available in each domain, a combination of measures is required. We consider 25 mitigation measures, comprising all measures analysed in *(7)* except better matching of aircraft size to mission, plus blended wing body and advanced turboprop aircraft. Broadly, they can be divided into new aircraft models, retrofits to existing aircraft, operational changes, and alternative fuels. These areas are discussed individually below. We omit measures aimed primarily at influencing demand, for example increased high-speed rail and telepresence, and measures which may result in a significantly different service being offered to passengers (for example, reduced baggage limits). For each measure we require fuel use, emissions, cost characteristics, the extent to which it can be (or is already) introduced, and any interactions with other measures. We use estimates from (*7*), updated and/or supplemented from academic studies, industry sources and our own calculations.

We divide the fleet into nine size classes, including Regional Jet (RJ), Single Aisle (SA), Twin Aisle (TA) and Very Large Aircraft (VLA) classifications. For each size class we use an existing aircraft model to measure relative benefits against, respectively the CRJ700; Embraer 190; Airbus A319; Airbus A320; Boeing 737-800; Boeing 787-800; Airbus A330-300; Boeing 777-300ER; and Airbus A380-800. These are chosen based on the proportion of global scheduled aircraft-km performed by each aircraft within its size class in 2015 *(21)*.

2.1.1 New Aircraft Models

Even if conventional aircraft technologies dominate into the future, we would still expect CO_2 per RPK to reduce. Fleet turnover will lead to older, less fuel-efficient aircraft being replaced (*17*), and new models of conventional-technology aircraft will become available. Over the 2015-2025 period these include the Airbus A350, A320neo and A330neo, Boeing 737MAX and 777-X, and Embraer E-Jet E2 families. Therefore we also need to estimate the fuel burn and costs of evolutionary improvements to existing technology.

Between 1959 and 1995, the cruise specific fuel consumption of new aircraft engines decreased by 40% (*19*), roughly 1.5% per year. Figure 1 shows the lowest representative mission fuel use per RPK for in-production jet aircraft over time, using the PIANO-X performance model (*20*). Representative missions, including passenger Load Factor (LF) are derived from global flight schedule and demand data (*21*), and typical seating configurations and production dates from historical fleet data (*22*). Within the nine size categories, Figure 1 indicates major improvements in technology occur roughly every 15-20 years. Following initial large reductions in fuel burn per RPK between 1960 and 1990, the reduction rate has slowed. Between 1990 and 2016, fuel burn per RPK declined on average between 1.1% and 0.3% per year by size class, an average of 0.7% per year. For example, the A320neo has fuel burn per RPK 20% lower than the original A320 for a 750 km mission with 76 % LF (*20*), equivalent to around 1% per year.

For the upcoming generation of aircraft models, we use published estimates of fuel use, cost and emissions (e.g. *23*-*29*), assuming a 30% discount from list price where appropriate. For future generations, we assume for our central case a 20-year gap between new models in each size class and 0.7% per year fuel burn reduction for comparable missions. We anticipate this reduction will be achieved by greater use of composite materials, higher bypass ratio engines and a greater lift/drag ratio. For costs, we use (*7*) for narrowbodies; for other aircraft types we assume costs will remain roughly consistent with the 2015-2025 aircraft generation in real terms. These characteristics are summarized in Table 1. Yearly cost changes are primarily maintenance-related.

We also model upper and lower scenarios for each variable. For the upcoming aircraft generation, these are based on the range of variation in different models and/or configurations within aircraft classes. For capital costs we assume 25-35% discount on list price if data on only one model is available. For future generations, the gap between generations is assumed to be 15-25 years, and the average improvement per year to be 0.5-1%.

As well as updates to existing technology, alternative engine and airframe technologies have been proposed which could have a larger impact on emissions. Different technologies may be appropriate for different size aircraft (*30*). We select concepts that are relatively established and for which cost estimates are available, including an optimized counter-rotating propeller (CRP) engine aircraft for narrowbodies (*7,26*), an advanced turboprop for smaller size classes (*26*) and blended-wing body (BWB) designs for widebodies (*30*). The assumed characteristics of these aircraft are summarized in Table 2. We assume capital and maintenance costs scale between size classes similarly to those for the present-day reference aircraft when no other scaling information is available. We also assume global availability of new aircraft models, and that operators in each region will decide which technology to purchase based only on the associated costs.

Many other aircraft concepts exist, including the NASA N+3 designs (*31*), and hybrid or battery electric aircraft (e.g. *25*). We exclude these because they are more speculative than the options currently considered, would require extensive infrastructure changes, and/or lack cost estimates.

2.1.2 Retrofits

More immediate impacts can be obtained by applying retrofits to currently-operational aircraft. Retrofit measures include blended winglets for aircraft types which do not already have them, re-engining (if a suitable engine exists), carbon brakes and cabin lightweighting. The impact of these measures can be complex; for example, electric taxi equipment increases weight, slightly increasing fuel use in non-taxi flight phases. Table 3 gives a summary of the assumed characteristics of retrofit measures. Many retrofit measures have already been applied to part of the fleet, limiting future applicability. We follow (*7*) in limiting uptake to take account of this based on current fleet composition.

