

# WAYPOINT 2050



AN AIR TRANSPORT ACTION GROUP PROJECT

Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: **a vision of net-zero aviation by mid-century.**



**SECOND EDITION:  
SEPTEMBER  
2021**



The air transport industry is the global network of commercial aircraft operators, airports, air navigation service providers and manufacturers of aircraft and their components. It is responsible for connecting the global economy, providing millions of jobs and making the modern, internationally-connected quality of life possible. The Air Transport Action Group (ATAG), based in Geneva, Switzerland, represents the full spectrum of this global business. ATAG brings the industry together to form a strategic perspective on commercial aviation's sustainable development and the role that air transport can play in supporting the sustainability of other sectors of the economy.

**[www.atag.org](http://www.atag.org)**

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# FOREWORD

## Net-zero air transport is a challenge, and an opportunity

There is a reason we have named this report 'Waypoint 2050'. Waypoints are an air navigation tool which provide a direction of travel for pilots – a clear trajectory for their mission and guidance on how to get to the destination.

Our destination as an industry is also clear. The ability to continue to connect the world over the coming decades, bridging the divide between cultures, linking families and ensuring businesses can grow and prosper.

The impact of the pandemic has shown the importance of those connections more than ever. But it has also highlighted another aspect of the mission with which we have tasked ourselves: to make that connectivity with an ever-decreasing impact on our climate.

Waypoint 2050 outlines the paths we can take towards the decarbonisation of air transport.

The first edition outlined how the sector could reach its goal of halving CO<sub>2</sub> emissions by 2050, compared with 2005. That trajectory was in line with the Paris Agreement “well below 2°C” goal and could be reached without resorting to out-of-sector emissions reductions as a central pillar of action.

This second edition of Waypoint 2050 goes a step further, exploring how the sector could meet a greater ambition of reaching net-zero carbon emissions globally by 2050, aligned with the 1.5°C stretch goal of the Paris Agreement and a target that the Intergovernmental Panel on Climate Change has identified is needed to avoid some of the worst impacts of climate change.

Net-zero is a waypoint on aviation’s path to decarbonisation, and it remains a significant challenge for an industry like air transport.

Unlike most other sectors, where technology solutions have already been proven to work, aviation has no off-the-shelf fix. We need to pursue a rapid and global energy transition away from fossil fuels and towards sustainable sources of energy, some of which are technologically mature but need massive scaling up. Others, such as fuels produced from low carbon electricity, are at the start of their journey from initial development into our wings.

And there have been remarkable advances in new concepts in propulsion, such as electric, hydrogen and hybrid aircraft. More work needs to be done to bring these to commercial reality. But if there is one thing you can say about aviation: we never stop innovating.

It took aerospace engineers around 30 years to get us from the first commercial air service to the jet engine. The last 30 years have seen us halve the CO<sub>2</sub> emissions for every passenger’s journey. The next three decades to 2050, and the ones that follow, will allow us to enter the third era of aviation: that of sustainable fuels, electric and hybrid flight and, eventually, zero carbon connectivity.

Pivotal in that quest will be bringing experts from across air transport together with governments and researchers. Collaboration and engagement of stakeholders from within and outside the aviation sector is essential, especially for disruptive concepts. It can be done, but only if we do it together. The challenge is considerable, but necessary and inspiring.

We are committed to making it a reality.

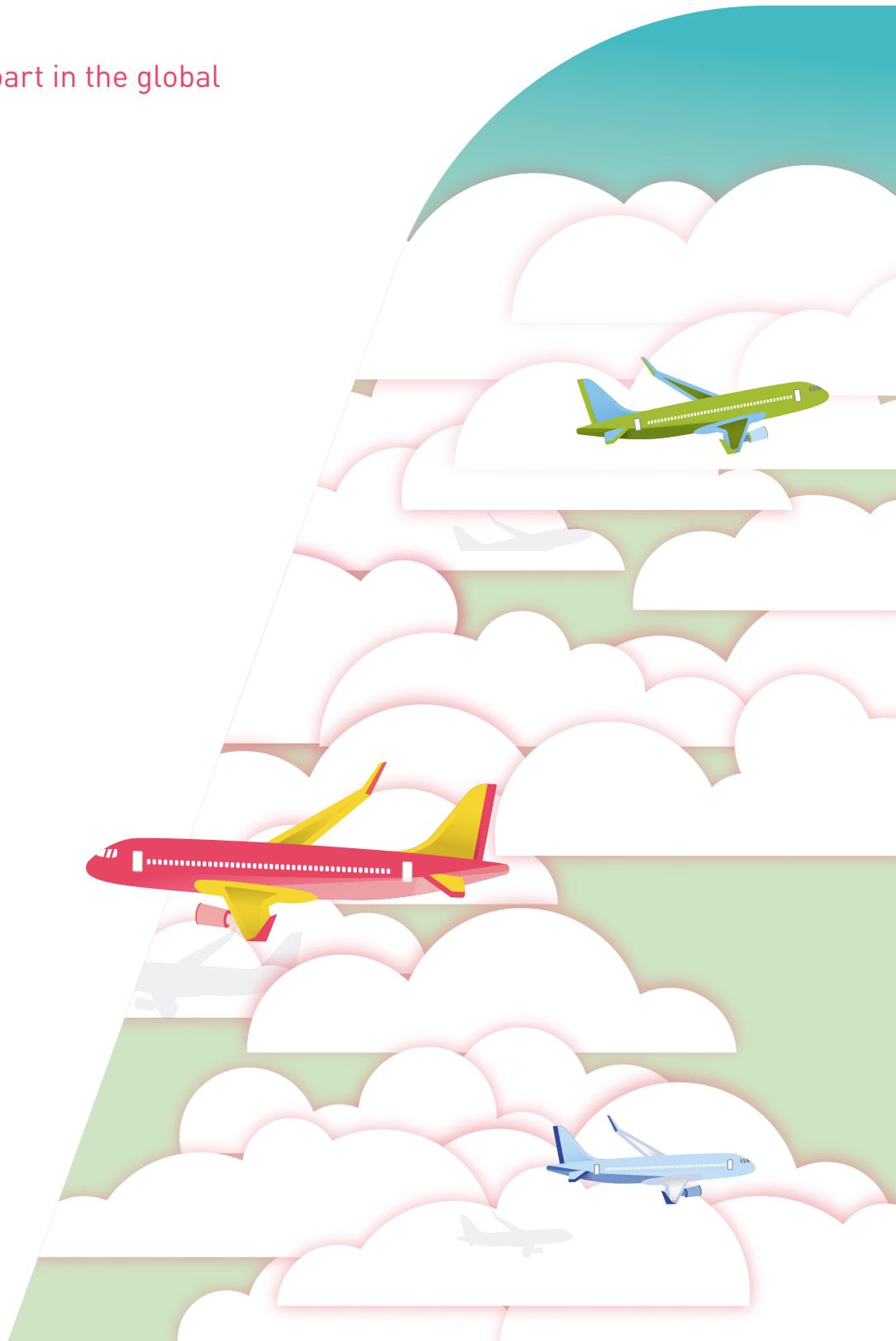
### Haldane Dodd Executive Director

On behalf of the Board of Directors of the Air Transport Action Group:

Airports Council International (ACI), Civil Air Navigation Services Organisation (CANSO), International Air Transport Association (IATA), International Business Aviation Council (IBAC), Airlines for America (A4A), Association of Asia-Pacific Airlines (AAPA), Airbus, Boeing, CFM International, GE Aviation, Pratt & Whitney, Rolls-Royce and Safran.

# EXECUTIVE SUMMARY

Aviation can play its part in the global  
climate mission



## WAYPOINT 2050 IS A COLLABORATION OF EXPERTS FROM ACROSS THE AVIATION SECTOR, LOOKING AT HOW THE INDUSTRY CAN ACCELERATE WORKING TOGETHER TO CONTRIBUTE TO THE WORLD'S CLIMATE ACTION MISSION. COLLABORATION IS NOT A NEW WAY OF DOING BUSINESS IN AVIATION: IT IS CENTRAL TO HOW THE SYSTEM FUNCTIONS. IN 2009, THE AIR TRANSPORT INDUSTRY SET ONE OF THE FIRST GLOBAL, SECTOR-WIDE, CLIMATE PLANS FOR ANY INDUSTRY.

In the decade since, airlines have spent over a trillion dollars on more efficient aircraft<sup>1</sup>; the aerospace sector has spent over \$150 billion on efficiency research and development<sup>2</sup>; CO<sub>2</sub> emissions per seat kilometre have improved by 21.5%<sup>3</sup>; ten new (and significantly more efficient) aircraft types have entered service (or are about to)<sup>4</sup>; over 365,000 flights have taken off on sustainable aviation fuel (which wasn't even certified until 2011); the world's first CO<sub>2</sub> standard for aircraft and the first carbon pricing mechanism for a single global sector were negotiated and adopted at the International Civil Aviation Organization (ICAO); and collaboration across the sector has driven efficiency improvements in air traffic management. It's been a busy ten years.

But while the industry is accustomed to working together, the race towards 2050 and beyond is going to require a considerable acceleration in efforts by partners working within the aviation sector and with other institutions, particularly governments.

Many countries and industry sectors are putting in place net-zero emissions goals for 2050, there are different speeds of decarbonisation underway in different parts of the world. The lack of readily-available solutions for aviation means that the sector falls into a category of 'hard to abate' parts of the economy.

Waypoint 2050 demonstrates, however, that there are potential options for the almost complete decarbonisation of air transport with the industry at a global level able to meet net-zero emissions by 2050, with offsetting through carbon removal taking account of residual emissions (some companies are working to reach this point sooner). This assumes the right level of support from governments, the finance sector, the energy industry and research institutions. The industry itself will need to redouble efforts as well.

There are a range of measures that can help drive aviation towards the technology, energy system and operational measures that are required to meet these ambitions. Many of these are incredibly challenging, but all are achievable with the right policy environment and the necessary focus of resources.

### a) reviewing traffic forecasts

By 2050, it is expected that over 10 billion passengers will be carried by air some 22 trillion kilometres each year and, without any additional improvement in technology, fuels or improvements in operations, this activity would generate close to 2,000 megatonnes (Mt) of CO<sub>2</sub>. Demographic shifts and population changes mean that the central forecast used in Waypoint 2050 suggests a slowing of growth when compared

with recent years (even without the impact of Covid-19). Taking into account the impact of Covid-19 on longer-term growth trends, we can expect a compound annual growth rate of 3.1% from 2019 until 2050, mainly from Asia-Pacific, the Middle East, Latin America and Africa, although there remains significant growth in North America and Europe. Three factors: environmental concerns from consumers; governments moving to reduce growth; or a shift to other modes of transport (such as rail), are expected to have limited impact on the overall growth picture. Despite this, the sector must innovate and accelerate the energy transition to low (and, ultimately, zero) carbon fuel sources in order to ensure its continued licence to operate.

### b) innovating with technology

Evolutionary technology will continue to be developed, bringing with it around a 20% improvement in fuel efficiency to each generation of aircraft. But in the next 30 years, the industry will likely see even more radical shifts. By 2050, it is expected that electric-, hybrid- and hydrogen-powered propulsion will have the potential to serve regional, short-haul and perhaps some medium-haul markets. Traditional liquid fuels are expected to remain necessary for long-haul aircraft and for the remaining short and medium haul aircraft that have not shifted to electric or hydrogen, but with a transition towards 100% sustainable and low carbon sources.

