Roadmap to decarbonising European aviation

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Executive Summary

Aviation is already a major and growing emitter. In Europe its emissions have doubled since 1990, and globally they could, without action, double or treble by 2050. Such emissions growth needs to be reversed and brought to zero by 2050 if we are to meet the goals of the Paris Agreement. Otherwise growth in aviation emissions could rapidly consume the limited carbon budget to remain within the 1.5 and 2°C targets of that Agreement.

Aviation however is at risk of having its emissions locked in due to the growth in passenger numbers and aircraft fleet. While uncertainties exist, we do know that the sector will have a substantial fuel demand well into the 2030s, 2040s and beyond, the period when our economy needs to increasingly decarbonise. This report puts forward measures to limit that fuel requirement, but ultimately the remaining and substantial fuel demand will need to have its carbon content eliminated. The process of cutting and then decarbonising that fuel demand is the focus of this report.

The report finds that the expected technology and operations improvements will not mitigate the expected fuel demand and emissions growth from aviation. Generating incremental efficiency improvements from current aircraft designs is becoming ever more costly and difficult. Further operational improvements remain possible but do not achieve decarbonisation and require the right policies to be in place. To significantly reduce the expected fossil fuel demand and ultimately eliminate it from the sector would require further measures.

Carbon pricing needs to play a central role in bringing forward further reductions in fuel demand. Exempt from kerosene taxation and with most European aviation emissions excluded from the EU ETS, there is much that needs to be done. Our report shows that introducing fiscal measures that combined represent a carbon price equivalent to €150 a tonne can moderate demand fuel demand growth from the sector through incentivising a combination of design and operational efficiency improvements and modal shift. Other measures highlighted by the report include stricter fuel efficiency standards and incentives to speed up fleet renewal. Our report finds that, combined, these measures could cut fuel demand by some 12 Mtoe, or 16.9% in 2050 compared to a business as usual scenario.

However that still leaves substantial and increased fuel demand in 2050. This report examines how the carbon footprint of the remaining fuel demand can be cut and, where possible, eliminated. The report finds that with today's technology this can only be achieved through the use of sustainable alternative fuels. The report demonstrates that this is no easy task, highlighting the issues faced in Europe to date in reducing the carbon intensity of fuels used for road transport.

To succeed in putting aviation on a pathway to decarbonisation, new types of alternative fuels need to be brought forward. The report focuses on synthetic fuels, namely electrofuels, which will be needed to close the gap. Electrofuels are produced through combining hydrogen with carbon from CO_2. With the hydrogen produced using additional renewable electricity and with the correct source of CO_2 (ideally air capture), such fuels can be close to near zero emissions and carbon circular. Again however strict safeguards are needed to ensure synthetic kerosene would be produced only from zero emission electricity.

If produced at scale, electrofuels are likely to cost between three and six times more than untaxed jet fuel. At a cost of €2,100 per tonne in 2050, electrofuel uptake will increase ticket prices by 59%, resulting in a 28% reduction in projected passenger demand compared to a business-as-usual scenario. However, compared to the ticket price with an equivalent CO_2 price of €150 a tonne, the ticket price increase would only be 23%. The report finds that introducing a progressively more stringent low carbon fuel standard (GHG target) on aviation fuel suppliers will leave all operators flying within or from Europe needing to purchase such fuels. These rising fuel costs will increase operating costs which will inevitably be passed onto consumers, causing a fall in demand for jet fuel compared to forecasts and reducing the volume of alternative fuels that will be required to replace kerosene.

Importantly for policy makers, the report highlights the enormous demand on renewable electricity if fuel demand remains high and electrofuels are the only way to decarbonise. Using electrofuels to meet the expected remaining fuel demand for aviation in 2050 would require renewable electricity equivalent to some 28% of Europe's total electricity generation in 2015 or 95% of the electricity currently generated using renewables in Europe. It is also important to keep in mind that other sectors will need additional renewable electricity to decarbonise, for example for green hydrogen to be used in industry. However, with today's technology, synthetic fuels are the only technically viable solution that would allow aviation to exist in a world that avoids catastrophic climate change.

A further note of caution in the report is that while the use of such fuels can put aviation on a pathway to decarbonisation, getting to zero emissions, the generally accepted term for decarbonisation, will be difficult because producing alternative fuels which, on a life cycle basis, are 100% carbon free is very challenging. Advanced biofuels could play a role in substituting fossil fuel demand in aviation. However, strict sustainability safeguards are needed to ensure advanced biofuels offer genuine emission savings - these are not yet in place. If fuels with poor environmental and climate credentials would be excluded, the potential supply of advanced biofuels would be very limited. Our report finds that they could play a role - meeting up to 11.4% of the remaining 2050 fuel demand in our scenario - but alone won't be available in the quantities needed. This is partly because non-transport sectors will also have a claim to biomass feedstocks, reducing availability.

This report does not rule out the role that radical new aircraft designs could play in significantly reducing aviation emissions, for example hydrogen or electric aircraft. However such aircraft are not expected to be in operation in significant numbers until the 2040s, and will find it especially challenging to replace conventional aircraft for long-haul flights. What is less speculative is that significant liquid fuel demand will exist right through to 2050, and for that reason, the report focuses heavily on how such fuels can be decarbonised. Should hydrogen aircraft technology develop more rapidly this would not be at odds with significant investment in synthetic fuels as hydrogen is a key input for electrofuels.

Decarbonising such fuel will require significant investment, and significant investment requires certainty. That is why policy-makers need to turn their attention now to the safeguards and policies needed to bring such fuels to market, so that the availability of these fuels can be ramped up in line with the sector's need to decarbonise.

Aside from decarbonising aviation fuels, the warming from aviation's non-CO_2 effects at altitude is considerable and is a challenge that is barely being touched. While the report discusses these effects and identifies possible mitigation approaches, there remains a lack of policy focus and investment in scientific research on this topic. This failure to act means we are unable to propose a suite of mitigation measures nor estimate their effects. What is clear is that the European Commission must meet its obligations under the EU ETS Directive to foster further research and, resulting from that, come forward with proposals on measures by the start of 2020.

The case for acting on aviation emissions is clear - a failure to do so will fatally undermine efforts to achieve the goals of the Paris Agreement. This report outlines what such action should look like: aggressively cutting fuel demand, moderating the expected growth in air travel, decarbonising the remaining fuel, and addressing the sector's non-CO_2 effects. Finally, the report does not recommend offsetting as this is a solution that is incompatible with the decarbonisation logic of the Paris Agreement.

Proposed measures

- Cut fuel demand from the sector below projected levels through a carbon price equivalent to €150 a tonne achieved through a range of measures including kerosene taxation and a strengthened EU ETS;
- Cut fuel demand through additional measures such as stricter aircraft CO_2 standards and incentives for fleet renewal;
- Further reduce the climate impact of aviation through a progressively more stringent low carbon fuel standard on aviation fuel suppliers, conditional on the necessary safeguards being in place, to bring aviation close to zero emissions by 2050; and
- Ensure the Commission brings forward proposals to address aviation's non-CO_2 effects by the start of January 2020, as required by the revised EU ETS Directive.

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List of acronyms

ASA	Air Service Agreement
ASTM	American Society for Testing and Materials
BaU	Business as Usual
EASA	European Aviation Safety Authority
ETD	Energy Taxation Directive
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas Emissions
Gpkm	Giga passenger-kilometres
HSR	High Speed Rail
ICAO	International Civil Aviation Organisation
ILUC	Indirect Land Use Changes
ktoe	Kilotonne of oil equivalent
Mtoe	Megatonne of oil equivalent
MTOW	Maximum Take Off Weight
RFNBO	Renewable Fuels of Non-Biological Origin
RED	Renewable Energy Directive
TWh	Tera Watt hours

1. Introduction

1.1. Purpose of this report

The purpose of this report is to examine whether a credible pathway to zero or near zero emissions exists for European aviation. For the purpose of this report that includes flights within and departing from Europe. That matches the scope of aviation's inclusion in the EU's 2030 target. It takes broadly accepted passenger and emissions growth forecasts out to 2050, considers the role that various policies can play in reducing fuel demand from the sector, and then proposes how the remaining fuel demand can be decarbonised.

1.2. The rise and rise of aviation emissions

Aviation is one of the fastest growing sources of GHG emissions and the most climate-intensive mode of transport. Globally, aviation emissions have more than doubled in the last 20 years[i] and, when including the significant non- CO_2 climate effects of aircraft flying at altitude, the sector is responsible for an estimated 4.9% of man-made warming[ii] (Figure 1).

Emissions from EU aviation increased 96% between 1990 and 2016[iii] while all other sectors, bar transport which grew 21%, reduced emissions. As a result, aviation emissions have grown from 1.5% of total EU emissions in 1990 to 3.6% today[1]. If the trend of traffic growth exceeding improvements in aircraft efficiency continues, aviation emissions are predicted to double or triple by 2050 and consume up to one-quarter of the global carbon budget[iv], undermining the Paris Agreement efforts to keep global warming to 1.5°C.

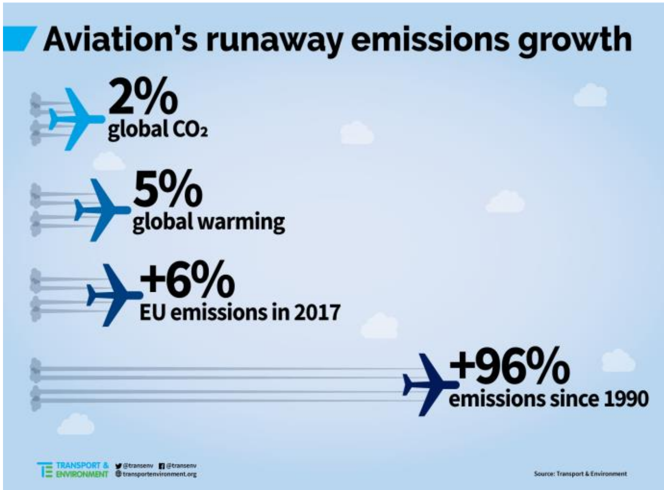

Figure 1: Global and European aviation growth

1.3. Can aviation be decarbonised?

The challenge in reducing aviation emissions is well known. Manufacturers are finding it increasingly difficult to deliver efficiency gains from new engines and aircraft designs and incremental improvements are declining. With aircraft having a lifespan of 20-30 years and current models having orders up until the mid-2020s, aircraft being delivered now are locking us into decades of fuel consumption. Truly sustainable alternative fuels are limited in volume and the significant price gap with tax-free kerosene is constraining uptake.