2.1.3 Operational Measures

Operational strategies include measures to decrease routing inefficiency and/or congestion at airports; increased maintenance to reduce performance deterioration; and changes in airline behavior, such as reducing tankering. The costs and benefits of these measures can be difficult to evaluate, and can have different impacts on different system stakeholders. Additionally, some measures have different regional impacts, for example depending on existing inefficiency levels or fuel price differentials between origin and destination. For this paper, we use a global aviation systems model which includes regional estimates of airline costs, fleet composition and system inefficiency (e.g. *18, 32*; Section 2.2). We assume similar percentage reductions in system inefficiencies are available by region worldwide. This likely underestimates the benefits achievable in regions with less-developed or more congested aviation systems. We also omit benefits which may be available on specific routes (for example, meteorology-optimized routing). Similarly, we assume tankering behavior worldwide is similar to that in the US. Table 4 shows the assumed characteristics of operational measures for this paper. Further discussion of what is included in each measure is given in (*7*) and (*33*); for example, surface congestion management includes collaborative decision-making (CDM)-type measures. Only airline costs are shown. We do not model costs to airports or air navigation service providers, i.e. we assume no pass-through to airlines for these costs, which are assessed in the supplementary material to *(7)*.

2.1.4 Alternative fuels

Several alternative fuels have been proposed and/or trialled in aircraft (e.g. *34*), with different lifecycle emissions, cost and fleet compatibility characteristics. For simplicity, we choose a single alternative fuel option. Drop-in biofuels can be used directly in existing engines and so have much faster potential for market entry than fuels that require major design modifications. Although algae-based fuels are potentially promising, they are associated with high uncertainty and potentially high cost *(35)*. Cellulosic biomass is a relatively abundant feedstock which has low impact on food production and favourable cost and scalability characteristics. Therefore we model drop-in synthetic Jet A from cellulosic biomass feedstock, as in (*7*). Given potential demands for biomass from other sectors, it is uncertain whether enough fuel can be produced to supply global demand. Using data from (*36*), (*7*) estimate that US biomass production potential is comparable to Jet A demand, and that costs of $3.0 – 3.6 per gallon are feasible for commercial-scale production beginning in 2020, with a reduction of 80 – 85% in lifecycle CO_2 compared to fossil-derived Jet A. For this paper, we use a cost curve model to estimate biofuel availability and price. Global biomass cost curves are taken from *(37)*, linearly adjusted according to *(38)*, and we assume the aviation industry will have priority access to biomass before other sectors, based on higher willingness to pay due to the relative difficulty of reducing aviation emissions by other means. We assume transport, plant investment and operating and maintenance costs add an additional $3.6 per gallon in 2020, falling to $1.8 ($1.3 - $2.3) per gallon in 2050, based on a range of different assumptions about economies of scale and conversion plant sizes *(7)*. Given current certification limitations, we limit the maximum biofuel blend to 50% *(39)*.

2.1.5 Interaction between measures

Many of the measures considered above interact. Care must be taken to avoid double-counting and/or the adoption of incompatible measures. We assume retrofit-type measures which are applicable to new aircraft are already included in the benefits from future aircraft models, unless there is evidence to the contrary. Similarly, we assume that measures which target the same fuel burn reduction opportunity are incompatible, e.g. single engine taxi and electric taxi. For compatible measures, we apply percentage reductions in emissions cumulatively and assume that applied measures do not alter the percentage benefits achievable from other measures.

2.2. Aviation Systems Modeling

To assess the cumulative benefits achievable from the measures discussed in Section 2.1, we use them as input to the open-source aviation systems model AIM2015 (*18*). AIM2015 models interactions between passengers, airlines, airports and other stakeholders into the future for a set of 878 global cities, containing 1169 airports and representing around 95% of global scheduled RPK. Passenger demand between cities is projected using a gravity model based on city population, income and fare, and distributed between airports and routes using an itinerary choice model. An aircraft size choice model projects which aircraft are used on each route; historical load factors are then used to project flight schedules and demand for aircraft, which in turn are used to project airport-level delay. The segment costs to airlines of flying this schedule with the given fleet are estimated and input to a fare model, which feeds back into the demand and itinerary choice calculations. When equilibrium is reached between supply and demand, output metrics including CO_2, noise and local emissions can be calculated. The structure and validation of these sub-models and of the overall model is discussed extensively in (*18*). Within this structure, technology adoption affects airline costs, which in turn impact on fare, demand and scheduling.

For this paper, we adapt the fleet and technology choice routines of AIM2015 to use the technology characteristics from Section 2.1. These routines have previously been used to assess the uptake of limited combinations of technology measures (e.g. *40*) but are here updated to consider many more technologies, to more fully model their impacts, and to include uncertainty. AIM2015 projects the number of new aircraft required by year, region and size class. We model technology purchase decisions based on Net Present Value (NPV), comparing existing reference aircraft in each size class against available alternative models with costs appropriate for each region (e.g. *18, 25, 40*). We assume a discount rate of 10% and an evaluation timeframe of seven years across all regions *(41)*. For retrofits, alternative fuels and operational measures, a simpler model is used in which airlines adopt a measure if the payback period is less than three years. The impact of changing these parameters depends on the balance between initial and ongoing costs for each measure, with shorter timeframes and higher discount rates favoring measures with low initial costs over those with longer-term benefits. However, since capital costs are amortized in the NPV model, the overall impact is relatively small. Operational measures and drop-in alternative fuels are assumed reversible if no longer cost-effective. The uptake of these measures is evaluated by world region, size class and year of aircraft age. Sales of older aircraft between regions are captured by a model based on regional GDP, as in (*40*).