### c) improvements in operations and infrastructure

These areas present a vital area of early action to help the pathway to 2050. A wide range of measures can be implemented by airlines, airports and air traffic management to reduce CO<sub>2</sub> from the operation, with collaboration playing a vital role. Importantly, continual improvements are needed to maintain (or enhance) existing operational efficiency and to ensure that increasing congestion does not degrade airspace efficiency.

### d) deploying sustainable aviation fuel (SAF)

Perhaps the single largest opportunity to meet and go beyond the industry's 2050 goal is the rapid and worldwide scaling up of sustainable aviation fuel and new energy sources. It is likely that aviation will need between 330-445 million tonnes of SAF per annum by 2050. Analysis shows that this is achievable, with rigorous sustainability criteria ensuring a transition that does not impact food or water use. Rather than relying on a single option, there are a range of feedstocks available, from non-food

crops to waste sources and eventually a shift to power-to-liquid fuels made from recycled or directly-captured CO<sub>2</sub> and low-carbon electricity. The scale-up will be a significant challenge: up to \$1.45 trillion worth of investment over the next 30 years will be required to develop this new energy system, although with the right support from government and the energy sector, it is far from insurmountable (annualised, it is the equivalent around 6% of typical oil and gas capital expenditure). Policy will play a core role in this shift – government support to channel feedstocks towards aviation and not to other transport sectors (where alternative energy sources are already available). It is estimated up to 14 million jobs could be created or sustained by this shift, creating new energy industries around the world: where 90% of fossil fuel oil comes from just 22 countries today, this new SAF path could open up opportunities in almost every country.

### e) investing in out-of-sector carbon reduction market-based measures

Aviation will need to turn to carbon offsets in the near-term to stabilise CO<sub>2</sub> emissions as it works on long-term, permanent, in-sector reductions through the ramp-up in alternative energy and new technology. It is not envisioned that investing in out-of-sector carbon reduction should be the primary means of meeting long-term goals. Due to the long time horizons of fleet turnover and the global nature of the industry, it is expected that there could be a need to remove residual CO<sub>2</sub> emissions, even if aviation manages to meet almost all of its energy requirements from SAF, and progresses radical new technologies. But the types of 'offsets' available in 2050 will likely be different to those available today as demand from other sectors also grows. Forestry, natural carbon sinks and carbon removal opportunities may play a role in 2050 and beyond.

Waypoint 2050 explores three consolidated scenarios for how air transport can meet its goal. Which of these scenarios plays out over time will be determined by a number of decisions in the course of the coming decades, including:

- » How do we prioritise investment in both sustainable aviation fuel deployment and radical new technologies?
- » Can energy providers massively scale up SAF and hydrogen production at the same time?
- » Will governments, finance institutions and consumers play the role they need to accelerate the energy transitions?

Whilst the solution will likely be some combination of all the scenarios, the important lesson learnt from the work in this report is that it can be done. Aviation can achieve net zero emissions at a global level, by 2050. There is enough feedstock to produce the necessary SAF and hydrogen is a possibility for some aircraft. Efficiency will continue to improve and modern air transport will remain a key driver of connectivity, business and social connections across the world well after the middle of this century.

- » *Due to the nature of technology developments, the energy transition and political realities constantly changing, it is envisioned that this report may also be subject to change as the outlook evolves.*



## 10 QUESTIONS

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### Q1

#### Can aviation meet net-zero CO<sub>2</sub> emissions by 2050?

Yes. But it will take an enormous effort by committed industry experts, governments, the finance sector and the research community to make it a reality. It will mean a rapid and massive transformation of aviation's 'drop-in' liquid energy supply using sustainable aviation fuel – from both traditional sources and new sources such as power-to-liquid – over the course of just 30 years. It will also require an acceleration in aircraft and engine technology development, including faster progress towards new types of propulsion: electric, hybrid and hydrogen powered aircraft. Net-zero will also likely require using carbon removals to deal with residual CO<sub>2</sub> emissions. It is possible, but it is going to be a significant challenge.

### Q3

#### Will aviation rely on offsets to meet its goals, or to shift to net-zero emissions?

The expectation is that offsets (or other forms of out-of-sector carbon reductions available in 2050) are not primarily relied on to meet the goal, although there will be some emissions that offsets can help mitigate and these will be needed to meet a net-zero 2050 goal. In the near term, high-quality offsets will be key to aviation meeting its climate obligations. In the long term, the removal of CO<sub>2</sub> from the atmosphere will be key, not just compensating for unavoidable emissions. Depending on the progress of technology development (both in carbon capture / direct air capture and for aviation technology and energy deployment), there may be an increased role to play for some form of market mechanism or offsetting as the sector transitions to wider use of new energies.

### Q5

#### When will passengers be able to board electric or hydrogen aircraft?

Already, there are small commercial aircraft being test flown using retro-fitted electric engines. The mid-2020s may see up to 19-seat aircraft flying on new forms of energy. Scaling this up to regional and some short-haul aircraft will take the next 15-20 years, but passengers might be able to purchase tickets for electric, hybrid-electric or hydrogen flights around the 2035 timeframe. There is a lot of work still to be done. Battery technology is progressing quickly but needs to be accelerated to provide enough energy for the right size of aircraft over reasonable distances. Hydrogen is an increasingly viable option, but aircraft and engine systems need to be developed and storage must be progressed. And then the manufacturers must complete safety and operational certification in completely new types of technology, as well as sell these novel aircraft types to airlines. Importantly for both options: increased production and new distribution systems of low carbon electricity and green hydrogen are required to make them a reality.

### Q2

#### What is the difference between the industry climate goal announced in 2009 and this analysis?

In 2009, the aviation sector became one of the first industries to develop a climate action plan at a global level. The long-term goal was to halve aviation CO<sub>2</sub> emissions by 2050, compared to 2005. This was in line with the 'well below 2°C' goal outlined in the Paris Agreement. As scientific evidence has grown on the difference between that 2°C goal and a 1.5°C trajectory, it has become increasingly apparent that reaching net-zero emissions by mid-century across all sectors is vital to hold off the worst effects of climate change. Therefore, this new analysis details how global aviation could reach net-zero around 2050. It builds on analysis in the First Edition of Waypoint 2050 by increasing the deployment of sustainable aviation fuels and determining the residual CO<sub>2</sub> emissions which would need to be offset to reach net-zero. Reaching the sector's climate goal set in 2009 was shown to be a significant challenge, but achievable. Going beyond our 2009 climate goal by demonstrating increasing ambition for net-zero is an even greater challenge, but with the right support from governments and particularly the energy sector, it is also achievable.

### Q4

#### Will shifting to sustainable aviation fuels require large amounts of land, or impact food and water use?

No. Airlines have committed to ensuring a shift to sustainable aviation fuel will be done with fuels "which conserve an ecological balance by avoiding the depletion of natural resources"<sup>5</sup>. Analysis has shown that 100% of aviation fuel by mid-century can come from sustainable sources – including some (non-food or rotational) crops, waste sources and fuels made from low-carbon electricity and CO<sub>2</sub> removed from the air. Robust mechanisms need to be put in place to ensure the sustainability of these fuels – a global industry can also lead to pockets of less stringent regulation – but a full shift to sustainable sources is possible.

## Q6

### Can we speed up the transition to fully sustainable aviation?

With enough money, anything can be sped up, but only as far as technology, materials and politics allow. At the same time as aviation is trying to decarbonise its energy system and develop radical new technologies, the rest of the world is also tasked with decarbonising other sectors in the economy. We believe the Waypoint 2050 scenarios presented here to be a realistic and still aspirational timeline for development. There is a good case for current fossil fuel subsidies around the world to be re-directed towards low-carbon energy which would help speed up the transition.

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## Q8

### Is it not easier to simply reduce passenger growth?

Reducing passenger growth (either by reducing supply with fewer seats or reducing demand by increasing ticket taxes) will not necessarily reduce CO<sub>2</sub> emissions in the way many think and will inevitably restrict air travel for less wealthy citizens. The steps taken in this report and our recommendations will allow us to restrict the growth of CO<sub>2</sub> emissions, but not the connectivity, societal or economic benefits that come from air travel being available to people everywhere. The growth rates identified in this report are also at a lower level, generally, than aviation has experienced in the last decade, signifying a shift to slightly lower levels of growth [and that growth taking place mainly in emerging economies whose citizens should have the chance to enjoy economic prosperity experienced in more established parts of the world for years].

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## Q10

### Some countries or regions have specific roadmaps for aviation climate action, how does this compare?

The Waypoint 2050 analysis is on a global basis and has tried to take into account the varying rates of decarbonisation and geopolitical environments in regions and countries around the world. Due to the nature of a global analysis, the timeframe and roadmap cannot be as precise as that for a specific country (or individual company), but the various technology and energy solutions should be aligned. ATAG encourages all parts of the industry to focus on how they can play a role in accelerating a decarbonisation pathway.

## Q7

### Will tickets cost more in future to pay for new technologies or new fuels?

It is likely that the cost of travel may increase, however this is not an easy question to answer, as airline ticket prices comprise a range of costs and the price to the public doesn't always reflect the underlying costs of things such as fuel or aircraft purchases. In addition, while the cost of sustainable aviation fuel may be higher than fossil fuel, it is unknown how much the cost of fossil fuel may evolve (particularly as other transport modes shift to electricity or hydrogen). Based on today's estimates, it is likely the cost of energy for aviation may be higher in the future, but this could also be partially offset by an increase in efficiency with new technologies and improvements in operational performance. What we do know is that aviation will continue to serve global connectivity in all parts of the world, even if tickets are more expensive in the future.

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## Q9

### How has Covid-19 and the shutdown of air traffic impacted the analysis?

Aviation has never experienced an impact on the system as severe as the one caused by Covid-19 in 2020. The immediate hit on the industry is obvious, but there will likely be a very long-term reduction in growth projections as a result of the slow recovery. The central traffic forecast used for Waypoint 2050 has reduced by around 8% in 2050, compared with the pre-Covid forecast. However, despite the severe financial state of the sector over the next few years, commitment to climate action remains strong.

## CALLS TO ACTION AS PART OF A DECARBONISATION PATHWAY

A range of actions will be needed to help reduce emissions in line with the scenarios presented in Waypoint 2050. In each section of the report, action points for different stakeholder groups are explored in detail. Here is a summary of the broad areas of action.

### Technology

- Significantly scale-up avenues for collaborative approaches – within industry, between industry and governments and with the research community and other stakeholders.

#### Aviation sector

- Accelerate research into radical airframe designs, electric and hydrogen propulsion.
- Form partnerships with non-aviation technology providers.
- Provide incubator opportunities for new green technology start-ups.
- Work to prepare for new energy requirements for electric and hydrogen aircraft.

#### Governments and policymakers

- Continue to fund research programmes where they exist, develop projects where they do not.
- Implement the ICAO CO<sub>2</sub> Standard.
- Develop wider energy strategy to, aside from deploying sustainable aviation fuel, include hydrogen and low-carbon electricity requirements of aviation.
- Prepare agencies for certification processes for next generation aircraft, including with unconventional airframe, materials and energy sources.

#### Research institutions

- Ensure research programmes for new technology reflect real-world requirements.
- Continue research in collaboration with industry into non-CO<sub>2</sub> effects of aviation.

#### Energy industry

- Plan strategic energy needs, including potential for aviation requirements for low-carbon electricity and low-carbon hydrogen.

#### Finance community

- Focus on funding new efficient aircraft acquisition and explore sustainable finance opportunities.

#### Other stakeholders

- Collaborate on synergies with automotive, battery and hydrogen sectors to encourage development of feed-in technology pathways for aviation.