Growth in air traffic remains strong; up 8.5% in Europe in 2017[v], exceeding growth of 7.6% globally[vi]. Certain measures could slow some of this growth - such as ending the fuel tax exemption and other subsidies or introducing effective aircraft efficiency standards.

1.4. Regulating at what level?

Following the failure of efforts to include all aviation emissions in the EU ETS, Europe focussed on efforts to regulate these emissions at a global level through measures to be adopted by the UN's aviation agency, ICAO. Two measures in particular were advanced - a CO_2 efficiency standard for new aircraft, and a global offsetting measure for emissions above 2020 levels.

[1] From Member State reporting to the UNFCCC. https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018

These measures have been extensively critiqued elsewhere[vii] - neither will reduce emissions from the sector in a manner consistent with the goals of the Paris Agreement. ICAO as an institution suffers from a number of flaws which, until they are resolved, make it highly unlikely that they will deliver meaningful measures to cut emissions, let alone decarbonise aviation.

1.5. European efforts

Aviation emissions have long been a weak spot in European climate policy. After earlier consideration of taxation, the EU included aviation in its ETS from 2012, but backed down later that year in the face of intense resistance from industry and a group of foreign states. As a result only flights within Europe are included for the time being. Meanwhile the sector continues to enjoy various tax exemptions (fuel duty, VAT), as well as state aid subsidies. The agreed ICAO efficiency standards for aircraft will have no significant impact on emissions[viii] and the uptake of sustainable alternative fuels has been minimal[ix].

In adopting its 2030 emissions target, the EU included all outbound aviation emissions - that is, emissions from all flights departing *from* Europe but not *to* Europe.[2] The 2030 target for the sector was set at 111 Mt CO_2e[x] - below its current level of 148 Mt CO_2e. Achieving this target will require a significant uptake in new technologies or fuels, or alternatively an increase in ambition in other sectors. However long-term decarbonisation, which Paris demands, requires the sector to bring its own emissions to zero - both CO_2 and non-CO_2.

1.6. Europe's decarbonisation strategy

The European Union is currently in the process of reviewing its long-term emissions reductions strategy, with a draft to be published in November 2018 and a final version to be adopted by member states in 2019. The revised strategy will detail Europe's contribution to the Paris Agreement objective of limiting a temperature increase to well below 2°C/pursuing efforts to limit an increase to 1.5°C. This is more stringent than the target which was the basis of the current emission reductions strategy, which also left the 2050 ambition open, setting a range of 80-95% cuts[xi] but in practice mostly working towards the lower end of that range. As a result the revised strategy will have to be more ambitious than today's. Considering that global temperatures have already risen at least 0.8°C[xii] and GHG concentrations are increasing rapidly Europe must decarbonise all sectors by 2050.

The EU's current long term emissions strategy includes emissions from outbound flights, but with relatively little detail on how reductions from the sector can be achieved. The revised strategy needs to continue to cover outbound aviation, make it clear that the aviation sector too must commit to zero emissions by 2050 and provide far more information on what sort measures and policies Europe will pursue to ensure the sector is decarbonised. It also needs to address aviation's short-lived non-CO_2 climate effects, whose transient (days to weeks) climate warming impacts equal or exceed those of aviation's accumulated CO_2 emissions[xiii].

1.7. T&E decarbonisation paper

This paper presents a decarbonisation pathway for aviation out to 2050. The scope of the analysis is the same as the EU's 2030 target - all emissions from outbound flights. As well as cutting Europe's own aviation emissions, these measures can spur similar action in other regions, by for example incentivising the development of new technologies or helping reduce their costs, by demonstrating the effectiveness of emission reduction measures, and, above all, by introducing low or zero carbon aviation fuels to the market.

[2] So Paris-Madrid and Warsaw-New York are included, but not Delhi-Rome

1.8. Methodology

T&E drew on aviation activity growth forecasts from the 2016 European Reference Scenario[xiv] to project total outbound aviation emissions from European airports up to 2050. We then modelled the application of a range of measures to reduce fuel demand to what we believe is the maximum extent possible through fuel, technical and operational efficiencies or limiting passenger number growth through price signals. The result is what T&E believes fuel demand from the aviation sector can reasonably be reduced to by 2050. We then focus on how to decarbonise that remaining fuel demand through the use of sustainable advanced biofuels and synthetic e-fuels (power-to-liquid, or PtL). Full details of the modelling approach are found in the Appendices.

2. Measures to cut fuel demand

2.1. Business as usual

The BaU scenario was developed from the 2016 European Reference Scenario. The effect of demand reduction from higher kerosene prices built into the Reference Scenario was decoupled, the result being that there is higher demand. This was undertaken to avoid double counting reduction measures and ensure that the measures added in this report are additional and not duplications. It also allows an assumption of constant fuel price, so that policy measures can be analysed in isolation, rather than on the reliance of volatile fuel prices to do the heavy lifting of decarbonisation.

The result is that aviation energy demand in 2050 under our BaU scenario is projected to be 71.3 Mtoe, compared to 65.5 Mtoe in the Reference Scenario. As passenger activity in the Reference scenario only draws on intra EU and domestic flights, an analysis of the available seat kilometres from aircraft transponder data was used as a proxy to extend this to all EU departing flights. In 2050 we calculate EU outbound passenger activity to be 6753 Gpkm, compared to the 1177 Gpkm projected for intra-EU flights from the Reference Scenario.

2.2. Design and operational efficiency

The design and deployment of more efficient aircraft and engines can play an important role in reducing fuel demand from the sector. The development of these aircraft, how quickly they enter the fleet, and their more efficient operation is open to speculation. We have divided our forecasting into the maximum possible reductions based on currently available technologies and what more radical designs may start to deliver closer to the 2050 timeline.

The EU reference scenario includes in its aviation energy demand projections an increase in fleet efficiency, measured in terms of fuel burn per passenger km, of 41% by 2050 compared to 2010. We take this to be a combination of technical and operational improvements, as a 41% improvement from current aircraft designs alone is not deemed possible.

This 0.9% improvement per annum is towards the higher end of what is possible. Within current designs, it is increasingly difficult and ever more costly to continue generating incremental efficiency improvements - for example using lighter material, more efficient variants of existing aircraft, or adding winglets etc. to reduce fuel consumption. However it's also true that we are not yet maxing out what is possible in terms of design improvements. ICAO commissioned an independent fuel burn expert group to identify the extent of achievable future fuel efficiency gains, which found that emission reductions beyond those expected under a BaU scenario were possible. But this level of improvements is not required by the ICAO CO_2 standard for both new and in-production aircraft designs. In addition, periods of low oil prices, such as the situation which has existed since 2014, also act to disincentivises fleet renewal and investments into increased efficiency - even more so when effective carbon pricing or fuel taxation is lacking.

Though this 0.9% per annum would be at the more ambitious end of what we expect is possible, our forecasting envisages a situation where governments adopt an ambitious range of measures to encourage both new designs and their deployment. For example the progressive implementation of an effective carbon price up to €150 a tonne will encourage new designs and their deployment across the fleet as well as accelerated phase outs of older aircraft. Europe could introduce other policies to encourage fleet wide efficiencies - for example fuel taxation, additionally taxing dirty aircraft to accelerate phase outs or linking the auctioning of slots at airports to aircraft efficiency. Europe could also introduce more effective aircraft efficiency standards through the EASA certification process.

Additional operational improvements could come about through the effective implementation by member states of the single European sky rationalisation of European airspace, which is essential if we're to reduce fuel demand to the maximum extent possible. It also includes accelerated upguaging (deployment of larger aircraft) and increased passenger density by curbing first and business class travel.

Our forecasting also takes into account potentially more radical aircraft designs entering the fleet from about 2040 onwards. These designs include strut systems (reducing drag), bubble designs, flying wings, hybrid and electric aircraft. New aircraft designs are obviously speculative. Their potential development is limited as, without clear government mandates, they will involve significant financial risks for manufacturers. A move to hydrogen powered aircraft will require enormous investments for manufacturers and airports. It is not at all yet clear that electric powered aircraft will have a flight range of commercial significance beyond short haul.

However under a scenario where governments aggressively mandate the development and deployment of radical new technologies, it is conceivable that from the 2040s such technologies will begin to penetrate the market, but it would take some time before they have a major impact on emission reductions.

Key drivers

- Implicit carbon pricing of €150/tCO_2 as considered below
- Stricter efficiency standards for new aircraft, either at international or, failing that, European level
- Further measures to incentivise new aircraft deployment, such as phase-out measures for the oldest aircraft
- Airport charges that are lower for more efficient aircraft.

Our estimates presumes additional fleet wide efficiency improvements of 0.2% per annum over the BaU. From 2040, more radical designs are assumed to be 30% more efficient than existing technologies. Aircraft and operational efficiency improvements could reduce fuel demand 6.3 Mtoe (or 8.8%) by 2050.

2.3. Pricing aviation and eliminating subsidies

Essential in efforts to decarbonise aviation is the introduction of carbon pricing, other forms of taxation and the phasing out of subsidies. This would have the effect of curbing demand, but also incentivising both design and operational efficiencies. Finally, it may encourage the uptake of low or lower carbon fuels by improving their business case.

Carbon pricing is the charging of those who emit carbon emissions based on the level of their emissions. It is increasingly recognised as an essential, though by itself insufficient, measure to ensure the world reaches its Paris Agreement target. Carbon pricing continues to be introduced in different jurisdictions - China and Canada at a federal level joining Europe in introducing such pricing, and with substantial subnational carbon pricing in the United States and Canada.

However the aviation sector remains lagging in the introduction of such pricing. Only flights within Europe, accounting for around 40% of the region's emissions[3], are included in EU ETS leaving long-haul flights completely unregulated. Domestic aviation is included in New Zealand's carbon market. Domestic fuel taxation exists in some jurisdictions, such as Japan, Brazil and India and to a limited extent in the US.

Outside of carbon pricing, other forms of taxation can also play a role in reducing fuel demand by limiting the growth in passenger numbers, and thereby reducing overall fuel demand. And finally, ending subsidies such as state aid to airports and airlines could also limit the growth in passenger numbers, again reducing the overall fuel demand.

