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Roadmap to climate neutral aviation in Europe





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In house analysis by Transport & Environment

Coordination: Andrew Murphy

Main modeller: Valentin Simon

Expert group: Thomas Earl, Jo Dardenne, Matteo Mirolo, Denise Auclair, Carlos Calvo Ambel, Laura Buffet,

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For more information, contact:

Andrew Murphy

Aviation Director

Transport & Environment

andrew@transportenvironment.org

Mobile: +32(0) 485 001214

Executive Summary

To bring Europe's aviation industry in line with our climate goals, binding measures have to go hand in hand with a smarter approach to corporate travel. That is the key finding of T&E's revised Roadmap to Decarbonising European Aviation, which we are publishing at a crucial time for the aviation industry as it struggles to address its ongoing climate problem.

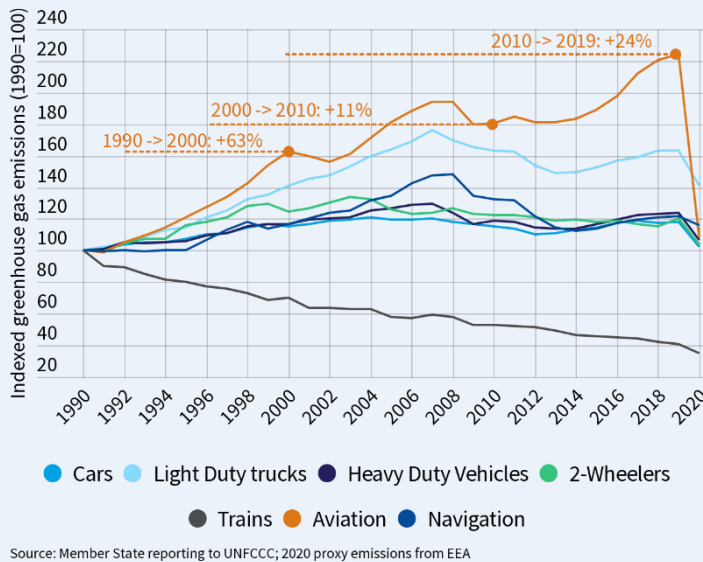


Figure E. 1: EU27+UK indexed transport emissions, 1990 to 2020.

That problem needs only a few facts and figures to underline its seriousness. Aviation traffic in Europe grew 67% between 2005 and 2019 and its emissions by 24% (see Fig. E.1), meaning they now represent 4.9% of the bloc's pre-Covid total [1]. And that just covers the CO₂ effects - more on the non-CO₂ effects below. The climate problem of flying is very much a wealthy European one - if everyone on earth flew like the wealthiest 10% of Europeans do, aviation would emit 23 GtCO₂ per year, two thirds of global CO₂ emissions in 2019.

How can we solve such a problem? Thankfully much has changed since we published our first version of this Roadmap in 2018. Progress in science and technology, and lessons learned throughout the pandemic mean there now exists a credible path to reduce aviation emissions before 2030, and eliminate its climate impact by 2050.

Such a pathway starts with not making the problem worse: we need to act urgently to prevent a rapid increase in aviation emissions post-pandemic. The two pillars to such an approach are an end to airport expansion in Europe, which has driven much of the growth in emissions, and reduction in corporate travel to 50% of pre-Covid levels. That reduction in corporate travel can cut CO₂ emissions by as much as 32.6 MtCO₂ by 2030.

This possibility for reduced corporate travel stems from what was learned from the pandemic. While we missed the connection that aviation brought, we also found new ways to work and stay in touch. Many companies were still able to continue their projects, maintain connections with customers and even grow.

This new approach to corporate travel means being smarter about how we work and how we connect. As our economic relations become ever geographically broader, the idea of sending workers to the four corners of the planet looks increasingly outdated and inefficient. Demand management is no longer a taboo subject - the IEA highlights the important role that even a limited reduction in flying can achieve, with a 12% reduction in flights cutting emissions by as much as 50%^[2].

The measures to achieve such a reduction will be an interplay between actions by large corporate flyers and actions by governments. Large corporate flyers can confirm, and in fact some already are confirming, that they won't return to pre-Covid levels of travel. Corporate climate commitments should be transparent about how they intend to reduce flying. However, governments should respond to such falling demand, not with continued subsidies to prop up a return to pre-Covid demand, but with a downward revision of forecasts for future growth, and recognising that the sector can and should be smaller. Governments and other public bodies should equally cut back on their own carbon intensive travel.

But demand reduction, though it provides by far the biggest source of emission reductions this decade, won't by itself be enough to get us to climate neutral aviation by 2050. To get there, we need a range of measures and policies to take the climate impact out of aviation. Our Roadmap is thorough in the measures and policies it considers.

First, it examines the role that technological and operational efficiency improvements can play. After all, it's often said that the greenest energy is the energy we don't use. However the problem for aviation is that demand-led growth has always outstripped efficiency improvements. This gap will only worsen as our Roadmap finds that efficiency improvements are becoming harder to achieve.

The second major policy we look at is better pricing of aviation emissions and ending the sector's outrageous tax exemptions. In 2022, there is no justification for why airlines should be allowed to buy fossil jet fuel tax free, and why the majority of Europe's aviation emissions should be exempt from the EU's increasingly effective carbon pricing mechanism.

There are plenty of policies which can rectify this under-pricing of aviation, and finally internalise its negative externalities. These include fossil jet fuel taxation, EU ETS, ticket taxes and minimum pricing. The Roadmap's modelling puts a price of €165 per tonne of CO₂ on all European aviation emissions by 2030, including flights departing from Europe not currently covered by EU ETS. Various legal and political barriers exist to achieving such a price on all emissions, but that doesn't undermine how essential it is to reduce aviation emissions this decade. Whether regulators overcome those barriers will be a measure of our seriousness in addressing aviation's climate problem. If they don't, the problem will be even harder--if not impossible--to solve.

Next, we looked at the role that revolutionary aircraft fuelling technologies, which have attracted much attention, can play in reducing aviation's climate impact. Airbus have certainly breathed new life into this debate, with their latest attempt to develop a hydrogen aircraft. They are joined by a range of new actors who are producing designs and models of electric and hydrogen aircraft. The emission reduction potential appears greater with hydrogen aircraft, but with them challenges abound, both technological and economic.

The question is less whether these aircraft can be developed, but rather when. Given the need for the sector to deliver immediate emission reductions, new aircraft, introduced in the 2040s, will arrive too late. To unlock any potential for these aircraft, we need a full-scale industrial strategy matched with ambitious binding regulations. The experience from accelerating electrification of road transport is that government regulations are essential to help ensure new technologies are developed and deployed. The aviation sector is no different in this regard. And by speeding up the deployment of these new technologies, we can protect and enhance the competitiveness of Europe's crucial aeronautics industry.

But with "traditional" jet engines set to continue to be in operation for decades to come, we need policies to switch from their fossil jet fuel to near-zero carbon alternatives, such as sustainable aviation fuels (SAFs). Doing so remains the core policy to ultimately decarbonise aviation and reduce its non-CO₂ effects. However, our Roadmap confirms that scaling up new fuels is no easy task. Biobased alternatives either compete with food and forestry, or have limited feedstocks.

More promising is the use of e-kerosene, produced from green hydrogen, with additional renewable electricity and with CO₂ captured from ambient air. When we published our first Roadmap in 2018, the possibilities of this fuel were not well known. Now European regulators have proposed an e-kerosene mandate, and production is (very) slowly beginning.

It's progress, but not fast enough. And we know that the incredible amounts of renewable electricity needed to decarbonise all of aviation with this fuel will be impossible to produce any time soon. Under scenarios where the sector grows unchecked, with a reasonable level of passenger demand it could consume up to 24% of European renewable electricity in 2050.

As we work to solve aviation's CO₂ problem, we also need to solve its non-CO₂ problem. These non-CO₂ effects aren't new or unknown, as some would have us believe. The IPCC have been reporting on these effects since the 1990s. However, too many vested interests have preferred to pretend otherwise, and have swept this problem under the rug.

This has been bad news for the climate, as we know that these non-CO₂ effects can have a greater warming impact than the CO₂ effects of flying. There is no shortage of potential measures: from the use of SAFs, to changing fossil kerosene refining, to aircraft rerouting, to pricing mechanisms. Our Roadmap outlines the pros and cons of each, but makes it clear that regulators must act now. An easy place to start is to mandate lower aromatics in fossil jet fuel - it's good for the climate, good for air quality, and would even be good for airlines, given the higher energy density of such fuel. But that alone won't be enough - we also need to look at rerouting flights to avoid atmospheric conditions especially conducive to contrail formation.

These policies need to be matched with the right finance mechanisms, which will steer funding away from expanding aviation and towards greening it. We can't afford another decade where hundreds of billions of euros go into jet aircraft, but only millions go into new fuels. Investors must be put on notice that pouring billions into a carbon intensive sector carries huge risk.

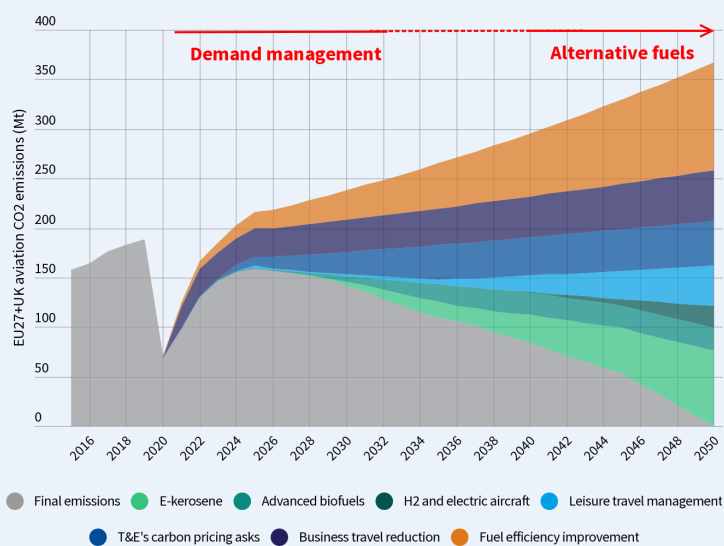


Figure E.2: EU27+UK aviation emissions up to 2050 - decarbonisation forecast.

Demand management is the most effective means to reducing emissions this decade, but if regulators adopt ambitious mitigation policies now, it can be overtaken in time by solutions such as alternative fuels and zero-emission aircraft (Fig. E.2). Our Roadmap finds that mitigation measures can increasingly be deployed from 2030 onwards, but that requires measures to be put in place now, with a start having been made with the EU’s “Fit for 55” package, and promised measures in the UK.

But these measures need to be strengthened for both CO₂ and non-CO₂ effects, and industry has to understand that its future survival depends on whether technology can overtake demand management as solutions to aviation’s climate problem. Industry needs to get behind the binding policies to support such measures, otherwise demand management will only accelerate to the point where the future of the industry is in doubt. This Roadmap outlines a credible path to a European aviation industry which is aligned with our collective climate ambition. If we succeed in implementing these pathways, both our aviation industry and our climate will benefit.

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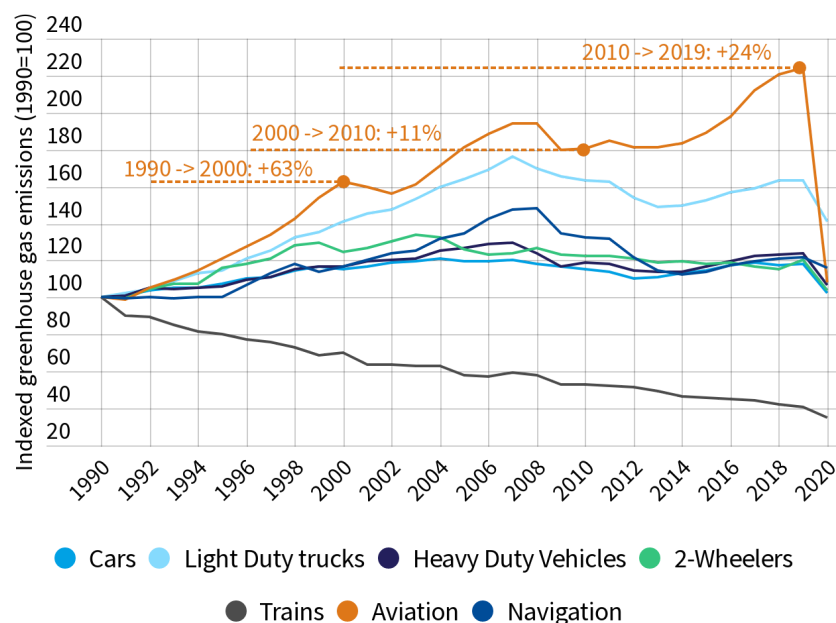
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1. List of acronyms

ASA	Air Service Agreement
CTP	Climate target plan
DAC	Direct air capture
EC	European Commission
EIB	European Investment Bank
EIS	Entry into service
ETD	Energy Taxation Directive
ETS	Emission Trading Scheme
GWP	Global warming potential
H ₂	Hydrogen
HSR	High-speed rail
ICAO	International Civil Aviation Organisation
ISSRs	Ice-supersaturated regions
MRO	Maintenance Repair and Operations
PtL	Power-to-liquid
RFNBO	Renewable fuels of non-biological origin
RPK	Revenue passenger kilometres
SAF	Sustainable aviation fuels
SES	Single European sky
TTW	Tank to wheel
UCO	Used cooking oil
UNFCCC	United Nations Framework Convention on Climate Change
VAT	Value-added tax
WTT	Well to wheel

2. Introduction

Aviation's climate impact is now widely known - in Europe, the sector is responsible for 3.7% of the bloc's emissions, up from 1.4% in 1990. Fig. 1 shows the growth of transport CO₂ emissions in the EU27 and UK (called EU27+UK in the remainder of this report), indexed from 1990. The increase in aviation emissions has only ever been slowed by international crises: in 2009 by the financial crisis, and most recently by the Covid-19 pandemic. Aviation emissions in 2019 were more than double those in 1990, with the 1990s showing the fastest decade of growth at 63%. In the nine years before the pandemic, aviation emissions grew by 24%. Moreover, the warming effect of these emissions is even greater when the non-CO₂ effects of flying are included [1].



Source: Member State reporting to UNFCCC; 2020 proxy emissions from EEA

Figure 1: EU27+UK indexed transport emissions, 1990 to 2020.

Though these numbers are accepted, what's less accepted is the reasons for why, pre-Covid, they were growing at such a fast rate. Some common reasons given are that more people want to fly, and so there are more emissions as a result, and that aviation is a sector that's 'difficult to decarbonise'. There's a grain of truth to both of these reasons, but they are also exaggerated. Understanding why gives us a better understanding of what steps we need to take.

A growth in passenger numbers, here in Europe and elsewhere, is certainly a reason for the growth in aviation emissions. However, that growth in passenger numbers is itself the result of government policies which promote the continued growth in demand. Keeping aviation jet fuel tax free [2], prohibiting the introduction of VAT on tickets [3], free allowances under the EU Emissions Trading Scheme (EU ETS) [4], support for airport expansion and subsidies for loss-making airports all contribute to artificially cheap

tickets, which result in more people taking more flights. As long as governments continue to subsidise fossil-intensive flights, this growing trend in emissions will only continue.

Instead of better pricing aviation emissions to reduce demand, or putting in place effective measures to decarbonise the sector, governments have instead left flights largely untaxed and emissions largely unregulated. The approach taken to date has been to work through the UN's aviation agency, the International Civil Aviation Organisation (ICAO), to adopt measures to reduce the sector's climate impact. Two decades of effort have resulted in an ineffective CO₂ efficiency standard, and an offsetting scheme that has lost all credibility in the face of repeated weakening of its rules [5].

What the sector therefore needs is an urgent and effective suite of measures to arrest its alarming growth in emissions, and to ensure the deployment of new fuels and technologies to put it on the path towards zero climate impact by 2050 at the latest. This report details what these measures should be, and makes the case for their urgent adoption.

2.1. What has changed

Since T&E published its Roadmap to Decarbonising Aviation in 2018, much has changed in the aviation world and in climate policy. In presenting that Roadmap, T&E first had to make the case that flying was a major climate problem, and that regulation at European level was urgently needed to address that problem. The case for both is now clear.

2.2. How Europe has changed

One of the key changes since 2018 is Europe's strengthened commitment to ambitious climate action. Europe has now committed to net-zero emissions by 2050 for all parts of its economy, including aviation. It has been joined by other major emitters in adopting such a target. The European Parliament and European Commission in office since 2018 have started our path towards a zero-emission Europe with a European Green Deal.

Central to that Green Deal's success is whether all parts of the economy and society contribute. Political support will disappear if car manufacturers and farmers are expected to transform their industries but aviation is left untaxed and its emissions unchecked. However, there are some signs that the aviation industry recognises that much more needs to be done.

2.3. How industry has changed

Perhaps it is the Covid-19 crisis, and the generous aid which came with it [6], which has upended industry calculations. But even before the crisis, there were some signs that industry was evolving, with a number of actors committing to more ambitious climate action. At the start of 2021, most of Europe's aviation industry came together to adopt their own path to zero emissions by 2050 [7].

In supporting net zero, industry has also called for support through European regulation. Long gone is industry's belief that a single global measure, led by the UN's sclerotic aviation agency, would act as a silver bullet. Industry knows that relying on a scheme is a one-way ticket to more customers walking away from flying [5]. Which brings us to the second big change from 2018.

2.4. How the consumer has changed

Even before Covid-19 grounded much of the aviation sector, the world had been introduced to the word “flygskam”, Swedish for “flight shame”. Often mistranslated as “flight shaming”, the movement is in fact an example of the public taking matters into their own hands: if industry won't decarbonise, if governments won't force them to cut emissions, then the public will walk away. After all, in many cases, flying is a luxury and not a necessity. That Swedish movement has already contributed to the closure of one airport in the country [8].

This reality was brought home when Covid-19 struck. Businesses (and even us NGOs) who long relied on city-hopping conferences and face-to-face contact learned to adapt. Suddenly, all that flying didn't seem so essential. In fact, we not only found ways to remain as productive, but also found ways to be more efficient and even focus on our employee wellbeing. And if flying remains as carbon intensive as it is today, more and more people, for business and leisure, will see flying as an avoidable luxury. Certainly, we now have a greater understanding of the benefits that cutting those long-haul flights can have.

2.5. Science catches up

The science doesn't change, but our understanding of it does. We've known the substantial climate impact from aviation's CO₂ emissions for a long time, but we now have a better understanding of flying's non-CO₂ effects, and the science is clear that they exceed the already substantial CO₂ warming effects. This is especially true for long-haul flights.

Our 2018 Roadmap was more cautious, calling for further examination and research. However, with further scientific evidence, we can be much clearer: regulators need to start introducing measures, such as rerouting and fuel treatment, in order to urgently cut these non-CO₂ effects.

2.6. But some things haven't changed

For all the tumult of recent years, some things haven't changed. Firstly, the aviation sector still needs to rapidly develop zero-emission drop-in fuels. There have been an increasing number of announcements made about new zero-emission aircraft and this Roadmap will highlight the role they can play under the right circumstances. However, aviation's existing fleet, and the fleet rolling out of factories, will need to burn something other than fossil jet fuel, and that something needs to be developed now.

Secondly, the aviation sector remains one of Europe's most important industries. When the crisis hit, few called for the sector to be allowed to go under. Aircraft manufacturing is one of the jewels of European industry. Our airlines have played an important role in connecting the continent.

As other sectors accelerate their decarbonisation, aviation risks being left out and left behind. For those of us who want a successful aviation industry, this is a major threat. However, with enough ambition, and determined political will, the aviation sector can join the path to decarbonisation, too. This Roadmap outlines how that can take place.

2.7. How to read this report

This report is divided into two parts. **Part I** contains our forecast for the sector, including baseline growth and the application of a range of scenarios and measures to bring down the sector's CO₂ and non-CO₂ emissions. Where necessary, those measures are detailed in that section. **Part II** examines the mitigation measures in detail, examining why we propose different measures.

3. PART I: FORECAST

4. Decarbonisation forecast

4.1. Methodology

T&E's 2018 aviation emissions forecast drew on aviation activity growth forecasts from the 2016 European Reference Scenario [9] to project total outbound EU27+UK aviation emissions up to 2050. It modelled the application of a range of measures to reduce conventional fuel demand through technical and operational efficiency, next-generation aircraft and carbon pricing. It then focused on how to decarbonise the remaining fuel demand through the use of sustainable aviation fuels (SAFs) such as advanced biofuels and synthetic e-fuels (power-to-liquid, also known as e-kerosene).

This work draws on our previous forecast. The scope was kept to flights departing from within the EU28, now the EU27+UK, as the UK is a major contributor to European aviation emissions and it will implement its own version of the measures we modelled in this forecast (carbon pricing including its own version of the ETS, zero-emission aircraft mandates, etc.). We updated the traffic projections to 2050 with the latest data available, taking into account the effect of the Covid-19 pandemic. We also deepened the modelling of aircraft that could enter the fleet in the next decades, including electric and hydrogen aircraft. Finally, we modelled policies to reduce post-pandemic business travel and manage leisure travel demand after recovery from the pandemic. Full details of the modelling approach can be found in Appendix A.

In the following sections, we will detail the different mitigation measures we propose and their abatement potential by 2050. Section 4.6 contains a summary of the results and the assumptions used for the modelling.

4.2. Baseline emissions

We derived baseline emissions by first calculating the emissions in a hypothetical “no-action” scenario in which no improvement in aircraft fuel burn would happen until 2050, and then modelling ambitious but achievable improvements in fuel efficiency.

4.2.1. Reference scenario without fuel efficiency improvements

Reference emissions were derived using aviation emissions reported to the UNFCCC up to 2019 as a starting point¹. We projected future emissions up to 2050 using the International Air Transport Association's (IATA) short-term (post-Covid) forecast² and the long-term yearly increase rate in CO₂ emissions derived in the European industry report “Destination 2050”, i.e. 2.2% [10, 11]. This figure excludes any improvement in aircraft fuel burn until 2050. This is not a realistic view of the future, but sets a reference for the forecast against which to compare alternative scenarios and policies. The result is that reference aviation emissions are projected to grow by 94% from 2019 to 2050, reaching 367 MtCO₂, as can be seen in Fig. 2.