### Operations and Infrastructure

- Significantly scale-up avenues for collaborative approaches – within industry, between industry and governments and with the research community and other stakeholders.

#### Aviation sector

- Work in partnership to implement optimised flight profiles as air traffic volumes recover to pre-pandemic levels.
- Work towards full implementation of fixed electrical ground power, weight-based efficiency measures, continuous approach and departure, airport collaborative decision making, aerodynamic efficiency opportunities and assisted taxiing opportunities.
- Collaborate to speed up investigating, testing and certification of new efficiency measures.
- Encourage efficiency action throughout the system.
- Investigate new approach technologies and procedures at all applicable airports.
- Investigate opportunities for increased use of intermodality, including for connecting air passenger traffic and for passenger access to airports.

#### Governments and policymakers

- Make military airspace flexible use.
- Implement the ICAO Aviation System Block Upgrades.
- Encourage and fund, where viable, intermodal transport planning.

#### Research institutions

- Focus on operational procedure improvements for aviation system.

#### Energy industry

- Work in partnership with airports to ensure low carbon energy supply.

#### Finance community

- Fund infrastructure upgrades and developments to meet system efficiency needs.

#### Other stakeholders

- Pursue community and aviation system engagement on new procedures and techniques for air traffic management.

## Sustainable aviation fuel

- Significantly scale-up avenues for collaborative approaches – within industry, between industry and governments and with the research community and other stakeholders.

### Aviation sector

- All airlines should investigate sustainable aviation fuel opportunities – small or large. Start by doing a first test flight.
- Make substantial and bold SAF offtake agreements at an early stage.
- Make the case to governments and the finance community for SAF scale-up.
- Bring passengers and major customers on board with sustainable aviation fuel financing.

### Governments and policymakers

- Foster a clean energy transition push across government, including for sustainable aviation fuel.
- Prioritise aviation (and other hard-to-abate sectors) as a user of alternative fuel.
- Explore potential for SAF development at a national or regional level.
- Support development of SAF industry, including attracting capital to expand SAF capacity through loan guarantee programmes (de-risking the early investment anxiety for new technologies), direct research and development activities for local SAF production pathways and new energy industries, committing to policy certainty.
- Demonstrate leadership with a commitment for government travel to be undertaken on SAF, adopt globally-recognised sustainability standards and work to harmonise global standards, encourage user-friendly sustainable aviation fuel accounting methods and work to harmonise global standards.

### Research institutions

- Implement SAF research programmes into technology pathways, feedstock and emissions reduction factor improvements, production efficiency improvements.

### Energy industry

- Demonstrate substantial commitment to sustainable aviation fuel production and scale-up.

### Finance community

- Focus funding on SAF opportunities worldwide.

### Other stakeholders

- Other transport modes should prioritise best available energy options.

## Offsetting or out-of-sector carbon reductions

- Significantly scale-up avenues for collaborative approaches – within industry, between industry and governments and with the research community and other stakeholders.

### Aviation sector

- Investigate partnership opportunities with future offset providers.

### Governments and policymakers

- Support the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and ensure it continues to evolve.
- Set a long-term CO<sub>2</sub> goal through ICAO.
- Do not duplicate market mechanisms.
- Base any domestic measures on CORSIA principles.
- Work with fellow governments to conclude UNFCCC Article 6 discussions.
- Promote development of carbon capture and removal opportunities.

### Research institutions

- Accelerate development of carbon capture and direct air capture efficiency.

### Finance community

- Support development of carbon capture and direct air capture opportunities.

### Other stakeholders

- Develop additional high-quality carbon credit products.



# THE CHALLENGE



**AIR TRANSPORT HAS CONNECTED THE WORLD FOR MORE THAN A CENTURY, WITH 88.3 BILLION<sup>6</sup> PASSENGERS HAVING FLOWN SINCE THE FIRST COMMERCIAL SERVICE TOOK OFF IN 1914. IT IS A SYSTEM RELIED ON BY MILLIONS OF PEOPLE FOR CONNECTIVITY TO THEIR LOVED ONES; BY BUSINESSES TO ENGAGE IN TRADE, DEVELOPMENT AND INNOVATION; BY GOVERNMENTS TO ENCOURAGE THE ECONOMIC BENEFITS OF TOURISM, AND TO SUPPORT NEARLY 87.7 MILLION JOBS WORLDWIDE.**

The world with modern, rapid, air transport is a rich and rewarding one. The fundamental challenge is to ensure that connectivity can continue, whilst working to significantly reduce its impact on the climate. But that overarching balance brings with it a number of underlying challenges which make up counterbalancing dynamics, sometimes working against each other.

**Challenge: growth is not taking place evenly around the world**

Political situations play a role when considering technological and policy solutions to global issues such as climate change. Whilst air travel has been growing very quickly in the last decade, the majority of that growth (and the growth to come in the next 30 years) is in emerging economies. These nations have a right to give their citizens access to the same business, tourism and travel opportunities that those in established economies have enjoyed in the past 30-40 years.

Around 80% of air transport emissions are from flights over 1,500 kilometres in length<sup>7</sup>, which have no alternative

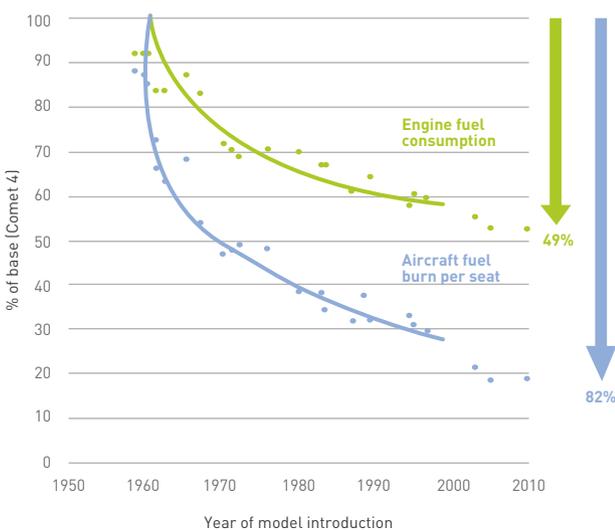
transport mode. A majority of these are international services and must therefore be dealt with by international rules which have to balance the need to help grow economies with the need to reign in CO<sub>2</sub> emissions. The framework of the International Civil Aviation Organization (ICAO) is the most effective place to achieve that balance. The aviation industry has played a leading and progressive role in pushing governments meeting at ICAO to adopt global climate standards, including the current process to develop a long-term goal for CO<sub>2</sub> emissions reduction.

**Challenge: forecasting**

There are a number of uncertainties when looking out ten years, let alone 30 or longer. How will traffic evolve? Will there be further shocks to the system that alter the fundamental growth patterns of mobility? What will be the price of fuel – will it rise or fall as other sectors shift more easily to alternative sources of energy? What will be the availability (and cost) of offsets or other carbon mitigation options? When will new technologies be available and how much can they contribute to

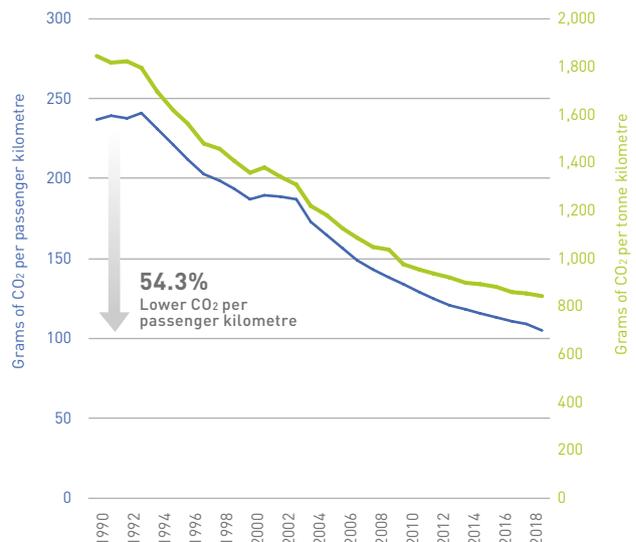
**Fuel efficiency through technology since the early jet age<sup>8</sup>**

The development of new airframes and engines has delivered an 80% + improvement in the efficiency of aviation.



**Operational efficiency since 1990, global numbers<sup>9</sup>**

Through deploying new technology, operational and infrastructure efficiencies and improvements in fleet utilisation, a flight a passenger takes today will, on average, produce 54.3% less CO<sub>2</sub> than the same flight in 1990.



reducing emissions? The interplay between these questions is also important: if traffic reduces significantly, will airlines have enough capital to invest in new fleets or sustainable fuels? Does the industry prioritise investing in technology development or in an energy transition?

Obviously, each of these tracks can generate many hundreds of different forecasts and scenarios. Bringing them together increases further the complexity. Waypoint 2050 attempts to focus on several likely scenarios that represent potential paths forward, as identified by industry experts involved in the analysis.

Inevitably, analysis with so many variables raise more questions. The hope is that Waypoint 2050 can provide a basis for further discussions about aviation's future emissions trajectory.

### Challenge: aviation is already remarkably efficient

Fuel efficiency has been a key driver of development since the dawn of the air transport industry. The sector has shown a consistent improvement in:

- » The efficiency of technology platforms (engines and airframe developments): **85% improvement since the first jet engines in the 1950s.**
- » Operational efficiency (the combination of technology across the entire aircraft fleet, the way these aircraft are operated, the infrastructure environment and the utilisation of assets – load factors on board flights): **54% improvement (combined technology, operations and load factor) since 1990.**

A passenger taking a flight today produces around the same amount of CO<sub>2</sub> as a small car with average occupancy. Each

generation of new aircraft improves fuel efficiency even further, but the gains through evolutionary technology are getting more and more challenging to achieve. This is because air travel tends to be very efficient on a per-kilometre basis already, given its speed and ability to cover large distances. Significant CO<sub>2</sub> savings will continue to materialise in the coming decade through continuous fleet renewal with today's new generation aircraft providing immediate 20-25% fuel- and CO<sub>2</sub> savings compared to the previous generation.

### Challenge: cost of the transition is high and the technology is not available... yet

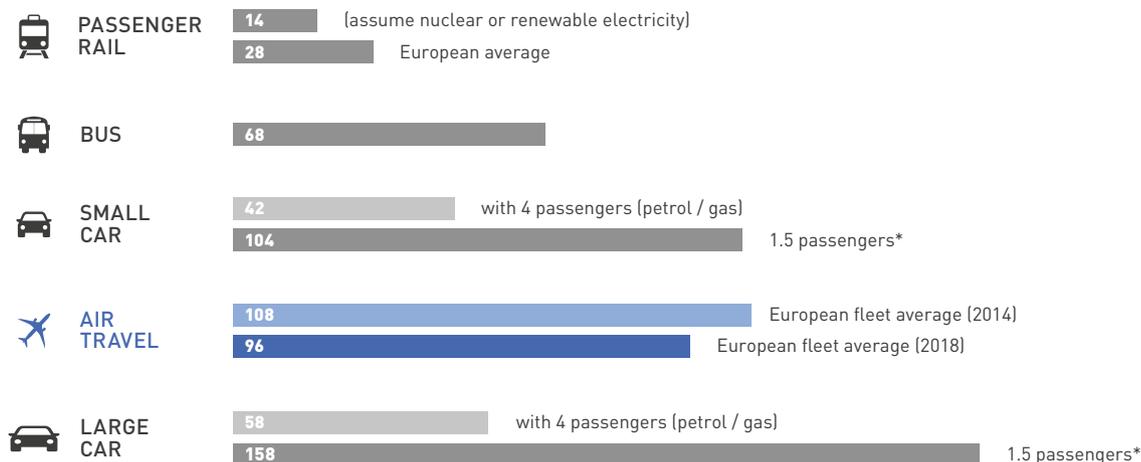
Aviation is inherently a costly business, with low margins for its frontline airline operators. Aircraft are high-value assets that take a long time to build, and a long time to pay off. Unlike cars and many other machines, aircraft can remain in useful service for 25+ years and so fleet turnover tends to be slow. An airline or lessor which has spent hundreds of millions on an aircraft is unlikely to want to upgrade without a reasonable return on investment.