Reining in aviation emissions growth, and putting the sector on a pathway to decarbonisation, cannot be achieved without all or a combination of the above measures, which have the end result of more correctly pricing aviation. Estimates put a Paris-compliant carbon price at €30 a tonne now, rising to €150 by 2050[4]. Below we consider some of the means by which such an effective carbon price can be applied to European aviation.

In describing the policies below, we also consider the revenue which can be raised. Revenue raising is secondary to the objective of decarbonisation, however it is not unrelated. The additional revenues could be used to reduce other taxes (e.g. labour taxes) or help governments raise revenue in order to fund the necessary investment required to decarbonise the economy as a whole or specific sectors.

2.3.1. Options for carbon pricing

Fuel taxation

Fuel uplifted for international aviation remains mutually tax exempt owing to language contained in bilateral aviation agreements, known as Air Service Agreements (ASAs), introduced in the period after the Second World War when states were encouraging international aviation to expand. Those exemptions remain in place, and are a barrier to the immediate introduction of kerosene taxation on international aviation. Globally, the exemption is valued at €60bn a year[xv].

Fuel taxation is possible at the EU level. The Energy Taxation Directive (ETD) permits taxation of kerosene for domestic aviation - however within the EU only the Netherlands did so. Norway and Switzerland also tax domestic fuel. The ETD also permits two or more member states to introduce kerosene taxation for fuel used on flights between those states provided this is agreed bilaterally. So far this has not happened - one reason being that air services agreements continue to provide mutual fuel tax exemptions for foreign carriers operating intra EU flights. But these operations have decreased dramatically in numbers and an intra EU kerosene fuel tax could be introduced with a de minimis provision which de facto exempts all foreign carrier operations. Amendments to the relatively few ASAs involved should also be pursued.

Applying kerosene taxation to fuel uplifted for flights from Europe requires the abolition of the mutual fuel tax exemption in air services agreements. However it is not inconceivable that as need for carbon pricing becomes ever more apparent, there are opportunities for such taxation to be introduced on a bilateral basis with non-EU countries, steadily expanding to cover an increasing share of European aviation emissions. In the event that all departing flights in Europe paid the ETD minimum tax on fuel uplifted, this would be equivalent to a CO_2 price of €130/tCO_2. A minimum price is precisely that - the level of the tax could be

[3] T&E analysis of UNFCCC and aircraft transponder data from PlaneFinder (2016). Transponder data were coupled with the ICAO fuel burn calculator methodology, and flights analysed based on journey type.

[4] There is an ongoing debate over what constitutes an appropriate carbon price. Research to date suggests that in the aviation sector a price in excess of €100 is required due to that sector's higher mitigation costs (Schafer et al, 2016). We chose a price of €150, which as outlined in this paper, is eminently achievable.

increased to achieve this paper's target of €150 a tonne, or higher if that would deliver greater mitigation benefits.

Emissions Trading Scheme

As explained above, only flights within Europe are currently covered by EU ETS. A further exemption for flights to and from Europe was granted in 2017 until the end of 2023. In recent years the system has suffered from an oversupply of allowances, bringing prices to as low as €5 a tonne, far below the sort of carbon pricing required to incentivise emission reductions. Combined with free allowances received by the sector, the scheme cost airlines only €150m in 2015 compared to EU airline profits of €7.4bn[xvi].

Since then, allowance prices have begun to recover, trading at over €25 a tonne by September 2018. Revisions to European legislation mean that from 2021 the number of aviation allowances issued each year will begin to decline, as is already the case for other sectors covered by ETS. There is also a commitment to review the number of allowances which are granted to airlines for free, rather than auctioned.

The effectiveness of the aviation ETS - in terms of revenues raised and emissions cut - will depend on the scope, the cap and allowance price. Were all emissions from Europe to be included in an effectively functioning ETS, then a path to the eventual decarbonisation of outbound flights would be clear. However achieving this scenario will require significant political ambition.

2.3.2. Other options for taxing aviation

Emissions trading and kerosene taxation put an almost direct price on emissions and are therefore the preferred policy options. However there are other means to price aviation, which while not directly putting a price on its emissions, nonetheless may reduce the growth in passenger numbers and therefore reduce fuel demand. For that reason they are considered as part of this paper.

Per plane taxes.

Ticket taxes are taxes levied on the act of passengers departing an EU airport, with costs built into ticket prices.

Per plane taxes, or "movement" taxes would be levied on aircraft/airlines by virtue of an aircraft departing an EU airport and paid directly by carriers to tax authorities with the additional costs built into ticket prices. Ticket taxes are levied in a very large number of countries around the world without legal challenge. Movement taxes on aircraft would be levied in a similar way.

The per plane tax can be based on various environmental criteria - the aircraft's certified noise rating or its certified MTOW which is a proxy for aircraft size and noise/air pollution. The tax could also approximate the flight's CO_2 emissions - which depend on the aircraft type and distance flown. A CO_2-based per plane tax could depend on MTOW, or the ICAO certified CO_2 metric value of the particular aircraft combined with a distance factor. The distance factor would need to be applied in bands as with ticket taxes, because a sliding tax applied proportionately to distance could be deemed a VAT or fuel tax contravening international agreements. The Dutch Government is currently studying movement taxes as an option for taxing Dutch aviation from 2020.

Ticket taxes

A number of member states have introduced ticket taxes on aviation, the UK as far back as 1993. These taxes are levied on all passengers and usually vary depending on distance of flight as well as in some cases the class of travel. Other states have followed the UK example, including Germany, Austria, Norway and Sweden currently such that more than half the EU market is now covered.

Ticket taxes are simple to administer, and can raise substantial sums of money; €3bn a year in the UK alone. There is no legal barrier to member states introducing such taxes, at whatever rate. They have survived numerous legal challenges from airlines. Ticket taxes are a common feature of many aviation markets around the world.

VAT

Alongside its fuel taxation exemption, aviation is also mostly exempt from sales tax/VAT. Though some European states levy VAT for domestic flights the exemption for intra EU flights is applied by all states and likewise none apply VAT to extra EU flight tickets. VAT exemptions are supposed to be primarily for essentials (medicines, food) however as with kerosene taxation, the VAT exemption for aviation is a hangover from an earlier era when all international aviation was tax free. The exemption distorts the market - encouraging consumers to spend money on this carbon intense mode of transport, instead of other, potentially lower-carbon, expenditures including rail travel.

Member states may introduce VAT on intra and extra aviation tomorrow, however the current legislation provides a practical barrier. If states were to introduce VAT, they could only do so for the portion of flights over their territory - a cumbersome way to levy such a tax, particularly as flight routes may vary and airlines could reroute to avoid such a tax.

The solution would be for the EU to amend its VAT legislation so that member states could levy VAT on the full price of the ticket at departure. The Commission has opened this possibility with a proposal earlier this year to simplify VAT rules[xvii], but these remain to be implemented. It could go further and make the levying of such VAT mandatory, but even the limited step of facilitating such a tax would be welcome.

Other subsidies

As well as the indirect subsidies from tax exemptions, aviation also receives direct subsidies for example through state aid for airports and airlines and government backed financial support granted to manufacturers. Though the EU has largely reduced direct investment in airport capacity, particularly following a damning report by European Court of Auditors[xviii], there is still some support granted to airport expansion from the European Investment Bank[xix].

At a member state level, substantial amounts of state aid continue to be granted to airports - including operational aid to airlines, which has the most distortive effect on competition. The levels of state aid are difficult to quantify but, with almost half of Europe's airports loss-making, are substantial. Often times such aid goes unreported, and in recent years the European Commission rather than attempting to rein in such aid, facilitated its provision and abuses by, for example, adding to the general bloc exemptions[xx].

State aid to this carbon intensive sector has no future in a Paris compliant scenario. And just as the EU has moved to ban state aid to the coal sector, it must also ban aviation state aid. In developing our model, the ending of these subsidies is factored into the €150 carbon price.

Key drivers

An effective carbon price of €150 can be achieved through one or a combination of the following policies:

- Introduce kerosene taxation on routes within and from Europe
- Reform EU ETS to ensure an effective carbon price (reduce free allowances, cut allowances at a faster rate and build support for its broadest possible application)
- A complete ban on state aid and other subsidies to the aviation sector
- Reform the VAT rules to facilitate member states introducing VAT on aviation tickets
- Introduce ticket taxes on all aviation tickets, pending the introduction of VAT
- Introduce per aircraft movement taxes

Our estimates are that introducing a carbon pricing of €150 on top of the design and operational efficiency measures can reduce total emissions a further 5.8 Mtoe (or 8.9%) by 2050. A carbon price of **€150 would result in an increase in ticket prices of approximately 19% in real terms.**

2.4. Modal shift

Shifting passengers from air travel to other modes of transport, especially rail, can play a role in reducing overall emissions. Particularly as rail has a viable pathway to decarbonisation through reliance on 100% renewable electricity. However it is important not to overstate the potential emission reductions resulting from such modal shift.

Flights under 600 km, which should be considered as targets for modal shift, account for only 7% of total aviation emissions in Europe[5]. Modal shift is not possible for many of these routes - due to the high cost of developing rail alternatives for what may be low frequency routes, or due to geographic barriers. There are certainly routes in Europe where the development of better and faster connections as well as additional high speed rail (HSR) services can help cut aviation emissions. Retention and reopening of night trains could facilitate a shift from aviation to rail for longer journeys. However the opportunities are limited, and there may be an excessive financial and environmental cost from expanding HSR.

In developing rail as an alternative to aviation, a range of measures will be required. Closing the price gap between the modes is essential - that includes taxing aviation as above, but also introducing stronger labour laws in the aviation sector to reduce the unfair competition resulting from the aviation sector undercutting the wages of other transport modes, and introducing greater competition in the rail sector in order to improve performance and drive down operating costs and fares.

Modal shift, or perhaps more precisely aviation demand reduction, can occur in other ways, however. A rising cost of flying, resulting from carbon pricing or the cost of alternative fuels or new technologies, could result in businesses finding alternatives to flying, such as greater use of video conferencing or rationalising the amount of business travel. Demand reduction could also take place in leisure travel - through changing destinations to reduce distance travelled, or taking fewer but longer holidays.