Analyses of historical technology adoption show uptake is not instant even when measures are cost-effective, but rather follows an S-curve dynamic over time (*42)*. This reflects several underlying effects. For example, some retrofits are only installable at major maintenance checks; production lines have limited capacity; airlines differ in their willingness to try new technology; and many aircraft are leased rather than owned by operators. Based on the timeframes discussed in (*42*), we implement initial limits on adoption for each technology to simulate this behavior.

2.2.1 Future scenarios and uncertainty

The adoption and impact of future technologies depends on many uncertain variables. Total emissions and technology penetration depend on demand growth, which depends on future developments in population, income and fuel price, amongst other variables. Additionally, technology characteristics are uncertain. We model ranges for all technology variables. Since the run time of AIM2015 is too long for Monte Carlo modelling, we incorporate uncertain variables using a lens approach (e.g *43*). Each lens is a linked set of input values chosen from the central, upper and lower cases described above. For example, we combine all central case variables into a central lens to explore the most likely outcome. An optimistic lens combines variables associated with early availability, lower fuel use, lower costs and other favourable outcomes, and a pessimistic lens similarly combines variables associated with late availability, higher fuel use and higher costs. Running the model with these three lenses allows an idea of the potential variation in outcomes due to variation in technology characteristics.

To model demand growth uncertainty, we use different scenarios for the country-level development of population, income and oil prices. Following (*18*), we use country-level population and GDP per capita scenarios from (*44*), and oil price scenarios from (*45*). These are summarized in Figure 2. We combine high oil prices with the low GDP growth SSP4 scenario, and low oil prices with the high GDP growth SSP1 scenario, to construct scenarios with slow and rapid demand growth respectively. The central SSP2 scenario uses central oil price projections. Each scenario is run with each lens, giving a total of nine combinations. Additionally we consider a range of carbon prices (panel (d)).

3. RESULTS

Aviation RPK growth, CO_2 and fleet size strongly depend on the socioeconomic scenario assumed (*18*). Global fleet composition by scenario/lens is shown in Figure 3. For 2050, global RPK varies between 16 and 34 trillion, and global fuel lifecycle CO_2 is 620-1690 megatonnes (Mt). Similarly, total fleet varies by a factor of two across scenarios. In the pessimistic lens, fleets are primarily evolutionary updates to current technology. The central lens has uptake of CRP and BWB aircraft, which is increased in the optimistic lens. These and other measures contribute to differences in carbon intensity between lenses. In the SSP2 central lens around 39 gCO_2 is emitted per RPK in 2050 on a fuel lifecycle basis. This value is 9% higher in the pessimistic lens and 10% lower in the optimistic lens. Biofuels account for somewhat over half of reductions in carbon intensity to 2050. If these scenario/lens combinations are run using only evolutionary updates to conventional aircraft, RPK varies between 16 and 32 trillion, and fuel lifecycle CO_2 is 1240-2740 Mt.

The central SSP2 scenario has average RPK growth of 4.4%/year from 2015-2035, comparable to Airbus and Boeing projections over the same time period of 4.6% *(3)* and 4.8% *(4)*. For North American narrowbody aircraft, the closest scope modelled here to the US domestic narrowbody fleet considered in (*7*), we see broadly similar outcomes once different biofuel assumptions are accounted for. In the SSP2 central lens, we see a 3.2% per year reduction in fuel lifecycle CO_2/RPK to 2050, compared to 2% from *(7)*. This is the result of higher biofuel use arising from the cost curve model used in this paper, which reaches 39% of fuel use by 2050; if biofuels are limited to the level assumed in *(7)*, we see a yearly reduction of 1.7%, consistent with later assumed introduction years for new aircraft models. All measures found to be cost-effective in (*7*) see some level of adoption. As the fleet considered is more diverse (in terms of geographic scope, size classes and age cohorts) we also see low uptake for measures which were not cost-effective in (*7*), for example surface polish and carbon brakes. No or minimal uptake is seen across scenarios for re-engining, engine upgrades and reducing tankering.

Globally, we find a smaller potential for cost-effective mitigation, ranging between 2.7 – 2.9 % per year reductions in fuel lifecycle CO_2/RPK to 2050 for the central lens (1.2 – 1.4% if biofuel is limited to the level assumed in *(7)*), and 1.9 – 2.7 and 2.9 - 3.0 %/year for the pessimistic and optimistic lenses respectively. This reflects the importance of biofuels in mitigating long-haul emissions, where high demand growth is expected (*3,4*). In comparison, reference scenarios featuring just evolutionary updates to existing technology demonstrate a 0.5 – 0.9 % per year reduction in lifecycle CO_2/RPK. Global RPK and CO_2 trajectories are shown in the left-hand panels of Figure 4. Past data on RPK and CO_2 is from (*47*) and (*48*); note that past CO_2 data includes all aviation sources including freight, military and unscheduled flights, which account for around an extra 30% of emissions *(18)* and are not modelled here. Although the differences in carbon intensity between lenses are substantial, their impact on total CO_2 is much smaller than the impact of different rates of scenario demand growth. Panel (e) of Figure 4 shows contribution by measure type over time in the SSP2 central lens. Rapidly applicable operational and retrofit measures are important initially, but by 2050 longer-timescale measures such as new aircraft models and biofuels dominate.