¹ UNFCCC aviation emissions are based on fuel sold in Europe and thus include cargo and passenger emissions

² At the time of writing, the EU Reference scenario 2020 had not been published, hence the use of IATA projections

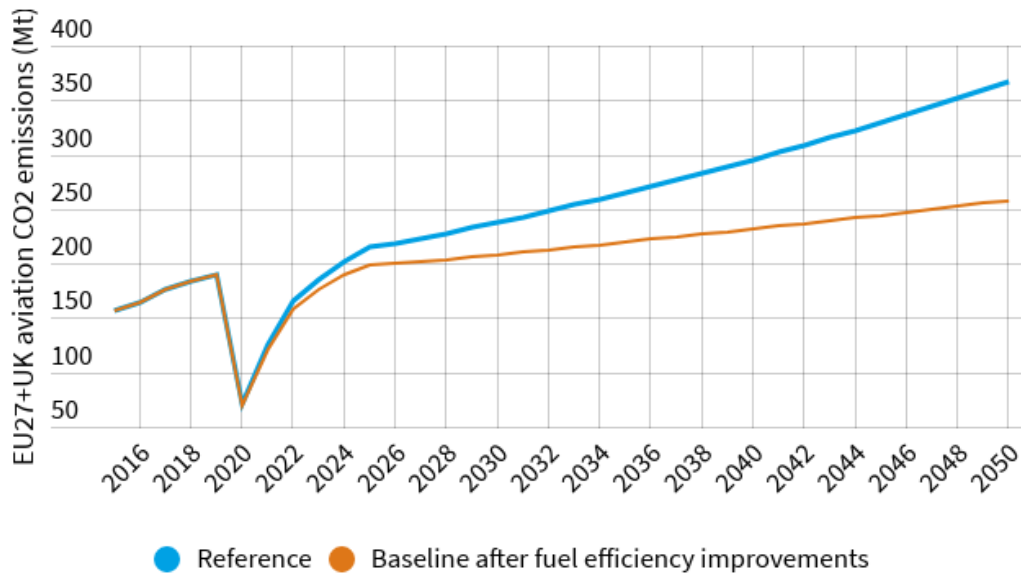


Figure 2: EU27+UK aviation emissions up to 2050 - reference and emissions after fuel efficiency improvements

4.2.2. Improvements in fuel efficiency from technology and operation

The design and deployment of more efficient aircraft and engines can play an important role in reducing fuel demand from the sector. We will take a closer look at the main technological innovations that are likely to be developed in the next decades in Section 7. To predict annual fleet efficiency improvements, we used the EU reference scenario 2016 prediction of 41% efficiency improvement³ between 2010 and 2050, and actual figures monitored by Eurocontrol from 2010 to 2017 [12]. Taken together, these correspond to a compound improvement rate of 1.1% per annum from 2017 to 2050. Fuel efficiency from 2010 to 2050 is shown in Fig. 3.

³ In terms of fuel burn per passenger.km (L/pax.km)

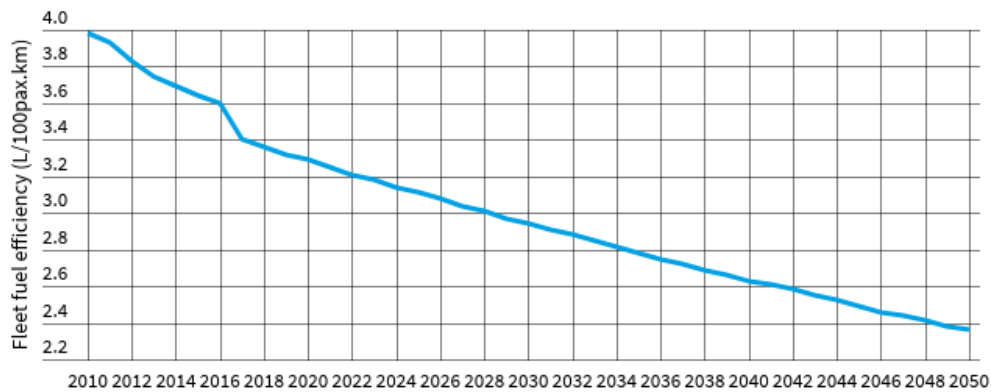


Figure 3: Forecasted fleet fuel efficiency from 2010 to 2050

In this improvement rate, we include ameliorations in aircraft and engine technology, load factor and aircraft size optimisation, as well as operational improvements. As will be explained in Section 7.1, incremental fuel efficiency improvements are becoming more and more difficult as technology advances. In the last 22.5 years, corresponding to the average aircraft life cycle [11], the fuel efficiency of new aircraft has improved by only 0.9% per annum, whereas it had improved by 1.8% in the previous cycle [13]. Load factors can still be optimised but are already well above 80%, hence the limited room for improvement. Similarly, increasing the average number of seats per aircraft has some limited potential [11]. Finally, Single European Sky (SES) and other operational improvements could bring up to a 5% emissions reduction according to “Destination 2050” [11]. However, modelling of operational improvements often fails to take into account potential rebound effects that negate the expected improvements, such as an increase in traffic due to reduced congestion at airports or from the increased passenger demand for cheaper tickets that airlines can offer due to the reduction in operational costs.

This 1.1% per annum would be at the more ambitious end of what we expect is possible, but our forecasting envisages a situation where governments adopt an ambitious range of measures to encourage both new designs and their deployment. It corresponds to 110Mt CO₂ abated per year in 2050, or 30% of reference emissions. Emissions after technological and operational improvement are calculated to be about 258 MtCO₂ in 2050, a 36% increase compared to 2020 (see Fig. 2). This figure is in close agreement with the results of the “Destination 2050” report, for which technological improvements were modelled more granularly. In the remainder of this section, we refer to emissions after efficiency improvements as “baseline emissions”. Such technological and operational improvements are challenging, and will require a suite of measures adopted at both national and European levels to be achieved. If we fall short, the challenge to decarbonising aviation will grow even greater.

4.3. Demand management and carbon pricing

With the exceptions of the recession of 2000 and the financial crisis of 2008, EU aviation traffic had increased steadily for more than three decades before the Covid-19 pandemic. Between 2005 and 2019,

European traffic increased by 83%⁴ (in Revenue Passenger Kilometres (RPK)) as more people travelled longer distances. This resulted in an uncontrolled growth in emissions which should not be allowed to resume after the pandemic. For this, reducing or capping passenger demand will be key because zero-emission fuels and aircraft will not be ready at scale before the 2030s. In this forecast, we look at business travel reduction and leisure travel management measures (i.e. a cap) to achieve this, and the effect that they would have on emissions up to 2050.

4.3.1. Carbon pricing

Contrary to other industries, aviation has been exempted from most fuel and carbon taxes until now. As will be discussed in Section 6, it is essential for aviation to start paying a fair price for its pollution, and this will have multiple benefits: incentivising design and operational efficiency, curbing demand, and encouraging the uptake of low carbon fuels. The two main pricing levers considered in this forecast are the inclusion of all flights departing from the EU in the ETS and the introduction of fuel taxation similar to that applied to fuels in the road transport sector.

The EU ETS currently covers only intra-EU flights, and part of the allowances are given freely, therefore European aviation pays for only a small share of its emissions, i.e. 18% of intra-EU+outbound emissions according to our estimation. On the positive side, the EU ETS has finally become more effective and EU ETS prices have briefly risen to €100/tCO₂ at the time of writing. We modelled what would happen if 100% of emissions were paid for starting in 2024. The EU ETS price is assumed to reach €100/tCO₂ by 2030, as predicted by some researchers [14], and €200/tCO₂ by 2050.

Applying jet fuel taxation to fuel uplifted for flights within Europe requires the abolition of the jet fuel tax exemption in the current EU Energy Taxation Directive (ETD). Europe can also apply a jet fuel tax for flights to and from Europe operated by non-EU carriers, provided that the Air Service Agreement (ASA) between the EU and the third country allows it. Most ASAs concluded in recent years allow for the mutual imposition of jet fuel taxation (except [15]). It is not inconceivable that, as the need for carbon pricing becomes ever more apparent, such taxation will be introduced on a bilateral basis with non-EU countries, steadily expanding to cover an increasing share of European aviation emissions. We modelled the gradual introduction of a €0.33/L tax from 2025 to 2035. Such a level would still be below the EU's average excise duty on diesel (€0.45/L [16]), but is still challenging to achieve, as governments have to date acted to protect the existing jet fuel tax exemptions.

Together, these two pricing mechanisms would be equivalent to a carbon tax of €165/tCO₂ by 2030 and €329/tCO₂ by 2050. By comparison, the EU's average excise duty on diesel corresponds to €171/tCO₂ and will likely rise well above that by 2050. For business travellers, we considered that carbon pricing would be one of the levers that contribute to reducing business traffic to 50% of 2019 levels, as explained below. For leisure travellers, we calculated that it would result in a reduction of 26% of traffic by 2050. This represents 18% of baseline emissions, or 45 MtCO₂. These figures are obtained before any fuel switch is

⁴ Data from Eurocontrol's STATFOR platform for passengers departing from the EU27+UK

modelled. In practice, effective fuel carbon pricing should decrease with time as sustainable fuels replace jet fuel.

4.3.2. Business travel reduction

Business travel has been a lucrative part of the aviation industry. Though previously concentrated among legacy carriers, all airlines target these passengers, who tend to be less price sensitive and therefore are prepared to pay more and to pay for higher quality service (i.e. business and first class, airport lounge access). Any reduction in business travel will therefore have significant consequences for the sector.

The Covid-19 pandemic has shown us that it is possible to drastically reduce travel, while still doing business. However, even before Covid-19, increases in the quality of video conferencing services and concerns about climate change were also calling into question the frequency of such trips [17]. Indeed it is worth examining whether reduced travel, with the resulting time lost and personal toll it can take, can actually improve productivity.

Some have predicted that business travel will not recover to its pre-pandemic levels, going as far as talking about a 50% business travel reduction [18]. In this forecast, we look at the effect of such a reduction. More precisely, the forecast assumes that business travel traffic, measured in RPK, does not recover to above 50% of 2019 levels. Based on various sources, we estimate that business travel represents about 30% of aviation emissions in 2019 (see Appendix A for more details). Moreover, a decrease in business travel could result in higher economy ticket prices and thus a further drop in demand, due to cross-subsidisation⁵.

As fuel efficiency per passenger increases with time, capping traffic levels means that the emissions attributable to business travel will decrease. Our forecast shows that 20% of baseline emissions, or 51 MtCO₂, would be saved in 2050 thanks to this measure. This reduction is ambitious but certainly achievable with the right policies. Such policies could be the result of “top-down” policies introduced by governments, such as limiting the use of Frequent Flyer Programmes or mandating disclosure of total corporate travel emissions; there could also be “bottom-up” policies adopted by major corporations to reduce their own travel. Corporate climate commitments must face greater scrutiny, and could be regulated to ensure that they must include emissions from corporate travel, part of “Scope 3” emissions. Any reduction in corporate travel will be through an interplay between voluntary commitments by businesses, and supportive measures by governments.

INFO BOX - Cross subsidisation of leisure travel with business travel

Even though business travellers make up a small share (about 20%) of total passengers, they generate a substantial part of airlines’ revenues, up to 75% according to some sources [19]. Business travellers are more likely to fly in premium classes or purchase last minute tickets which are more expensive,

⁵Higher priced premium tickets, favoured by business travellers, make up most of the airlines’ revenues [19]. Without these revenues, airlines will have to raise economy ticket prices to keep their margin

generating more revenues. This allows airlines to reduce the price of economy tickets and fill their planes, a form of cross subsidisation. Given the already thin margins of airlines before the pandemic, a potential drop in lucrative business passengers would need to be compensated by raising prices elsewhere, most likely economy tickets. In turn, this could result in a drop in demand. We haven't included this effect as it is still speculative at this point, but calculations show that a 50% drop in business passengers could result in at least a 4% drop in leisure passengers, even if aircraft configurations are adapted to reduce premium seats in favour of economy seats. Further details on this calculation can be found in Appendix A.

4.3.3. Leisure travel management and modal shift

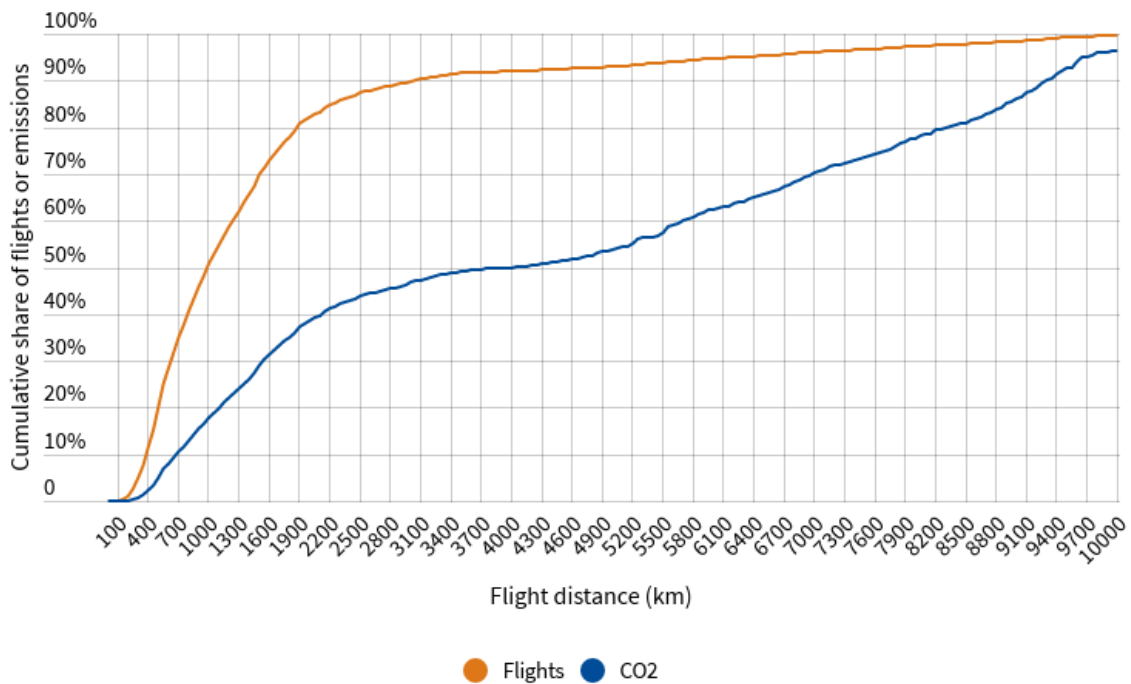
If all the people in the world flew as much as the richest 10% of Europeans, aviation globally would emit 23 GtCO₂ per year, two thirds of global CO₂ emissions in 2019⁶. This figure shows how unsustainable and unequal our flying habits have become, and it is essential to stop the unlimited expansion of aviation. As explained in our 2018 Roadmap, modal shift can play a role in reducing aviation emissions, but it is important not to overstate its potential emission reductions. Research shows that a shift from air to rail could only deliver a 2-4% reduction, even with ambitious scenarios for rail improvement, such as connecting all major cities with high speed rail [24]. On the other hand, 8% of the flights departing the EU(+UK), those longer than 4000 km, are responsible for 50% of the block's emissions⁷. This can be seen in Fig. 4.

⁶ Extrapolation based on:

- the air travel carbon footprint of the richest 10% of Europeans, 3.0 tCO₂, from [20]
- a world population of 7.87 billion people [21]
- Annual global CO₂ emissions in 2019 [22] [23]

In practice, airports and airspace capacity would be insufficient to achieve such levels.

⁷ In-house calculation of 2019 EU28 emissions based on ICAO calculator methodology, using AIS aircraft data purchased to PlaneFinder



Source: in-house calculation of emissions based on ICAO emission calculator methodology, using AIS aircraft data purchased to PlaneFinder.

Figure 4: Cumulative share of emissions and flights departing the EU27+UK in 2019, as a function of the flight distance.

Reducing the number of long-haul flights would thus be the easiest way to tackle emissions in the short to medium term. Ending support for airport expansion, as the EIB has already agreed to, is an important first step towards achieving such an objective. Planned airport expansion often overstates the economic benefits and understates the climate impact [25]. Emissions from existing airport capacity could be reduced by limiting utilisation through extended bans on night time landings and take-offs. Introducing floor ticket prices and ticket taxes proportional to the climate impact of flights could help curb demand further. Alternative fuels (hydrogen, sustainable advanced biofuels and e-kerosene) will be more expensive than jet fuel, increasing ticket prices and reducing demand, as will be explained in Section 4.5.3. Finally, further reductions in leisure travel could be achieved by promoting European tourism as an alternative to intercontinental travel, facilitating the possibility to take fewer but longer holidays and improving the quality of life in cities for staycations or city breaks closer to home (more green space, space for leisure activities, less traffic & reduced pollution, improved public transport and infrastructure). A crucial step towards achieving such an objective would be to ensure long-haul flights are equally covered by EU climate policies such as EU ETS, which as discussed above, is presently not the case.

Considering it a realistic goal, we modelled a cap on leisure travel traffic equivalent to 2019 levels (in RPK), meaning that leisure traffic would not keep increasing after 2024, the year of expected full traffic recovery. This cap was applied after the demand reduction due to carbon pricing, and represents a further reduction of 16% of baseline emissions, or 41 MtCO₂, by 2050.

4.3.4. Summary of demand management measures

In Fig. 5, we summarise the effect of the three demand management levers modelled on 2050 emissions. Together, they represent a 53% reduction from baseline, which corresponds to 137 MtCO₂.

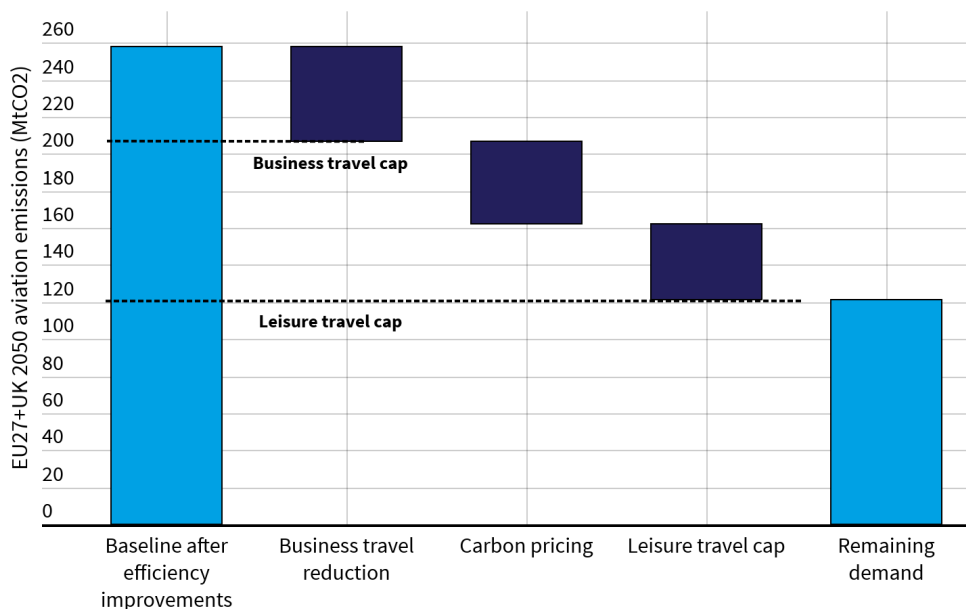


Figure 5: Impact of demand management measures on EU27+UK aviation emissions in 2050

4.4. Zero-(CO₂)-emission aircraft

Development plans and concepts for several zero-emission aircraft have emerged in the past years. With the right measures in place, electric, hybrid-electric and hydrogen planes could start flying in the 2030s, but different technologies require different aircraft sizes, ranges and entry into service (EIS) year. Our detailed analysis of upcoming zero-emission aircraft is presented in Section 7.2.6 and informed our decision to divide the forecast into four aircraft segments: regional (<80 passengers, <1000km), short range (80-165 passengers, 1000-2000 km), medium range (165-250 passengers, 2000-7000 km) and long range (250-325 passengers, 7000-10,000 km).

4.4.1. Regional zero-emission aircraft: electric, hybrid-electric and fuel cell aircraft

Even though battery technology has vastly improved in the last decades, the fundamentally limited gravimetric energy density of batteries currently makes them unusable for planes flying beyond short range and for planes bigger than the regional segment. Whereas current battery pack specific energy is around 200 Wh/kg, according to Schafer et al. [26], packs of 800 Wh/kg would be necessary to fly

A320-sized aircraft for 600 nm (1,111 km) and could be available by mid-century. On the other hand, Wright says it is targeting 2030 EIS for 186-seat, 800-mile (1287-km) range electric aircraft, which would seriously defy the above prediction [27]. In the absence of more detail on the matter, we have chosen to follow the general consensus in the literature, which is that fully electric short range aircraft are still a few decades away.

Hybrid-electric propulsion, combining battery electricity and jet fuel to power planes, would allow them to fly further but would achieve smaller emission reductions. Hydrogen fuel cell systems should also allow longer ranges provided that some technological challenges are overcome, such as reducing hydrogen tank weight and increasing fuel cell power density. This technology emits no CO₂ and very little non-CO₂, and could thus become the dominant propulsion system in the regional segment. All in all, our forecast assumes an EIS date of 2035 for regional zero-emission aircraft and a fleet replacement cycle time of 20 years for all segments, which is slightly faster than the current average of 22.5 years. The share of EU27+UK emissions corresponding to planes of less than 80 people flying less than 1000 km is only 2.3%⁸, so decarbonising this segment will have limited impact on 2050 emissions, but can bring some improvements to local air quality and noise pollution at the affected airports.

4.4.2. Short range zero-emission aircraft: hybrid hydrogen aircraft

Short range (as defined above) aircraft represent 14.9% of emissions in Europe and could be powered by a combination of hydrogen fuel cells, powering electric motors and rotors, and direct combustion of hydrogen in an adapted jet turbine. This combination takes advantage of the higher efficiency and lower climate impact of fuel cells and the higher power density of hydrogen propulsion through combustion. Such a system isn't without challenges though, and the hydrogen aircraft concept has already been studied, in the 2000s, before being dropped [28]. It is thus necessary to be prudent on the potential for hydrogen aircraft to decarbonise the fleet. Nevertheless, in this forecast we assume that hydrogen aircraft will become a reality, with short range aircraft entering the fleet in 2040, and a fleet replacement cycle time of 20 years. This date is five years later than McKinsey's predicted EIS [29]. We justify that by the fact that Airbus has not yet committed to actually develop a hydrogen aircraft, and will likely not do so before 2025. Moreover, if an aircraft is ready by 2035, it will likely carry around 100 passengers for 1,000 nm (~1850 km) [30], with less CO₂ reduction potential than the "short range" segment considered in this forecast.