Key drivers

- Close the price gap with rail through taxing aviation, strengthening labour rights in the aviation sector and introducing greater competition to the rail sector

Our forecast is that modal shift will have only a limited impact in reducing fuel demand in 2050. As these reductions are limited, they are included in the passenger demand reductions resulting from carbon pricing as such carbon pricing is the policy measure expected to contribute most to modal shift. As shown in Figure 2, the combined measures described above could reduce the final aviation energy demand by 12.1 Mtoe, or 16.9%.

[5] T&E analysis on plane transponder data covering two weeks of flights in 2016, using the ICAO emissions calculator to calculate fuel burn methodology. Available: https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf

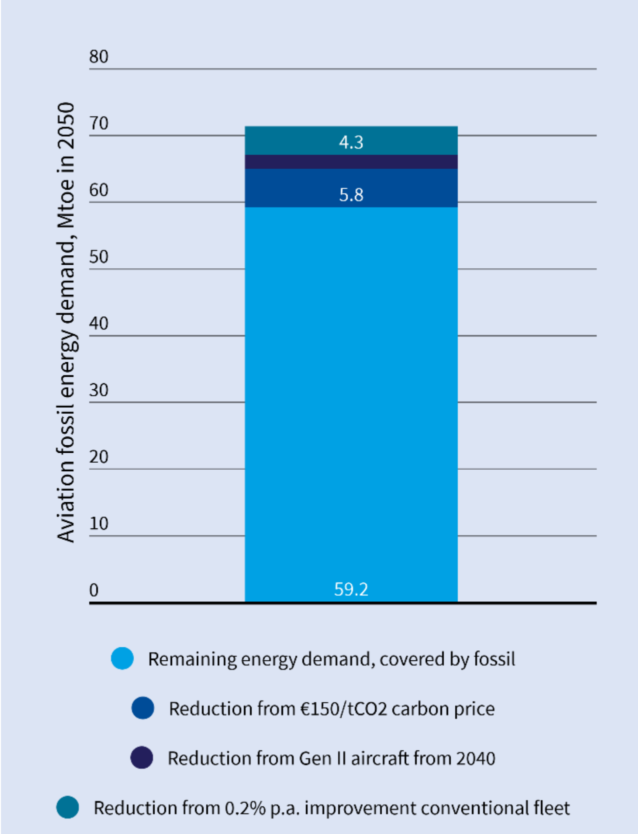

Figure 2: Contributions of technology, operational efficiency, and carbon pricing on kerosene demand in 2050. Note that 59.2 Mtoe of kerosene is 183 Mt CO_2, approximately equivalent to business as usual 2025 emissions.

3. Decarbonising aviation fuels

The above measures are estimated to bring down the sector's fuel demand from 71.3 Mtoe under a BAU, to 59.2 Mtoe under the policy scenario we have described. Decarbonisation of aviation by 2050 will therefore depend on decarbonising that remaining fuel demand.

We look at two pathways to do this - deploying sustainable advanced biofuels, and renewable fuels of non-biological origin (RFNBO). Though there are similarities between the two in terms of the existence of price gaps, issues with supply etc., there are also key differences relating to environmental integrity, how their uptake can be incentivised and most importantly, scalability. We therefore consider the two alternatives separately

3.1. Advanced biofuels

Advanced biofuels are defined as biofuels produced from waste and residues. To date alternative fuel uptake in the aviation sector has been extremely limited, largely due to the price gap between the alternative fuels currently available and traditional kerosene fuels.

Before considering measures to realise an uptake of advanced biofuels, it is important to look at what constitutes sustainable advanced biofuels, what volumes are likely to be available in the future, and what 'share' of these fuels aviation could reasonably expect to use.

The issues with many, particularly first generation, biofuels are well documented. Europe's experience with mandates for the road transport sector demonstrated that many of the biofuels used resulted in total emissions which were greater than the fossil fuels they replaced[xxi]. This was due to what's known as indirect land use change - the use of land to grow crops for biofuels displaces land which was previously used to grow crops for food. This displacement sparks further deforestation and conversion of grassland, to ensure sufficient land is cultivated for both fuel and food. This deforestation and conversion resulted in a total increase in emissions. In addition, even if we were to ignore these ILUC affects, the amount of land required to produce significant volumes of aviation biofuels would be enormous (powering the world's aviation fully with biofuels in 2050 would, directly or indirectly, require more than 3.5 million km^2 of land[6]) and would run counter to the efforts to increase negative emissions and carbon sinks, which will be required as part of the Paris Agreement.

So in assessing the future availability of biofuels, we limit our forecast to only those advanced biofuels from waste and residues which deliver real and sustainable reductions in emissions. Such feedstocks are incidental to other processes, and so will be limited in availability. Our projection is that in 2050, availability of sustainable advanced biofuels for the aviation sector will total 7,500 ktoe, meeting 11.4% of European aviation fuel demand (if the above efficiency and carbon pricing measures are realised, otherwise advanced biofuels could make up to 10.5% of BaU oil demand).

This is based on previous T&E research on the future availability of sustainable advanced biofuels[xxii]. In making this projection, our assumption is that other sectors, particularly road transport, will have transitioned entirely to direct electric or renewable hydrogen propulsion, and by 2050 will have no need to decarbonise through the use of alternative fuels. This assumption underlines how essential it is to drive electrification of all types of road transport, and how necessary it is to adopt an overarching emissions strategy for all transport modes. Non-transport sectors will also have a claim to biomass feedstocks, and this is factored into our assumptions. Were demand from the non-transport sector for advanced biofuels feedstocks to exceed what is in our assumptions that would have implications for the availability of this fuel for the aviation sector.

Sustainable advanced fuels will contribute to decreasing GHG emissions, but there are not so many which show pathways towards zero or negative emissions through their life-cycle. If some fuels, for example, achieve 80% emission reductions, then their use will still result in emissions from the sector; i.e. not achieve decarbonisation. To contribute to the decarbonisation of aviation, their production and entire life cycle impact (including indirect impacts) must be zero carbon. Therefore decarbonising aviation is coupled with broader efforts to decarbonise the economy, as reducing the carbon intensity of other activities such as heat, industrial processes and electricity generation will help reduce the lifecycle emissions from advanced biofuels. It is crucial for EU policies to account for all GHG emissions (also indirect) from advanced fuels. For accounting purposes, we assign zero emissions to these fuels in our modelling exercise.

Our forecast is that an availability of 7,500 ktoe of alternative fuels will contribute to reducing fossil kerosene demand by 6.8 Mtoe (or 11.4%) of aviation fuel demand in 2050.[7]

3.2. Synthetic e-fuels

In the context of this report, renewable fuels of non-biological origin (RFNBO) refers to the use of additional renewable electricity to extract hydrogen from water through electrolysis, which is then combined with CO_2 captured from the atmosphere, to produce a drop-in liquid hydrocarbon fuel. In this report, these fuels are referred to as electrofuels. We only examine drop-in electrofuels - i.e. electrofuels which can be used by aircraft through combustion in a jet turbine, with minimal or no modifications to the aircraft, engines or ground refuelling infrastructure. This draws a line with other types of fuel, such as hydrogen, which requires completely new aircraft designs and new airport refuelling infrastructure, the potential emission reductions out to 2050 of which are accounted for under Sec 2.2. However, it is important to note that a hydrogen

[6] Own calculations: international aviation will consume around 800 Mt of fuel in 2050. The NCV of kerosene is 44.1 TJ/kt. That equals 35.28 EJ = 843 Mtoe by 2050. 1Ha produces 100 GJ of biofuel.

[7] An increasing uptake or blend of biofuel will reduce the CO_2 price, and the associated demand reduction.

scenario has similar, though slightly lower, implications to synthetic fuels in terms of costs and additional electricity needs.

The emission reductions resulting from the use of electrofuels depend mainly on what electricity is used to produce the hydrogen and the choice of the source of CO_2 leads to different impacts. Using CO_2 from a fossil carbon origin, such as the one being emitted in a steel or a power plant, means the fuel is not carbon circular because the CO_2 ends up in the atmosphere anyway. Designing a synthetic fuel production chain around carbon capture risks locking-in one sector to decarbonise the other, creating a disincentive to move towards full decarbonisation. In a 2050 timeframe, the alternative is to use CO_2 captured directly from the atmosphere - a more expensive process, but one which ensures the electrofuels is fully circular.

Despite these cost impacts, our decarbonisation proposals argues that as fuel efficiency improvements will not decarbonise aviation, and with sustainable advanced biofuels unable to meet all of aviation fuel demand in 2050, if the sector wishes to decarbonise, it must steadily and in a sustainable manner increase electrofuels production to meet the remainder of its fuel demand. At least until more radical technology breakthroughs become available.

However the cost implications of electrofuels will remain substantial. Direct air capture costs are falling but will remain considerable for some time. And while renewable electricity costs are falling, and in some cases reaching parity or falling below non-renewable electricity costs, the fact that electrofuels production requires enormous quantities of electricity means that its cost will likely exceed that of untaxed kerosene.

It's unlikely that, even with carbon pricing, electrofuels will reach cost parity with kerosene. As a result, policies will need to be put in place to ensure the uptake of electrofuels. These policies are detailed below, but any policy which requires airlines to purchase a more expensive fuel will result in an overall increase in operational costs. At least some of that increase can be expected to be passed onto consumers, increasing the price of tickets, and thereby reducing demand. In our forecasts, we factor in the impact that this reduced demand will have on air traffic and thus the overall demand for fuels.