For example, the combined fleet value of the ten largest leasing companies in the world – comprising 6,863 aircraft, or just under 20% of the world fleet – is \$205 billion<sup>11</sup>. Airlines have spent over a trillion dollars on new aircraft orders since the industry climate goals were agreed in 2009<sup>12</sup>.

The transition to radical new technologies will require significant investment by the commercial aerospace sector, research institutions and governments. Once a new technology has been identified, the aerospace sector must work to commercialise at scale in order for prototypes and commercial versions to be produced, sold to airlines, put through rigorous testing and certification procedures and

### Comparison of operational fuel efficiency between different modes of transport, 2014 EU<sup>10</sup>

Using European Union data, this chart shows the operational CO<sub>2</sub> emissions of air transport compared with other European averages (data for 2014, with update to aviation figure in 2018. If analysis only included the latest generation of aircraft, the potential is for around 50g of CO<sub>2</sub> per passenger kilometre).

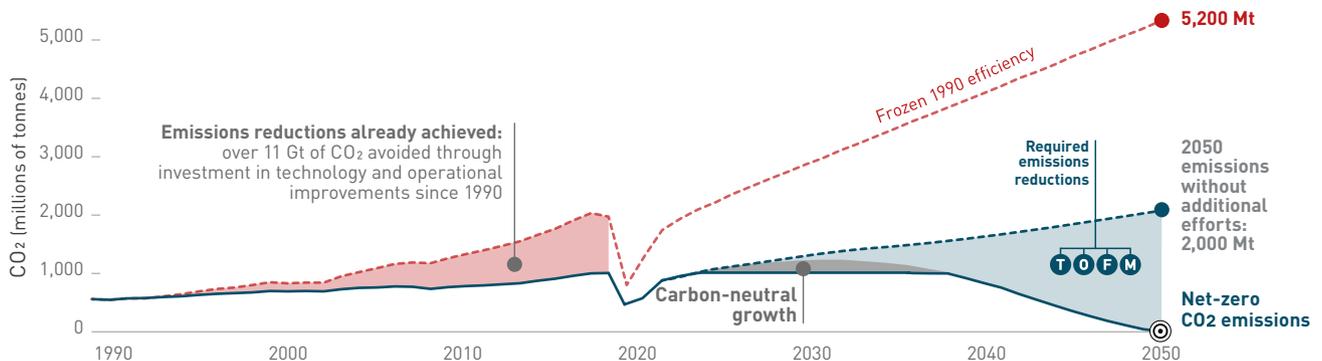


Grams of CO<sub>2</sub> per passenger kilometre

\*Average occupancy of cars is around 1.5. These figures do not include embedded emissions from construction and maintenance of infrastructure, which are less important for aviation.

## Efficiency improvements have been impressive, more work needed

Efficiency measures have already saved 11 Gt of CO<sub>2</sub> since 1990, but further work is needed to get the sector down to the industry goal in 2050 (the required emissions reductions are explored in this publication), towards net-zero at a global level.



then entered into service. The development of a new aircraft type using evolutionary technology can be up to ten years and cost tens of billions of dollars<sup>13</sup>. To introduce radical technical changes (such as hybrid, hydrogen or electric aircraft) will command a similar or greater level of investment.

On top of the aircraft themselves, their operation brings with it incentives to reduce fuel use (and therefore emissions), with airlines spending \$188 billion on fuel in 2019. This represents just under a quarter of operating costs (and the same amount as spent on labour)<sup>14</sup>. The development of a new energy system for aviation will also require significant investment. The most attractive option is through drop-in sustainable aviation fuel which can make use of existing fuel systems in aircraft and at the world's 3,780 commercial airports. There are still high levels of investment required in the production and distribution of the sustainable fuel, but not to the extent of building a whole separate network as would be needed with, for example, hydrogen.

This is against a backdrop of a race for all other sectors also to decarbonise – with many of the other transport and industrial sectors able to make the transition sooner, due to existing technologies already being available.

### Challenge: CO<sub>2</sub> is not the only consideration

This report, and the analysis that underpins it, concentrates on the reduction of CO<sub>2</sub> emissions from commercial aviation services. However, air transport also produces other greenhouse gases. Whilst carbon dioxide is the greenhouse gas that has the most long-term impact, there are other emissions from flight. Recent analysis has shown that the full impact of aviation may be around 3.5% of all anthropogenic climate impact<sup>15</sup>.

The exhaust of a jet engine is made up of:

- » 5% to 6% CO<sub>2</sub>;
- » 2% water vapour;
- » around 0.03% nitrogen oxides, unburned hydrocarbons, carbon monoxide and sulphur oxides;
- » traces of hydroxyl family and nitrogen compounds and small amounts of soot particles; and
- » between 91.5% and 92.5% is normal atmospheric oxygen and nitrogen.

It is important to note that not all gases have the same climate impacts. CO<sub>2</sub> is the most notable greenhouse gas because of its long life, whereas some other gases (such as methane from agriculture and waste) have a much stronger impact on climate change, but a very short life.

One of the most visible signs of aircraft movements are the contrails left behind as flights move through some areas of the atmosphere. These are made up of ice crystals from the condensation of water vapour (like naturally-occurring clouds) produced from the combustion process inside the engine.

The impact of contrails (and the hazy cirrus clouds they sometimes generate as they dissipate) on climate change is complex and still includes large uncertainties, despite advances in research. Some recent studies have shown that contrail-induced cirrus could help cool the planet during the day, but warm it at night, similar to ordinary clouds.

It is actually possible to avoid creating contrails, either by flying around the areas of super-saturated cold air in which they form, or flying at a different altitude. However, this brings with it some downsides, as airlines could use more fuel (and therefore emit more CO<sub>2</sub>) to avoid these areas. The emission of any additional unnecessary CO<sub>2</sub>, however, needs to be prevented wherever possible.

A number of airlines and aviation experts are engaged with research teams to investigate the impacts of contrails further. While chances are good to avoid contrail formation with almost negligible CO<sub>2</sub> penalties, the bigger challenge is to obtain highly reliable meteorological data and to re-arrange flights on fewer flight levels in busy airspaces.

Some of the technology solutions being developed and explored in this report also have a positive impact on the other non-CO<sub>2</sub> impacts of aviation. Sustainable aviation fuels can reduce contrail formation as they contain no sulphur nor aromatic hydrocarbons, their exhaust is almost free of particulate matter, which is necessary to make water vapour condense into contrails. Electric and hydrogen energy supply would have virtually no contrail formation. Using hydrogen leads to increased water vapour emissions, but due to the lack of particles contrail formation is suppressed<sup>16</sup>. Each new type of energy would burn cleaner than fossil jet fuel and would also therefore likely produce fewer particulate matter emissions.

The important focus is how to bring down CO<sub>2</sub> emissions in balance with reducing other environmental impacts of the sector.

# A NOTE ON COVID-19



**THE IMPACT OF THE COVID-19 CRISIS ON ALL ASPECTS OF THE ECONOMY AND SOCIETY IS WELL KNOWN. THE IMPACT ON AVIATION HAS BEEN PARTICULARLY ACUTE, EQUIVALENT TO ADDING TOGETHER THE EFFECTS OF PREVIOUS SHOCKS (9/11, SARS, THE GLOBAL FINANCIAL CRISIS AND EYJAFJALLAJÖKULL ERUPTION AIRSPACE CLOSURE) INTO ONE 'BLACK SWAN' EVENT WHICH WILL HAVE FAR-REACHING IMPLICATIONS ON THE INDUSTRY FOR MANY YEARS.**

Whilst the size of the crisis is unprecedented, history has shown that air transport services and the desire to travel does return, eventually. The Covid-19 crisis may have several impacts on the analysis of this report, and the changes it is intended to drive. Some of those (for example a potential impact on investment capacities) are commented on below but not included in this analysis, as they are not immediately qualifiable.

**Traffic forecasts**

There have been reductions in passenger traffic caused by shocks in the past, but never a near total shutdown of the full global system. At the peak of the shutdown in mid-April 2020, the number of flights operating globally was an average of a quarter the number operating just six weeks earlier<sup>17</sup> (and many of these flights were operating with very limited occupancy: revenue passenger kilometres fell some 94.3% compared with April 2019<sup>18</sup>).

The re-opening of routes is going to be slow, as a result of government health measures and the concerns of passengers to travel too far from home. This, accompanied by the broader economic conditions resulting from Covid-19 suggests that there will be a prolonged period of soft demand. Many industry analysts suggest the industry may not return to pre-Covid-19

levels of passengers or traffic until 2024. Particularly impacted will be the long-haul traffic which makes up a large proportion of industry revenue passenger kilometres, the key metric used in Waypoint 2050 analysis.

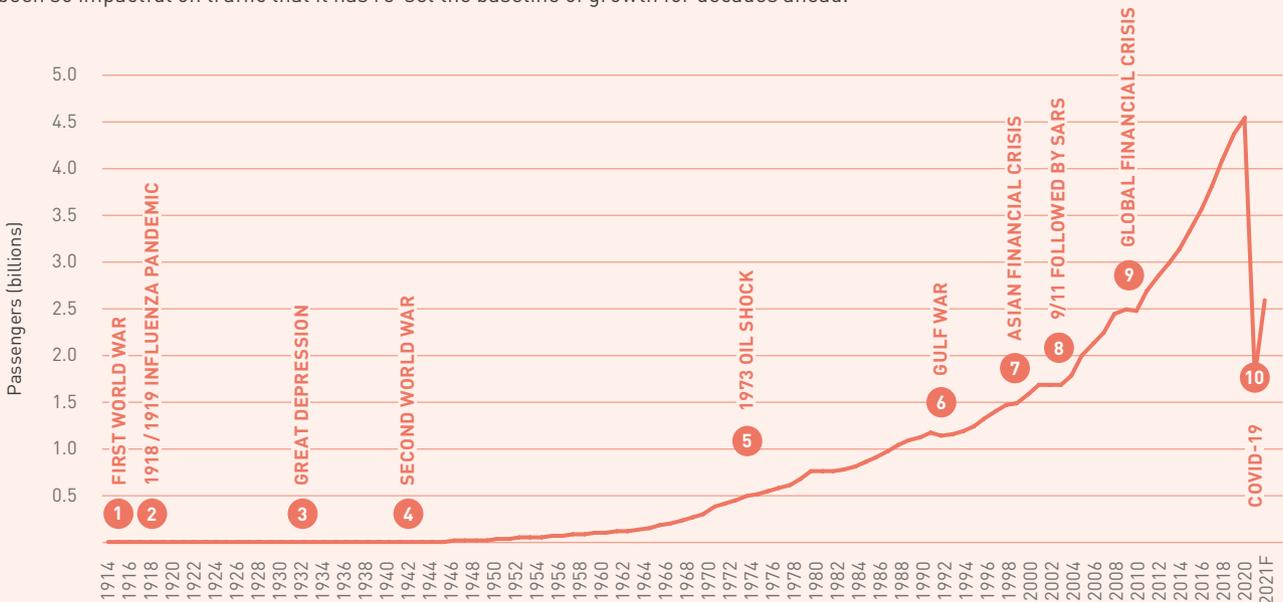
Shocks to air traffic growth in the past have always been followed by a reversion to trend, but the severe nature of this shutdown and the slow return to travel may have much further-reaching implications than expected. The central passenger growth scenario used for Waypoint 2050 was already based on lower growth rates than had been experienced in the last decade and which are likely lower than some other forecasts. But the analysis also now includes a reflection of what will likely be a 'new normal' in air travel: an industry smaller than was expected in 2019.