We also see a small rebound effect associated with better technology. In 2050, compared to the central lens, optimistic lens runs have approximately a 4 % increase in RPK travelled; scenarios using the pessimistic lens have a 3 – 4 % decrease. These changes reflect overall changes in airline costs and fare per RPK of 2 - 4% between the different lenses.

Projected energy intensity reductions increase as fuel-related costs increase, making more measures cost-effective. If a carbon price is applied to aviation, as in the EU Emissions Trading Scheme (ETS) and CORSIA, we would expect within-sector emissions reductions as well as reductions outside the sector funded by aviation carbon allowances. A full analysis of CORSIA is outside the scope of this paper, but the EU ETS price has never risen above the equivalent of 40 year 2015 US dollars and is currently much lower than this, suggesting CORSIA initial carbon prices will be similarly low (*46*) and its impact will be small.

To test system responsiveness to increased carbon price, we run each scenario/lens combination with different carbon prices, as shown in Figure 2(d). The carbon price in 2050 in these model runs is 50, 100 and 150 \$/tCO_2 respectively. This is much higher than current EU ETS prices; it represents an additional 47-142 cents on the price of a gallon of fuel. For comparison, the SSP2 fuel price is 3.7 dollars per gallon in 2050.

The right-hand panels of Figure 4 shows how RPK, CO_2 and measure contribution to CO_2/RPK reduction varies in 2050 by carbon price. Due to fleet turnover timescales, emissions in 2050 also depend on historical carbon price trajectories. The impact on RPK and relative contribution by measure type is small. However, increased overall uptake of mitigation measures is seen with increased carbon price. For a carbon price of \$50/tCO_2 in 2050, emissions are reduced 1–20% across the range of scenario/lens combinations from the case with no carbon price. This is due to earlier and greater uptake of biofuels and other mitigation measures, plus a 1-2% reduction in RPK from increased fares. Measures with little or no uptake in scenarios without carbon prices are typically not cost-effective at the carbon prices used here. We see diminishing returns for greater carbon prices. For a carbon price of \$150/tCO_2 in 2050, RPK is reduced by 2 – 5% from scenarios with no carbon price and fuel lifecycle CO_2 by 3 – 23%. This corresponds to a global reduction in aviation fuel lifecycle CO_2 per year of 2.5 – 3.1 % per year to 2050 (2.6 – 3.0 %/year in the central lens).

Although not directly modelled, we also expect reductions in aviation non-CO_2 emissions and other externalities. This arises from several sources: the overall reduction in fuel use; a reduction in excess distance flown, which will reduce contrails; and a reduction in NOx emissions indices associated with some technologies, for example open rotor engines.

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper we significantly extended an analysis of the costs and benefits of new technologies which could be used to reduce aviation carbon intensity, and used the characteristics of these technologies as input to an aviation systems model to project likely technology uptake and use. This modelling suggests that cost-effective mitigation options exist which could be used to reduce global fuel lifecycle CO_2 per RPK by around 2.7 – 2.9% per year on average to 2050, assuming central values for all input variables. Considering more pessimistic or optimistic assumptions, this value may range from 1.9 – 3.0 %/year. However, these values are strongly dependent on biofuel availability, which typically accounts for over half the total reductions and dominates outcomes for long-haul flights. As noted by *(7)*, more diverse opportunities exist for smaller aircraft. Introducing a carbon price led to reductions in carbon intensity, but these were typically small. The overall impact of changes in aviation carbon intensity on CO_2 emissions also remains smaller than that of the socioeconomic scenario used to project demand. Using a range of plausible future scenarios (*44*) we project demand in 2050 of between 16 and 34 trillion RPK. Although world regions with slower projected demand increases may experience carbon-neutral growth using the technologies considered here (*7*), this is unlikely to happen globally for more than a brief period, even in the lowest demand growth scenario considered.

Given that CORSIA is intended to reduce CO_2 emissions outside the sector to offset growth in aviation emissions, the rate at which emissions can be reduced within-sector may seem unimportant. However, this ignores the climate impact of aviation non-CO_2 emissions (*6*), as well as the increasing difficulty over time of further reducing emissions in other sectors. One avenue for further research would be to more explicitly model the impact of technology adoption on aviation non-CO_2 impacts such as NOx and contrails. Another would be to investigate more radical new technologies, for example fully- or hybrid-electric aircraft, which have the potential to radically reduce externalities at the cost of what may be substantial changes in infrastructure and aircraft capabilities.

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TABLE 5 Assumed Characteristics of Updates to Conventional Aircraft Technologies Compared to Existing Reference Technologies