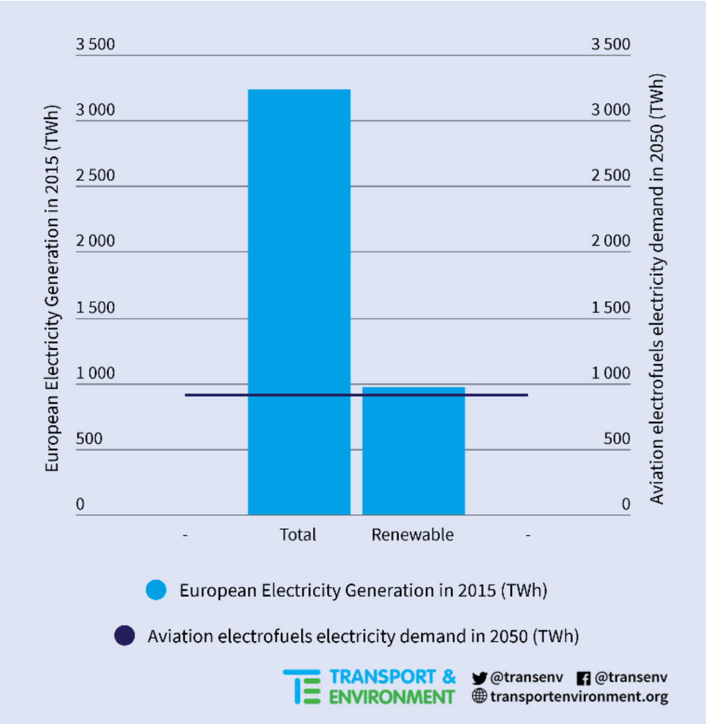

Figure 3. Electricity required to produce electrofuels for EU aviation in 2050

It's worth nothing the impact that electrofuels uptake will have on overall electricity demand - our forecasts are that meeting aviation fuel demand with electrofuels will require 912 TWh. This amount is equivalent to 28.2% of Europe's total electricity generation of 3234 TWh in 2015, or 94.4% of the 966 TWh of renewables generation [xxiii] (Figure 3). Note that this electricity used in the production of electrofuels will have to be renewable and additional for the resulting fuel to be considered zero carbon. Also, other sectors, such as industry, are expecting to use some types of electrofuels as a way to decarbonise. Such demand will have a considerable impact on broader efforts to decarbonise the European economy - it could mean that additional renewable electricity is used to create electrofuels, when it could have been used in a more efficient manner by other sectors of the economy. These competing demands for additional renewable electricity need to be taken into account to assess the realistic amounts of electrofuels which could be used in aviation.

In the production of electrofuels only a portion will be suitable for use in the aviation sector. We've put that share at 80% - a very optimistic assessment - meaning there will be residual fuels from this process which may be of use to other sectors.

As with sustainable advanced fuels, there is a risk of some residual emissions from electrofuels. And as stated above, the zero carbon status of these fuels is dependent on their potential displacement impacts, the manner of their production and therefore on the broader decarbonisation of the economy.

In our scenario electrofuels are produced from 100% additional renewable electricity using direct air capture CO_2**. With a cost of €2,100 per tonne in 2050, electrofuel uptake will increase ticket prices** a **further 23% compared to a ticket price with a €150/tonne CO_2** equivalent price, resulting in a 28% reduction in projected passenger demand compared to a business-as-usual scenario.

Policy options

Our policy recommendations are broken into two categories which are relevant for both types of alternative fuels - safeguards and uptake. Only when the former are in place should policy makers move to the latter.

3.3. Safeguards

3.3.1. Advanced sustainable biofuels

The legislative basis for use of advanced sustainable biofuels in Europe is the revision to the Renewable Energy Directive (RED II), which concluded several months ago. Contrary to the 2009 RED, the new law does not force member states anymore to support first generation biofuels and will phase out the support to those first generation biofuels which have the most damaging impact on the climate and the environment.

However the REDII revision falls short of ensuring only sustainable biofuels, which deliver maximum emission reductions, are used. For that to have been achieved, the revision would have had to completely phase out the support to first generation biofuels and contain sustainability criteria which would have included indirect impacts. When it comes to advanced biofuels listed in Annex IX of the Directive, no matter whether they are used in road or aviation, the list still includes some problematic items such as unsustainable forest feedstocks. In addition, the sustainability criteria are not fit to tackle impacts of this variety of biofuels, on soil carbon for example. There is also uncertainty on how biofuels produced from feedstocks not in this annex or which are not crop biofuels will be treated.

In order to ensure that these fuels are a partial long-term sustainable option for aviation, support should be limited to biofuels produced from wastes or residues, in line with the waste hierarchy, which deliver significant GHG savings after taking into account both direct and indirect impacts and other concerns such as loss in biodiversity, soil degradation or water pollution. This will greatly limit the availability of advanced sustainable biofuels, and is the reason biofuels cannot be relied on to fully decarbonise aviation.

3.3.2. Electrofuels

Safeguards are essential in order to ensure that electrofuels results in actual emission reductions, without negative side effects on other sectors. As discussed above, the two areas of concern are the supply of electricity and the supply of CO_2.

The RED II Directive addresses neither of these concerns effectively. The Directive doesn't include a requirement for electrofuels to use air capture and doesn't ensure that only renewable electricity will be used to produce electrofuels and will be additional. The Commission is expected to develop a methodology which could address these issues.

Our recommendations, and the related projections, are that strict sustainability safeguards are put in place[xxiv]. Briefly, electrofuels should be produced from additional renewable electricity, the CO_2 source should be from air, and strict sustainability criteria should be developed regarding land and water use.

3.4. Current limits to fuel blending

The industry certifying body ASTM currently sets different blending limits for alternative fuels (biofuels and synthetic) which depend on the fuel and vary from as low as 10% to up to 90%. These limits are set to ensure an appropriate level of safety and to guarantee the smooth operation of aircraft engines because lubricity can be an issue with alternate fuels. These blending limits obviously restrict the emission reductions currently possible from using alternate fuels. Over time these blending restrictions may be reduced or potentially abolished through new approaches to engine tuning or the development of new engine additives. Our report is based on the expectation that such solutions will be found.

3.5. Achieving fuel switching

Our forecasts are that, in part owing to the necessary safeguards for both sustainable alternative biofuels and electrofuels and the electricity requirements for electrofuels, a significant price gap will exist between these alternative fuels and the kerosene they are seeking to replace.

Currently, there are limited measures in place to encourage an uptake of aviation alternative fuels. The EU ETS recognises alternative fuels, with airlines able to reduce their allowance purchase obligations if they can demonstrate alternative fuel use. However low prices of allowances in recent years removed any incentive for airlines to switch to alternative fuels.

Important for aviation in the REDII is a de facto binding 2030 target of 7% for advanced biofuels including biofuels from waste and residues, electrofuels, renewable electricity and recycled carbon fuels. Renewable energy use in aviation can be counted towards achieving the overall 14% target of renewable energy use by 2030 and after 2020 the contribution of advanced fuels used in the aviation sector will be counted as 1.2 times the fuel's actual energy content towards meeting the 7% subtarget for advanced fuels. This is meant to incentivise fuel producers to bring alternative fuel into the aviation market, but it is unclear whether a multiplication factor of 1.2 will actually result in such fuels going to the aviation sector. The majority of the targets are likely to be filled by the road sector.

Our projected carbon price of €150 may encourage some fuel switching towards fuels which are on the lower end of the price spectrum. However full fuel switching will require different measures.

Fuel mandates have a chequered history in terms of environmental effectiveness, for example in Europe where a fuel mandate for the road transport sector has resulted in the wide scale use of food-based biofuels to reach the required targeted. As a result, any obligation on fuel supplied to the aviation sector in Europe will need to be crafted so as to ensure it does not incentivise the production of alternative fuels with negative environmental effects, like crop based biofuels.

One avenue to ensure that a fair share of advanced fuels is targeted at aviation, would be by requiring fuel suppliers to split their advanced fuels target proportionally between land and air transport[xxv]. Such a policy for advanced aviation fuels, which would cover both sustainable biofuels and synthetic fuels, needs to be based on these fuels' climate performance, not just on whether they are labelled 'renewable' or not.

So member states should be encouraged to adopt a low carbon fuel standard as this offers the best framework for incentivising the delivery of renewable advanced low-carbon fuels. The REDII allows member states to change their energy targets into a low carbon fuel standard provided the required level of renewable energy is realised by 2030. When all direct and indirect emissions are accounted for, it provides a performance-based differentiation and a competition for best performing technologies while giving clear market signals and incentives for clean fuel investments in the EU[xxvi]. Germany for example regulates alternative fuels through a GHG target.

3.6. A new dedicated EU policy for alternative fuels in aviation

However it is unclear whether member states will implement the RED II in a way which will enable a real uptake of advanced fuels in aviation. One way to overcome this would be for the EU to develop a specific amendment to the policy framework, in the form of a dedicated GHG target i.e. a low carbon fuel standard for sustainable advanced fuels in aviation. Such a standard would require fuel supplied on the EU aviation market to meet a progressively lower GHG intensity by using only sustainable advanced fuels.

At the same time, it would be crucial to ensure that such an additional policy tool does not lead to an increased demand in overall volumes for advanced biofuels compared to what is already required by the RED II. This is especially relevant for sustainable advanced biofuels feedstocks which are available only in limited quantities. Additional growth should be focused on electrofuels - which can be scaled sustainably - and the law should be crafted in a way that achieves this goal.

3.7. GHG – low carbon fuel standard for aviation

The Commission could propose an amendment to the REDII which requires suppliers placing aviation fuel on the EU market to comply with a gradually lower carbon intensity. Suppliers would be given several years to meet each level of the GHG intensity target which would apply either across the EU or at member state level. Member states would be required by EU legislation to enforce the GHG intensity target at member state level in a similar manner to the way Fuel Quality Directive (FQD) standards are currently implemented. A system of registration of aviation fuel suppliers would need to be established (that for road fuel suppliers was established through the tax provisions of the ETD.) The legislation could include a malus/bonus penalty on fuel suppliers for not achieving/over-achieving the requirement. “Aviation fuel suppliers” would need to be defined to include refiners, airport fuel farms and fuel importers etc.

All fuel uplifted for commercial aviation in the EU would be affected - i.e. for both intra and extra EU flights. The retail price of fuel sold to airlines across the EU would rise to reflect suppliers’ higher costs. Safeguards might need to be considered to ensure suppliers did not cross-subsidise higher aviation fuel costs by passing some of the increased costs onto the road sector. The low carbon fuel standard would need to be drafted in such a way as to ensure suppliers acted in tandem across the EU to avoid regional price distortions and potentially airline tankering.

Policy

- Introduce sufficient safeguards to ensure that sustainable alternative biofuels and electrofuels deliver promised emission reductions without negative consequences on sustainability;
- Member states should require fuel suppliers to split their advanced fuels target proportionally between land and air traffic and adopt a GHG target/a low carbon fuel standard as this offers the best framework for incentivising the delivery of renewable advanced low-carbon fuels;
- An amendment to the RED II requiring all fuel suppliers placing aviation fuel on the EU market to meet a decreasing carbon intensity, with the purpose of bringing all fuel sold to near zero carbon by 2050.