The post-Covid-19 revision of long-term growth suggests that the central traffic forecast used for Waypoint 2050 is around 8% lower in 2050 than it was in a pre-Covid world. This is due to:

- » a slow recovery from a severe drop-off in traffic in the 2020 year, likely to not recover to 2019 levels until 2024, and completely re-baselining the growth of air travel;
- » a longer-term impact on GDP growth in economies around the world;

**Global air passengers (billions) 1914-2021F<sup>19</sup>**

Previous crises have resulted in a fairly rapid return to trend. The Covid-19 situation will likely see a much slower recovery and has been so impactful on traffic that it has re-set the baseline of growth for decades ahead.



- » a reduction in the propensity to travel due to concerns over health situation at destinations and the potential for quarantine inconvenience – this will recover as the world eases out of the Covid-19 crisis, but there may be a long tail of concern, particularly amongst older travellers;
- » a reduction in business travel in the medium-term, due to a soft corporate financial situation and the reliance on video conferencing and remote working during the shutdown leading to a change in behaviour amongst corporate travellers.

### Efficiency improvements

The reduction in air travel has had a dramatic impact on the use of aircraft. At its peak, the Covid-19 shutdown saw 64% of the global jet fleet grounded<sup>21</sup> and, given the long recovery expected, some of those aircraft will not re-enter service. At the same time, a backlog of 11,650 new aircraft were due to enter service over the coming years, prior to the shutdown<sup>22</sup>. A number of these orders may be delayed or cancelled, but many of them are already in production or awaiting delivery. This could lead to competing efficiency outcomes:

- » An accelerated retirement of older (less efficient) aircraft.
- » A higher percentage of newer (more efficient) aircraft in fleets.
- » A short-term reduction in the delivery of newer aircraft.
- » A medium-term reduction in the purchase of newer aircraft.

Already, airlines have announced retirements of older model aircraft, particularly large four-engine models such as the Boeing 747-400, Airbus A340 and A380. However, a number of narrowbody older generation aircraft are also being permanently parked because of the crisis.

How these short- and medium-term developments will impact the fuel efficiency of the sector remains to be seen, however the timelines being considered in Waypoint 2050 will not likely be impacted by these short-term developments.

### Investment environment

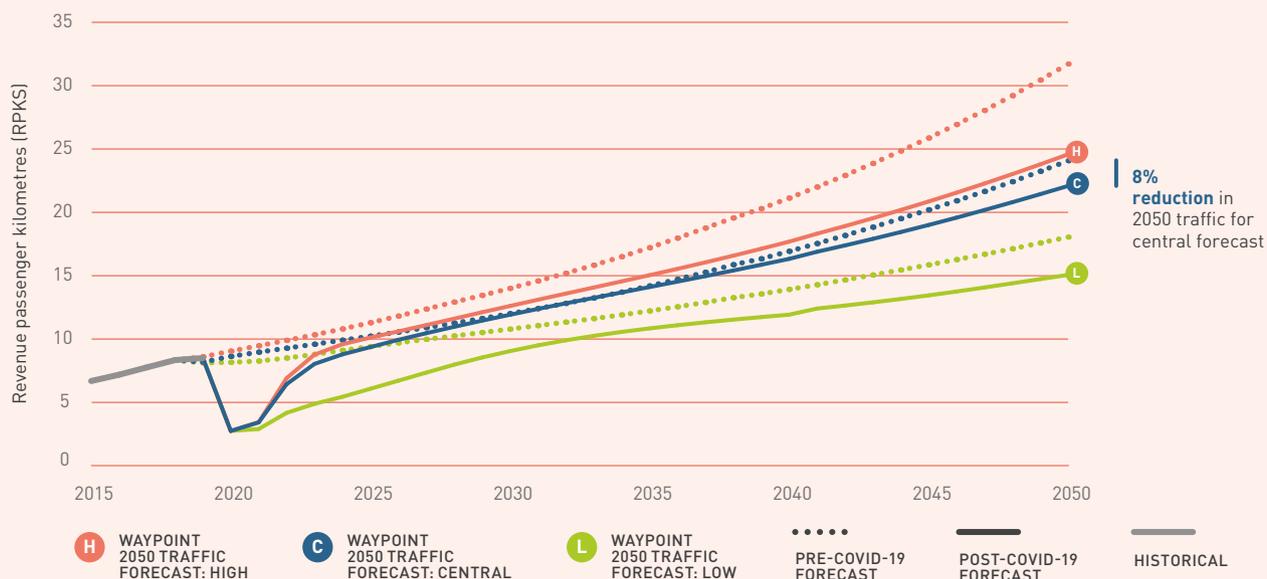
The area where efficiency may be impacted in the medium-term by the Covid-19-associated economic recession will be the investment environment. This has several possible impacts:

- » The ability for airlines to invest in new aircraft, at least for a few years, may be dampened as they fight for survival. Coupled with the extremely low cost of fuel during the initial stages of the pandemic, there could be an incentive to retain older aircraft longer. However, it is unlikely that brand new aircraft will not be delivered, and that the price of fuel has already rallied. Indeed, airlines are already placing orders for new-generation aircraft again.
- » Airlines, governments and energy suppliers may find it challenging to invest in the infrastructure and forward purchase agreements required to facilitate the energy transition needed towards sustainable aviation fuel. This, however, is a vital step for an industry with few other options for energy sources and is in need of acceleration: governments should see this crisis as an opportunity to build new energy industries across the world as part of a green recovery.
- » Airframe and engine manufacturers are also facing a significant financial impact which may create a challenging investment environment for development of new conventional aircraft and research into radical technology shifts.

Despite these challenges, the industry has committed to maintaining its efficiency and long-term emissions reduction strategy, even in the face of the unprecedented crisis of 2020. In fact, there has been an acceleration of climate commitments by the sector during Covid-19, rather than a slow-down: at the beginning of 2020, 11 airlines had committed to net-zero goals. At the time of printing 61 airlines representing 52% of global passenger traffic had made individual corporate commitments to net-zero by 2050 (or earlier).

### Global air passenger traffic forecast comparison, pre- and post-Covid<sup>20</sup>

Comparison between the traffic forecasts used before Covid-19 hit and those used in the Waypoint 2050 report: the deep impact of Covid-19 on passenger traffic, as well as the long recovery will mean an 8% reduction in traffic in the central scenario in 2050.





# WAYPOINT 2050

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**IN AVIATION, WAYPOINTS ARE SIGNIFICANT POINTS ON A FLIGHTPATH THAT PILOTS USE IN NAVIGATING THEIR DIRECTION OF TRAVEL. THEY ARE NEITHER THE START NOR THE END OF A JOURNEY, BUT A GUIDE TO WHERE THE FLIGHT NEEDS TO GO. IN DEVELOPING A LONG-TERM GOAL, THE INDUSTRY HAS TAKEN THIS PHILOSOPHY TO ACKNOWLEDGE THAT 2050 IS NOT A DESTINATION, BUT A MARKER ON A PATH TOWARDS TOTALLY ZERO CARBON EMISSIONS FROM AIR TRANSPORT.**

The sector’s framework for climate action is underpinned by advances in new technology, operational efficiency, new types of fuels, the development of more efficient infrastructure and, for the mid-range goal, the world’s first carbon mechanism for any global sector.

**Scope of project**

Waypoint 2050 covers the next 30+ years in commercial aviation from a CO2 perspective. It does not include military or most general aviation (i.e. smaller privately held aircraft used for hobby purposes). Nor does it include the burgeoning fields such as unmanned aerial vehicles (drones) or their use in urban air mobility (air taxis). Whilst these may have an impact on airspace capacity and are an important component for planning purposes, they are generally small scale when it comes to exploring the global impact of aviation on climate change and were not included in the scope of this study.

In addition, these smaller vehicles appear to already test and embrace new forms of lower-carbon energy sources e.g., electric, hybrid electric, hydrogen. They may help and become the initial test bed for larger aircraft in the future. The re-emergence of supersonic flight possibilities has also not been included, as it will likely remain a niche section of the market and should be expected to comply with rigorous aircraft CO2 standards developed at the International Civil Aviation Organization (ICAO).

The Waypoint 2050 project focuses on the trajectory of CO2 emissions from aircraft operations and the use of jet fuel. Whilst a lot of work is going on to reduce the emissions from ground-based sources (such as improving the efficiency of office buildings and airport terminals, and shifting ground vehicle fleets to alternative energy sources), these are not included in the scope of the Waypoint 2050 analysis, except where they have an impact on aircraft fuel use.

	ICAO	UNFCCC Paris Agreement
<p><b>Included in industry</b>  <b>2050 goal:</b> emissions from the global (commercial) use of jet fuel</p> <p>Emissions from military, government, general aviation and air taxi mobility services not included in the industry goals.</p>	<p>» CO2 emissions from international aviation (fuel burn gate-to-gate)</p>	<p>» CO2 emissions from domestic aviation (fuel burn gate-to-gate)</p> <p>» Airport emissions</p> <p>» Emissions from ground service equipment and road vehicles</p> <p>» Terminals, maintenance facilities, offices</p> <p>» Air traffic control</p>

**This report, the result of three years of work by experts from across the sector, builds on previous analysis to outline how air transport can meet net-zero carbon emissions by mid-century.**

## A VISION FOR 2050

Those working in the aviation sector in 2050 will have an industry that is, in some ways very familiar to that of 2020 and in many ways very different. At that point aviation (both international and domestic services) should be in a position to achieve net-zero CO<sub>2</sub> emissions, despite transporting over 10 billion passengers a year (more than twice 2019 levels), supporting 180 million jobs and over \$8.8 trillion in economic activity<sup>23</sup>.