4.4.3. Medium range zero-emission aircraft: hydrogen combustion aircraft

Beyond a short range, hydrogen fuel cell systems become too heavy and only hydrogen turbines can be used for propulsion. Liquid hydrogen has a volumetric energy density about 4 times lower than jet fuel, and extra insulation must be provided, so bigger fuel tanks will be necessary to fly hydrogen aircraft for the same distance as conventional aircraft. The main challenge will be to limit the weight penalty of these tanks by optimising the ratio between the weight of hydrogen carried and the total weight of the filled tank. Such a plane could realistically be ready by 2045 and the segment corresponds to 35% of EU27+UK emissions, which is the largest of the four segments defined above.

⁸ In-house calculation based on 2019 AIS traffic data purchased to PlaneFinder

4.4.4. Long range zero-emission aircraft: hydrogen combustion aircraft

According to McKinsey [29], and informal talks we have had with industry and academic players, hydrogen aircraft with a range up to 10,000 km are technologically achievable, although not for several decades. A further barrier is cost. As explained above, hydrogen aircraft incur a weight penalty due to their bigger tanks. For planes of the long range segment, this would result in about a 40% increase in fuel energy demand [29]. Additionally, the hydrogen aircraft comes with additional CAPEX maintenance and productivity costs. Evolutions in hydrogen technology and renewable fuel prices will determine which technology will prevail.

In our base forecast, we assume long range zero-emission aircraft will enter the fleet in 2050. That means that the long range aircraft segment, representing 28.5% of EU27+UK emissions, will have to be decarbonised by other means. In the following section, we will look at the effect of introducing hydrogen aircraft earlier than in our base forecast. In all cases, we considered that hydrogen aircraft with more than 325 passengers and 10,000 km range are not achievable by 2050. This segment currently represents 19.3% of emissions.

4.4.5. Emission reductions from zero-emission aircraft

The different assumptions used to model the deployment of zero-emission aircraft in the EU27+UK fleet are summarised in Table 1. “Base case” assumptions were described in the previous sections and will be used for the decarbonisation forecast. As explained above, we took a slightly more conservative stance on hydrogen aircraft EIS than, for example, McKinsey’s “Hydrogen-powered aviation” and the “Destination 2050” report. It is worth analysing the effect that faster or slower hydrogen aircraft development and introduction would have on emissions. We thus modelled an optimistic scenario, i.e. hydrogen aircraft introduced five years earlier than in the base case, and a pessimistic scenario, i.e. hydrogen aircraft delayed by five years. Market penetration times were set to 15 and 25 years respectively instead of the current 22.5 years. The optimistic scenario allows us to estimate the highest potential for hydrogen aircraft to reduce emissions, whereas the pessimistic scenario shows what would happen if hydrogen aircraft development was once again delayed.

Aircraft segment	EU27+UK 2019 share of emissions	Entry Into Service			Market penetration time		
		Optimistic	Base case	Pessimistic	Optimistic	Base case	Pessimistic
regional (<80 passengers, <1000km)	2.3%	2030	2035	2040	15 years	20 years	25 years
short range (80-165 passengers, 1000-2000 km)	14.9%	2035	2040	2045			
medium range	35.0%	2040	2045	2050			

(165-250 passengers, 2000-7000 km)							
long range (250-325 passengers, 7000-10,000 km)	28.5%	2045	2050	2055			
very long range (more than 325 passengers and 10,000 km)	19.3%	After 2050			Not applicable		

Table 1: EIS and market penetration time in the different hydrogen aircraft deployment scenarios analysed

Fig. 6 shows the CO₂ saved by hydrogen aircraft depending on the technology maturation scenario. In the base case, zero-emission aircraft could represent 18% of the fuel demand by 2050. This would correspond to 8% of baseline emissions, or 22 MtCO₂⁹. The reasons why we find that less than 20% of the jet fuel demand can be replaced by zero-emission aircraft are that aviation fleet replacement is slow and that zero-emission technologies are still very much in their infancy, meaning that the aircraft which have the most potential to decarbonise the sector (i.e. mid and long range) won't be zero-emission for several decades. This view is already more ambitious than IEA's recent "Net Zero by 2050" Roadmap, which forecasts that only 2% of global aviation energy will be provided by electricity and hydrogen by 2050 [31], and IATA's plan to achieve net-zero carbon emissions by 2050, which estimates that new propulsion technology such as hydrogen could represent 13% of 2050 fuel demand [32].

The amount of CO₂ abated by hydrogen aircraft almost triples in the optimistic uptake scenario, representing 60 MtCO₂ or 23% of baseline emissions in 2050. This shows the potential of accelerated hydrogen aircraft development on the impact of this technology by 2050. Such a scenario could be brought about through much more aggressive regulatory invention, i.e. technology forcing standards. On the contrary, delaying the introduction of hydrogen aircraft further than our base case would mean that there will be almost no CO₂ reduction thanks to this technology by 2050 (1.8% of baseline).

These different hydrogen aircraft development scenarios come with different challenges in terms of fuel and aircraft production. 6.9 Mt of liquid hydrogen would have to be produced in the optimistic scenario, or half of the fuel demand after demand management (in energy content), and 1300 to 2600 planes would have to be built¹⁰. In the central case, the figures would be 2.5 Mt of hydrogen and 600 to 1200 planes. As a comparison, there are currently about 5000 planes in the fleet of airlines based in the EU27+UK.

⁹ The former figure corresponds to the case when demand management is achieved as proposed above, the latter to the case where no demand reduction happens.

¹⁰The number of hydrogen aircraft to build depends on the utilisation rate of these aircraft. The more distance they will cover in a year, the less aircraft will be needed to save a certain amount of CO₂. More details on our assumptions for this estimation can be found in the appendix.

Naturally, without demand reduction, CO₂ abatement could be higher, but the challenge in terms of hydrogen aircraft and fuel production would be much greater. This underlines the risk in relying exclusively on future technologies. In the case where demand is unmanaged, an optimistic hydrogen aircraft scenario is unrealistic because it would require 16.1 Mt of hydrogen to be produced for the aviation sector, a figure well above that contained in the “Destination 2050” industry report, which estimated 12.3 Mt, including the hydrogen needed for biofuels and e-kerosene production [33].

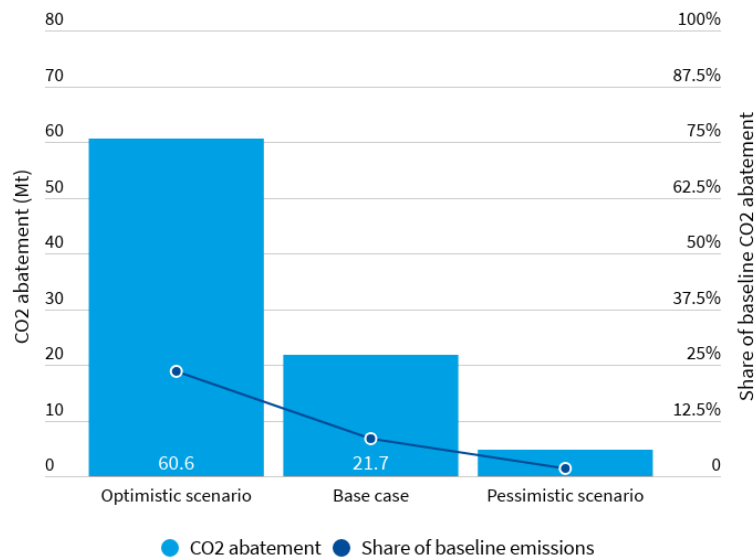


Figure 6: Emissions abated by zero-emission aircraft in 2050 under different technology adoption scenarios, and corresponding share of baseline CO₂ abatement

4.5. Drop-in sustainable aviation fuels (SAF)

If all the sustainability measures mentioned above are applied, there will still remain 99 MtCO₂ emitted in 2050. Without demand management, that figure would rise to 203 Mt. This means that at least a third of the decarbonisation effort¹¹ will have to come from SAF. We look at two pathways to achieve this - deploying sustainable aviation biofuels and renewable fuels of non-biological origin (RFNBO), also called ‘power-to-liquids’ (PtL), e-fuels or e-kerosene.

4.5.1. Advanced biofuels

Advanced biofuels are defined in European legislation through a list of feedstocks that are comprised mostly of 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 fossil jet fuel, and the absence of measures to bring about their uptake. In a previous analysis, we estimated biofuel supply potential in the EU27+UK to 1.7 Mtoe in 2030 and 7.5 Mtoe in 2050 [34]. We reused these values in this forecast and modelled advanced uptake of biofuels with an S-curve starting in 2020. Advanced

¹¹ Compared to a baseline + expected efficiency improvement scenario

biofuels represent 3.4% of the forecasted energy demand¹² in 2030 and 19.1% in 2050, which in turn represents 9% of 2050 baseline emissions, or 23 MtCO₂.

INFO BOX - Estimating SAF supply potential from advanced biofuels in 2030 and 2050

As advanced biofuel production in the EU is still in its infancy and little policy support exists at this time, it is difficult to estimate what quantity of SAF could be available for the aviation sector in ten years' time, let alone later. In a previous analysis, we considered only a small number of feedstocks that are both true waste and residues and also sustainable, not the whole list included in EU law [24]. For our modelling purposes, we did not include biofuels from Used Cooking Oil (UCO) or animal fats, which are not considered 'advanced' in EU law. On the basis of these feedstocks, we estimated a EU27+UK advanced biofuel supply of 1.7 Mtoe in 2030 and 7.5 Mtoe in 2050 [34]. Scaled to the EU27, these figures become 1.3 Mtoe and 5.8 Mtoe, respectively. We compared our estimations to recent work on the availability of SAF from advanced biofuels in the EU27. The ICCT calculated the theoretical peak production of SAF to be 12.2 Mt by 2030 [35]. Taking into account technical, economic and deployment constraints, they estimated the actual potential to be between 1.2 Mt and 3.4 Mt, depending on government support. Our estimate thus corresponds to the lower bound of their range¹³. Another study commissioned by T&E to Cerulogy estimated that between 650 ktoe and 2.1 Mtoe advanced biofuels could be produced for EU27 aviation in 2030, making our current estimate a central case [36]. For 2050, our estimate of 5.8 Mtoe corresponds to about 50% of ICCT's theoretical peak potential in 2030, which is reasonable given that the goal should be to reduce waste production rather than to increase it, and that multiple sectors will compete for the use of these feedstocks.

4.5.2. PtL e-kerosene

As mentioned above, though large scale commercial PtL plants do not exist at present, several are under development and our forecast demonstrates that this fuel will have to make up the bulk of aviation fuel supply in 2050 if the sector is to decarbonise. Indeed, there remains 76 MtCO₂, or 30% of baseline emissions, to abate in 2050 after the measures mentioned in the previous sections. E-kerosene from PtL plants will thus have to represent the biggest share of CO₂ abatement measures by then. We modelled the uptake with an S-curve starting in 2023, reaching 20 ktoe in 2025¹⁴, 1340 ktoe¹⁵ in 2030 and 24.7 Mtoe in 2050. The 2030 figure corresponds to 2.7% of the fuel energy demand that year, after the reduction measures. Based on the same study as above, such an amount is deemed challenging but achievable if adequately strong government support begins now [36]. Note, however, that e-kerosene production shouldn't be considered infinitely scalable without challenges and such expansion would not be considered automatically sustainable. It is therefore essential to use all the decarbonisation measures mentioned previously to reduce SAF and renewable electricity requirements.

¹² Energy demand after demand management measures

¹³ Our estimations were given in units of energy (Mt), whereas ICCT's estimations are provided in units of mass (Mt). As 1 Mt of biofuel represents roughly 1 Mtoe of energy, we assume these to be comparable for this discussion

¹⁴ A study commissioned by T&E showed that 16 ktoe of e-kerosene could be produced in 2025 in the EU27, which would scale to about 20 ktoe in the EU27+UK [36]

¹⁵ 2% of the fuel demand if demand is unmanaged, 2.7% if it is managed

4.5.3. Effect of hydrogen and SAF prices on demand

In our previous roadmap, we pointed out the fact that advanced biofuels and e-kerosene will cost more than fossil jet fuel. This will also be the case with hydrogen. The estimated cost of advanced biofuels varies widely depending on the feedstock. Recent sources estimate the minimum viable price of sustainable advanced biodiesel at €1654-2308/t¹⁶, that of e-kerosene produced in the EU in 2050 at €1186-1906/t and that of liquid hydrogen at €642-963/tke¹⁷ (in 2050) [11] [37]. For hydrogen, airlines will incur an additional cost increase due to higher CAPEX, Maintenance Repair and Operations (MRO) and productivity costs. In 2050, renewable fuel prices could thus be up to three times higher than jet fuel at €690/t¹⁸. These are, of course, forecasts, and such prices could decline faster than anticipated, as has occurred with other technologies such as batteries and renewables.

A price gap between fossil jet fuel and these alternatives is, however, likely to persist for some time, meaning that without proper incentives and mandates, there will be no uptake in these fuels. A fair level of pricing, as suggested in this report, would bring the effective price of jet fuel to €1730/t by 2050 and would make alternative fuels competitive with it [29]. We estimated that replacing jet fuel with alternative fuels as described above would result in a demand reduction of leisure travel of 12% to 22%, depending on the price of these fuels. In the model, we considered this demand reduction part of the leisure travel cap.

4.6. Base decarbonisation forecast - summary of results

From the above discussion, Table 2 summarises the assumptions used for the so-called reference and baseline scenarios, and the resulting emissions in 2030 and 2050. Table 3 summarises the measures, the assumptions used for the modelling and the resulting CO₂ abatement in absolute and relative terms for the years 2030 and 2050. These results are conditional on all demand management measures being applied. As a reminder, the results for carbon pricing are obtained before any fossil fuel replacement is modelled in order to show the maximum potential of that measure.

Scenario	Assumptions	CO ₂ - 2030	CO ₂ - 2050
Reference	IATA short-term forecast. "Destination 2050" yearly traffic increase excluding fuel efficiency improvement.	238 MtCO ₂	367 MtCO ₂
Baseline after efficiency improvements	EU 2016 reference scenario improvement rate of 1.1%/year.	208 MtCO ₂ (12.4% below reference)	258 MtCO ₂ (29.8% below reference)

¹⁶ As per our definition of sustainable advanced biofuels in the INFO BOX above and for the cheapest conversion pathway, i.e. gasification-FT

¹⁷ €/tke: euro per tonne of kerosene equivalent, i.e. the price of hydrogen to deliver as much energy as one tonne of kerosene, for easy comparison to kerosene and other fuels with a similar energy density

¹⁸ Using the kerosene price forecasted in the "Destination 2050" report

Table 2: Assumptions used for the reference and baseline scenarios and resultant CO₂

Measure	Assumptions	CO ₂ abatement vs. baseline - 2030	CO ₂ abatement vs. baseline - 2050
Business travel cap	50% of 2019 traffic levels. Business travel = 27% of 2019 emissions (calculated).	32.6 MtCO ₂ (15.7%)	50.7 MtCO ₂ (19.7%)
Carbon pricing	Tax: €0.33/L ETS: all outbound flights included from 2024, €100/tCO ₂ in 2030, €200/tCO ₂ in 2050.	22.8 MtCO ₂ (10.9%)	45.2 MtCO ₂ (17.5%)
Leisure travel cap	100% of 2019 traffic levels	1.7 MtCO ₂ (0.8%)	40.8 MtCO ₂ (15.8%)
Hydrogen & electric aircraft	4 aircraft segments with EIS in 2035, 2040, 2045 and 2050	0.0 MtCO ₂ (0.0%)	21.7 MtCO ₂ (8.4%)
Advanced biofuels	S-curve beginning in 2020, 1.7 Mtoe in 2030 and 7.5 Mtoe in 2050	5.1 MtCO ₂ (2.5%)	23.1 MtCO ₂ (9.0%)
E-kerosene	S-curve beginning in 2020, 1.2% of fuels in 2030 and 63% in 2050	4.5 MtCO ₂ (2.2%)	76.3 MtCO ₂ (29.6%)

Table 3: Summary of decarbonisation measures, CO₂ abatement and assumptions for this forecast

Fig. 7 shows the path to decarbonisation from now until 2050. With fleet efficiency improvements alone, emissions would amount to 208 MtCO₂ and 258 MtCO₂ in 2030 and 2050, respectively. Cumulative emissions over the 2022-2050 period would be 6410 MtCO₂. Implementing the sustainability measures of this forecast would reduce emissions to 141 MtCO₂ in 2030 and would achieve decarbonisation in 2050. Cumulative emissions would be reduced by 55% to 2872 MtCO₂ (2.9 GtCO₂). This would still be above the remaining carbon budget to limit global warming to 1.5°C above pre-industrial levels with a 50% chance. We calculated this budget to be 2.4 GtCO₂ for EU27+UK aviation, based on the recent IPCC AR6 report [38] and following a grandfathering approach¹⁹.

¹⁹ When calculating the remaining CO₂ emission budget for a sector, the grandfathering approach consists in allocating to that sector the same share of the remaining global budget as its current share of global CO₂ emissions. We use this approach for its simplicity. Determining the best way to allocate carbon budgets is considered to be outside the scope of this study.

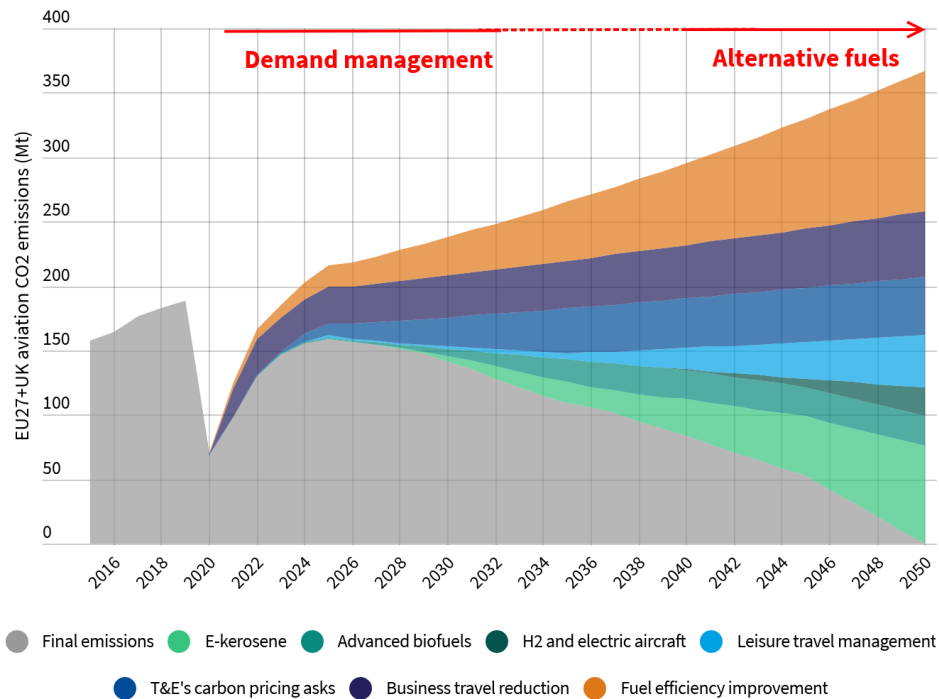


Figure 7: EU27+UK aviation emissions up to 2050 - decarbonisation forecast

Fig. 8 helps us visualise the impact of the different measures on the CO₂ abatement, taking into account the progressive replacement of fossil jet fuel by SAF. In 2030 most of the CO₂ abatement (85%) comes from demand management and pricing measures, whereas in 2050 alternative fuels participate in about half the decarbonisation effort. The contribution of business travel reduction will be particularly important in the coming decade, representing half of the savings in 2030. It is also interesting to note in Fig. 7 that higher SAF prices and T&E's proposed carbon pricing suffices to keep leisure travel below 2019 levels until about 2035, after which additional policies are needed to keep the emissions from growing again. Finally, the contribution of e-kerosene itself grows from 7% of savings in 2030 to 30% in 2050.

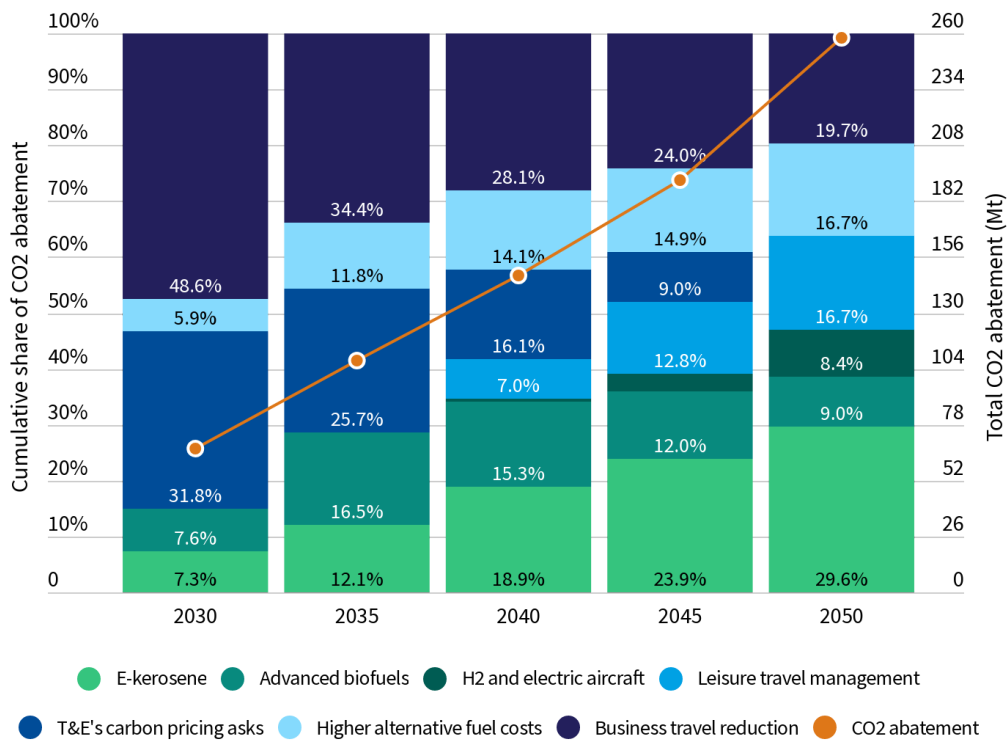


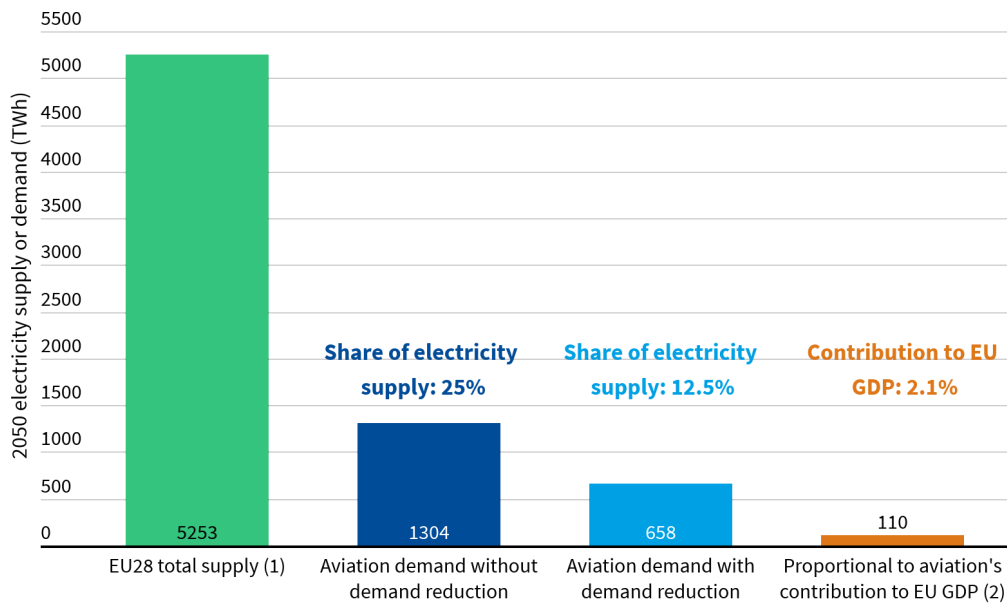
Figure 8: Relative contribution of different sustainability measures to CO₂ abatement between 2030 and 2050 compared to baseline.