4. Decarbonising aviation results

From the above discussion, Table 1 summarises the scenarios, the assumptions, and the resultant effect on aviation energy demand and aviation passenger activity. In a BaUs scenario, passenger activity is expected to grow by 80% from 2015 to 2050, from 722 million departing passenger movements to 1,117 million. Full details of calculation methodology can be found in the Appendices.

Table 1: Summary of aviation CO_2 mitigation scenarios

Scenario	Energy demand	Passenger demand	Notes
BaU	The fleet is assumed to improve 1% p.a.	No Change	Taken from Reference Scenario 2016. Energy demand increases 23% from 2015 to 2050. Fleet improvement is a combination of technical and logistical improvements. The Reference Scenario assumes 940€/ktoe for fuel in 2050. With the same methodology as is used to reduce demand with an increase in price, the BaU energy demand is increased with a constant and lower €600/ktoe price.
Fleet efficiency	Additional fleet improvements of 0.2% p.a.	No Change	No rebound considered from cheaper tickets based on lower fuel consumption
Gen II aircraft	30% more efficient than conventional fleet, picks up 1% demand p.a.	No Change	No rebound considered from cheaper tickets based on lower fuel consumption. Gen II are bubble type, strut wings, etc.
Aviation pricing	Reduction driven by change in passenger demand	€150/tCO_2 results in 12% reduction in demand.	There is 3.15 tCO_2 per tonne of fuel. Fuel cost assumed to be 25% of short haul ticket price and 20% of long haul. Passenger weighted elasticities (see Appendix B) from intra-vistas and long term income elasticities are adjusted to -0.48 for all EU departing flights. Ticket prices increase 17% over BaU.
Biofuels	7500 ktoe available in 2050	No Change	Growth following an S-curve, beginning from 2020
PtL demand	100% aviation demand met by 2050	Demand reduces from additional cost.	Reduced demand from €150/tCO_2 is nullified. PtL consumption from 2020 follows an S-curve.

The results of the different measures are presented below. A sensitivity analysis is provided in the Appendices.

Figure 4 (left) shows the CO_2 emissions trajectories from 2000 to 2050. Rapid decarbonisation is shown to occur from 2030 onwards, where the combined measures of demand reduction, efficiency measures, advanced biofuels and electrofuels curb CO_2 emissions to approximately 2010 levels. From that point on and with the increasing uptake of electrofuel and renewable electricity production, a rapid decrease ensues. In 2050, the CO_2 emissions from the departing flights in the EU is zero. Figure 4 (right) shows how the measures stack up in terms of liquid fuel consumption.

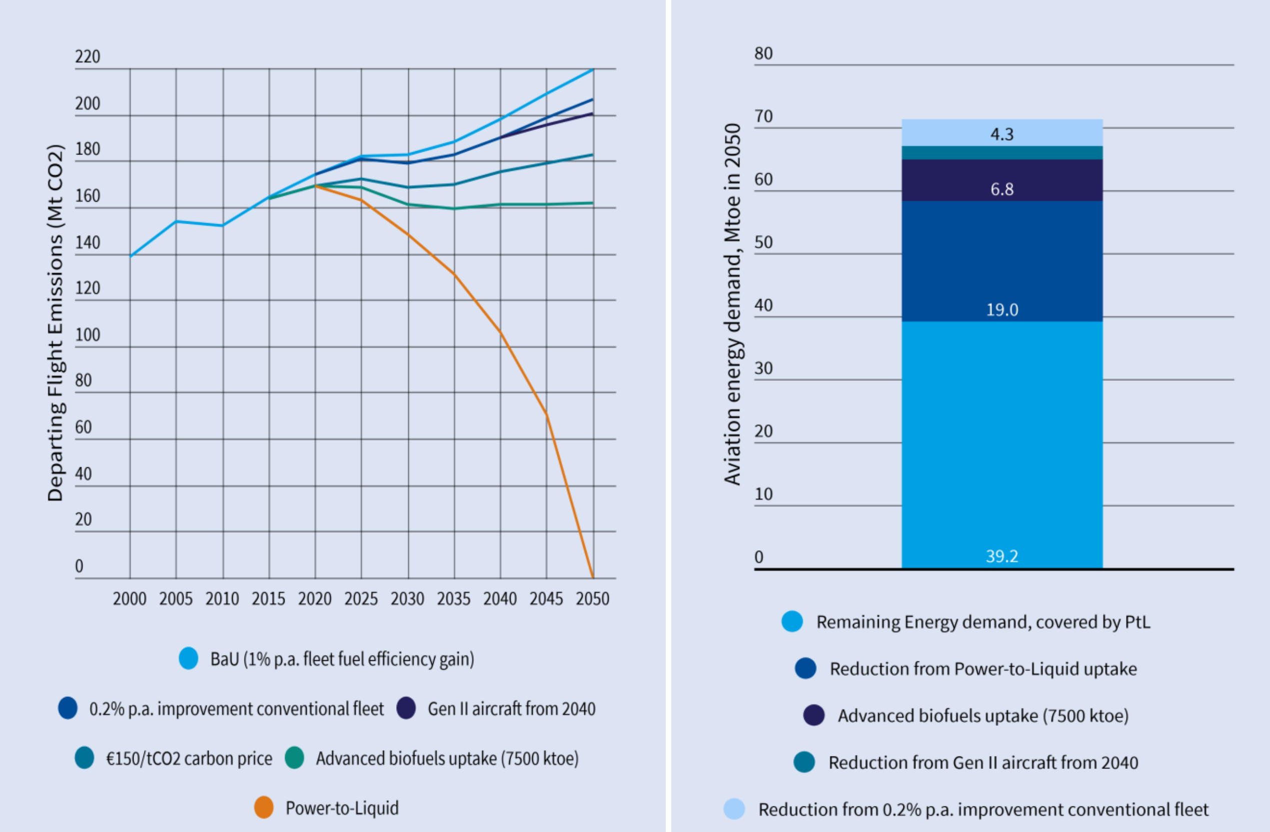

Figure 4: (Left) Reduction in European departing flight CO_2 emissions. (Right) PtL consumption of European departing flights in 2050 after demand reduction measures have been applied.

One of the biggest measures in and of itself is the reduction in demand from PtL. Note that in 2050, the demand reduction from the charges equivalent to €150/tonne of CO_2 have been nullified, as the kerosene no longer has a fossil component. Aside from being a driver for more efficient aircraft and their operations, the importance of the carbon pricing can be seen in the cumulative emissions savings. They have been calculated to reduce emissions by 180 Mt CO_2 cumulatively over the 2020 to 2050 period, compared to no price. With the remaining 39.2 Mtoe, at the price of 2,100€/t of fuel, this equates to an annual fuel bill for airlines fueling in Europe exceeding €82 billion. This compares to approximately €35 billion today spent on fossil kerosene.

The passenger activity for the BaU and the two scenarios that affect passenger demand are shown in Figure 5. As can be seen, this analysis shows that demand levels off from 2030 with an increasing share of PtL, owing to both its uptake and price. The 2050 passenger activity is equivalent to the business as usual activity in the early 2030s, thus an increase in overall passenger activity is still envisaged in this analysis. However, as passengers will be travelling further, this does not equate to a greater number of total flights. Modal shift will be most successful for short segment flights, while longer flights contribute significantly to the passenger activity metric as a single flight can usually take more passengers a multiple further. Thus, growth in activity does not justify increasing the capacity of airports, particularly in Western Europe where many airports are at capacity. Limiting growth by simply avoiding airport expansion is an effective way to keep downward pressure on demand.

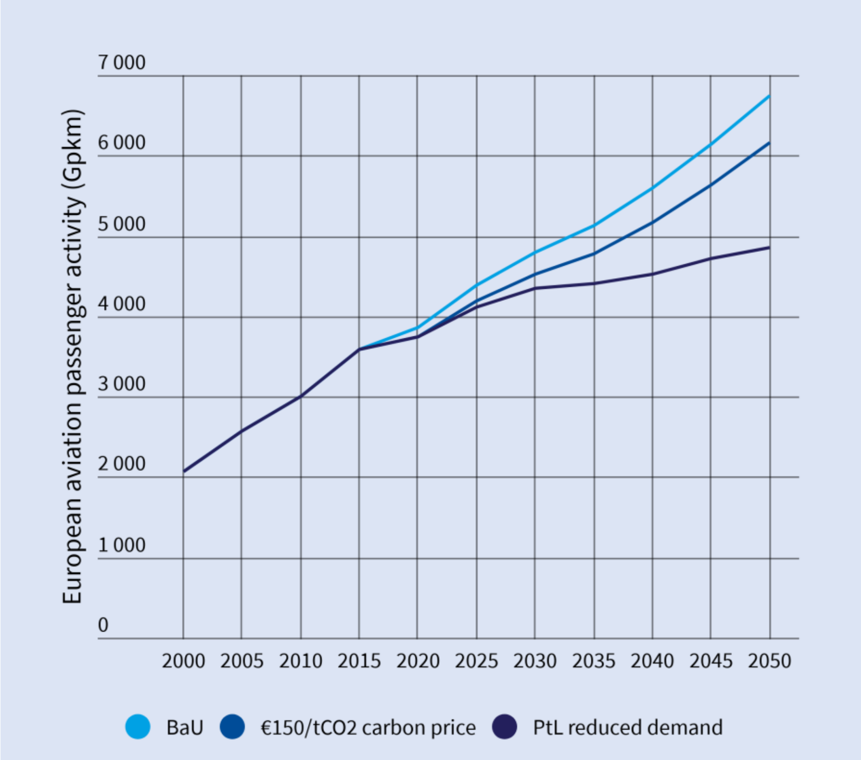

Figure 5: Passenger activity from demand reduction

5. Aviation's non-CO_2 effects

Aviation's non-CO_2 climate effects include NO_x emissions at altitude, contrails, cirrus cloud formation, soot and water vapour etc. and can equal or exceed the climate impact of aviation CO_2. Despite the ongoing uncertainties as to how these effects impact the climate and their extent, it is essential when drawing up an aviation decarbonisation strategy that policies to address these non-CO_2 effects are included, particularly where varying the fuels aircraft use is being considered.