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in block fuel use, %	References
Next generation conventional	Small RJ	2020 (2018-2025)[a]	40.9 (35.7-46.1)	-0.35 (- 0.3 - -0.47)	16 (15-21)	24; 25
	Large RJ	2020 (2018-2025)	53.6 (46.8-60.4)	-0.4 (-0.35 - -0.55)	16 (15-21)	24; 25
	Small SA	2019 (2018-2020)	69.6 (64.7-74.6)	-[b]	20 (15 – 22)	23; 7; 26
	Med SA	2016	75.8 (70.4-81.3)	-	20 (15 – 22	23; 7; 26
	Large SA	2018 (2017-2019)	88.9 (82.5-95.2)	-	20 (15 – 22)	23; 7; 26
	Small TA	No update; reference aircraft is already based on the 787-800				
	Med TA	2020 (2018-2022)	211 (189 – 233)	-0.026	12 (10 – 14)	23; 27
	Large TA	2020 (2018-2022)	251 (233-270)	-0.35 (0 – 0.07)	21 (17.5 – 23.7)	23; 28
	VLA	2020 (2017-2022)	305 (284-323)	-0.2 (0 – 0.4)	4	29
Subsequent generation conventional	Small RJ	2040 (2033-2050)	41 (36-46)	-0.35 (- 0.3 - -0.47)	28 (25 – 32)	-
	Large RJ	2040 (2033-2050)	54 (47-60)	-0.4 (-0.35 - -0.55)	28 (25 – 32)	-
	Small SA	2039 (2031-2045)	75 (68 – 82)	-	30 (26 – 34)	7; 24
	Med SA	2036 (2031-2041)	83 (75 – 90)	-	30 (26 – 34)	7; 24
	Large SA	2038 (2032-2044)	97 (87 – 106)	-	30 (26 – 34)	7; 24
	Small TA	2032 (2027-2037)	123 (114 – 132)	-	14 (12 – 14)	-
	Med TA	2040 (2033-2047)	211 (188 – 233)	-0.026	24 (22 – 24)	-
	Large TA	2040 (2032-2047)	251 (233 – 270	-0.35 (0 – 0.07)	31 (29 – 33)	-
	VLA	2042 (2039-2045)	306 (284 – 324)	-0.2 (0 – 0.4)	17 (15 – 17)	-

[a] Values in brackets indicate the estimated range of potential values for each variable, which are later used to define the optimistic and pessimistic lenses used in Section 2.2.1.
[b] A dash in cost data indicates no cost change relative to reference aircraft; a dash in the references column indicates new calculations for this paper.

TABLE 6 Assumed Characteristics of New Aircraft Technologies

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in block fuel use, %	References
Advanced Turboprop	Small RJ	2030 (2025-2035)	22 (19 – 24)	1.7 (0.9 – 2.6)	43 (37 – 46)	26
	Large RJ	2030 (2025-2035)	28 (24 – 31)	1.7 (0.9 – 2.6)	43 (37 – 46)	26
Optimised CRP	Small SA	2035 (2030-2040)	73 (61 – 85)	0.4 (0.2 – 0.5)	41 (40 – 45)	7; 26
	Med SA	2035 (2030-2040)	98 (82 – 115)	0.4 (0.2 – 0.6)	41 (40 – 45)	7; 26
	Large SA	2035 (2030-2040)	99 (83 – 116)	0.4 (0.2 – 0.6)	41 (40 – 45)	7; 26
Blended-Wing Body	Small TA	2040 (2035-2045)	217 (180 – 289)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	30; 26
	Med TA	2040 (2035-2045)	233 (194 – 310)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	30; 26
	Large TA	2040 (2035-2045)	249 (207 – 332)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	30; 26
	VLA	2040 (2035-2045)	364 (303 – 485)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	30; 26

TABLE 7 Assumed Characteristics of Retrofit Measures

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in fuel use, %	References
Blended winglets	Small SA – Med TA	2015	0.85 – 1.9[a]	-[b]	3 (2 – 4)[c]	7; 12
Surface Polish	Small RJ – Med TA	2015	0.03 – 0.13	0.03 – 0.16	1 (0.5 – 1.5)	7; 12
Carbon Brakes	Small RJ – VLA	2015	-	0.015 – 0.045	0.15 (0.1 – 0.2)	7
Engine Upgrade Kit	Small RJ – Med TA	2015	0.5 – 1.8	-	1 (0.5 – 1.5)	7; 12
Re-engining	Small RJ – Med TA	2015[d]	7.1 – 16.6	-	12.5 (10 – 15)	7; 12
Electric Taxi	Small RJ – VLA	2018	0.3 – 4	-	2.8 (1.8 -3.8)[e]	7
Cabin Weight Reduction	Small RJ – VLA	2015	0.2 – 2.3	-	1.2 (1.2 – 2.1)	7; 12

[a] Where characteristics vary by size class, the range over all size classes is shown [b] Dash indicates no change from reference aircraft [c] Cruise only; reduced benefits for other phases (*12*) [d] Assumed only applicable to aircraft over 20 years old [e] Average impact on block fuel.

TABLE 8 Assumed Characteristics of Operational Measures

Measure	Size class	Available from	Cost, million US$(2015)	Change in fuel use, %	References
Surface congestion management	Small RJ – VLA	2015	0.015 – 0.06	15 (10 – 20)[a]	7; 33
Single engine taxi	Small RJ – VLA	2015	0 – 0.06	30 (20 – 40)[a]	7
Optimize departures	Small RJ – VLA	2015	0.2 – 0.6	20 (10 – 30)[b]	7; 33
Reduce cruise inefficiency	Small RJ – VLA	2015	0.07 – 0.13	5.5 (2.8 – 8)[c]	7; 33
Optimize approach	Small RJ – VLA	2015	0.2 – 0.6	40 (15 – 50)[d]	7; 33
Reduced fuel reserves	Small RJ – VLA	2015	0 – 0.5	0.01 – 0.4	7
Reduced tankering	Small RJ – Large SA	2015	0[e]	0.26 (0.34 – 0.27)	7; 12
Increased engine maintenance	Small RJ – VLA	2015	0.001 – 0.002	2.4 (1 – 4) [f]	8
Increased aerodynamic maintenance	Small RJ – VLA	2015	0.001 – 0.002	1 (0.2 – 1.5) [f]	8
Engine wash	Small RJ – VLA	2015	-0.1 – 0.09	0.75 (0.25 – 1)	7; 12
Increased LF / reduced frequency	Small RJ – Large SA	2015	0.2 – 7.6	0[g]	7
Increased turboprop use	Small RJ – Large RJ	2015	2.6	30 (25 – 32)	7