4.7. Renewable electricity requirement and SAF production challenges

The main implication of aviation’s heavy reliance on e-kerosene is that the sector will require a huge amount of renewable electricity to decarbonise. We calculated that by 2050 660 TWh of renewable electricity per year will be necessary to produce the alternative fuels mentioned above, among which are 24.2 Mt of e-kerosene, 7.3 Mt of biofuels and 2.5 Mt of hydrogen. As shown in Fig. 9, this corresponds to 12.5% or one eighth of the total electricity production in the EU28 forecasted by the EC in its Climate Target Plan document²⁰ [39]. Though flying brings undoubted economic and social benefits, it is worth noting that those benefits are at present disproportionate to flying’s climate impact and the effort needed to address that impact: commercial aviation currently contributes to only 2.1% of the EU’s GDP [40] and it is estimated that 1% of the population emits 50% of aviation’s CO₂ globally [41]. Aviation’s forecasted electricity demand in 2050 would have a considerable impact on broader efforts to decarbonise the European economy, and there will be competing demand for renewable electricity by all sectors. This highlights that demand reduction not only makes an important contribution to immediately reducing the climate impact of flying, but in the long term also enables an easier transition to decarbonised aviation. Such benefits will be undermined, however, if the demand management and carbon pricing measures

²⁰ Figure 46, scenario ALLBNK

proposed in this paper are not put in place. In such a scenario, 1304 TWh of electricity would be necessary, or 25% of 2050 total electricity.



(1) EGD CTP projection, scenario ALLBNK, including all renewable electricity sources but biofuels

(2) Based on aviation's share of EU GDP, i.e. 2.1%, as stated on https://ec.europa.eu/transport/modes/air_en (21/06/21)

Figure 9: Aviation's 2050 renewable electricity demand and comparison to projected supply and "fair share" demand

INFO BOX - PtL production efficiency caveats

Two elements in relation to PtL production efficiency must be taken into account when considering electricity demand projections. First, there is some uncertainty on the efficiency of future PtL production plants. Efficiency figures used in the literature can vary a lot depending on the assumptions made, in particular on waste heat recovery. The PtL production efficiency we have used, i.e. 61% by 2050, assumes that waste heat from the Fischer-Tropsch synthesis is sufficient to completely cover the heat demand for CO₂ separation [42]. In that case the efficiency of PtL production would be close to that of liquified hydrogen, i.e. 64% by 2050. Other reports, such as McKinsey's [29], use more pessimistic PtL production efficiency. Depending on the actual efficiency of future PtL plants, the electricity demand could be higher than estimated above.

The other important caveat of PtL production is that only around 50% of e-fuels produced in a PtL plant can be used as jet fuel (i.e. e-kerosene), while the remaining 50% would be by-products [36]. In our calculation of aviation's renewable electricity needs, we included only the share of electricity corresponding to the share of e-kerosene in the PtL product slate. In practice, the PtL plant will require about double that amount of electricity to produce the jet fuel and other by-products. This means that

almost twice²¹ the amount of electricity would be required to produce all the renewable jet fuel necessary for the EU27+UK. The by-products obtained in the process would need to be used by other sectors so as not to be wasted, but in most cases direct electrification or other alternative fuels (e.g. hydrogen and ammonia) are more efficient solutions for decarbonisation. This means that producing PtL for aviation comes with an additional penalty in terms of renewable electricity requirements.

4.7.1. Impact of demand management on cumulative emissions

CO₂ emissions persist in the atmosphere and will contribute to heating up the planet for many years. Cutting the cumulative amount of CO₂ emissions in the coming years is the most important metric for limiting climate change: the IPCC has calculated carbon budgets that correspond to the cumulative anthropogenic greenhouse gas emissions allowable to limit warming to different temperatures compared to pre-industrial levels [38]. Counting on a fast ramp up of sustainable fuels in the 2040s is thus insufficient. Effort is required in the 2020s, and our forecast shows that only carbon pricing and demand management can noticeably contribute in the coming decade. Compared to the base case²², letting demand grow freely would result in 27% higher emissions in this decade (1708 MtCO₂ vs. 1343 MtCO₂ in the 2022-2030 period) and 34% from now to 2050 (3864 MtCO₂ vs. 2872 MtCO₂ in the 2022-2050 period). Following a grandfathering approach to calculate carbon budgets, EU27+UK aviation should emit 2.4 GtCO₂ or less²³ to keep temperature increase below 1.5°C. A trajectory without demand management would be closer to a 1.7°C rise even if decarbonisation is reached by 2050, as can be seen in Fig. 10. As shown below, business travel reduction will be of particular importance. If traffic reached 100% of 2019 levels again, cumulative emissions would increase by 15% compared to a 50% business traffic cap.

²¹ The renewable electricity required to produce hydrogen does not have to be doubled in this calculation

²² Caps on business and leisure travel at 50% and 100% of 2019 traffic levels, respectively

²³ Less than 2.4 GtCO₂ corresponds to a more than 50% chance to achieve that goal

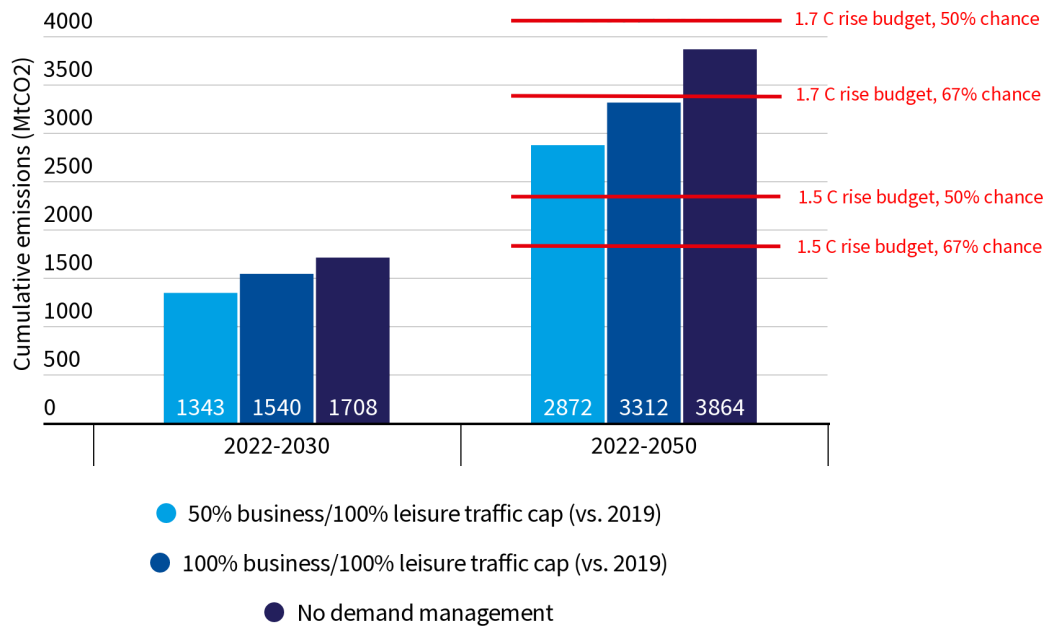


Figure 10: Comparison of the cumulative emissions over the 2022-2030 and 2022-2050 periods in different demand reduction scenarios

4.8. Conclusions on the decarbonisation forecast

Aviation emissions will keep growing if, as in the past decades, policymakers keep failing to regulate the sector. Even with the most optimistic forecasted aircraft fuel burn improvements, which will not happen without effective regulation, emissions would rise by 36% by 2050 compared to levels in 2020. Such improvements are important as they could help save almost a third of emissions, but alone they will not prevent them from rising.

To advance towards decarbonisation, we found that flight demand management is essential for several reasons. Firstly, cumulative emissions are what counts for global warming and the aviation sector cannot wait for the alternative fuels supply scale-up in the 2030s and 2040s to start reducing its emissions. We calculated that if aviation traffic keeps growing as expected, there will be 1 Gt CO₂ more in the atmosphere compared to a scenario where demand is managed, even if decarbonisation is reached by 2050.

Secondly, achieving decarbonisation with only technology improvements and sustainable fuels would require more than one fifth of the EU's projected domestic renewable electricity supply.

Thirdly, over-reliance on e-kerosene to decarbonise the sector is a risky strategy given that the scale and speed at which this technology will be developed is still uncertain. Finally, cutting flights is the only way to mitigate aviation's total climate impact, something sustainable alternative fuels cannot achieve.

For all of these reasons, we investigated the potential impact of several carbon pricing and demand management measures. Reducing corporate travel by half compared to 2019 could save 20% of emissions by 2050 and would benefit the employees, the environment and businesses. Introducing a tax on kerosene, as is already the case with other transport fuels, and reforming the ETS to apply a price on all of airlines' pollution, could reduce travel demand by up to 18%. Further leisure travel management, particularly targeting the most polluting long-haul flights, could bring 16% more emissions reduction compared to carbon pricing only if traffic can be capped to 2019 levels. Together, these measures thus have the potential to halve emissions calculated after efficiency improvements.

Clearly, clean fuels will be needed to decarbonise the sector completely. Having the highest efficiency and no emissions, the electric aircraft is a great technological innovation, but will likely have a limited impact due to its physical constraints. Hydrogen propulsion has more potential, but the industry's 20-year long stall in developing the technology will likely prevent it from saving more than 10% of emissions by 2050. The project is worth pursuing however, and we have shown that CO₂ savings could be tripled if industry players work urgently to get all the elements right, including the economics. This will be conditional on adequate government regulation and support, and regulation to close the price gap between cheap kerosene and green hydrogen. Policymakers should be motivated by the fact that hydrogen has less non-CO₂ impact than other fuels, that it is simpler to produce than e-kerosene, and that it will require less renewable electricity²⁴. For the part of the fleet not running on electricity or hydrogen, sustainable biofuels and e-kerosene will be necessary. Biofuels won't achieve more than 9% CO₂ savings as their feedstocks are limited and hardly scalable. E-kerosene production will thus have to ramp up to supply at least two thirds of the fuel demand by 2050 and achieve one third of CO₂ emissions savings. This would require 650 TWh of renewable electricity, or one eighth of the EU's domestic supply.

The final conclusion of this forecast is regarding non-CO₂ emissions and total climate impact. Currently, it is estimated that total aviation climate impact is about three times that of CO₂ alone. Some of this impact will remain even as fossil jet fuel is replaced by sustainable alternative fuels. In fact, we have shown that total climate impact in 2050 could be as high as 2019 CO₂ impact alone. This shows the importance of putting measures in place to reduce non-CO₂ emissions in the future.

The subsequent chapters provide further details on the forecasts and measures discussed above, with recommendations for policymakers on the next steps needed to ensure a sustainable future for aviation.

²⁴ PtL being made of renewable hydrogen, its production efficiency is lower than that of hydrogen. More information on this can be found in Appendix A Section 10.10.

5. Part II: Policies in support of mitigation measures

6. Pricing aviation and shifting subsidies away from fossil fuels

The aviation sector has remained undertaxed and oversubsidised for too long, which has allowed emissions to continue growing (as mentioned in Section 4.3.1). After decades of exemptions, finally applying the polluter pays principle to the sector will ensure ticket prices reflect the effect aviation emissions have on the climate. But, if disruptive technologies and clean fuels are to be effectively deployed in the coming years, effective pricing should also be accompanied by supportive financial measures. Private and public funding should go hand in hand with effective pricing of aviation emissions. Both measures will send signals to the market and investors that it is time to shift investments away from fossil jet fuelled planes towards greener alternatives.

6.1. Why is pricing pollution so important?

Effective pricing of CO₂ emissions from aviation presents a number of technological, economic and social benefits.

- **Driving fuel efficiency and new aircraft technologies:** one of the reasons for the delay in increasing the uptake of fuel-efficient technologies for aircraft (as described in Section 7) is linked to the availability of cheap untaxed jet fuel, reducing the incentive for airlines or aircraft manufacturers to market disruptive fuel-saving technologies. Increasing the price of burning polluting fossil fuel could therefore encourage airlines to invest in more fuel-efficient aircraft as well as cleaner fuels. Economically, it becomes more advantageous for them to invest in fuel-saving technologies when jet fuel becomes more expensive to use. Research confirmed that taxes on aviation fuel in Japan resulted in less CO₂ emissions [43].
- **Eliminating distortions and reducing price gaps with clean fuels:** the liberalisation of the aviation market, combined with a lack of effective pricing of emissions, has led to the price of flying decreasing considerably in comparison with other modes of transport, such as rail. The emissions linked to the production of electricity used for rail transport are priced and the fuel used for road transport is taxed, but jet fuel enjoyed decades of exemptions from taxation. This created a distortive market where a polluting mode of transport was cheaper to use than cleaner alternatives. Making fossil jet fuel more expensive will also reduce the price gap with SAFs, which currently remain costly due to lack of regulatory incentive to market them. Pricing emissions will also generate revenue streams for governments who can re-invest these into cleaner modes of transport or sustainable fuels, kick-starting the production of expensive but essential technologies like synthetic kerosene.
- **Contributing to social and environmental justice:** the aviation sector has so far managed to enjoy preferential treatment, receiving tax cuts and unfair fossil fuel subsidies. Other industries covered by the ETS (such as power generation or industry plants) decreased their emissions by 8.9% while aviation continued to grow by 1.5% in 2019. It is politically and socially unfair for the

sector to continue escaping its environmental responsibilities while all other sectors and taxpayers are asked to reduce their emissions. Research showed that the top 1% of the population cause half of aviation emissions globally [44], so pricing aviation pollution is also a way to address this inequality. Failing to correctly price emissions from flying leads to subsidies being given to the richest people, while the rest of the population (of which more than half don't fly at all[45]) pick up the bill through lost tax revenue and the cost of climate change. Those super-emitters, who have a disproportionate impact on the climate, using private jets or travelling for business, are the ones who can and should bear the cost of these emissions through effective pricing policies.

INFO BOX - Offsetting is not pricing

After the EU legislated for the inclusion of international flights within its EU carbon market (EU ETS), the UN's aviation agency (ICAO) launched an initiative to attempt to address aviation emissions through the creation of a global offsetting scheme for international aviation, known as the Carbon Offsetting Scheme for International Aviation (Corsia). Unfortunately, Corsia has increasingly been reported to be a cheap ineffective scheme that will never deliver sufficient price signals to encourage the sector to decarbonise [5]. This is why the EU should implement its own measures to address international aviation emissions, such as re-integrating long-haul aviation emissions in its carbon market and taxing the fuel sold for extra-EU flights.

- **Offsetting enables aviation emissions to continue growing:** Corsia does not require airlines to reduce their own emissions, but to pay someone else to reduce emissions while they keep burning fossil fuels. This is incompatible with the Paris Agreement as well as the EU's Green Deal climate targets.
- **Offsets don't actually lead to CO₂ savings:** none of the offsetting programmes approved under Corsia meet all of the required sustainability criteria. All have issues with double counting: many existing projects are delivering emission reductions in sectors that are already covered by their respective country's current climate targets and therefore double counted.
- **Offsets are too cheap to decarbonise:** Corsia will benefit from an oversupply of cheap offsets (less than 1€), which would potentially add at maximum €0.17 [46] to the price of a ticket. These offsets will never incentivise any change in behaviour from citizens or airlines, motivating them to use cleaner fuels or zero-emission aircraft.
- **Global schemes lead to weaker and unchecked ambition:** a scheme crafted by over 180 different countries will lead to decisions being adopted at the lowest common denominator, penalising those regions who want to be more ambitious. ICAO also lacks the power to enforce Corsia itself, as it is up to member states to implement it. It cannot therefore ensure that any of the environmental measures it adopts will be fully implemented by all countries.

6.2. Putting an effective price on flying

This section presents policy pathways to put an effective price on flying, through carbon pricing, ticket taxes and various pricing mechanisms.

6.2.1. Carbon pricing

A combination of different carbon pricing measures can be implemented to try and integrate the cost of emitting CO₂ emissions into the price of a flight. A fuel tax puts a direct price on CO₂ emissions as linked to the carbon content of the fuel, whereas market-based measures like the EU ETS enable cost effective ways of pricing emissions by capping emissions and letting the market determine the price of polluting instead. The effectiveness of these measures depends on the level of the carbon price as well as the scope of the emissions covered.

- **Jet fuel taxation at EU and national levels**

Despite having the option under European law to tax jet fuel domestically and bilaterally since 2003, member states and the EU have been reluctant to change aviation's preferential taxation regime due to lack of political will and strong international pressure, despite other countries like Japan and the US taxing jet fuel on flights within their internal market. The European Green Deal finally proposes to introduce EU-wide jet fuel taxation by removing an exemption in the Energy Taxation Directive (ETD). A report for the European Commission found that taxing jet fuel sold in Europe would cut aviation emissions between 6-15% while raising almost €7 billion in revenues every year if applied to intra-EU flights [47].

All airlines flying to, from, and within Europe should pay a fuel tax if the EU can ever hope to effectively price emissions from burning jet fuel. However, the EU included fuel tax exemption clauses within its air service agreements (ASAs) with some third countries (like the US and Canada)[15], which means the EU cannot yet ask airlines from these countries to pay a tax on the fuel they buy in Europe, unless it asks for a waiver to be negotiated, as already provided for by the EU-US ASA. Furthermore, most of the ASAs renegotiated in recent years no longer include these clauses. The EU should therefore renegotiate the very few ASAs that include fuel tax exemption clauses, in order to allow for a bigger scope of emissions to be covered. This would allow EU governments to tax jet fuel on all flights within Europe irrespective of the airline's nationality, as well as on flights from Europe to and from third countries. In the meantime, until these clauses are re-negotiated, the revision of the ETD should already apply fuel taxes to flights within Europe and extra-EU flights covered by ASAs which provide for fuel taxation.

Despite the EU ETD revision proposing to tax jet fuel, unanimity requirements have been a long-standing obstacle to revising the rules in the past, with member states reliant on aviation using their veto to block a crucial revamp of jet fuel taxation rules. According to T&E analysis, in the EU, the top 6 emitting states & regions alone (Germany, Spain, Nordics, Benelux, France and Italy) account for 72% of intra-EU fuel emissions, while the smallest 13 emitters (including Malta, Cyprus, and Eastern countries) account for 10%. Given this ratio, Europe cannot afford to let a small number of countries block crucial environmental and fiscal reforms.

However, if unanimity rules impede the EU's ability to tax jet fuel at the European level, member states should enter into bilateral jet fuel tax agreements and domestically tax jet fuel, as these options are currently already authorised under the EU's ETD. A series of bilateral taxation agreements focussing on the top intra-EU emitters, combined as necessary with measures to address ASAs fuel tax exemptions,

offers an immediate pathway to introducing fuel taxation in Europe. If a small number of top emitting EU member states and regions (Germany, Spain, Nordics, Benelux, France and Italy) were to agree on a series of bilateral tax agreements, [48] up to €3.7 billion per year in revenue could be raised, covering 59% of intra-EU emissions.

The rate of any fuel tax should be at least as high as the fuel taxes applied to the road sector. In order to address the disproportionate impact private jets have on the environment, the fuel used for these flights should also be priced at a much higher level, as they can be 10 times more polluting than commercial aviation[49].

- **CO₂ emissions trading (EU ETS)**

The EU ETS is a cap and trade system under which airlines (as well as other sectors covered, such as industry and electricity) need to buy allowances to pay for their CO₂ emissions. The system has a decreasing amount of allowances to buy in order to encourage sectors to decarbonise. Initially all flights were included, but, due to pressure from industry and third countries, only intra-EU flights were included in the scheme in order to give the UN aviation agency (ICAO) time to develop Corsia to address extra-EU emissions. But this international offsetting scheme fails to encourage emission reductions (as discussed above) and cannot be considered as setting an effective price on emissions. Studies have shown that the cost of Corsia will represent only a minor share of operating costs[50].

Data analysis has shown that, thanks to the EU ETS's scope being reduced to only intra-EU flights [51], some of Europe's biggest airlines don't pay for over 70% of their emissions. On top of addressing on average only 40% of aviation's total EU emissions, the EU ETS allows airlines to buy allowances from other sectors covered by the scheme, which in practice means that no hard limit is put on aviation emissions. Airlines are always able to buy allowances to counter their emissions growth, as the poor design of the scheme has created an oversupply of allowances over the past decade. Despite carbon prices finally increasing as of 2018, and surplus of allowances being absorbed over time, thus putting a higher price on pollution, airlines still receive a number of free allowances. In 2019, airlines got nearly half of their emission permits for free, resulting in a subsidy of around €900 million. The European Court of Auditors found that free allowances to the sector supported carbon-intensive air travel to the detriment of rail transport [52].

In order to fully account for the cost of EU aviation emissions in the EU ETS, the price signal of the scheme and its scope must be enlarged [53].

6.2.2. Other pricing mechanisms

A growing number of member states have implemented taxes on flights and others are discussing applying minimum pricing for tickets or frequent flyer levies. Despite these measures not being directly linked to a flight's fuel consumption or emissions like the carbon pricing mechanisms mentioned above, they can provide additional ways for governments to address aviation's lack of effective pricing.