There are currently no measures in place to address aviation's non-CO_2 climate impacts. When aviation was being included in the EU ETS Directive in 2008, Parliament sought to add a non-CO_2 multiplier to airline's obligations to purchase allowances, but this was rejected. A study for the Commission proposed the imposition of a cruise NOx charge with distance, but this was not acted upon[xxvii]. Since then, research into determining the exact climate impacts of these non-CO_2 effects has continued. The understanding of contrail-cirrus effects and their climate impact has improved over the years and potential measures involving changed flight trajectories so as aircraft avoid climate sensitive areas are being put forward[xxviii]. On the other hand, the aerosol-cloud effects of aircraft, if they exist, remain largely unknown. Sulphate aerosols from jet engines which may vary with fuel properties might change the properties of low level clouds which cool while emitted soot particles might trigger cirrus which might cool or warm.

In the 2017 revision of the EU ETS Directive, a requirement was included for the Commission to come forward by January 2020 with proposals to address these non-CO_2 effects if appropriate (Art 30(4) of the revised Directive). In the meantime, further research is expected to be published which might reduce uncertainties regarding the climate warming impact of some of the non-CO_2 effects.

Measures to reduce fuel demand and thus commercial traffic will reduce non-CO_2 effects insofar as they result in less flight activity. And since non-CO_2 effects are transient - hours or months (with the exception of CH4 cooling from NOx emissions, which will diminish in decades) - the reduced warming will be immediate - whereas CO_2 once emitted persists in the atmosphere along with its warming impact at diminishing levels for thousands of years.

The exhaust from biofuels and e-fuels will contain less soot than that from kerosene and can be expected to result in some reduction of non-CO_2 effects[xxix] but because water vapour and NOx will continue to be emitted from the engines, the principal sources of aviation non-CO_2 warming will persist. So the overall non-CO_2 impact of a switch to using cleaner fuels cannot be quantified here.

When aircraft operate at certain flight levels and atmospheric conditions conducive to ice crystals forming (as the hot and humid exhaust cools and mixes with the environment) climate warming contrails and cirrus cloud can form. If aircraft are rerouted (changed flight levels, route deviations) to avoid these atmospheric conditions, then the contrails/cirrus will not form. How much climate warming can be mitigated in this way is open to debate but estimates suggest very significantly[xxx]. Changing flights levels and deviating may incur small additional flying time and fuel burn penalties/costs which are the main reasons why industry opposition has ensured such measures have not been adopted. Such opposition is likely to continue but the sorts of CO_2 reductions outlined in this decarbonisation pathway would far exceed any CO_2 penalties from aircraft rerouting and allow a clear case to be made for adopting measures to have aircraft avoid climate sensitive areas. Such measures would require much improved weather forecasting 12 hours out to identify sensitive climate areas and allow for flight plans to be changed.

We have not sought to quantify the possible reductions from the above alternatives. Neither are the possible impacts of a transition to electric or hydrogen aircraft on non--CO_2 effects considered here, because the deployment of such aircraft in a meaningful commercial quantity is beyond the 2050 timeline we have analysed, the technologies remain speculative and the science about non-CO_2 impacts unclear.

Policy

Mitigating aviation's non-CO_2 effects must be included in any long-term emissions reduction strategy. Rerouting around climate sensitive areas holds promise and needs to be considered as a viable option. Reductions in CO_2 burn from measures we have outlined would likely more than compensate from any fuel burn penalty or rerouting. A switch to cleaner fuels may well reduce non- CO_2 impacts but these cannot be quantified here. Any aviation decarbonisation strategy must include the provision of significant additional funding into non-CO_2 issues and in particular to understand the non-CO_2 impacts of low/zero carbon fuels, the potential reductions in non-CO_2 warming of flights by avoiding climate sensitive areas, and the enhanced weather forecasting capabilities etc. that such measures would require. The Commission has a little over a year now to meet its obligations under the EU ETS Directive to come forward with potential non-CO_2 mitigation measures by January 2020.

6. Conclusions

Since its deregulation, European aviation emissions have taken off. Artificially cheap tickets through tax exemptions and through government subsidies have propped up and propelled the industry. Unfortunately, there is little awareness of the severe climate impacts and dangers that this mode of transport causes. As it stands, aviation flies in the face of the Paris Agreement, the goals of which are essential for the environment, society, and the economy.

If Europe is to pursue a zero-carbon economy, it must address this major and rapidly growing source of emissions. Europe's climate policy to date has either neglected this sector, or pursued false solutions such as offsetting. The IPCC's most recent report warns that time is rapidly running out to limit a dangerous increase in temperatures; there is no more time for delay.

This report outlines the measures needed to put aviation on a pathway to decarbonisation, and does not shy away from the challenges this poses. Fuel demand can be cut substantially, but only when aggressive policy measures are put in place. Its fuel can be decarbonised, but there are substantial challenges. Non-CO_2 effects must finally be addressed if we are serious about arresting aviation's climate impact.

The longer action is delayed, the greater the challenge of decarbonisation will be. With the EU revising its long-term decarbonisation strategy, now is the time to ensure Europe acts. This report therefore shows one of many possible pathways to decarbonise aviation. Passenger demand must not increase to the levels that many analysts predict, but largely plateau, and as soon as possible. This will mean ending the tax breaks, the government subsidies, and airport expansions.

Significant effort and resources will be required to collect and process sustainable feedstocks to produce the maximum amount of advanced biofuels to reduce the amount of electrofuels required to cover the remaining kerosene demand. This pathway therefore requires significant amounts of additional renewable electricity to be rapidly installed which will be required to produce electrofuels at considerable cost.

Finally, the decarbonisation pathway presented in this report requires active engagement from policy makers to ensure a decarbonised future. Multiple, concrete, feasible, and legally sound measures are proposed that need to be urgently implemented, that policy makers, politicians, and citizens can push for.

Appendix A: Calculations and inputs

In order to calculate the effects of efficiency gains and pricing policies on the future of European aviation, the 2016 EU Reference Scenario is utilised. This is used as a basis to generate a BaU scenario in this report (see Section 2.1). The key factors used in this report are shown in the table below, for two salient years. Alternative fuel uptake is assumed to increase in line with a logistic function (or an S-curve), other measures are assumed to increase linearly.

Parameter	2015	2050	Description/notes
Aviation Energy Demand (Mtoe)	53.3	71.3	All departing flights from the EU. Final demand adjusted from 65.5 Mtoe to account for differences in fuel cost
Population (million)	505	522	The GDP per capita over this period is thus projected to increase by 62%
GDP (in billion €$_{2013}$)	13,400	22,500	

There are several assumptions already built into the EU Reference Scenario that we take advantage of. The first is the fleet efficiency, which improves on average 1% per year from 2010 to 2050. As mentioned above, the price of fuel in the 2016 Reference Scenario is projected to increase to approximately €930/t; we correct the aviation demand for this by assuming that the fuel price remains constant at €600/t, which results in a 13% cheaper ticket price. This is calculated based on the assumptions detailed in Appendix B. This is step was undertaken in an attempt to unpick the demand reduction measures built into the Reference Scenario to avoid double counting them, and to avoid relying on an increase in fuel price to reduce demand.

Further inputs are shown in the table below.

Parameter	2020	2050	Description/notes
Kerosene price (€/t)	600	600	Assumed constant
Fuel price fraction of ticket price (domestic & intra EU)	25%	25%	See Appendix B for how the extra-EU flights increase their share
Fuel price fraction of ticket price (extra EU)	20%	20%	
Extra improvement on fleet compared to the BaU	0%	6%	0.2% per annum from 2020. This metric includes fuel and operational efficiency
Gen II aircraft	0%	3%	From 2040, 1% per year ingress of 30% more efficient aircraft design
Advanced biofuels (ktoe)	50	7500	In 2020 the amount of 50 ktoe is assumed to be available[xxxi], requires 33% year on year growth.
CO_2 price (€/t)	30	150	From ETS, VAT, kerosene tax
PtL price (€/t)	5000	2100	Mallins (2017) *What role is there for electrofuel technologies in European transport's low carbon future?*
PtL conversion efficiency	38%	50%	Schmidt, P., & Weindorf, W. (2016). *Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*. Dessau-Roßlau. Mallins (2017) *What role is there for electrofuel technologies in European transport's low carbon future?*

When applying efficiency measures, no rebound effect is assumed that may result from airlines passing on fuel savings to customers. Similarly, the introduction of advanced biofuels are assumed to cause no reduction in demand due to their higher price, to simplify the analysis. As these fuels only attain a blend of 13%, if they were double the price of kerosene, the change in ticket price would be around 3%, implying a demand in reduction of only 1.5% in 2050.

The measures are applied in the same order as outlined in the report: The fuel fleet and operational efficiencies are applied, on top of which a carbon price, followed by advanced biofuels, and finally electrofuels. The implication of this is that an uptake of biofuels has the effect of reducing the CO_2 price proportionally to the blend. The remaining fossil kerosene is then replaced by electrofuels, which reduce the carbon price to zero by 2050, however owing to the 2050 price of €2100/t (equivalent to a the effect of a carbon price of €500/t), there is still a significant drop in demand resulting from the uptake of this fuel. The way in which fuel and carbon prices affect the ticket price, and thus passenger demand, are described further in Appendix B.

As mentioned previously, electrofuel uptake is assumed to follow an S-curve, increasing from small amount in 2020, reaching half the required capacity in the year 2045 (denoted y_0) and meeting 100% of fossil kerosene demand in 2050. The growth rate factor, k, was 0.2, where the amount of PTL produced for a given year, y, is:

$$PTL_y = \frac{PTL_{2050}}{1 + e^{-k(y-y_0)}}$$

The Reference Scenario only includes passenger activity for the intra-EU segments, while included energy demand for all outbound flights. From a combination of analysis of transponder data from PlaneFinder, Eurostat passenger numbers, and an assumption that in 2050, extra EU flights will on average be 7000 km, the passenger activity from all departing passengers was calculated and projected to 2050.

Appendix B: Elasticities

This Appendix gives greater detail on how each measure effects aviation demand.