[a] Taxi phases only [b] Takeoff and Climb only [c] Cruise only [d] Approach only [e] 14% increase in regional fuel costs assumed [f] Age-dependent, maximum benefit for 30-year old aircraft shown [g] Per flight; impact of 5 – 10 % increased load factor on frequency and performance is modelled in the systems model, below.

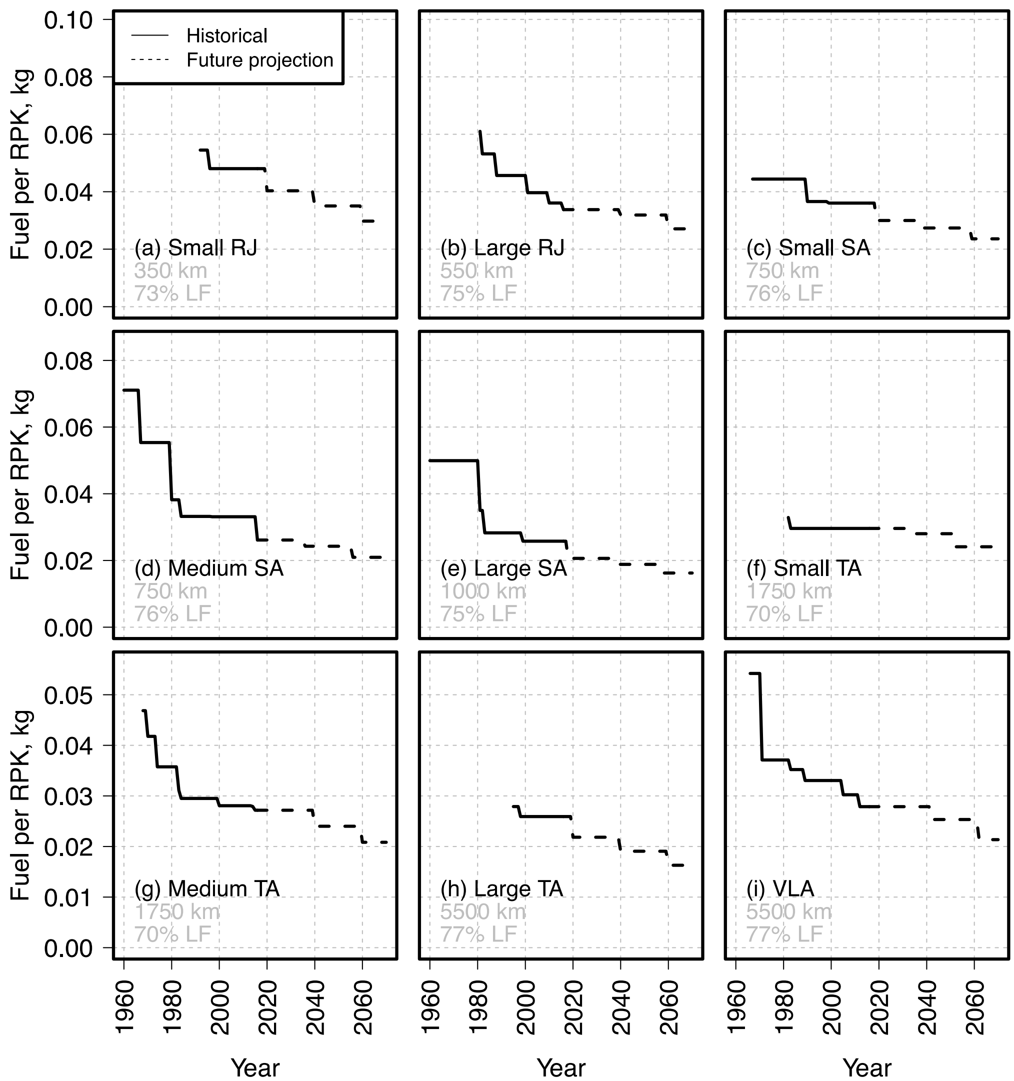

FIGURE 5 Lowest modelled sample mission fuel burn per RPK available from in-production Regional Jet (RJ), Single Aisle (SA), Twin Aisle (TA) and Very Large Aircraft (VLA) models over time, by increasing aircraft size class (a) – (i).