- **Ticket taxes to replace lack of VAT applied to flights**

The VAT Directive (2006/112/EC) allows member states, under certain conditions, to exempt passenger transport from value added tax (VAT), by applying reduced rates or a zero VAT rate. This has led to significant distortion of the price of flying compared to other modes of transport as all member states apply a zero rate to international air transport, while only 17 charge VAT on domestic air tickets, either at a reduced rate or at the standard rate of VAT. If all EU countries would agree to a fixed VAT rate of 15% on air tickets, this could generate an additional €17 billion from both intra and extra-EU flights [2].

Given the legislative difficulties in agreeing unanimously to update VAT rules, let alone agreeing to implement a new EU wide air ticket tax, member states should be encouraged to apply their own ticket taxes to fill the gap of not applying VAT. In order to improve the environmental credentials of these flight taxes, member states can link these to the distance flown, by differentiating rates for short, medium or long-haul routes. In addition, the scope of a ticket tax can more easily be applied to extra-EU flights than a fuel tax, as it does not require the renegotiating of some ASAs [54]. A tax applied to extra-EU flights can therefore be an effective measure to address the biggest chunk of airlines' emissions coming from long-haul flights.

A number of EU member states and their neighbours (Austria, France, Germany, Italy, the Netherlands, Portugal and Sweden, together with Norway and the UK) apply ticket taxes with different features. The following elements should be considered when member states implement ticket taxes:

- Include differentiated tax rates based on flight distances, at least between short-haul and long-haul, as they do not have the same environmental impact, for example a specific tax rate for flights of up to 6,000 km, and then a higher tax rate for flights over 6,000 km.
- Remove any exemptions for transit/transfer passengers with origin and destination outside Europe, as these can represent up to 15% of all passengers on aircraft departing from EU airports [55], so the impacts of the ticket tax would be reduced if exempted. Ticket taxes should apply to each segment/flight of a trip.
- Apply multipliers increasing the tax depending on the passenger class in order to address the disproportionate impact of premium & business classes and private jet flights.

- **Minimum pricing and frequent flyer levies to be explored**

Germany, Austria, and France have discussed implementing minimum ticket prices to counter the cheapening of air travel, linked to the development of low cost airlines. Cheap prices are intimately linked to the oversubsidisation of the sector which has contributed to aviation emissions' rapid growth over the last 10 years. Member states should be allowed to apply minimum ticket prices, as it can contribute to effectively pricing the aviation sector's cost on the climate and society.

In order to address the fact that only a handful of frequent flyers cause the bulk of aviation emissions, levies based on the frequency of travel could be implemented to penalise those who fly the most, as they would increase proportionally to their CO₂ impact. However, one of the main incentives for frequent flyers to increase their travel relates to the benefits provided to them by frequent flyer programmes and the need to continue collecting points to conserve special status. These loyalty schemes have stimulated demand for air travel by incentivising travelers to take flights and collect points to benefit from financial

advantages like discounts in stores or credit card programmes in banks. Regulators should address the incentives these frequent flyer programmes provide in order to cut down on excessive frequent flying.

These measures contribute to incentivising behavioural change, but they should not replace carbon pricing which is more directly linked to the actual CO₂ emissions of flying and effectively contributes to governmental budgets that can support the right decarbonisation technologies.

6.3. Channelling subsidies and investments in the right direction

In order to ensure the aviation industry can meet the EU's decarbonisation goals by mid-century, significant investments need to be channelled towards filling the market's gap in developing the right clean technologies for aviation. Public and private funding need to make up for decades of poor environmental regulation, and excessive fossil subsidies that have delayed and disincentivised the market from deploying carbon cutting technologies.

5.3.1. Public finance: ending distortive state aid

Public financing should set an example to markets as to what is an environmentally and economically sound investment in aviation by changing its state aid rules and ensuring that taxpayers' money is linked to strong environmental conditions.

- **State support to be phased out and conditioned to effective environmental conditions**

The Covid-19 crisis put the spotlight on the extent of financial aid given to the aviation industry, as EU airlines received over €37 billion to cope with the impact of fleets being grounded [56], almost entirely without binding environmental conditions. Some of the airlines that received bailouts were already in financial difficulties even before Covid-19, putting into question the use of taxpayers money to finance economically unviable companies.

The current EU guidelines on state aid for aviation allow for operating aid to airports to continue until 2024, but most of the airports receiving operating aid remain unprofitable. This type of aid remains one of the most distortive as it continues to artificially support an unprofitable business despite it contributing to emissions growth. A 2019 analysis of all EU airports served by Ryanair has found that almost one-quarter of these airports are likely to be receiving state aid [57], which contributes to artificially lowering airfares. Public aid should stop supporting airports who have failed to find a path to profitability over the past decade. An evaluation of the EU's state aid guidelines found that aid to airports might not always be the most efficient use of public resources to promote regional development.[58]

In times of climate and economic crisis, there is no justification for public funds to continue financing unsustainable aviation business models, which is why no bailout or state-backed financing should be awarded to the aviation sector without regulators first conducting long term sustainability assessments and imposing strict environmental conditions. For example, the EU and member states should only allow taxpayers' money to support aviation if a sector-wide decarbonisation plan is implemented and binding on the industry, including better pricing of flying and the rapid development of new fuels such as

e-kerosene. The aid provided to airlines during the Covid crisis had no such significant conditions attached to it. [59]

- **Public investments to be geared towards e-fuels & zero-emission aircraft**

Government financing should create the right support to develop zero-emission aircraft and SAFs, rather than serve the ill-fated purpose of supporting aviation's environmentally damaging reliance on fossil fuels.

The European Investment Bank has already announced that it will stop financing airport capacity expansion and conventionally-fuelled aircraft, which is a principle all EU institutions and member states should apply to their own investment policies for aviation [60]. Investments through EU and national funds should focus on scaling up the availability of truly sustainable fuels for aviation, including investing in DAC facilities to produce e-kerosene with carbon captured from the atmosphere. Public funds should also play a central role in identifying technologies that can reduce aviation's non-CO₂ effects.

5.3.2. Private funds on the path to trigger aviation decarbonisation

To further stimulate investments in clean technologies, private financing can also complement public financing, by prioritising investments into decarbonisation rather than expansion of the sector.

- **Aviation recognised as risky carbon intensive investment**

The airline industry has always been known for having high costs and fluctuating revenues which make return on investments for shareholders very uncertain. However, investors have continued channelling funds towards the aviation industry, mostly prompted by the belief that this loss-making industry is too big to fail and will undoubtedly be supported by government finance when in crisis. Their support for fleet and airport expansion has been instrumental in growing the sector's climate impact, and without a change in that direction, the sector's emissions will continue to grow.

However, not only has Covid-19 cast further doubts on the air travel industry's profitability and reliance on business travel revenues, but growing concerns around climate mitigation have only increased investor uncertainty. Private investors are increasingly aware of the associated risks of investing in a sector that has difficulty decarbonising. As demand to address emissions across the economy strengthens, financial markets will seize opportunities to invest in those sectors that will contribute to decarbonising the economy, and therefore provide long term profitability rather than supporting polluting and costly industries whose mitigation pathway remains unclear.

This is a trend already being consolidated for the oil and gas markets, where the cost of capital for long-term petroleum investments is now much higher (around 20%) than renewables' projects which can be funded at a capital cost of 3 to 5% [61]. This attests to longer-term market expectations that the value of petroleum and gas assets is simply worth less. According to the Boston Consulting Group, no big industry performed worse for shareholders in the second half of the decade than oil and gas [62].

This trend should also be applied to aviation-related assets, given the increasing pressure to address the sector's emissions, as investors fear being stuck holding an unsellable and reputation-damaging asset [63]. Private investment must be directed towards the substantial decarbonisation of the sector, by financially rewarding companies and investors that commit to put decarbonisation before expansion.

- **Private investors commitments & green finance needed for uptake of clean technologies**

Investors play an important role in increasing pressure on the aviation industry to commit to ambitious decarbonisation targets. This can, for example, take the form of strict environmental conditions being attached to aviation industry executives' bonuses or salaries rather than only focussing on share price growth. Investors can also start attaching emission reduction targets to their financial investments. Mainstreaming the need to reduce corporate air travel should also increasingly be part of shareholders requests to companies in exchange for their financial support.

When it comes to green finance, in order for investors to support the decarbonisation of the sector while avoiding greenwashing risks, more transparency is needed on whether or not an investment can be considered green. For aviation, greenwashing risks are high as the industry has too easily misused facts in the past to push "green" credentials forward and mislead consumers and investors into believing an airline is "green" by using, for example, sufficient amounts of unsustainable SAFs such as crop-based biofuels or dubious offsetting schemes.

The EU's classification system (taxonomy) of green activities is meant to help investors identify the actual greenness of their portfolios by setting technical criteria assessing whether the activity they are financing is sustainable, transitioning or enabling the move to a zero-emission economy. At present, no activity enables aviation to be green, given its heavy reliance on fossil fuel and the lack of widely deployed zero-emission technology. Taxonomy criteria should therefore acknowledge that until zero-emission aircraft are available, the only way for the aviation industry to prove it is serious about addressing its climate impact is to stop expanding fleets, replacing them with much cleaner options and increasingly using SAFs as they become available in the coming years. Sustainable finance should therefore only focus on supporting the production and deployment of zero-emission aircraft and e-kerosene, as well as airlines with ambitious targets to reduce their CO₂ emissions through these technologies.

6.4. Conclusions and recommendations

Any measure to apply more effective pricing to aviation is essential to eliminate long-standing price distortions that have artificially boosted air traffic and its emissions, and reduced incentives to deploy new technologies. The EU needs to get rid of jet fuel tax exemptions and free allowances under the EU ETS, but member states should also be allowed to pursue their own policies to finally put the right price on aviation pollution. Pricing emissions should be done through a combination of taxes and market-based mechanisms, focussing on covering as many emissions departing from Europe as possible. The larger the scope, the bigger the impact. **T&E's recommended carbon price would be equivalent to €165/tCO₂ by 2030 and €329/tCO₂ by 2050 (Section 4.3.1).** In addition, public and private funds should be geared towards developing the right technologies instead of subsidising the use of fossil fuels or expanding unprofitable & polluting aviation industries.

To achieve these objectives, T&E highlights the following key recommendations:

- **Fuel taxes should be implemented as a matter of priority:** Revising the ETD to apply fuel taxes to flights within Europe and extra-EU flights covered by ASAs which provide for fuel taxation. Renegotiating ASAs which still provide for fuel tax exemptions (mainly the US and Canada)
- **Reform and expand EU ETS:** Europe's EU ETS is proving increasingly effective in reducing emissions, however its price needs to be further strengthened and then applied to flights departing from Europe
- **Ticket taxes should counter the lack of effective taxation of the sector:** member states should implement differentiated ticket taxes on intra and extra-EU flights, based on flight distance and without exempting transfer passengers
- **Private jets & business classes' disproportionate impact to be reflected in pricing rules:** given their disproportionate impact on the climate, any ticket or fuel taxes applied to private jets and premium classes should be higher than for commercial aviation, in order to create much-needed revenue to invest in the decarbonisation of the sector
- **Public financing should set an example to private investors as to what is an environmentally and economically sound investment in aviation** by changing its state aid rules to only support zero-emission technologies and e-kerosene, as well as ensuring that any taxpayers' money is conditioned to strong environmental commitments.

7. Aircraft technology forecast and recommendations

The design and deployment of cleaner aircraft and engines can play an important role in reducing aviation's climate impact. The development of these aircraft, how quickly they enter the fleet, and whether they operate more efficiently is open to speculation. However, in the past years, several assessments and announcements have been made that allow us to paint a picture of what future aircraft design could look like. In this section, we present the technologies most likely to be introduced between now and 2050, estimate their potential to decarbonise the fleet, and give our recommendations to policymakers on how to foster aircraft innovation. The information presented below is based on publicly available reports and informal conversations with various actors from the industry.

7.1. State of play of aircraft design in 2021: improvement in aircraft fuel efficiency is slowing down

Today, commercial aircraft still have the same tube-and-wing configuration they had 60 years ago. Their fuel efficiency has improved a lot over the years but the pace of improvement has slowed down in the last decades. To illustrate this fact, the fuel burn trend of new aircraft from 1960 to 2019, extracted from ICCT's recent study [13], is displayed in Fig. 11. It shows that during the last aircraft design cycle time, i.e. 22.5 years²⁵, the fuel burn of new commercial aircraft has improved by 0.9%/year on average (compound rate). By comparison, the previous 22.5 year cycle saw an improvement of 1.8%/year. Moreover, many models, including the Airbus A320neo, Boeing 737 MAX and Boeing 787 families were introduced into the fleet recently (2014 to 2020). As aircraft replacement times are long and the only known new aircraft models on the horizon are the 777X [13] and A321XLR [64], there is a risk of an innovation gap in the 2020s. This will result in a slowdown in fuel efficiency improvement in the late 2020s and early 2030s once the improvements in the current state-of-the-art fleets have been fully exploited. This is an outcome highlighted by both research institutions and the industry [13, 65].

²⁵ Based on the average airframe retirement age of 22.5 years, from the report "Destination 2050" [11]

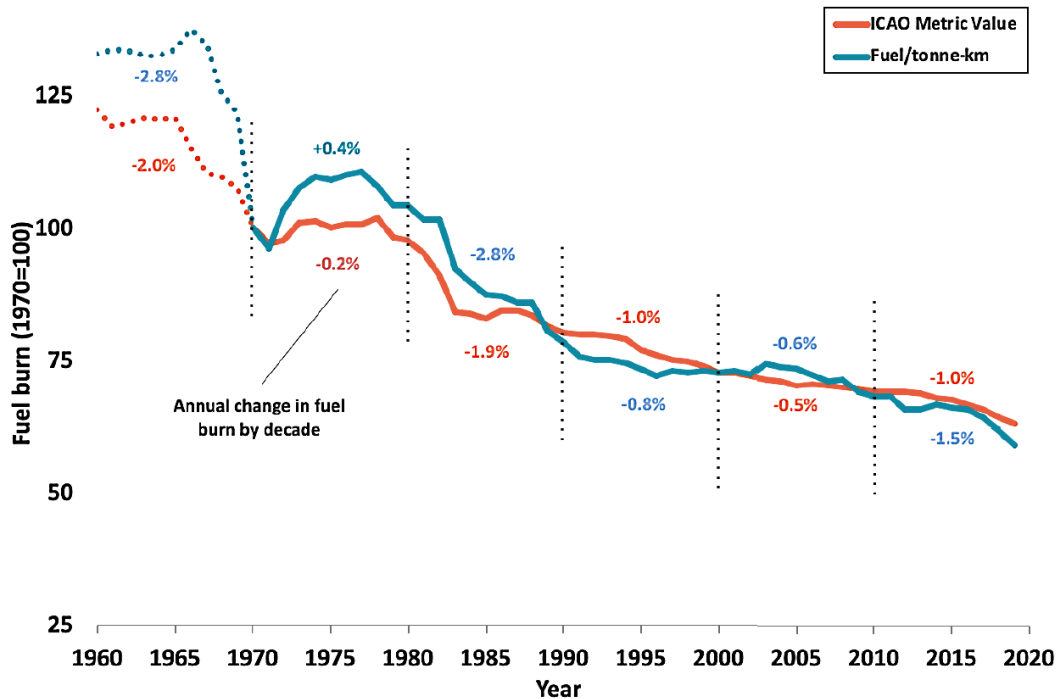


Figure 11: Average fuel burn of new commercial jet aircraft, 1960 to 2019 (1970=100), from [13]

This slowdown can be partially explained by the fact that increasingly diminishing returns are available from technological advances in the current aircraft configuration, but low fuel prices and political failure to regulate aircraft emissions have played their role too [66]. Indeed, oil prices have remained low ever since they nosedived in mid-2014 [67]. With jet fuel king due to its low cost, even more so when effective carbon pricing or fuel taxation is lacking, incentives to renew fleets, increase efficiency and look past fossil fuels are still scarce.

The entry into the market of Chinese aerospace manufacturer Comac (founded in 2008), will not change this lack of innovation in the design of current aircraft configuration, as even the appearance of a new entrant will not solve the problem of diminishing returns in aircraft design [68].

The duopoly between Airbus and Boeing is gradually becoming unbalanced, which may not be good news for innovation, either. Boeing's failures in recent years, including the Boeing 737 MAX fiasco, means that Airbus had almost no competition on the medium-haul narrowbody market, and will soon dominate the long-haul narrowbody market with its new A321 XLR. Boeing therefore finds itself in an especially difficult situation, which raises questions as to its financial provisions to fund the development of a new aircraft family. As for Airbus, while it could make use of its advantage over Boeing to gain a further technological edge [69], it is equally possible that this situation reduces the incentives for taking the risks required to create a new aircraft programme.

Finally, it is noteworthy that the first year and a half of Covid-19 has impacted airlines balance sheets, with the loss of hundreds of billions of dollars in revenue in the wake of the collapse in travel demand.

This has had knock-on implications for manufacturers and resulted in a decrease in R&D spendings, -15% for Airbus and -23% for Boeing in 2020 [70]. While such cuts are temporary, they may delay the development of innovation in the sector, which cannot afford any further delay.

7.2. Aircraft technological improvements in the coming decades

7.2.1. Evolutionary technologies

Evolutionary technologies in aviation refer to those that can be applied to the classical tube-and-wing aircraft configuration with gas turbine propulsion [65]. Until now, the biggest efficiency improvements have been achieved on engines, in particular by increasing their bypass ratio²⁶. Since about 2015, the CFM International LEAP engine has been replacing previous generation CFM56 engines with an approximate improvement of 15% fuel burn, for example from the A320 to the A320neo family. A future ultra-high-bypass ratio (UHBR) engine, ready for the next aircraft generation (around 2030), would only improve fuel efficiency by a further 5-10% [72].

There is still room for improvement with evolutionary technologies, though, as the ICCT pointed out in a 2016 study [73]. In their study, the ICCT estimates that less than 50% of possible efficiency improvements are achieved by recent aircraft designs compared to what would theoretically be achievable on an evolutionary aircraft with 2024 technology. The technologies most likely to improve aircraft efficiency further are aerodynamics (camber, riblets, winglets and wingtips), materials and structure (advanced and lightweight composite) and equipment and systems (monitoring, advanced control, etc.). Some of the material and structural improvements allow the placement of bigger, more efficient engines on the airframe. However, until now, about half of the evolutionary potential has been untapped for several reasons. First, developing “clean sheet” aircraft with new aerodynamics and material technologies is costlier for manufacturers than re-engineering existing airframes with more efficient engines [73]. Development cycles are longer and extra work may be needed to ensure the safety of more innovative technologies. Using re-engined aircraft also benefits airlines in terms of commonality in parts and reduced training requirements for pilots. Low fuel costs and policy failures have encouraged this situation. The long grounding of the Boeing 737 MAX was due to deficiencies in the pilot training protocol regarding a critical safety feature to prevent stalling. These flaws were directly responsible for two crashes with 346 fatalities. This is a tragic example of what can happen when manufacturers put an undue emphasis on short-term cost cutting.

To give an order of magnitude, evolutionary technologies are estimated to be able to bring 15-30% fuel burn improvement for the next aircraft generation (2030-2035), but incentives such as higher fuel prices will be necessary to reach the higher end of that range.

²⁶ The bypass ratio of a turbofan engine is the ratio between the mass flow rate of the bypass stream to the mass flow rate entering the core [71]. A higher bypass ratio improves engine efficiency but comes with design challenges.

7.2.2. Propulsion technologies using liquid fuel

Liquid fuel-based revolutionary propulsion technologies mainly correspond to the open-rotor design and boundary-layer ingestion (BLI). The open rotor technology (Fig. 12a) has been researched for several decades but was slowed down by low fuel prices. The open rotor has two counter-rotating, unshrouded fans and will be about twice the diameter of current turbofans. This makes its integration on the aircraft challenging, brings extra safety concerns, and will require a new certification process [74]. It is also subject to high noise levels and further strengthening of noise regulations around airports could mean its use is forbidden. The open rotor could, with the right policies, enter service around 2030 and bring a 20%-30% fuel burn reduction (20% for the next generation). Safran is working towards that goal, but the engine manufacturer has seen some of its decarbonisation technologies ignored by aircraft manufacturers before (see below for their electric taxiing system).

Boundary-layer ingestion (Fig. 12b) consists in moving engines towards the rear of the aircraft so that air flowing around the fuselage enters the engine to be accelerated. The aim is to reduce the weight and drag of engines by distributing thrust on the main structure of the airframe, which, according to NASA research, could improve engine efficiency by up to 8% [75]. Such a design change is difficult because boundary layer air flow is highly distorted, affecting fan performance and operation. EIS is expected for 2035 at the earliest [65].

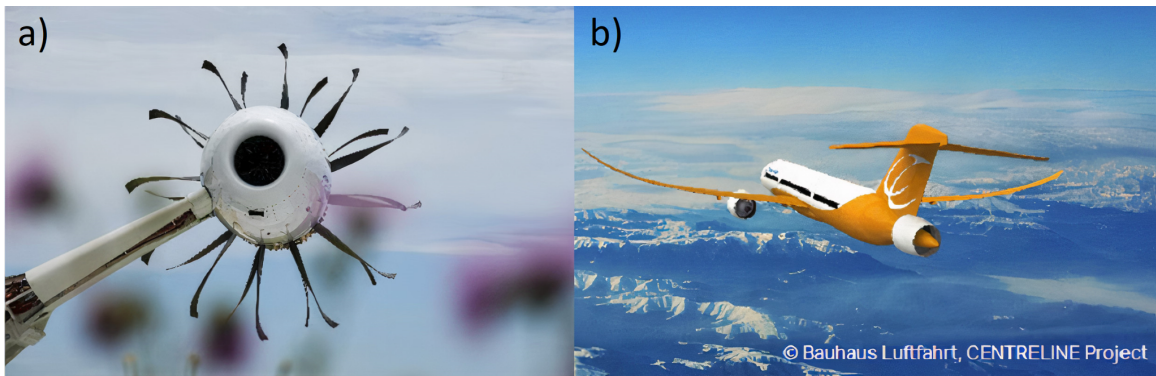


Figure 12: New propulsion technologies. a) Open-rotor engine b) Boundary-layer ingestion

7.2.3. Revolutionary designs

Many designs which break away from the conventional tube-and-wing configuration have been studied in the past decades. These include strut-braced wing (SBW), blended wing body (BWB), box-wing, flying-V and double-bubble fuselage aircraft. However, until now most concepts heralded by manufacturers have never made it to the skies.