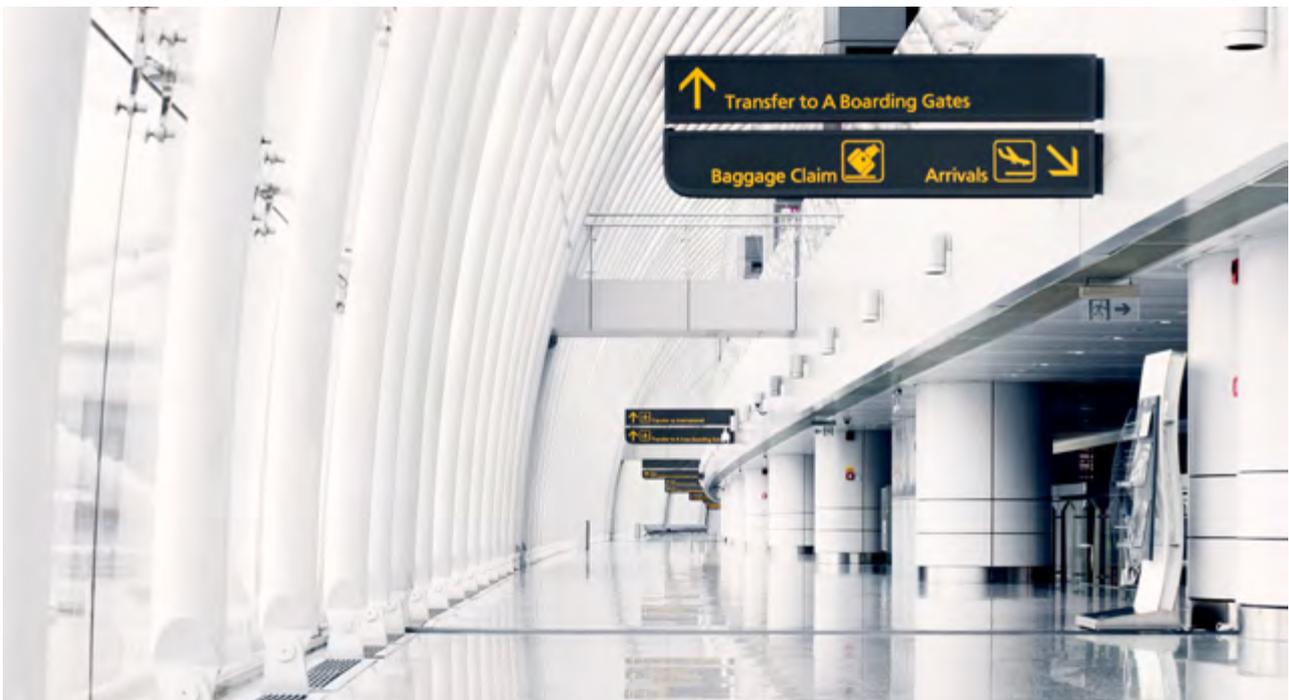
Much of the growth out to 2050 will have taken place in Asia-Pacific, the Middle East, Africa and Latin America, allowing the citizens of those societies to benefit from the social, family, cultural and business connectivity that was a century earlier the reserve of the wealthy in Europe and North America.

For short-and medium-haul routes, a series of new energy sources will provide much of the power needed for those flights – and with virtually no CO<sub>2</sub> emissions at all. Electric and hybrid-electric aircraft will connect secondary cities and small communities with larger hubs for connection to long-haul routes. Hydrogen powered aircraft will have entered the fleet for almost zero emissions flights on short-haul domestic and international services. Most long-haul operations will be taking place with aircraft a generation beyond those that are flying today, but nearly completely powered by sustainable aviation

fuel from a variety of sources (including fuels that are made by combining low carbon electricity with CO<sub>2</sub> removed from the air).

Airports will be hubs of renewable energy production and distribution, taking a leadership role in their local communities for new energy and clean transportation options. The whole industry will have adopted a zero-waste strategy, applying the best circular economy practices, pioneering the use of new materials and the recyclability of materials and ensuring the proper dismantling and recycling of aircraft at the end of their life.

The path to get from where we are now to this eventual world is not an easy one. Sustainable aviation fuel production will need to ramp up from around 0.05 million tonnes today to as much as 445 million tonnes per year by 2050. Aircraft with new forms of propulsion technology are researched; they will be prototyped, tested, and will need to be flown and purchased by the world's airlines. The whole industry will need to come together to maximise the operational and infrastructure improvements needed to help reduce emissions further and narrow the gap between growth and the sector's climate goals. And all this while the rest of the economy is also racing to reduce emissions and push forward with new ways of doing business.



Cost buckets	Primary actors involved
Research into new aircraft, engines and supporting technologies (batteries, hydrogen storage, etc)	<ul style="list-style-type: none"> <li>» Aircraft and engine manufacturers</li> <li>» Research institutions</li> <li>» Government support</li> </ul>
Development, industrialisation and certification for new architecture aircraft, engines and systems	<ul style="list-style-type: none"> <li>» Aircraft and engine manufacturers</li> <li>» Government support</li> </ul>
Purchase and operationalisation of new aircraft (training of flight and cabin crews, maintenance, etc)	<ul style="list-style-type: none"> <li>» Airlines</li> </ul>
Deployment of new air traffic management technologies and airspace infrastructure design	<ul style="list-style-type: none"> <li>» Air navigation service providers</li> </ul>
Installation of fixed electrical ground power at all airport gates	<ul style="list-style-type: none"> <li>» Airports</li> </ul>
New distribution systems for green electricity for aircraft supply, hydrogen and low-carbon energy at airports	<ul style="list-style-type: none"> <li>» Energy providers</li> <li>» Airports</li> <li>» Government support</li> </ul>
Scale-up of sustainable aviation fuel production facilities	<ul style="list-style-type: none"> <li>» Airlines</li> <li>» Energy providers</li> <li>» Government support</li> </ul>
Research for new sources of sustainable aviation fuel	<ul style="list-style-type: none"> <li>» Research institutions</li> <li>» Government</li> <li>» Energy producers / providers</li> </ul>
Emission reductions purchased from 'out-of-sector' projects to compensate for unavoidable CO <sub>2</sub> emissions in aviation.	<ul style="list-style-type: none"> <li>» Airlines</li> <li>» Governments (for policy and accounting)</li> </ul>
'Offsetting' opportunities such as forestry, natural carbon sinks and novel approaches such as carbon capture or direct air capture must be matured and brought to market	<ul style="list-style-type: none"> <li>» Carbon markets</li> <li>» Governments</li> <li>» Airlines and airports (as purchasers)</li> </ul>
Research on understanding the impact of non-CO <sub>2</sub> aviation emissions	<ul style="list-style-type: none"> <li>» Research organisations (with government support)</li> <li>» Aircraft and engine manufacturers</li> <li>» Airlines</li> </ul>

## The cost of transition

This project has not considered the cost of the transition, except for the investment needed in new energies and SAF deployment, given the multiple uncertainties that exist when trying to analyse this at a global level and over such a long time period. The main focus has been on the practical and technical ability to meet the industry carbon goals, whilst understanding that the full cost will be considerable: both to the various parties in the industry and to the governments and finance institutions that will need to underwrite the transition. The list below may give an idea of the major cost areas that will need to be considered.

Additionally, the analysis has not concentrated on the impact of any carbon price – it has formed a basis for the SAF deployment work in particular, but the uncertainty over the cost of carbon 30 years into the future is high. Whilst CORSIA has been developed at a global level, it touches international services only and this report looks at both international and domestic traffic. To try and place a carbon price filter on the entire aviation industry for forecasting purposes would have added another layer of complexity.

## There is not just one pathway

In order to reduce the complexity of forecasting across a wide range of variables, this report has identified three specific scenarios. These are built on a range of sub-scenarios which will be explored in the coming chapters covering a) traffic growth forecasts, b) technology developments, c) operations and infrastructure improvements, d) sustainable aviation fuel, and e) the role of out-of-sector market-based mechanisms to fill any remaining gaps.

The central traffic growth projection used shows that, by 2050, over 10 billion passengers will fly each year a distance of 22 trillion revenue passenger kilometres. Without any intervention (keeping the current fleet and current level of operational efficiency), this activity would generate close to 2,000 megatonnes of CO<sub>2</sub> and require over 620 Mt of fuel.

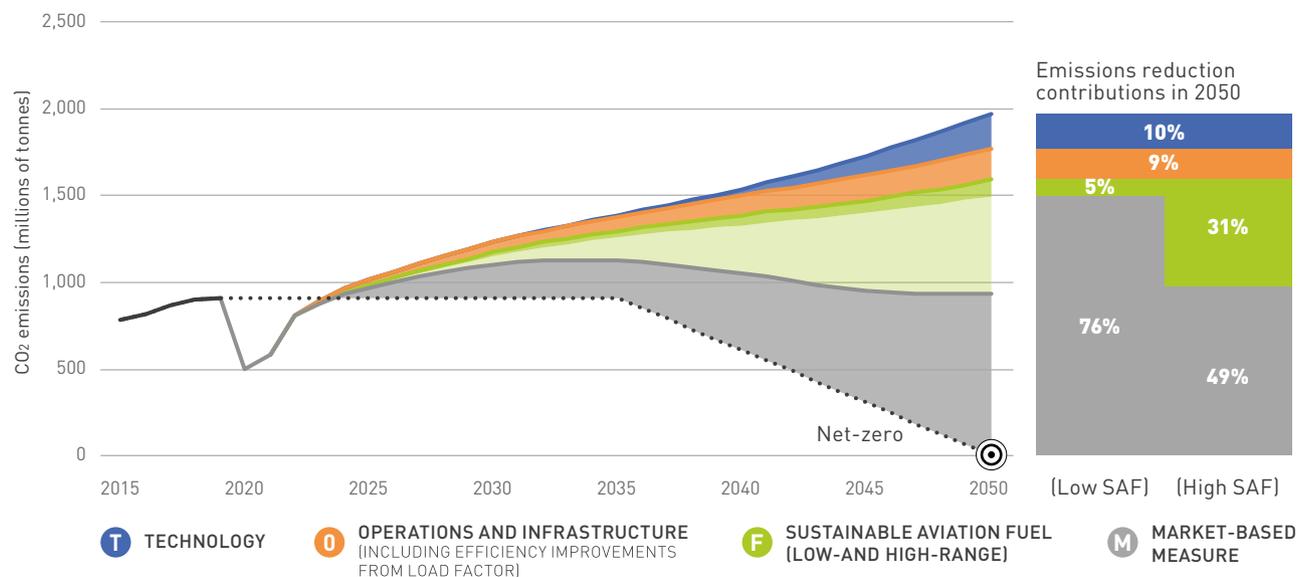
The scenarios below outline how the industry would use technology, operations, infrastructure and sustainable aviation fuels to bring this down to net-zero CO<sub>2</sub> in 2050, and towards decarbonisation in the years afterwards. The baseline (scenario 0) is a continuation of the current efficiency trends across all pillars of action, with no acceleration of improvements.

## Scenario 0: baseline / continuation of current trends

Traffic forecasts are in the 'central' range of around 3.1% per annum compound growth. Technology improvements are conservative (i.e., assuming no- to little-risk by shifting to unconventional platforms) and therefore show a continuation of the current rate of improvement, with another wave of new aircraft joining and starting to replace the fleet around 2030-2035. Despite mid traffic growth,

investments in operations and infrastructure result in some net improvements and CO<sub>2</sub> reductions. Sustainable aviation fuel is developed and introduced based on current rates resulting in approximately 30 to 195 million tonnes in 2050. Under this scenario, offsets (either the traditional offsets as used today, or new options such as carbon capture) are required and will have to play a major role in 2050.