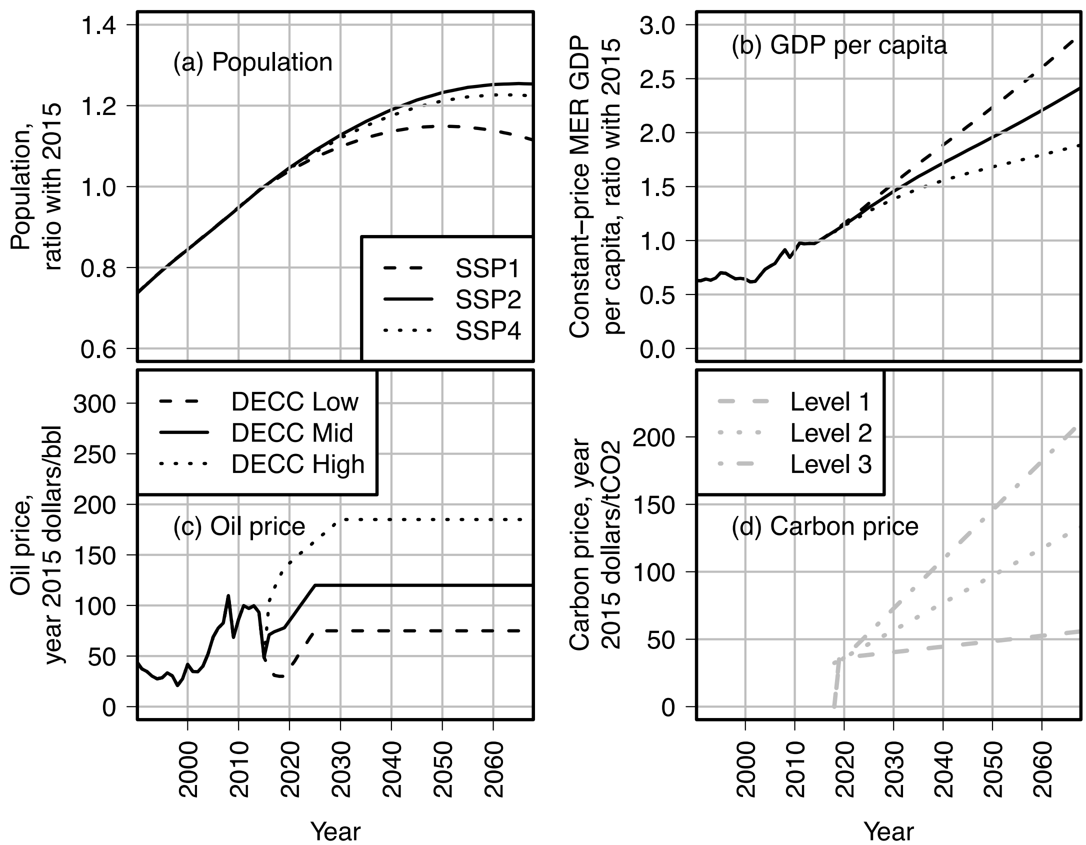

FIGURE 6 Future scenario characteristics used in this paper; (a) population, (b) GDP per capita, (c) oil price and (d) carbon price.