Boeing and NASA's Transonic Truss-Braced Wing, a type of SBW aircraft, could be the first "revolutionary" design to fly in the 2030s if the challenges associated with its bigger wingspan can be resolved (see Fig. 13). As the aircraft wouldn't fit normal airport gates, folding wings would be required and fuel would need to be stored elsewhere. This design, however, would not "revolutionise" aircraft fuel burn, improving the efficiency by a modest 9% over a 3500 nm journey [76]. This poses the question of whether high

development costs associated with this new aircraft concept wouldn't be better spent on technologies bringing more benefits, such as aggressive evolutionary improvements or hydrogen propulsion. The structure may, however, facilitate the introduction of other technologies such as open-rotor engines and hybrid propulsion, unlocking double-digit fuel burn savings.



Figure 13: Boeing and NASA's Transonic Truss-Braced Wing concept. (Boeing Creative Services illustration)

The other, more disruptive aircraft configurations mentioned above are not expected before the 2040s and will thus have a limited impact on aviation's emissions by 2050. This includes, for example, the BWB concept (with hydrogen propulsion) unveiled recently by Airbus (see Fig. 14). Such designs should be pursued nonetheless, as some of them could bring substantial fuel burn improvement (25-50% depending on the designs and ranges [65] [72] [77]) and noise reduction in the long run. It is clear, however, that revolutionary designs won't suffice to reach a 2050 decarbonisation target and that zero-emission propulsion methods will be key.



Figure 14: Airbus' blended wing body concept with hydrogen propulsion

7.2.4. Electric aircraft

The interest in electric aircraft has increased in the past decade and more than 200 electric aircraft development plans were recorded in 2019 [78]. However, such planes are expected to tackle only a small share of the emissions in the coming decades because of the fundamentally limited gravimetric energy density of batteries compared to other fuels (hydrogen and JET FUEL). Indeed, even with the expected improvements in battery technology, electric aircraft won't be able to fly much further than 1,000 km with 80-100 passengers by 2050 [11] [26] [29]. Wright says it is targeting 2030 EIS for a 186-seat, 800-mile (1287-km) range electric aircraft, but it is not clear how they will achieve the battery densities that would be necessary for such a feat [27].

Whereas all flights below 1,000 km represent 18%²⁷ of total EU emissions (from departures), those carrying up to 80 passengers that distance currently represent only 2.3%. It remains to be seen whether airlines would switch conventional airplanes for small electric airplanes. This will depend on the economics of these planes and potential future legislation on the ban of fossil fuel on short-haul flights. The development of electric aircraft is worth pursuing, however, as it is the only technology that is truly zero-emission. Furthermore, short-haul aviation will remain necessary where rail cannot be developed or has insufficient capacity. Electric propulsion is also well-suited for private jets since these are small and most of their flights are short-distance ones. Europe has the chance to lead in developing a useful technology with synergies with other sectors such as road transport, and which can become an important export to other markets.

7.2.5. Hybrid-electric aircraft

Hybridisation is seen by some as a necessary intermediate step towards a fully integrated electric propulsion system [79]. Hybrid-electric aircraft combine electric propulsion with the high power density of jet fuel when it is needed, such as during landing and take-off. Various concepts have been studied, achieving potential fuel burn reductions from 5-10% (Onera Dragon [80]) to about 50% for 900 nm range (SUGAR research, co-lead by Boeing and NASA [81]). The higher end of the range is conditional on technological developments such as achieving a battery energy density three times higher than current state-of-the-art technology. At current learning rates, such an improvement isn't expected for several decades [26]. Moreover, hybrid aircraft fuel burn quickly rises with flight range, making them less advantageous for medium and long-haul travel segments, which represent the majority of aviation emissions. For large aircraft, hybridisation remains complicated to implement and batteries are insufficiently advanced, which explains why no major manufacturer has announced the development of a hybrid-electric plane yet. The tradeoff between the costs and potential benefits of this technology should be taken into careful consideration and compared with other potential propulsion methods such as hydrogen fuel cells and hydrogen powered turbines.

²⁷ In-house calculation based on 2019 AIS traffic data purchased to PlaneFinder

7.2.6. Hydrogen aircraft

Aircraft propelled by hydrogen can be classified into three types: fuel cell aircraft, using hydrogen fuel cells to power electric motors; hydrogen combustion aircraft, powered by hydrogen burnt in turbines; and hybrid hydrogen aircraft, using a combination of the two propulsion methods. Liquid hydrogen has a volumetric energy density about 4 times lower than jet fuel and extra insulation must be provided, so bigger fuel tanks are necessary to fly hydrogen aircraft for the same distance as conventional aircraft. A first challenge for the hydrogen aircraft is thus to limit the weight penalty incurred due to these tanks. Of the three hydrogen aircraft types, fuel cell aircraft have the shortest range due to the extra weight of the fuel cell system. Their role will likely be limited to the regional aircraft segment [29]. A six-seater fuel cell aircraft was flown in 2020 [82] and regional aircraft could enter the fleet in the early 2030s, provided that technological challenges, such as reducing hydrogen tank weight and increasing fuel cell power density, are overcome. Hybrid hydrogen aircraft, taking advantage of the higher efficiency and lower climate impact of fuel cells and the higher power density of hydrogen turbine propulsion, could be used for short-haul travel and enter the fleet a few years after fuel cell aircraft. Beyond short-haul, hydrogen fuel cell systems become too heavy and only hydrogen turbines can be used for propulsion. Medium and long-haul hydrogen aircraft are at least two decades away because fuel tanks must be integrated into the airframe and their technology has to be improved to make them light enough [29]. Because of their higher weight, medium and long-haul hydrogen aircraft will require substantially more fuel than aircraft flown on SAFs, and it is thus not guaranteed that they will be cheaper.

When Airbus unveiled new zero-emission concept aircraft powered by hydrogen in September 2020, the manufacturer created considerable expectations. One of its concepts, which Airbus publicly claims is scheduled for entry into service in 2035, would fly between 120 and 200 passengers for a range extending to 2,000 nautical miles thanks to hydrogen combustion [83]; this would enable the decarbonisation of most intra-European flights and 46% of the aviation sector's cumulative CO₂ emissions in Europe in its largest configuration.

However, it is important to nuance these high hopes for hydrogen planes. In fact, Airbus itself is reported to have admitted to senior EU policymakers, just a few months after its announcement, that only 50 to 100-seater regional aircraft (around 5% cumulative CO₂ emission reduction potential) would be ready in the 2030s, and that hydrogen aircraft might not be widely used across short and medium-haul fleets [84] until 2050 at the very earliest. This raises serious questions about Airbus' real level of range and passenger-load ambition with hydrogen aircraft ability and about the time it will take for this potential new aircraft to replace fossil fuel-based fleets. And there are two underlying uncertainties in all this.

Firstly, does Airbus have the financial and engineering firepower to bring such an ambitious programme to completion by 2035, or even to attract enough public and private investments for it to happen, while at the same time pursuing evolutionary aircraft improvements? The risks are high: who would make the kind of investment needed to develop a speculative new airplane for which no clear market exists? The second major uncertainty is whether fuelling infrastructure roll-out will be fast enough and whether airports will be willing to have two energy systems in parallel.

There are two other structural vulnerabilities associated with relying on the technology to solve aviation's climate problems. Firstly, most emissions are caused by long-haul flights, which hydrogen will not be able to power in the foreseeable future because of engineering constraints linked to weight and volumetric penalty associated with the large fuel tanks that would be needed. Secondly, it is still unsure what the non-CO₂ effects of hydrogen planes will be (see section 4.4.3. for more details). On the one hand, hydrogen combustion produces water vapour, which is one of the causes of contrail formation, while on the other, combustion does not generate any particulate matter.

But the real challenge, as is so often the case with hydrogen technologies, is cost. Aircraft designs would need to be adjusted; hydrogen storage tanks added; and refuelling and storage infrastructure created around airports. Fuel costs, which make up around 40% of aircraft operating costs, would also be higher. Our calculations show a 165-seater hydrogen aircraft would cost 14% to 33% more than an aircraft running on conventional jet fuel [85]. And that's without counting any of the development or hydrogen supply chain costs.

As a result, even if hydrogen medium-haul planes were to be made widely available in the 2050s, they won't be the silver bullet to solve aviation's climate problems. However, this does not mean that hydrogen aircraft are not a project worth pursuing. First, they enable us to diversify the sources of aviation decarbonisation, and not solely rely on SAFs. Second, even if no scientific consensus currently exists, hydrogen is likely to have smaller non-CO₂ effects than other fuels, SAFs included. It is therefore important that governments support the development of hydrogen aviation by introducing technology forcing standards and establishing an industrial strategy in support of such zero-emission aircraft development programmes.

7.2.7. 100% SAF compatible aircraft

As will be explained in Section 8, SAFs hold one of the most readily available keys to aviation decarbonisation, given that they are drop-in ready, that is to say they don't require any infrastructural or technological overhaul. It is, however, important to note that the maximum blend of SAF in an aircraft's tank is currently limited at 50% [86]. This is due to the fact that fuel seals in most aircraft were engineered to need petrochemical compounds known as aromatics, which are naturally found in fossil jet fuel, to function normally in the long run. SAFs have less or even no aromatics, which means that seals have to be re-engineered with different materials to mitigate this. As a result, the road to 100% SAF certification still presents some engineering challenges which will have to be overcome. The fact that most engine manufacturers are already working on such programmes brings reasonable confidence on the matter. That being said, even with 100% SAF-compatible aircraft, the biggest barrier to the uptake of SAFs remains their high cost compared to fossil jet fuel, which makes the case for an appropriate level of policy support, as further explained in Section 8.

7.2.8. Other ways to improve fuel burn

7.2.8.1. Electric taxiing system

E-taxiing technology enables aircraft to be taxied across the tarmac using electricity, and could reduce fleet emissions by 3 to 5% if applied widely [11] [87]. Engine manufacturer Safran has had the technology ready for retrofit for several years but aircraft manufacturer Airbus has decided not to take advantage of it, deeming it economically disadvantageous [88]. This is a good example of the lack of incentive for aircraft manufacturers and airlines to use technologies that would reduce their climate impact so long as the fuel they use remains cheap and untaxed. The technology *should* be adopted in next-generation aircraft which will not enter the fleet before the 2030s, meaning that for more than a decade, up to 5% of emissions that could easily be avoided will continue to fuel aviation's growing climate impact. Pricing mechanisms such as EU ETS and kerosene taxation, as well as regulatory support such as the Alternative Fuel Infrastructure Regulation, will support the deployment of this technology.

7.2.8.2. Flight speed and altitude optimisation

Optimising flight speed and altitude can be seen as an operational measure but it could also entail design changes e.g. to make aircraft optimally efficient at lower speeds. Research in the area is scarce but should be stimulated as work done at the MIT shows that, with no aircraft redesign, optimising speed and cruise level of planes could still represent a 2.6% fuel reduction on a typical day of US air traffic. Moreover, research led by Bauhaus Luftfahrt found that designing a long-haul hydrogen aircraft to fly at Mach 0.7 instead of the typical cruise speed Mach 0.82 would save 10% fuel, while having virtually no influence on the average utilisation per aircraft [89]. This is because long-haul aircraft spend on average 20 to 30% of their time unutilised on the ground (after maintenance and turnaround) [90], so a slightly longer travel time does not necessarily result in a loss of productivity for the airline. Reducing the flight speed for shorter flights, for example intra-EU, would likely have an impact on productivity and utilisation, particularly for low cost carriers that have a fast turnaround time at airports. Given the share of long-haul flight emissions, however, these types of optimisations are worthwhile endeavours.

INFO BOX - supersonic aircraft

A number of companies have announced efforts to bring back commercial supersonic transport. But, as research shows [91], the extraordinary negative environmental impact of these aircraft, especially the climate impact, is often overlooked.

Supersonic aircraft have very high fuel consumption and therefore generate significant CO₂ emissions, far exceeding those of subsonic aircraft.

Policymakers should therefore be wary of facilitating the return of supersonic commercial flight, and devise measures to ensure that any potential reintroduction does not result in a net increase in civil aviation's climate impact compared to a 'no supersonic' scenario. Given that manufacturers have not put forward such measures, the most prudent approach would be to fully reject a reintroduction of supersonic transport.

Caution should also be advised when it comes to those supersonic aircraft that would run exclusively on SAF, thus aiming to be carbon neutral. Indeed, not only is it highly unlikely that enough alternative fuels would be available in the short term, this also risks diverting SAFs from conventional aircraft for a highly polluting niche segment that will only cater to the wealthiest travellers. [92]

7.2.9. Summary of upcoming decarbonisation technologies

In Table 4 we summarize the main upcoming aircraft technology that could participate in decarbonising the fleet in the next decades, their CO₂ reduction potential, EIS and challenges.

Technology	Applicable aircraft range (km) and size	CO ₂ reduction potential vs. 2015 aircraft [26] [29] [72]	Fleet CO ₂ reduction potential by 2050	EIS for short-haul commercial aircraft	Main challenge(s)
Evolutionary technologies (aerodynamics, materials and structures, equipment and systems)	all	15-30%	15-30%	Limited continuous improvement, next generation not before 2030	Lack of incentives for costly development Gap in innovation until 2030s
Propulsion technologies using liquid fuel (open-rotor, BLI)	all	20%-30%	20-30%	2030	Noise and safety (open-rotor) Blade engineering (BLI)
Revolutionary designs	depending on design	30%-50%	<5%	> 2040	Safety Development costs
Electric aircraft	~1000 km, regional jets mostly	Electric: 100%	<10%	2030-2035	Battery weight
Hybrid-electric aircraft	1000-2000 km, short-haul	Depends on size and range of aircraft	<10%	2030-2035	Increased complexity for large airframe
Hydrogen aircraft			²⁸		Economic viability Safety Fuel tank weight
- Fuel cells	~1000 km, regional	100%	~5%	2030	
- Hybrid (fuels cells and combustion)	~2000 km, narrow-body	100%	~10%	2035	

²⁸ These numbers heavily depend on the EIS of different hydrogen aircraft and fleet replacement times

- Combustion	>2000 km, mid-size	100%	~20%	2040	Scaling of production
SAF (incl. e-kerosene)	all	100% ²⁹	75-100% ³⁰	Now: 50% SAF 2030: 100% SAF	
Flight speed and altitude optimisation	all	Up to 10% (to be researched further)		Next generation (2030)	Scarce research No incentive

Table 4: Main possible technological improvement categories for aircraft design in the next decades

7.3. Policy support for aircraft design improvement: fostering innovation in the aviation sector

It is clear from the above that new aircraft designs hold one of the keys to aviation decarbonisation. However, relying on the industry alone to develop such ambitious programmes would be ill-advised. Not only is the aviation industry in a somewhat fragile situation in the context of the Covid-19 pandemic, its actors are only best geared towards short and medium-term decision making. The EU and European governments therefore have the means and the responsibility to help foster more innovation in the aviation sector. This would not only help Europe meet its climate targets, it would also help establish Europe as the global leader in climate forcing mitigation technologies for aviation and give a boost to multiple innovative chains in the decarbonisation of the EU economy: green hydrogen, e-kerosene production, electric propulsion, composite materials, etc.

It is therefore essential that the EU puts in place strict efficiency standards for new aircraft. Such a target could begin with an earlier obligation to use ZE aircraft on certain short-haul routes as well as for all private jet flights, which are particularly well-suited to spearhead these emerging technologies. This will provide an adequate sense of urgency, forcing industry stakeholders to think in the longer term.

To achieve this primary recommendation, four areas of policy support can be singled out:

- **Incentives:** First, decision makers should introduce policies to encourage fleet wide renewals - for example fuel taxation, additionally taxing dirty aircraft to accelerate phaseouts, or linking the auctioning of slots at airports and airport charges to aircraft efficiency. Second, decision makers should create more “investor certainty” regarding funding new aircraft programmes by making sure that zero-emission aircraft are included in the EU’s taxonomy of sustainable investment. Fiscal signals should also be given to make sure that zero-emission aviation becomes gradually more affordable compared to conventional flying.
- **Supporting R&D:** Governments should support fundamental and applied research into new aircraft designs while making sure that their funding supports projects strictly geared towards reducing aviation’s overall climate impact.

²⁹ Depending on deployment and lifecycle emissions of SAFs

³⁰ Depending on deployment and lifecycle emissions of SAFs

- **Supporting industry cooperation:** Innovation relies on more vertical and horizontal industry cooperation. Governments should therefore encourage industry stakeholders to come together and engage in both new aircraft research and development, as in the case of the French Strategic Advisory Board for Civil Aviation Research (CORAC in French).
- **Faster testing and certification (incl. hydrogen aircraft certification):** The rapid development of zero-emission aircraft very much depends on an equally rapid testing and certification period, in full compliance with the highest safety standards. While hydrogen or electric commercial passenger aircraft are in development, certification authorities should already be prepared with the necessary procedures, which depend on their ability to quickly master the new technology.

7.4. Conclusions and recommendations

New aircraft designs currently hold a significant, but not sufficiently exploited, potential to reduce aviation's climate impact. Evolutionary technologies could bring 15% to 30% emissions reduction, but low (and tax-free) fuel prices currently don't provide the necessary incentives to meaningfully follow this pathway. Revolutionary designs (departing from the conventional tube-and-wing configuration) won't be ready in time to make a significant difference to aviation's emissions by 2050, even assuming that manufacturers will embark on these highly risky ventures. The same goes for electric propulsion, for which constraints around the energy density of batteries raise doubts over whether technology can power more than commuter aircraft, a drop in the ocean of aviation emissions.

Hydrogen aircraft provide more hope, namely their ability to eliminate almost half of aviation CO₂ emissions and possibly even non-CO₂ effects. Caution must be observed: not only is hydrogen currently incapable of powering long-haul aircraft, Airbus itself recognises that hydrogen short and medium-haul aircraft won't be widely used before 2050 at the earliest. Furthermore, there are currently many more questions than there are answers as to the economic viability of hydrogen aircraft, especially when factoring in their high development costs. In addition to these structural constraints, the state of innovation in the aviation industry is currently challenged by the aftermath of the Covid-19 pandemic.

It is therefore vital that policymakers help untap the potential of new aircraft designs for sustainable aviation by setting strict efficiency standards for new aircraft. To help the industry achieve this ambitious goal, governments and the EU should accelerate their support mechanisms, most notably in the four areas described in Section 7.3: incentive schemes, R&D support, industry cooperation and certification processes.

8. Fuels

Developing Sustainable Aviation Fuels (SAFs) is a core policy to bringing flying's CO₂ climate effects close to zero. While in the short and medium term, reduced flying can have the greatest impact, and while new zero-emission aircraft may play an important role in the future on certain routes, ultimately the sector needs a sustainable alternative to fossil jet fuel to power its existing and future aircraft fleets, especially for long-haul flights where zero-emission aircraft will struggle to penetrate.

While the right SAFs can bring aviation's CO₂ climate effects close to zero, they can also play a role in reducing the sector's non-CO₂ effects. That's because such fuels can have a lower amount, or even absence, of aromatics, a chemical compound contained in fossil fuels which contributes to aviation's non-CO₂ effects, as described in Section 9. The level of potential reduction in aromatics, and the benefits that would bring in mitigating these non-CO₂ effects, remains unknown and requires further study.

Developing the right SAFs for the sector is a major challenge, given its current lower availability and higher costs relative to untaxed fossil jet fuel. There are risks which must be managed, and the right suite of measures must be adopted in order to bring about an uptake of these fuels in a sustainable and effective manner.

8.1. What type of fuels to develop

The greatest determinant in the environmental effectiveness of SAF policy is the type of feedstocks used to develop the fuels. That's because the actual emissions reductions can vary wildly, from fuel derived from crop-based feedstocks whose emissions can actually be higher than the fossil fuels they seek to replace, to synthetic e-kerosene derived from additional renewable electricity and CO₂ captured from ambient air, which can have close to zero emissions if produced correctly. At the same time, many feedstocks can have considerable negative environmental (biodiversity, water) and social (land use, indigenous rights) impacts. To avoid this, any SAF policy for aviation must choose its preferred feedstocks wisely, and ensure sufficient climate, environmental and social safeguards are in place.

The process has begun in Europe, with the European Commission's July 2021 ReFuelEU proposal including binding targets for the use of SAF. As detailed in this section, that proposal is a start, but further work and further safeguards are needed.

8.1.1. Crop-based biofuels

The first step is to exclude the use of **crop-based biofuels**. Under the provisions of the Renewable Energy Directive (RED), these have been the dominant feedstock for alternative fuels used in the road transport sector in Europe; however, the climate impact of such fuels are in fact negative when the indirect land use change (ILUC) effects are taken into consideration [93], especially for virgin vegetable oils. When existing agricultural land is turned over to biofuel production, agriculture has to expand elsewhere to meet the existing (and growing) demand for crops for food and animal feed. This happens at the expense

of forests, grasslands, peatlands, wetlands, and other carbon-rich ecosystems, and in turn results in substantial increases in greenhouse gas emissions.

ILUC is a key factor that shows why crop biofuels are not an effective decarbonisation option for transport. Issues relating to impacts on biodiversity, water use, local communities and food prices are also considerable.

Used Cooking Oil (UCO), as well as some types of animal fats, currently play a major role in providing feedstocks for alternative fuels used in Europe. They are recognised under European legislation, though falling outside the category of advanced biofuels. They are considered preferable to crop-based feedstocks as they do not compete with land for food. However there are serious doubts as to the sustainability of these feedstocks and the claims which surround their positive environmental benefits. Such doubts largely relate to the sourcing of such feedstocks, and in particular whether they are not competing with other uses. [94]

8.1.2. Advanced biofuels

In order to avoid some of these negative effects, a potential alternative option is **advanced biofuels**. These are biofuels produced from waste and residue. Such feedstocks include municipal waste, straw, and forestry residues. The development of these fuels comes from a desire to support those feedstocks which do not compete with land, and so to avoid the ILUC issues raised above. The Annex IX of the RED provides a list of eligible feedstocks. However the feedstocks listed in this Annex are not without issue, for example some feedstocks are not real waste or residues, they have displacement effects as some already have uses (their use as a fuel drives an undesirable uptake of other, more damaging, feedstocks) and some feedstocks have a limited ability to be scaled-up. Further distinctions within feedstock types is also important. For example, for municipal waste only biowaste that is separately collected should be considered.