Price elasticities

There are a number of factors that influence air travel demand, as outlined by IATA's *Air Travel Demand* study from 2008[xxxii]. In most general terms, increasing the cost of flying reduces its demand. The reduction is not universal across the market, as it depends on factors such as the choice and utility of other modes of transport to undertake the journey (such as train, bus, or car), and how wealthy the passenger is. In this study, price and income elasticities are calculated based on *Air Travel Demand*, and are described in further detail in this Appendix. Furthermore, the income elasticities are modified in the context of more recent studies, such as *The income elasticity of air travel: A meta-analysis*[xxxiii] and *UK Aviation Forecasts*[8].

In the first step, the relevant elasticity coefficients for the flight segments based on distance band, price increase coverage, and geography are listed.

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[8] UK Aviation Forecasts - Moving Britain Ahead. (2017) Department for Transport. Available: assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674749/uk-aviation-forecasts-2017.pdf

Code	Disaggregation of flight segments	Elasticity coefficient	Description
LH	Long haul	1	Short haul flights have more options available to avoid the flights (such as car, train, bus)
SH	Short haul	1.1	
RL	Route level	1.4	Route level taxes can push passengers to cheaper routes (highly price sensitive), and national taxes can result in re-routing to other countries. This study assumes EU wide measures, i.e. at the supra-national level, which reduces passenger options for modal shift.
NL	National level	0.8	
SL	Supra-national level	0.6	
EU	Intra EU	1.4	Geographical location determines the cost sensitivity based on fast growing developing markets, and mature developed markets.
TA	Trans Atlantic	1.2	
AS	EU - Asia	0.9	

Combining the appropriate factors gives the following price based demand elasticities.

Segment	Elasticity	Elasticity coefficient combination
Domestic	-0.92	-1 * SH * SL * EU
Intra EU	-0.84	-1 * LH * SL * EU
Extra EU	-0.63	-1 * LH * SL * (TA + AS) / 2

According to these elasticities, an increase in ticket price of 10% for an intra-EU flight will result in a 8.4% reduction in demand.

Income elasticities

The price elasticities described above will not tend to be constant in time. Another key driver of aviation demand is wealth, whereby as people become richer, they tend to fly more. Income elasticities are computed from the segments for flights originating from developed economies. An elasticity of greater than 1 tends to indicate a luxury item.

Code	Segment	Elasticity	Description
SH	Short haul	1.3	As people become wealthier, they tend to demand more air travel. Long and very long haul flights become increasingly desirable with wealth.
MH	Medium haul	1.4	
LH	Long haul	1.5	
VH	Very long haul	2.2	

Combining the appropriate factors gives the following income based demand elasticities:

Segment	Elasticity	Elasticity coefficient combination
Domestic	1.3	SH
Intra EU	1.5	(MH + LH) / 2
Extra EU	1.9	(LH + VH) / 2

According to these income elasticities, a per capita increase in wealth of 10% will result in an increase in 15% of intra-EU flights, *ceteris paribus,* assuming ticket prices remain stable. As can be seen from Appendix A, Europeans are projected to be 62% times as wealthy in 2050 as they were in 2015. It is not clear to what extent the EU reference Scenario has used these elasticities, but it is assumed that these elasticities are causes in accelerating aviation demand to the levels that are projected. These elasticities have been used to compute the passenger share evolution in each flight segment, as described below.

There is evidence that as markets mature, these elasticities reduce. Gallet & Doucouliagos (2014) suggest that when taking both income and price elasticities into account, the income elasticity would be 0.633. The UK Department for transport foresee long term income elasticities of 0.6, also significantly lower than those presented in the IATA study. This assumes that the market is mature.

Accounting for price and income elasticities

When combining price and income elasticities, the standard approach would be to sum the net effects of both elasticities on the demand. For example, if a ticket price increase would result in a 10% reduction in passengers, but an increase in wealth would increase demand by 5%, the net effect would be a 5% reduction. In this analysis, however, passenger demand is assumed to have price and income elasticities built in. Therefore, the standard approach is not suitable in this case.

In this study, the income elasticity of 0.6 is applied directly to the price demand in 2050. If wealth considerations were not included, the segment weighted elasticity in 2050 would be -0.79. However, adjusting the elasticities based on wealth considerations gives a final segment and wealth adjusted price demand elasticity of -0.48 in 2050. This indicates a mature market where wealthier travellers are less affected by price increases.

The underlying reasoning behind using price and income elasticities is to see how pricing mechanisms such as a CO_2 price can reduce aviation passenger demand, which will reduce the amount of electrofuels the EU would need to produce. These elasticities are highly uncertain, however. To have a clearer view of how this can change the results, a sensitivity analysis is conducted and is presented in Appendix C.

Evolution of aviation segments projections

The income demand elasticities show that long and very long haul flights are expected to increase at a greater rate than domestic and intra-EU flights. The departing passenger numbers, *P*, of 2016 provided by Eurostat[9] have their 2050 projections weighted by the income elasticities, *E*, as per the following formula:

$$P_{i,2050} = \sum P_{i,2015} \cdot L_i \cdot (1 + G) \frac{E_i \cdot P_{i,2015} \cdot L_i \cdot (1 + G)}{\sum E_i \cdot P_{i,2015} \cdot L_i \cdot (1 + G)}$$

For the domestic, intra-EU, and extra-EU segments, *i*, with total passenger number growth measured in pkm *G* = 75%, taken directly from the reference scenario projections between 2015 and 2050. The passenger weighted average length of the domestic and intra-EU segments are calculated from transponder data in 2016, and are assumed to be constant. Extra-EU flight segment lengths are assumed to be 7000 km on average. This results in the following growth rates for each segment, shown in passenger numbers.

Flight segment	Departing passengers 2015 (millions)	Growth in pkm (2015-2050)	Departing passengers 2050 (millions)
Domestic	158.0	33%	210.2
Intra EU	393.2	48%	583.6
Extra EU	170.7	89%	323.3

[9] Eurostat, Table: avia_paoc. Accessed September 2018

Appendix C: Sensitivity analysis

This paper presents policy requirements that Europe needs to pursue in order to decarbonise aviation by 2050. This Appendix explores additional scenarios, where efficiency measures, SAFs, and other demand reduction measures are not taken, and the sensitivity analysis on the use of income elasticities. The results of this analysis is presented in the table below, showing the effect final passenger numbers and the

Sensitivity analysis scenario		2050: Passengers Activity in Gpkm (% reduction from BaU in 2050)	2050: Electricity demand for electrofuel in TWh (% EU 2015 generation)
0	Business as usual	6753	N/A
1	Pathway to decarbonisation as detailed in this paper	4853 (-28%)	912 (28.2%)
2	No efficiency, alternative fuels, or demand reduction	4853 (-28%)	1191 (36.8%)
3	Scenario 1 with no long term income elasticity adjustment	3587 (-47%)	628 (19.4%)
4	Scenario 2 with no long term income elasticity adjustment	3587 (-47%)	880 (27.2%)
5	Scenario 1 without advanced biofuels	4853 (-28%)	1086 (33.6%)

The results show that if short term measures are not applied as a long term strategy to decarbonisation, the required PtL production will increase by 31%, or to 36.8% of 2015 EU generation of 3234 TWh. Between Scenarios 1 and 2, there is no difference between passenger demand as when there is 100% SAFs and SEFs in the blend, there is no CO_2 price demand reduction. Passenger demand is 28% less than projected in 2050, or roughly equivalent to 2030 levels. Scenarios 3 & 4 show the effect of applying unadjusted price elasticities. In the case where price elasticities were to be constant, the price of electrofuels would result in nearly halving the passenger demand from the business as usual scenario, equivalent to passenger activity in 2020. The implication is that with lower passenger activity, there is less requirement to produce electrofuels. Finally, scenario 5 shows the electrofuel required in the case where no advanced biofuel is available to aviation, which may be the case based on the demand from competing sectors for the biomass and from increasingly stringent sustainability criteria that may be legislated for. The result here shows that almost 20% more additional and renewable electricity would be required to produce enough electrofuels.

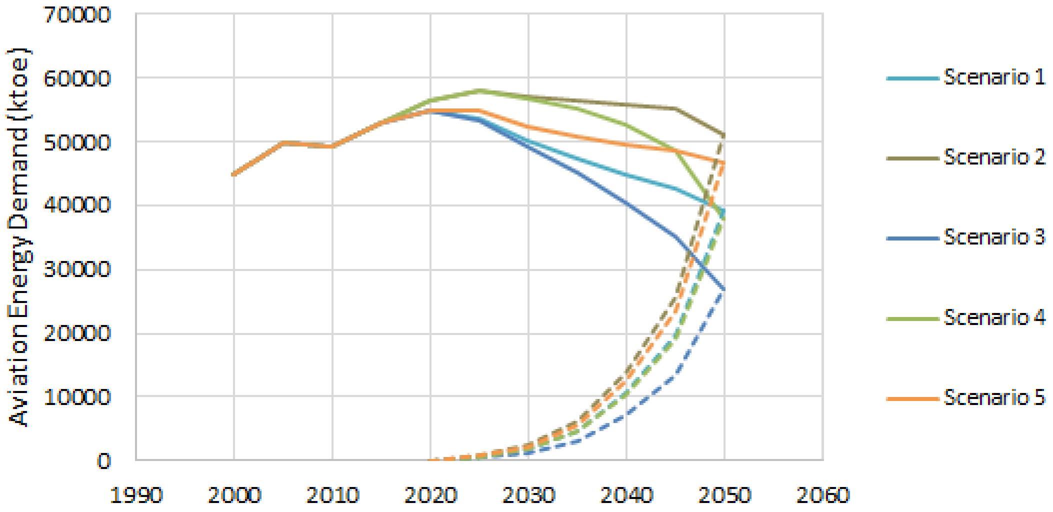

Figure 6: Results of sensitivity analysis scenarios. Dashed lines indicate the PtL production curve following an S-Curve required to meet fuel demand by 2050.

Selection of appropriate elasticities is thus crucial to approximating the future passenger and energy demand of aviation, particularly how they will evolve over the next 30 years to 2050. There is an underlying assumption that elasticities are constant irrespective of the price change. From the literature review conducted to attain the elasticities used in this report, there has been no discussion on the fairness of this assumption. For example, the assertion that a proportional change in demand will be the same for a 5% change in price compared to a 50% change is not verifiable. The main takeaway from this analysis is that demand reduction is necessary to reduce the amount of additional renewable electricity capacity required in the EU, irrespective of whether long term elasticities change or not. The final values attempt to give an order of magnitude appreciation of how much additional renewable electricity this will equate to.

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