<b>Traffic growth</b>	<b>C</b>	Central scenario: 3.1% compound annual growth rate (CAGR) 2019-2050
<b>Technology developments</b>	<b>T<sub>2</sub></b>	Continuation of current development cycle and performance improvement (the next generation of 'tube-and-wing')
<b>Operations and infrastructure improvements</b>	<b>O<sub>2</sub></b>	Mid-range improvements and airline load factor improvements
<b>Sustainable aviation fuel</b>	<b>F<sub>1</sub></b>	F1 to F1 high+ continuation of current investment curve delivering between 30 – 195 Mt (40 – 240 billion litres) of SAF with a 100% emissions reduction factor by 2050
<b>Offsets (or other carbon mitigation options)</b>	<b>M<sub>0</sub></b>	Required to meet goal, in the order of 970 – 1,500 Mt of offsets



### Comparison with industry -50% long-term goal set in 2009

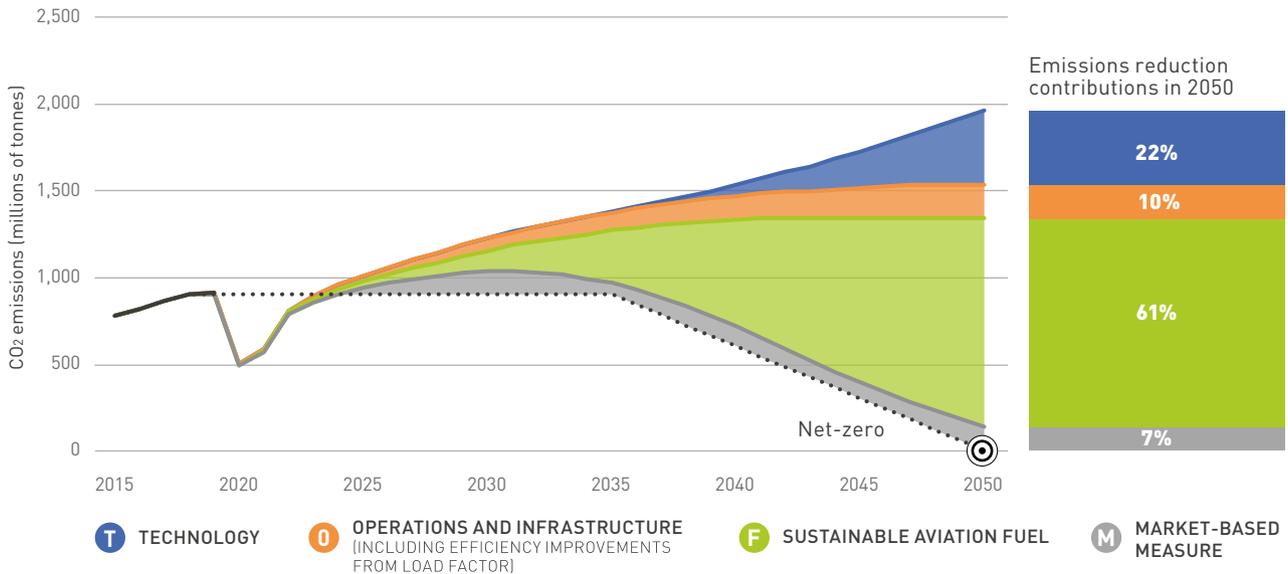
In order to meet the industry long-term goal of -50% by 2050 compared to 2005 levels, Technology would contribute 12% of emissions reductions. Operations and infrastructure improvements 11%. Sustainable Aviation Fuels would show a low- to high-range continuation of current investment curve delivering between 30 - 195 Mt (40 - 240 billion litres) of SAF with a 100% emissions reduction factor by 2050 (between 6 and 37% of 2050 emissions reductions). The remainder required to meet goal would need to be met with out-of-sector carbon removals or offsets, in the order of 650 – 1,200 Mt in 2050.

## Scenario 1: pushing technology and operations

Under this scenario, technology improvements are prioritised and ambitious with the expectation of the emergence of unconventional airframes and a transition of the fleet towards hybrid/electric aircraft from 2035/40. Significant investments in operations and infrastructure improvements result in substantial improvements and CO<sub>2</sub> reductions. The gap between CO<sub>2</sub> emissions after technology and operations and infrastructure

improvements and the 2050 carbon goal is fulfilled with the use of sustainable aviation fuels. This will require significant quantities of SAF with high emissions reduction factor over their lifecycle. Under this scenario, offsets will be needed to clear up any residual emissions in 2050 but may be required during 2035-2050 as a transition mechanism.

<b>Traffic growth</b>	<b>C</b>	Central scenario: 3.1% compound annual growth rate (CAGR) 2019-2050
<b>Technology developments</b>	<b>T<sub>4</sub></b>	Prioritised development of electric and hybrid electric aircraft in the short-range and <100 seat category with entry into service from 2035/2040 and further enhancements for larger aircraft.
<b>Operations and infrastructure improvements</b>	<b>O<sub>3</sub></b>	High-range improvements and airline load factor improvements
<b>Sustainable aviation fuel</b>	<b>F<sub>2</sub></b>	Backcast of what is required (around 1,200 Mt CO <sub>2</sub> reduction) to replace 90% of conventional jet fuel: 380 Mt (480 billion litres) of SAF with a 100% emissions reduction factor by 2050
<b>Offsets (or other carbon mitigation options)</b>	<b>M<sub>1</sub></b>	Around 135 million tonnes worth of offsets may be required to close the emissions gap to net-zero



### Comparison with industry -50% long-term goal set in 2009

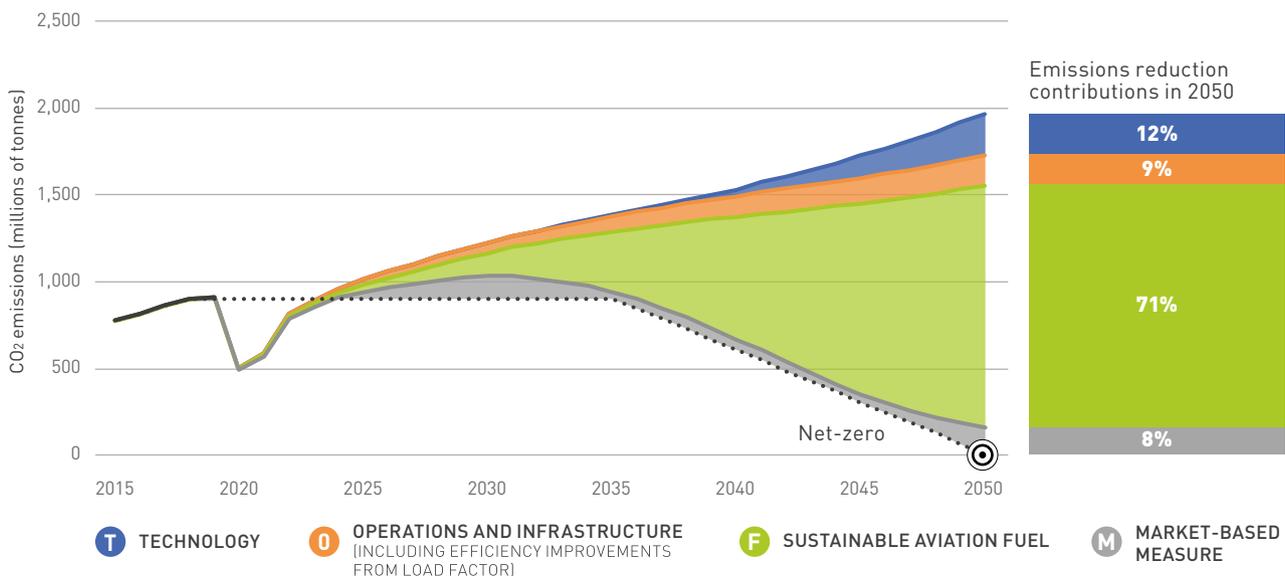
In order to meet the industry long-term goal of -50% by 2050 compared to 2005 levels, Technology would contribute 26% of emissions reductions. Operations and infrastructure improvements 12%. A back-cast to meet the goal would require 320 Mt (400 billion litres) with a 100% emissions reduction factor by 2050 (62% of emissions reductions), or a mix of SAF and offsets in the form of carbon removals.

## Scenario 2: aggressive sustainable fuel deployment

Under this scenario, technology improvements are ambitious with new aircraft configurations such as blended wing body options, although those are based on current powerplant and technologies (not a significant shift to electric or hybrid, with the industry prioritising investment in sustainable fuels). Despite mid traffic growth, investments in operations and infrastructure result in some net improvements and CO<sub>2</sub>

reductions. The gap between CO<sub>2</sub> emissions after technology and operations and infrastructure improvements and the 2050 carbon goal is fulfilled with sustainable aviation fuels (requiring significant amounts of SAF with high emissions reduction factors). Under this scenario, offsets will be needed to clear up any residual emissions in 2050 but may be required during 2035-2050 as a transition mechanism.

<b>Traffic growth</b>	<b>C</b>	Central scenario: 3.1% CAGR 2020-2050
<b>Technology developments</b>	<b>T<sub>3</sub></b>	New airframe configurations with substantial aerodynamics performance such as blended wing body
<b>Operations and infrastructure improvements</b>	<b>O<sub>2</sub></b>	Mid-range improvements and airline load factor improvements
<b>Sustainable aviation fuel</b>	<b>F<sub>3</sub></b>	Backcast of what is required (around 1,400 Mt CO <sub>2</sub> reduction) to replace 90% of conventional fuel: 445 Mt (555 billion litres) of SAF with a 100% emissions reduction factor by 2050
<b>Offsets (or other carbon mitigation options)</b>	<b>M<sub>2</sub></b>	Around 155 million tonnes worth of offsets may be required to close the emissions gap to net-zero



### Comparison with industry -50% long-term goal set in 2009

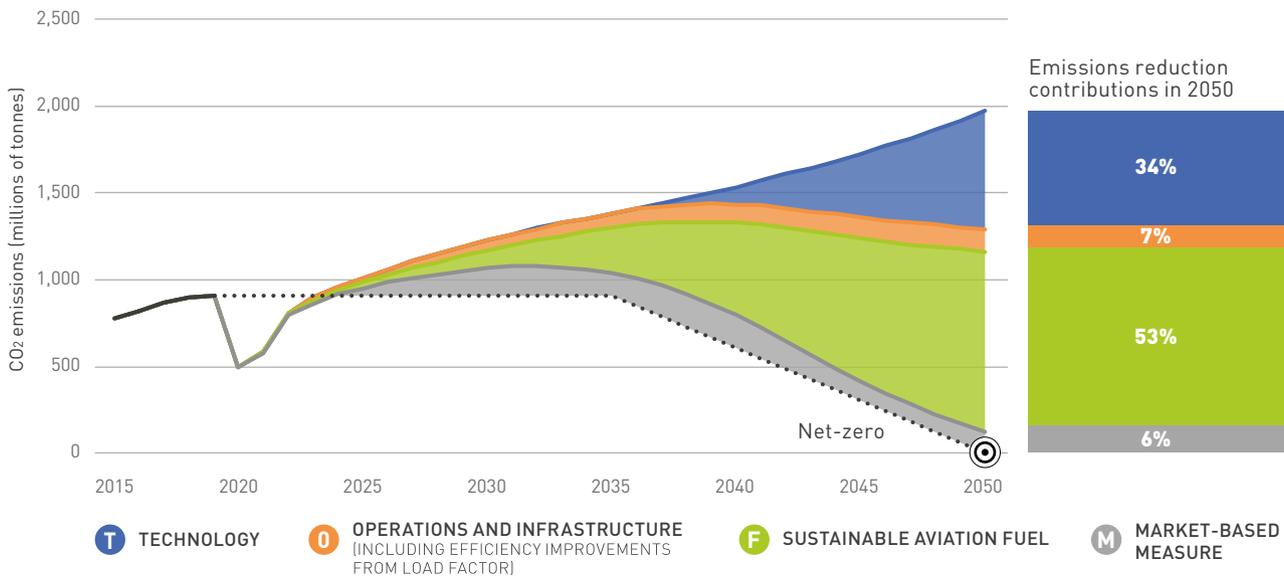
In order to meet the industry long-term goal of -50% by 2050 compared to 2005 levels, Technology would contribute 14% of emissions reductions. Operations and infrastructure improvements 11%. A back-cast to meet the goal would require 390 Mt (490 billion litres) with a 100% emissions reduction factor by 2050 (75% of emissions reductions), or a mix of SAF and offsets in the form of carbon removals.