Because of these limitations on sustainable feedstocks, it will not be possible to meet the fuel demands of the aviation sector through such fuels, regardless of the level of demand. Our forecast, detailed in Section 4.5.1, suggests that a maximum of 1.3Mtoe in 2030 (corresponding to 3.4% forecasted energy demand) and 7.5Mtoe in 2050 is feasible. Any effort to set targets higher than this would result in either targets which are missed, or targets which rely on the use of unsustainable feedstocks.

While advanced biofuels can never be scaled up to meet even the majority of aviation's fuel demand, they can play a role in the overall mix of SAFs used to displace the use of fossil kerosene in the aviation sector. Particularly in the short term, while more promising long-term alternatives such as e-kerosene (below) are developed, they can help the aviation sector move away from its current almost 100% reliance on fossil fuels.

8.1.3. E-kerosene

E-kerosene, sometimes known as e-fuels or synthetic kerosene, is generated by combining hydrogen (H₂) and carbon dioxide (CO₂). Our briefing explains this fuel in more detail [95]. Two conditions are essential for e-kerosene to have near zero greenhouse gas emissions. First, hydrogen needs to be produced using additional renewable electricity (so-called “green hydrogen”). Second, carbon dioxide needs to be captured from ambient air, a process otherwise known as direct air capture (DAC). This way, the life cycle of e-kerosene will, apart from some residual emissions, be close to CO₂ neutral.

E-kerosene is a more viable option to decarbonising aviation than crop-based and advanced biofuels since its primary feedstock, renewable energy, has the potential to be scaled up to meet the fuel demands of the aviation sector given certain conditions, primarily a management of the level of overall demand. However, to get e-kerosene produced in the correct manner (additional renewables and DAC), and to get that production scaled up to reduce emissions from the sector, represents a particular challenge.

As mentioned above, for e-kerosene to deliver on its promised emission reductions, production needs to be done right. That primarily relates to ensuring that the renewable electricity used to produce green hydrogen is additional, in order to avoid diverting renewables needed to decarbonise other sectors of the economy. This is particularly important given the enormous amount of electricity required to produce e-kerosene, which is a result of the inefficiencies in the production process. Even in scenarios where aviation demand is managed, as discussed above, through reductions in corporate travel and capping leisure travel, by 2050 660 TWh of renewable electricity per year will be necessary to produce e-kerosene to meet aviation’s fuel demand. That’s equivalent to 12.5% or one eighth of the total electricity production in the EU28 forecasted by the EC in its Climate Target Plan [96].

There are numerous means of ensuring such additionality, with the clearest being a requirement for e-kerosene producers to construct renewable capacity matching their electricity needs alongside construction of their production facilities. Other options include a requirement to support, less directly, the construction of renewable electricity and design of market conditions which will bring about enhanced renewable capacity in response to the additional demand from e-kerosene production. One mechanism which could be pursued is a requirement for producers of e-kerosene to negotiate Power Purchase Agreements [97], which are agreements between producers and consumers to deliver renewable electricity at an agreed price [98].

Alongside the additionality of renewable electricity, an important requirement for e-kerosene is that its production uses CO₂ taken directly from the atmosphere, known as direct air capture (DAC). An alternative is to capture CO₂ emitted from industrial facilities, a technique called point source (PS); however, this lacks the circularity of taking from the atmosphere, and risks continuing the use of fossil fuels in that combustion process. Another option is to capture CO₂ from biogenic sources, namely the combustion of biofuels for the purpose of generating electricity. This is claimed to be circular, as the production of biogenic feedstocks extracts CO₂ from the atmosphere; however, it is an inefficient use of

land, and the production of the quantity of biogenic feedstocks needed raises issues of biodiversity and land rights.

While PS may for a period provide some of the CO₂ required, it is essential to scale up the production of DAC CO₂ to meet the growing demands for e-kerosene. As with any new technology, and particularly with a new technology required to reduce emissions, the early stage of its deployment is marked by high costs and low supply. Increasing supply and decreasing costs is therefore essential, and governments can ensure that by adopting the sort of policies which have traditionally delivered such outcomes: R&D supporting the technology and mandates for their use, thus giving strong signals to both producers and investors.

In the case of DAC CO₂, regulators should require that a minimum and then growing share of the CO₂ used in e-kerosene production comes from DAC. This mandated demand would create a market and thus attract the right investment in DAC, helping scale up production and drive down cost. Costs can then further be reduced by providing R&D support for this technology. A report commissioned by T&E on the role of DAC in the development of e-kerosene has found producing this fuel with 100% DAC in 2050 would require 365 Mt/yr of CO₂ to be captured, which could be met by a land area of 950 km², the equivalent to around 6% of the land area of Belgium [99]. That estimate is based on the 2018 Roadmap's higher demand for e-kerosene, and would therefore be lower according to this Roadmap's forecast.

An associated challenge is the cost for such a transition. The aviation industry has enjoyed an extended period of low fuel costs, caused in particular by the fact that fossil jet fuel remains untaxed anywhere in Europe. E-kerosene will, due to its status as a new technology, and due to its considerable electricity demand, have a higher cost at the start of production. The cost will come down over time, and could someday reach parity with the price of taxed fossil jet fuel.

Some sections of the aviation industry have stated that the increased cost of SAFs is a reason to oppose higher targets. Such a concern is misplaced. Current proposals under consideration by the EU would introduce SAF mandates (advanced biofuels and e-kerosene) as low as 5% in 2030 and 15% in 2035. Such targets can be increased further, but an increase would still not have a substantial impact on the balance sheets of airlines.

A far greater threat to airlines is that the sector remains disproportionately reliant on fossil jet fuel. That would only further drive calls for more drastic reductions in flying, and would create an even greater gap with the decarbonisation which is occurring at a greater rate in other sectors such as road transport. The exclusive reliance on fossil fuels also leaves the sector vulnerable to price fluctuations and issues with sourcing such fuels from sometimes geopolitically unstable regions.

8.2. European Commission's ReFuelEU proposal

The European Commission's July 2021 "Fit for 55" package of measures includes its ReFuelEU legislative proposal, which contains a mandate for both advanced biofuels and e-kerosene starting at 2% for both fuels in 2025, increasing to 5% by 2030, but with a minimum share of 0.7% e-kerosene. The target then

increases further to reach 63% SAF in 2050, with e-kerosene constituting 28% of that. The proposal for binding targets is welcome, especially with a subtarget for e-kerosene; however, the targets themselves are short of what is needed to sustainably decarbonise the sector. In particular, given the scarcity of sustainable feedstocks and competing uses by other sectors, the targets for advanced biofuels are too high and the subtargets for e-kerosene are too low.

How to successfully implement binding targets for such fuels is detailed in our position paper [100], published in advance of the Commission's ReFuelEU initiative. But a priority is to fix the level of targets correctly, and to rectify that proposed imbalance between advanced biofuels and e-kerosene.

8.3. Conclusions and recommendations

Developing truly sustainable SAFs for the aviation sector is an urgent project, and it will be extremely challenging to scale them up to meet the sector's substantial fuel demands. It is important therefore that regulators adopt an ambitious suite of measures, including the safeguards necessary to ensure that these fuels are truly sustainable.

Such ambitious measures must begin with binding targets for the use of such SAFs. The July 2021 ReFuelEU proposal falls far short of such necessary ambition. **Its target for e-kerosene needs to be raised to 2% by 2030, with the target for advanced biofuels reduced.** Such a target for e-kerosene is extremely ambitious; however, it can be achieved with the right combination of European and national policies, and coordination of public and private investments. Industry actors, particular airlines and fuel producers, could contribute to such a target through setting their own ambitious targets for e-kerosene use.

As discussed above, and in other T&E publications in support of ReFuelEU, **additional safeguards are needed to ensure that e-kerosene produced is truly sustainable** [100]. That includes ensuring that the renewable energy used to produce such fuels is additional, and that the CO₂ used in production is sourced from DAC. This should begin with a requirement for a minimum share of 30% DAC at the start, increasing over time so that ultimately only DAC is used in production [100].

Advanced biofuels used should stick to strict sustainability criteria, which require amendment to the RED's generous definition of what is considered a sustainable advanced biofuels feedstock.

9. Non-CO₂ effects of aviation

Policymakers and industry have swept aviation's non-CO₂ effects under the carpet for years. Several requests were made by some policymakers to address the issue back in 2008, but no binding policy to mitigate these effects has yet been adopted despite these effects now representing **over two thirds of aviation's total climate impact** [101]. However, studies have recently updated the scientific understanding of these effects and highlighted the need to finally address one of aviation's long-ignored climate problems.

9.1. Different non-CO₂ effects

When an aircraft burns jet fuel, it releases carbon dioxide (CO₂), but it also produces emissions which change the chemical composition of the atmosphere and contribute to global warming.

9.1.1. Contrails and NO_x: main drivers of non-CO₂ effects

Aviation's main non-CO₂ effect is caused by contrails, the long cloudy strips that usually form at high altitude and through cold and humid air, where moisture in ice-saturated air freezes around soot particles released when jet fuel is burned. While most contrails disappear within minutes, others persist, spread and eventually form cirrus clouds. These have a strong greenhouse effect by trapping heat radiating from the earth's surface, especially at night when on a net basis such clouds trap heat but do not have any incoming heat to reflect.

Nitrogen oxides (NO_x) also create ozone (O₃) that traps heat radiation from lower altitudes and warms the air. NO_x also leads to the destruction of ambient methane (CH₄), which has a cooling effect, but NO_x remains a net positive warming agent overall. The largest aviation non-CO₂ impacts are those from net-NO_x and contrail cirrus.

- **Other non-CO₂ effects**

Other non-CO₂ climate warming chemicals released when burning jet fuel include water vapour and oxidised sulphur species such as soot and sulphate aerosols.

Water vapour is the main product resulting from the combustion of hydrocarbons. Overall, water vapour only has a small warming impact. However, this is only true for the present-day fleet and doesn't take into account the potential impact of new technologies. Research suggests that any future supersonic fleet would fly at higher altitudes than current subsonic aircraft and emit water vapour into the dry stratosphere, which could result in an additional climate warming. In addition, hydrogen aircraft would also release more water vapour than conventionally fuelled fossil aircraft, which could also increase the formation of contrails, although it remains unclear whether these would be persistent, i.e. those having a climate effect.

When it comes to soot and sulphur particles, they originate from the jet fuel combustion process. In the atmosphere, the direct effect of sulphur particles is a small positive cooling caused by their reflection of solar radiation back to space, while, due to their trapping of infrared radiation, the direct effect of the small 'black' particles of soot is warming. Although these direct effects are rather small, the indirect

effects could potentially be large, as they can influence the formation of clouds; however, current scientific estimates remain uncertain .

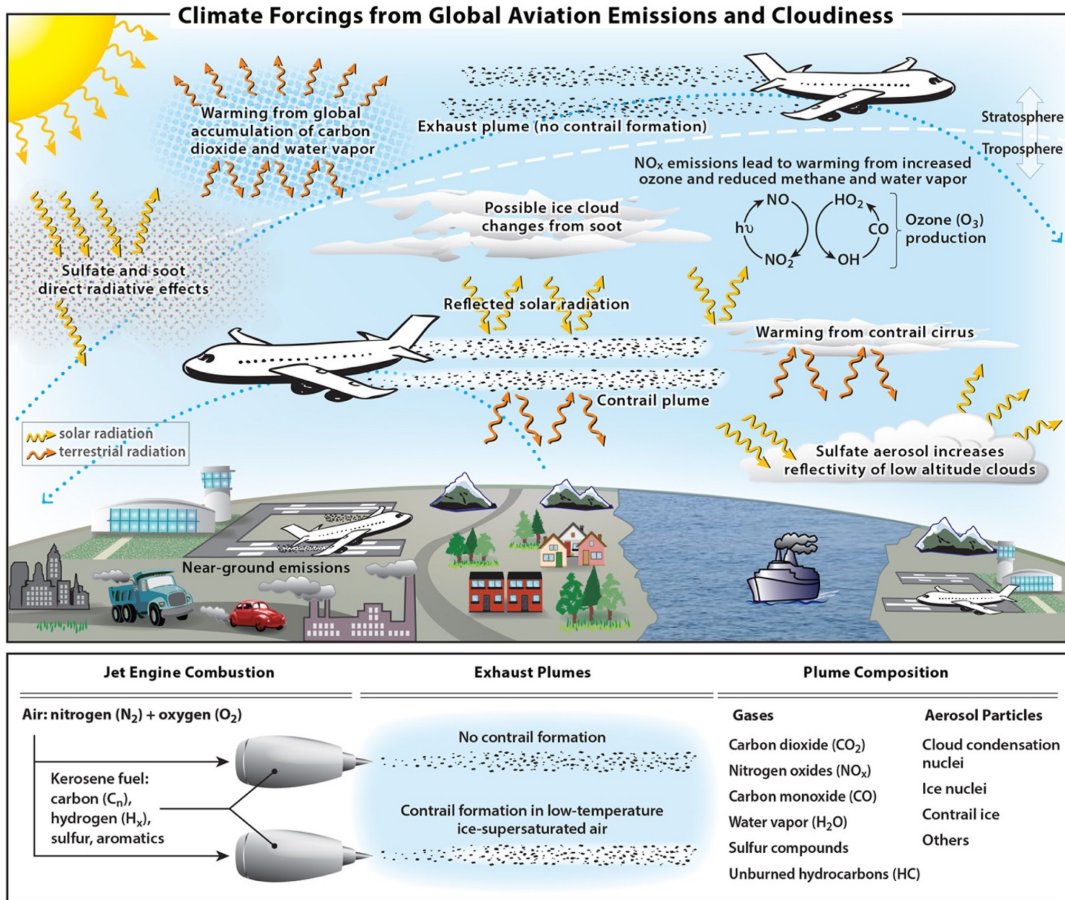


Figure 15: Representation of climate forcings from aviation emissions, from [102]

9.1.2. How to measure aviation’s total climate impact?

Unlike CO₂ emissions, which stay in the atmosphere for hundreds of years, non-CO₂ effects can be short-lived: they can disappear over the space of a few hours to a few weeks. This doesn’t prevent them from actually warming up the climate significantly more than CO₂, but the difference in their lifetime makes quantifying their impact and comparing it to CO₂ more difficult. Many different metrics exist to help measure the global warming impact of non-CO₂ effects and to compare them with those of CO₂.

- **Radiative Forcing (RF):** RF measures the change in the balance between radiation entering and exiting the atmosphere that is caused by changes in atmospheric concentration relative to a pre-industrial atmosphere. This metric is largely used by the scientific community as a way of measuring expected global temperature change due to the presence of greenhouse gases in the atmosphere. However, RF does not account for second-order effects in the atmosphere, such as short-term reduction in natural cirrus clouds as a result of contrail formation, which reduces the

ambient humidity. RF therefore cannot directly provide any emission equivalence on the climate impact of CO₂ and non-CO₂ emissions.

- **Effective Radiative Forcing (ERF):** like the RF metric above, this metric quantifies how much aviation has warmed the climate since the start of the industrial revolution (1750), but it takes into account the rapid adjustments and interactions between the different climate forcing gases in the atmosphere. It therefore calculates some of the non-CO₂ effects of aviation more accurately. According to the most up to date scientific understanding, the ERF from the sum of non-CO₂ effects from aviation leads to a **net warming effect that accounts for two thirds (66%) of aviation's net warming in 2018**. Using this metric, scientists estimate that the contribution of global aviation in 2011 was 3.5 % of overall global warming [102] which is considered to be a similar ratio to 2018.
- **Global Warming Potential (GWP):** this metric is more forward-looking than the ERF, as it tries to model the warming impact of different gases (or non-CO₂ effects) over a delimited time period. For example, by taking GWP 100, we assess the warming impact of 1 tonne of CO₂ emitted today over 100 years. It's a climate measure which is often used to create CO₂ equivalencies, making it easier to compare different sectors' impact on global warming. However, given non-CO₂ and CO₂ emissions of aviation have different impacts across the years, a smaller GWP (over a shorter period of time) will calculate stronger effects for non-CO₂ than a higher GWP (over 100 years for example) which will have a more limited impact of non-CO₂.
- **GWP*:** is [103] whereby the CO₂-equivalence of short-lived climate pollutant emissions is predominantly determined by changes in their emission rate. This resolves the issues of timescale (to 100 year equivalence), which paints a useful picture of the overall climate impact of aviation. According to most recent calculations using GWP*₁₀₀, aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO₂ emissions alone, **which means that two thirds of aviation's climate impact are linked to non-CO₂ effects**. Using this metric, some researchers have calculated that aviation contributed to 5.5% of total global warming in 2018 [104].

Therefore, depending on the metrics used, aviation contributed between 3.5% and 5.5% to global warming in 2018, which is much more than the figures used [105] by the industry to quantify its climate impact. Although there are multiple ways of measuring the climate impact of non-CO₂ effects, these still lead to substantial warming and need to be urgently addressed.

In Fig. 16, we present an estimation of the total climate impact that EU27+UK aviation would have by following the decarbonisation strategy outlined previously. We used McKinsey's estimates for Global Warming Potential (GWP) to 2100 as a basis for our calculations [29]. More detail on the assumptions used for this calculation can be found in Appendix A. As can be noted from the central case (green line), reaching decarbonisation by 2050 would still mean that aviation's total climate impact will be as high by

then as peak CO₂ effects (in 2019) if no measures other than those outlined in the forecast are taken. Including scientific uncertainty, the impact could actually be between 51% and 185% of 2019 CO₂ impact.

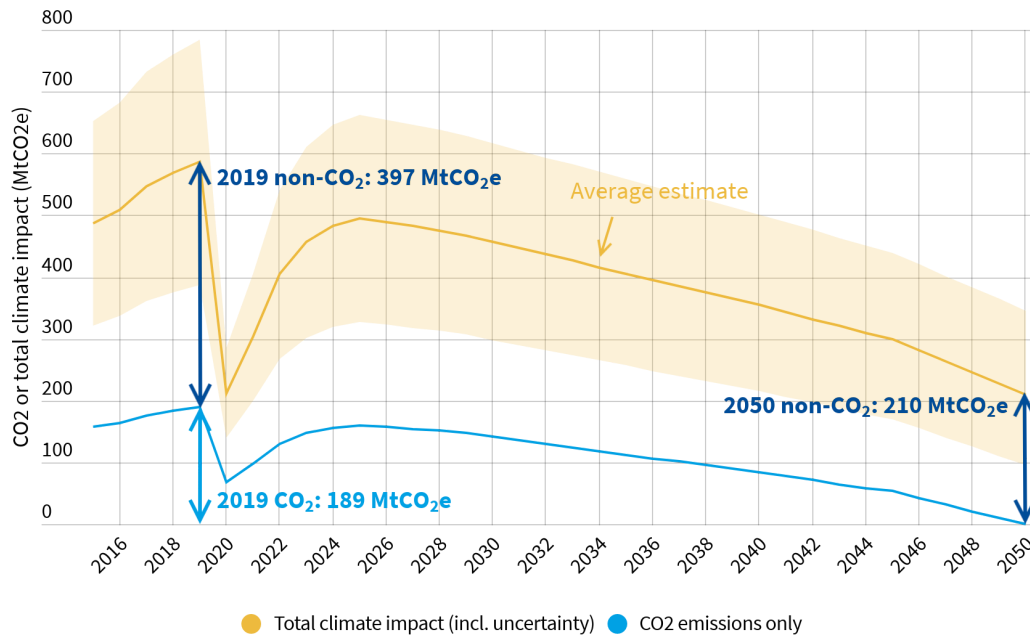


Figure 16: CO₂ emissions and total climate impact (including uncertainty) from EU27+UK aviation

9.2. Mitigation options

There are several technical and operational measures that aircraft, airlines, traffic controllers and other stakeholders can take to mitigate non-CO₂ effects, with some measures needing additional research to ensure they do not lead to increasing aviation’s CO₂ impact.

9.2.1. No regrets: flying less, using SAF and improving fossil jet fuel

An important aspect of any mitigation policy for non-CO₂ is to take into account the trade-off with CO₂. Policies to reduce non-CO₂ should not lead to significant increases in CO₂ emissions, as this stays longer in the atmosphere and contributes to global warming for longer. For example, some have found that measures to reduce NO_x emissions in aircraft engines can actually lead to increased CO₂ emissions [106], which is why **no regrets policies should be pursued in priority**, pending more research into the potential trade-offs of other mitigation measures.

- **Reducing non-CO₂ by flying less**

By flying less and reducing the number of aircraft taking to the skies, we can reduce most non-CO₂ effects as less water vapour and soot emissions would be released in the atmosphere. Studies quantified the impact of the Covid-19 induced reduction in air traffic on contrail formation in 2020, **showing that reduced traffic (a 72 % reduction in flight distance compared with 2019) caused a reduction of 78% in contrail length, resulting in over 54% less net warming in 2020 compared to 2019** (see Fig. 17) [107].

Some research estimated that, due to air traffic growth, the climate impact of contrail cirrus could be even more significant in the future, tripling by 2050 [108, 109]. This impact will be stronger over North America and Europe, the busiest air traffic areas on the globe, but will also significantly increase in Asia. **Given that non-CO₂ emissions are only expected to grow with air traffic potentially bouncing back after the Covid-19 pandemic**, reducing air traffic until zero-emission technologies are fully deployed is the most effective no-regret option to significantly reduce non-CO₂ effects today.

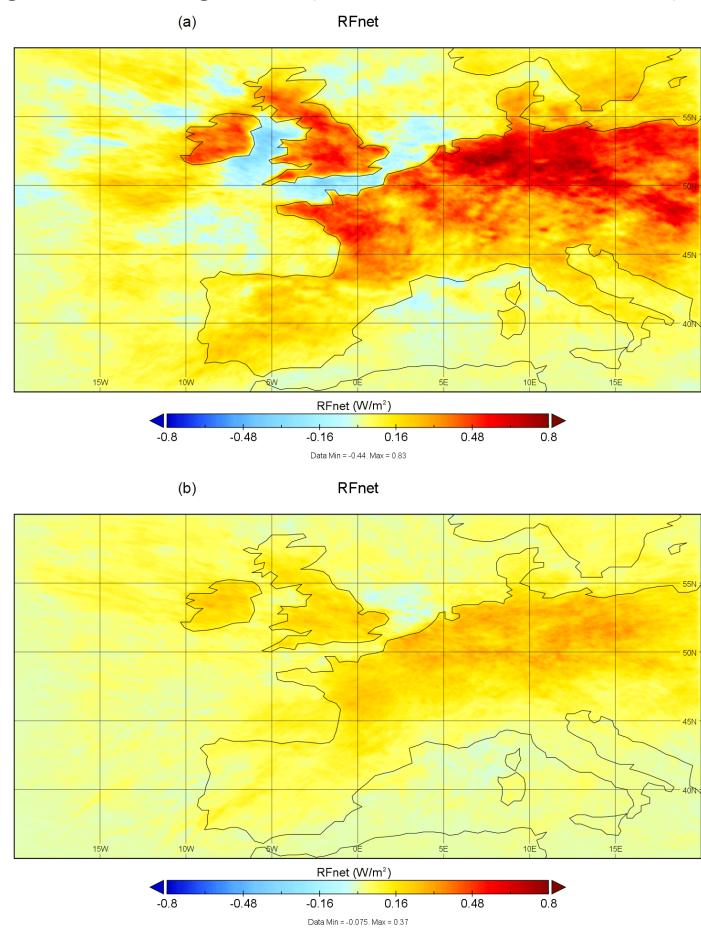


Figure 17: Mean net Radiative Forcing in Wm⁻² from contrails from March–August in 2019 (a) and 2020 (b) from Ulrich Schumann et. al (2021) [107]

- **Using SAF to reduce contrail formation and persistence**

Some SAFs have reduced aromatics, or contain none at all, which leads to a significant reduction in Particulate Matter (PM) emissions, thus reducing the optical depth and lifetime of contrail cirrus clouds.