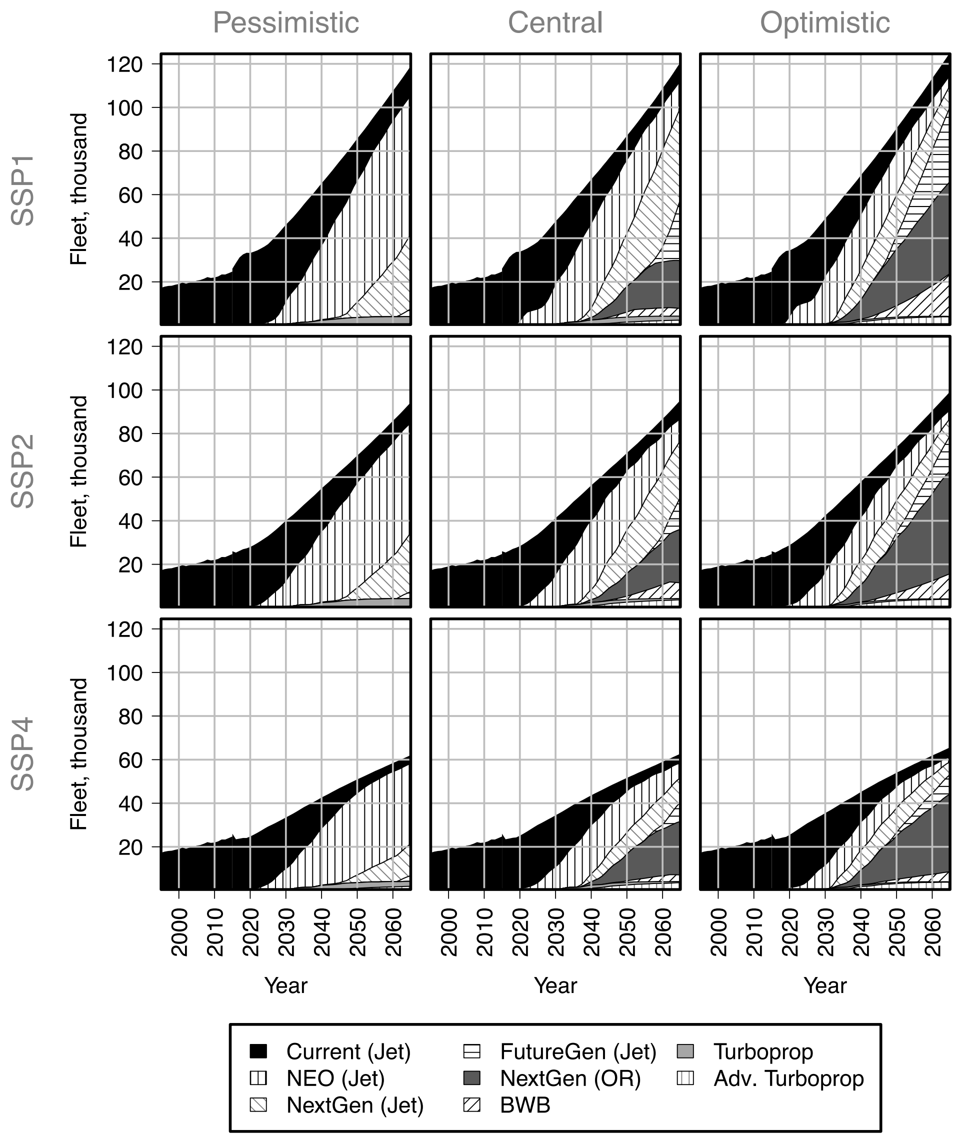

FIGURE 7 New aircraft technology uptake by lens and scenario in the model runs with no carbon price.

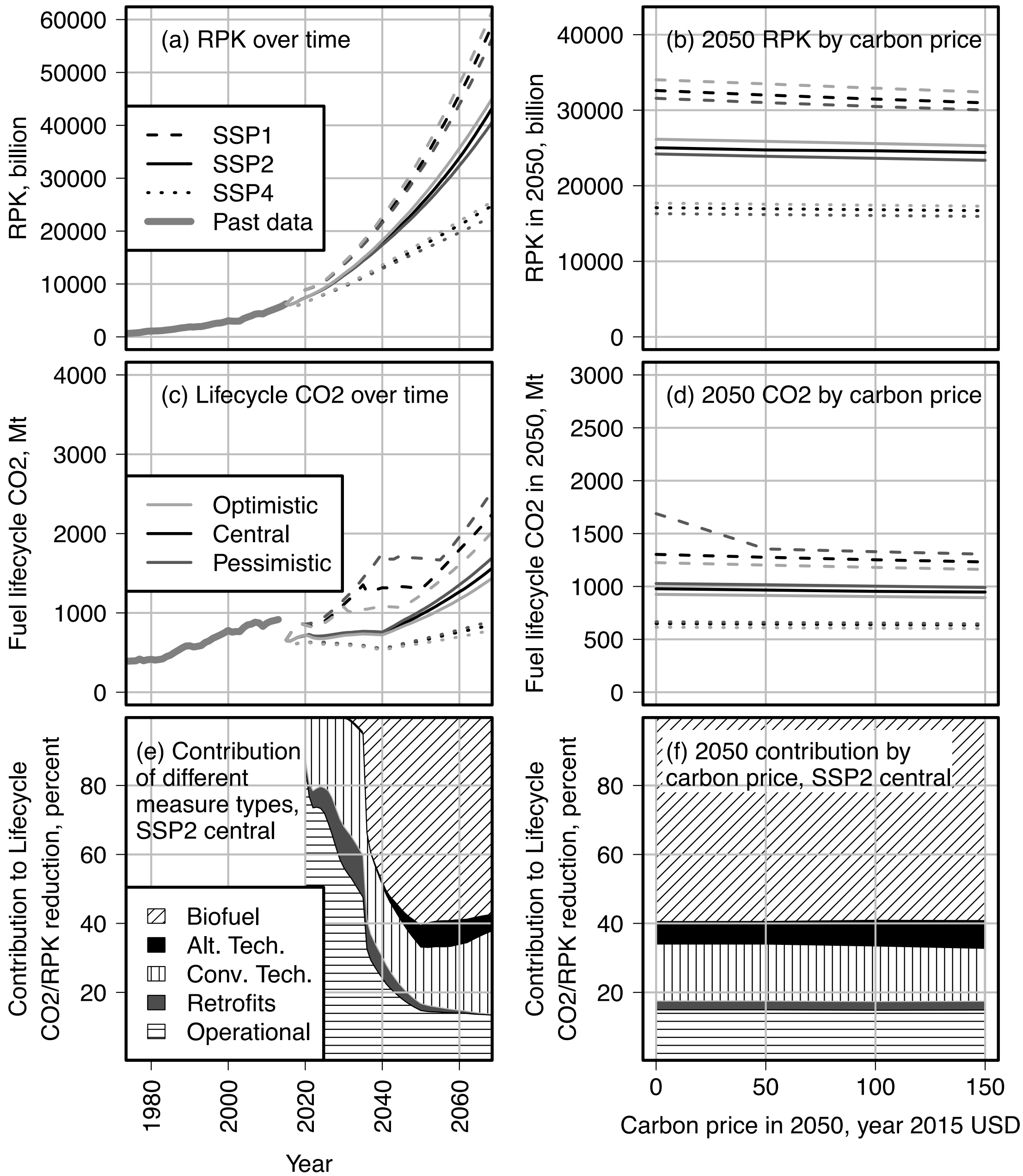

FIGURE 8 Relationship between RPK, global fuel lifecycle CO2 and carbon price; (a) total RPK, (b) RPK in 2050 by carbon price, (c) total fuel lifecycle CO_2, (d) fuel lifecycle CO_2 in 2050 by carbon price, (e) contribution to reduction in fuel lifecycle CO_2/RPK by measure type, SSP2 central lens, from 2020, (f) contribution to reduction in fuel lifecycle CO_2/RPK by measure type in 2050 by carbon price, SSP2 central lens.