Research suggests that **advanced biofuels or synthetic fuels can reduce by half the amount of soot particles released in the atmosphere**; this can reduce the number of contrail ice crystals by 45 to 74%, which in turn reduces its thickness and radiative forcing [110]. More research is needed to quantify the relative impact of the various SAF production pathways on persistent contrail formation.

Mandating the use of SAFs in aviation through a blending mandate, which is the objective of the ReFuelEU initiative as well as in other countries like the UK and Norway, would therefore constitute a “no-regrets” solution to mitigate both aviation CO₂ emissions and non-CO₂ effects.

In the meantime, **additional research should be conducted to properly quantify the non-CO₂ impact of hydrogen-powered aircraft**. We can already estimate that these new aircraft would reduce NO_x emissions by 50 to 80% compared to fossil-fuelled aircraft, according to initial studies. [29] Furthermore, hydrogen combustion produces water vapour emissions which will increase contrail formation, but, given the absence of soot particles, reduce their lifetime and climate impact. According to initial simulations, this could reduce the warming impact of these contrails by 30 to 50% compared to fossil kerosene. [111]

- **Regulating fossil jet fuel to limit aromatic content**

In parallel to promoting SAFs, there are ways of improving the specifications of current jet A1 fossil jet fuel for it to contain less aromatics, thus reducing the likelihood of contrail formation. For example, a process known as hydrotreatment can be used to reduce the aromatic content, and brings additional benefits such as improvements to local air quality. Improvements to fossil jet fuel are important, as fossil jet fuel will continue to dominate fuel supply to the aviation sector for some time to come. Regulators could mandate the use of these fuels through a fuel quality directive for aviation, or through the ReFuelEU Regulation, which, as a Regulation focussed on aviation fuel suppliers, may be the most appropriate.

Research is needed to identify the level of aromatics that these new standards could set, bearing in mind both new engine capabilities and the need to avoid negative trade-offs on other types of emissions. However, a minimal first step would be improved transparency on the actual rates of aromatics in fossil jet fuel, as at present little verified information exists.

9.2.2. Smart contrail avoidance

Avoiding specific areas of the atmosphere with higher risks of creating long-lived warming contrails, as well as using new zero-emissions aircraft, can significantly reduce aviation’s non-CO₂ effects. However, additional research is required to ensure these solutions do not lead to other negative environmental impacts, which might counter the benefits of reduced non-CO₂ effects.

- **Diverting aircraft to avoid ice-supersaturated regions**

Changing flight paths to avoid low-temperature ice-supersaturated regions (ISSRs) is one of the mitigation options that can significantly reduce the radiative forcing of contrail cirrus, especially as a small proportion of flights produce a large proportion of contrail cirrus. Indeed, real-life research projects that have already been conducted in Japan and the UK have demonstrated that a partial mitigation of around 40% of contrail distance would come at a negligible cost in terms of flight time. **A recent paper**

looking at flights in Japanese airspace concluded that diverting 1.7% of the flights could reduce the energy forcing from contrails by 59.3% with only a 0.014% fuel burn penalty [111, 112].

However, additional research is needed to address two main issues. Firstly, the formation of contrails is intimately linked to the meteorological conditions which vary from day to day, even hour to hour. Therefore meteorological prediction models need to be effectively designed for airlines and air traffic managers in order to identify in advance how to adapt flight paths to avoid ISSRs correctly. Some contrails may also have cooling effects, meaning that predictive models should help identify and target flights that will lead to the formation of long-lived warming contrails. Recently, British start-up Satavia teamed-up with Microsoft to produce an advanced and multi-factorial modelling of the atmosphere which enables better contrail forecasting, and thus mitigation [113].

Secondly, avoiding ISSRs by flying over or under them could entail a small fuel penalty, leading to some additional CO₂ emissions being released, even though changing altitudes could sometimes lead to more favourable wind conditions, in turn leading to fuel savings. **Operational measures to avoid these areas need to have the smallest impact on fuel burn as possible, so as to avoid increasing aviation's overall climate impact.** Another trial is ongoing through Eurocontrol's Maastricht Upper Area Control (MUAC) [114] to examine how relatively minor operational measures, such as small flight path changes, can influence contrail formation in the airspace over Belgium, the Netherlands, Luxembourg and northwest Germany. It will specifically examine whether reduced warming from contrails outweighs the extra fuel burn generated by a small number of diversions.

Although contrail avoidance can potentially entail a small fuel burn penalty, it is important to note that today most flights are not eco-optimised, but cost-optimised, meaning that flight paths are determined by what is cheapest for the airlines - which goes beyond fuel burn - rather than what is less harmful for the environment. Airlines choose to fly faster or divert from the shortest route to go through preferred airspaces in order to avoid paying higher air traffic fees. **Compelling airlines to respect more efficient routes could actually resolve the extra fuel burn linked to avoiding contrail formation areas.**

It is therefore crucial that institutions such as the European Commission and Eurocontrol initiate or support projects like these, and further explore pathways to accelerate trajectory optimisation, for example by integrating the measure within the Single European Sky (SES) reform. Implementing pilot projects or trials across the Atlantic or with the UK would help in the design of effective contrail avoidance measures, as this airspace is known to have ISSRs.

9.2.3. Pricing of non-CO₂

There is currently no financial incentive for airlines or air traffic controllers to reduce non-CO₂ effects. The price of polluting remains too low and the cost of using cleaner alternatives too high because the sector continues to enjoy fossil fuel subsidies. Even if ISSRs were identified and cleaner fuels developed, no pricing measure would encourage airlines or air traffic managers to use them to reduce their climate impact. Pricing non-CO₂ effects can play a useful role by providing incentives for aviation actors to use available mitigation options effectively to reduce costs associated with flying.

- **A NOx charge:** previous studies have recommended the development of a cruise NOx charge to be applied to airlines, dependent on flight length. This pricing mechanism would charge NOx emissions of flights departing from EU airports, calculated on the basis of certified Landing and Take-off (LTO) NOx emissions which are relatively well-quantified through engine certification data, as well as an estimate of cruise NOx emissions which are not as well defined, but are linked to LTO NOx. This charge would encourage aircraft manufacturers to reduce LTO NOx emissions during the engine design process, and airlines to minimise NOx emissions in operation. Further research would need to quantify the exact relationship between the amount of NOx emitted during the cruise and LTO phases in order to determine the overall NOx emissions of a flight, depending on its location.
- **Including non-CO₂ effects in the ETS:** either by including NOx emissions in the ETS or by applying a multiplier/factor to CO₂ emissions, representative of the actual overall climate impact of flying. Integrating NOx emissions under the ETS would require further data clarification as highlighted for the NOx charge (i.e. calculating the whole NOx emissions of a flight). Given that long-haul emissions and therefore extra-EU flights have a stronger potential to create persistent contrails, the EU ETS scope could be enlarged to cover all of these emissions; it would thus provide a stronger price incentive than international schemes like Corsia for airlines to reduce their CO₂ emissions (and therefore non-CO₂ effects). Another option is to apply a factor to the existing CO₂ emissions reported by airlines under the ETS, in order to cover the added impact of non-CO₂ effects.
- **A climate charge:** a location and time-dependent climate charge would be a way of creating a financial incentive for airlines to minimise flight time and emissions in highly climate sensitive regions. It would extend the existing charging system of air traffic control to cover a specific additional climate charge. Airlines would therefore be required to pay an additional charge when going through specific areas of the airspace. This option would require the development of predictive meteorological models to identify the areas of the airspace where the charge would apply.

Overall, each pricing mechanism presents challenges and benefits which need to be further researched, but without these pricing mechanisms, Europe risks losing time and resources developing solutions to address aviation's non-CO₂ impact which will never be used by the industry. After mandating the use of clean new fuels and increasing the price of polluting fossil jet fuel, the EU should start developing a pricing mechanism for non-CO₂ effects on the basis of the options above.

9.3. Conclusions and recommendations

Aviation's non-CO₂ effects are responsible for over two thirds of the sector's total climate impact [64]. It is therefore clear that focussing solely on reducing aviation's CO₂ effects is far from enough to reduce the sector's climate impact and would risk jeopardising our common objective to limit global warming to 1.5°C above pre-industrial levels.

Given the increased awareness and understanding of non-CO₂ effects of aviation, it is critical for European institutions and agencies to take ownership of the issue and propose urgent and effective policy mitigation measures, like those included by EASA in its report in November 2020, and prioritise doing the following:

- In the short term, making full use of so-called “**no-regrets**” **solutions**, since they tackle both CO₂ and non-CO₂ effects at the same time. These include flying less and increasing the volume of SAFs used in aviation by mandating their use and supporting production.
- **Reducing aromatics of conventional fossil JetA1 fuel:** the EU should regulate the use of lower aromatic fossil jet fuel through a European Fuel Quality Directive or a Delegated Act.
- **Deploying contrail avoidance (smart flying) mechanisms on all flights.** Given its well-integrated airspace, the EU can easily develop pilot schemes to optimise the concept so as to reduce, or even eliminate, fuel burn penalties.
- **Creating incentives for airlines to reduce their non-CO₂ impact by pricing these emissions.** Options include a NOx charge, the inclusion of non-CO₂ effects in the ETS, and a time and location-specific climate charge.

10. Appendix A: Decarbonisation forecast calculations and inputs

10.1. Block diagram of the model

A block diagram of the model built for the decarbonisation forecast is shown in Fig. 18. Reference emissions are derived from UNFCCC reporting until 2019, and projected using the IATA short-term forecast and the “Destination 2050” long-term yearly increase rate in traffic [10, 11]. Efficiency improvements are modelled using Eurocontrol’s data up to 2017 [12], and the projections until 2050 from the EU 2016 Reference scenario [9]. The emissions calculated at this stage are called “baseline” emissions. The sustainability measures are then applied successively, starting with demand management, followed by the introduction of hydrogen aircraft and the use of advanced biofuels. The remaining energy demand in 2050 is assumed to be provided by e-kerosene. The model allows us to calculate CO₂ savings from each measure, remaining CO₂ emissions for each year, and the amount of fuels and renewable electricity needed to decarbonise the sector.

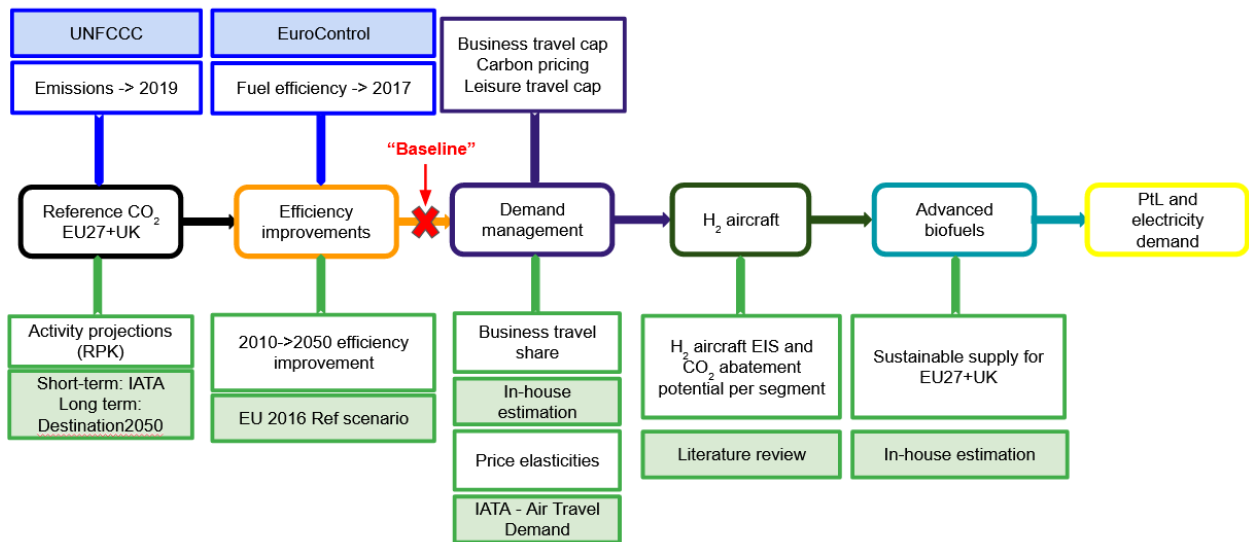


Figure 18: Block diagram of the model built for the decarbonisation forecast

10.2. Key assumptions and parameters

The assumptions used to derive reference and baseline emissions from 2010 to 2050 are shown in Table 5. After these emissions were calculated, we used the assumptions given in Table 6 to model the effect of the different decarbonisation measures on the emissions.

Scenario	Assumptions
Reference	IATA short-term forecast until 2024 [10, 11] “Destination 2050” yearly traffic increase rate, excluding any fuel efficiency improvement: 2.2%/year (compound) [11]

Baseline after efficiency improvements	EU 2016 reference scenario efficiency improvement from 2010 to 2050: 41% [9]. Eurocontrol fuel efficiency figures from 2010 to 2017 [12]. Combining the above results in a yearly efficiency improvement rate of 1.1%/year (compound)
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Table 5: Assumptions used to derive reference and baseline emissions from 2010 to 2050

Measure	Assumptions
Business travel cap	Share of emissions from business travel: 27% in 2019 (see calculation below). 50% of 2019 traffic levels.
Carbon pricing	Tax: €0.33/L., linear increase from 2025 to 2035. ETS: price increasing linearly from €25/tCO ₂ in 2020 to €100/tCO ₂ in 2030 and €200/tCO ₂ in 2050, all outbound flights covered from 2024. Currently about 18% of outbound emissions are paid for by airlines (see calculation below)
Leisure travel cap	100% of 2019 traffic levels
H ₂ & electric aircraft	4 aircraft segments: <ul style="list-style-type: none"> • regional (<80 passengers, <1000km): 2.3% emissions, EIS 2035 • short range (80-165 passengers, 1000-2000 km): 14.9% emissions, EIS 2040 • medium range (165-250 passengers, 2000-7000 km): 35% emissions, EIS 2045 • long range (250-325 passengers, 7000-10,000 km): 28.5% emissions, EIS 2050 Fleet replacement time of 20 years
Advanced biofuels	S-curve beginning in 2020, 1.7Mtoe in 2030 and 7.5Mtoe (max. potential) in 2050.
PtL	S-curve beginning in 2020, 1.2% of fuels in 2030 and remaining fuel demand (63%) in 2050.

Table 6: Assumptions used to model the different decarbonisation measures

Other key parameters used in the model are detailed in Table 7, including different fuel prices and the share of fuel costs in plane ticket prices.

Parameter	2020 (pre-COVID)	2030	2050	Notes
Jet fuel price (€/t)	557 [115]	604	690 [11]	Linear increase after 2024 recovery
Fuel price fraction of ticket price	22.5%	22.2%	21.4%	Calculation based on [115] and [116]
Hydrogen fuel price (base case, €/t)		2,650	2,250	Average of minimum and maximum prices from Table 11 in [11].
Biofuels price (€/t)	1,654-2,308			Range of levelised cost of production for SAF from Gasification-FT pathways in [37]
E-kerosene price (base case, €/t)	2,393-3,424	1,624-2,770	1,186-1,906	Range of levelised cost of production from [117].

Table 7: Other parameters used in the model

Further detail on the different calculations are given in the following sections.

10.3. Share of emissions from business travel

Estimating the share of CO₂ emissions that is attributable to business travel is not an easy task because the information available on this subject is scarce. We used the sources and assumptions detailed in Table 8 to approximate this share to the best of our ability and calculated the share to be 27%. To derive this number, we had to make assumptions on the shares of business and leisure travellers who fly in premium classes (25% and 4%, respectively). We validated these by calculating the share of premium emissions in total passenger emissions and comparing it with the result of a recent study by the ICCT [118]. Although, since there are two degrees of freedom, other combinations of assumptions could work, our result looks reasonable. It also implies that the load factor of premium seats is roughly 60%, a figure in agreement with experts' estimations [119].

Parameter	Value	Source
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Share of business travellers in total travellers	20%	Data purchased to EuroMonitor: number of outbound air travels for business and leisure purposes for 9 EU countries.
CO ₂ intensity of premium over economy on narrowbody aircraft	3.7	[118]. The factor is 4.3 on widebody aircraft.
Share of business travellers who fly premium	25%	Assumption, adjusted using the validation step below
Share of leisure travellers who fly premium	4%	Assumption, adjusted using the validation step below
Share of business emissions in total emissions	27.4%	Result of the calculation based on the above
Validation		
Share of premium emissions in total passenger emissions	23.8%	[118]
Share of premium emissions in total passenger emissions	24.8%	This calculation

Table 8: Sources and assumptions used to calculate the share of CO₂ emissions attributable to business travel and validation of the result

10.4. Cross subsidisation of leisure travel with business travel

To get an estimation of the potential drop in leisure travel due to the loss of revenues from business travel, we used the sources and assumptions detailed in Table 9. This calculation relies on many assumptions, but it gives an idea of the impact that a drop in business travel could have on leisure travel demand due to the decrease in revenues incurred by airlines and their need to increase economy ticket prices.

Parameter	Value	Source
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Premium class to economy class price ratio	4	https://www.farecompare.com/travel-advice/business-class-when-is-it-worth-the-cost/
Share of premium passengers	8.2%	Our previous calculation about business travel
Share of revenues from business class	26.3%	Calculation based on the above
Business travel traffic reduction	50%	Input for the calculation
Number of economy seats which can replace a premium seat	2	Area-wise the ratio is higher, but these extra seats will be hard to fill
Loss in revenues due to loss in business travellers	8%	Calculation
Increase in price of economy tickets to keep revenues constant	5%	Calculation
Passenger weighted airfare elasticity	0.807	See section below
Drop in leisure passengers	4.2%	Calculation

Table 9: Sources and assumptions used to estimate the cross-subsidisation effect between business and leisure travel

10.5. Airfare elasticity of demand

Our approach to calculate the effect of an increased cost of flying on its demand has not changed since our previous Roadmap, and the interested reader will refer to Appendix B of that document to understand our methodology [120]. We used a passenger weighted airfare elasticity to calculate the effect of different measures impacting ticket prices on the demand for them. These measures include carbon pricing and the uptake of alternative fuels with prices different to those for jet fuel.

We assumed income elasticity of air travel demand was built into the reference scenario from IATA and “Destination 2050” and thus did not further correct the emissions using this parameter.

10.6. Carbon pricing modelling

We assumed that the increase in carbon pricing would not affect business travel further than the travel cap already modelled in the forecast. Business travel is less sensitive to price signals than regular customers, and we have not found any study trying to quantify this effect.

Similarly, the increase in ticket price due to the use of more expensive alternative fuels is assumed to impact only leisure travel demand.

10.7. Current share of emissions paid for under the ETS

We estimated that currently 18% of EU27+UK outbound emissions are paid for under the ETS, using the following figures:

- 2019 CO₂ emissions for ETS countries, from UNFCCC [23]: 198.4Mt
- 2019 ETS emissions reported: 68.2 Mt [121]
- Share of verified emissions paid by airlines in 2018: 53% [122]

10.8. Share of emissions corresponding to the different hydrogen aircraft segments

The shares of emissions corresponding to different aircraft segments, i.e. maximum capacity and range, was calculated based on our in-house processing of AIS traffic data purchased from PlaneFinder, and validated by comparison with Eurocontrol's figures for the ECAC area (all aircraft sizes combined).

10.9. Number of hydrogen aircraft to build by 2050

The number of hydrogen aircraft to build by 2050 is calculated based on the emissions saved by these aircraft on each segment. As explained in the report, each segment covers a share of emissions, and the technology penetration rate allows calculation of how much emissions can be saved by hydrogen aircraft by 2050. We convert these emission savings to RPKs using the CO₂ intensity of typical aircraft from [118]. We then use our in-house EU aviation model based on PlaneFinder data to calculate the maximum distances flown in 2019 by typical aircraft. We assume that at the most, hydrogen aircraft will cover the same distances, although in practice slower refuelling could reduce aircraft utilisation. Table 10 shows the maximum yearly distance and the assumed passenger capacity for hydrogen aircraft of each segment. With this we calculate the minimum number of hydrogen aircraft necessary by 2050, assuming a load factor of 90%. The maximum number of aircraft is obtained by using half the maximum yearly distance, as we noticed there is a large spread in yearly distance flown among the fleet.

Aircraft segment	Maximum yearly distance flown (km)	Passenger capacity
Regional	1,300,000	80
Short range	3,300,000	165
Medium range	4,700,000	250
Long range	5,600,000	325

Table 10: Maximum yearly distance flown and passenger capacity of hydrogen aircraft of different segments

10.10. Hydrogen and PtL production efficiencies

In Table 11 we present the WTT and TTW efficiency figures used in this forecast (projected in 2050), based on the study by Ricardo Energy & Environment we commissioned in 2020 [117].

Fuel	WTT efficiency	TTW efficiency
PtL	61.2%	42.9%
H ₂ turbine	63.8%	42.9%
H ₂ fuel cell	63.8%	55.1%
Battery electric	94.0%	84.9%

Table 11: Projected WTT and TTW efficiencies of different aviation fuels and propulsion methods in 2050.

10.11. Total climate impact calculations

We based our calculation of the total climate impact of EU27+UK aviation on McKinsey’s ranges of fuel total GWP relative to CO₂ GWP, which they estimated for fossil jet fuel, e-kerosene, H₂ fuel cell and H₂ propulsion [29]. For the simplicity of the analysis, we assumed that advanced biofuels have a similar impact to that of e-kerosene.

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