### Scenario 3: aspirational and aggressive technology perspective

Under this scenario, technology improvements are very ambitious with electric aircraft up to 100-seat, zero-emissions aircraft (powered by green hydrogen) for the 100-200 seat segment and hybrid-electric powered unconventional aircraft configuration for larger aircraft. Despite a mid-level of traffic growth, investments in operations and infrastructure result in some net improvements and CO<sub>2</sub> reductions. The gap

between CO<sub>2</sub> emissions after technology and operations and infrastructure improvements and the 2050 carbon goal is fulfilled with sustainable aviation fuels (requiring significant amounts of SAF with high emissions reduction factor (ERF)). Under this scenario, offsets will be needed to clear up any residual emissions in 2050 but may be required during 2035-2050 as a transition mechanism.

<b>Traffic growth</b>	<b>C</b>	Central scenario: 3.1% CAGR 2020-2050
<b>Technology developments</b>	<b>T<sub>5</sub></b>	Very aggressive acceleration of the introduction of electric, hybrid and zero-emissions (hydrogen) aircraft in the 2035-2040 timeframe
<b>Operations and infrastructure improvements</b>	<b>O<sub>2</sub></b>	Mid-range improvements and airline load factor improvements
<b>Sustainable aviation fuel</b>	<b>F<sub>4</sub></b>	Backcast of what is required (around 1,000 Mt of CO <sub>2</sub> ) to replace 90% of conventional fuel: 330 Mt (410 billion litres) of SAF with a 100% emissions reduction factor by 2050
<b>Offsets (or other carbon mitigation options)</b>	<b>M<sub>3</sub></b>	Around 115 million tonnes worth of offsets may be required to close the emissions gap to net-zero



#### Comparison with industry -50% long-term goal set in 2009

In order to meet the industry long-term goal of -50% by 2050 compared to 2005 levels, Technology would contribute 41% of emissions reductions. Operations and infrastructure improvements 8%. A back-cast to meet the goal would require 260 Mt (330 billion litres) with a 100% emissions reduction factor by 2050 (51% of emissions reductions), or a mix of SAF and offsets in the form of carbon removals.

## Compatible with the Paris Agreement

Although the Paris Agreement does not establish sector-specific goals for addressing potential temperature rise, analysis shows that the aviation sector's 2050 goal to halve net CO<sub>2</sub> emissions on a 2005 baseline was in line with the Paris Agreement goal to limit global temperature rise to "well below 2°C above pre-industrial levels". A net-zero 2050 pathway will bring aviation in line with the 1.5°C stretch goal.

The 2015 Paris Agreement for the first time ensured a global climate change response built on voluntary pledges of emissions reductions by all States (known as nationally-determined contributions, or NDCs). The key provision of the Agreement outlines the world's goal:

*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change.*

Analysis from the Intergovernmental Panel on Climate Change (IPCC) has shown that there is a significant difference in how the world will meet the 2°C goal versus the 1.5°C goal, as well as the benefits for doing so, including a reduction in population exposed to extreme heat, lower sea level rise and fewer species lost<sup>24</sup>.

While the industry goal announced in 2009 (to reach -50% CO<sub>2</sub> in 2050, compared with 2005) is in line with the 2°C Paris Agreement goal, the IPCC has published several

pathways to meeting 1.5°C, requiring a peaking of emissions across the economy between 2020 and 2030 and a rapid reduction in emissions following that, with net-zero emissions by the 'mid-century'.

For hard-to-decarbonise sectors such as air transport, meeting the 1.5°C goal and keeping a small percentage of overall human emissions will be a major challenge. For aviation to play a role in helping to achieve the 1.5°C pathway, it is likely that global aviation would need to reach net-zero emissions in the middle years of the century. This is in line with the projected 2050 situation outlined in this report, finding that aviation could reach net-zero emissions by mid-century (with the right support from Governments and the energy sector, and removing residual CO<sub>2</sub> through offset options), but assumes all other sectors also make aggressive cuts in CO<sub>2</sub> emissions in line with their technical ability to do so. Governments are now taking action and setting ambitious climate targets.

However, aviation will not be in a position to reduce emissions fast enough to meet earlier 2030 projections at a global level – the technical options and scale-up of sustainable aviation fuels are not going to be achieved as quickly as some other sectors are able to complete this.

Some regions are in a position to move faster than others, so 2030/35 reductions may materialise faster than in other parts of the world.

## WHY CAN'T ALL LEVERS BE PUSHED TO THEIR FULLEST EXTENT?

There are always trade-offs given the constraints in realistic scenarios. Accelerating the development of new technology comes with a significant price tag, that will need to be borne by players across the aviation system.

If airlines are investing in new aircraft, they may have less ability to also invest heavily in sustainable aviation fuel scale-up. Likewise, some significant decisions need to be made: does it make more sense to have a singular focus on traditional liquid sustainable aviation fuels, or wait for electric or hydrogen aircraft to be available?

The reality is the sector will need to investigate all options and pursue those that make the most sense, but there is unlikely to be bandwidth, financing or resources to push all levers to their full extent at once. The scenarios presented here are therefore a mix of these levers to demonstrate what might be possible and realistic.

The aviation sector is not in direct control of all mitigation measures. Technology, operations and air traffic management (ATM) enhancements will have to play their role but are not the one silver bullet to get to the industry's ambitious goals.

The energy question is central. The sector is highly dependent upon the energy transitions that will occur

around the globe to fight climate change for the global economy. While collaborations amongst the aviation stakeholders is a must, public policy support, political willingness, and early engagement with energy providers are also needed to incentivise the mix of options that the aviation sector needs to perform its transition towards ambitious goals. It is therefore important that aviation is taken into account in the development of those energy transition strategies to maximise the opportunity to meet its goal.

Financing the transition of the aviation sector is also a key question. Innovative solutions may need to be developed to support the aviation sector with fostered investments in key areas to push the mix of options that the sector urgently needs. All options should be considered in a balanced way offering the flexibility to the sector to adapt and transition while taking into account the various approaches that are possible through the basket of measures.

More concretely, efforts in technology development (research and technology) to continue improving the energy efficiency of vehicles and flights have to be maintained and even increased, new policy frameworks may have to be created to incentivise the use of sustainable aviation fuels and alternative energies and to facilitate a smooth and affordable transition to carbon neutrality.





# TRAFFIC FORECASTS

**AIR TRANSPORT HAS SEEN A REMARKABLE GROWTH IN TRAFFIC OVER THE 107 YEARS IT HAS PROVIDED COMMERCIAL SERVICES. THIS HAS BOTH DRIVEN AND BENEFITED FROM A RISE IN LIVING STANDARDS AROUND THE WORLD. THE DEREGULATION OF THE INDUSTRY, FIRST IN THE UNITED STATES, THEN EUROPE AND IN OTHER COUNTRIES HAS LED TO A SIGNIFICANT INCREASE IN MOBILITY AND THE BENEFITS OF THAT CONNECTIVITY HAVE BEEN FELT BY MORE AND MORE IN SOCIETY.**

There are still preconceptions that air travel is the reserve of the rich, but while wealthy people do use airline services more often than lower income (in line with wealthier people generally owning larger houses, driving bigger cars and consuming more products and services), there is no doubt that the increasing affordability of air travel has opened opportunities for billions more citizens across the economic spectrum. Not to mention provided jobs within aviation and many industries the sector supports.

When trying to forecast how traffic may evolve over the coming 30 years, hundreds of variables come into play. Historically, air travel on a global level has tended to double every 15 years. But how reliable is this metric for future growth? The traffic forecasting group looked at a number of drivers for traffic growth:

- » Demographic trends, including aging populations in a number of traditionally large aviation markets.
- » Economic circumstances and living standards improvements.
- » The cost of travel.
- » Capacity constraints, particularly in key regions.
- » Regional variations of growth based on underlying economic growth projections.
- » A need to re-baseline forecasts based on the severe impact of the Covid-19 shutdown on even long-term traffic growth in aviation.

In order to avoid gratuitous complexity, the Waypoint 2050 project has concentrated on one central forecast, with an upper and lower alternative.

## The central forecast for passenger demand growth

With an annual growth rate average of around 3.1%, the Waypoint 2050 central traffic forecast scenario (22 trillion revenue passenger kilometres (RPKs) in 2050, 2.5 times higher than 2019 levels of 8.49 trillion RPKs) is reflective of a continuation of changes in population, economic development and other demographic factors such as age structure (an aging population resulting in a reduction in the number of potential flyers in countries such as China, Germany, Italy, Russia and Japan. And an increase due to more 'flying-age' population in Mexico, Canada, India, Indonesia, United States and Brazil). The last decade has seen above-average growth patterns which, even absent the Covid-19 situation, will likely have slowed in the coming decades. That is reflected in this central forecast.

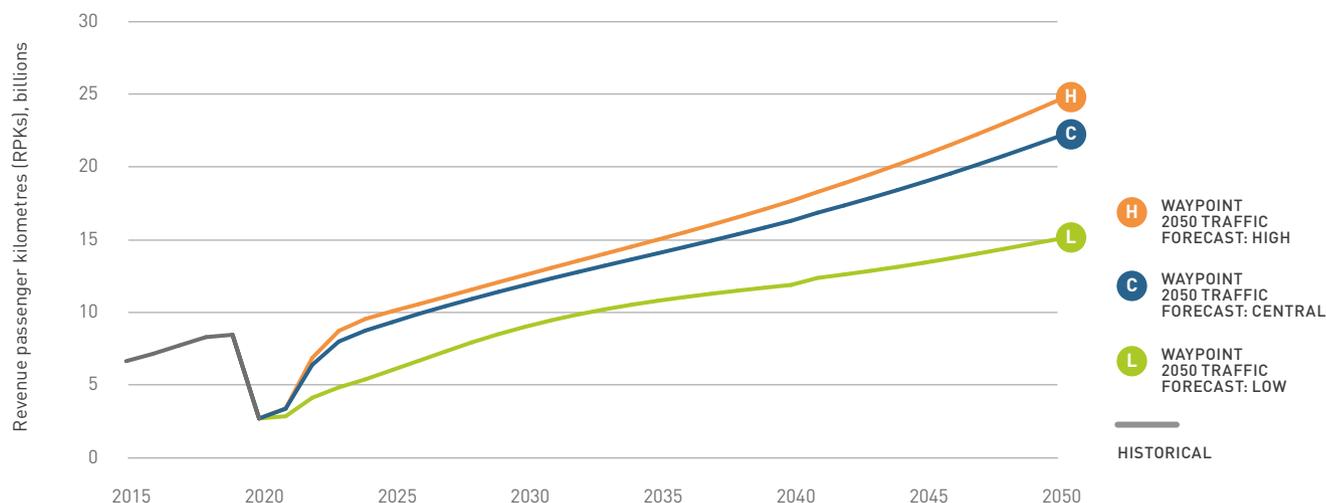
This scenario is influenced by strongest drivers of air markets in Africa over the coming 20 years, significant headwinds to air market expansion in several countries due to population and demographics, particularly the ex-Soviet states. The biggest expected change in absolute passenger numbers from this source is forecast to be in the United States. There is also some potential for generation of demand due to price stimulation if markets are opened up. Demographic factors will be significant constraints in Spain, Italy, Germany and Russia.

## Modelling

The W2050 Project used a hybrid modelling approach for fleet evolution and CO<sub>2</sub> emissions estimations through the study period. The passenger and belly freight operations were modelled using detailed aircraft-specific fleet evolution modelling as described in the section 'Methodology of Waypoint 2050 analysis'. This segment of the aviation market accounts for approximately 90% of total CO<sub>2</sub> emissions. The remaining CO<sub>2</sub> emissions, comprised of dedicated freighters (about 8-9% of total CO<sub>2</sub> emissions) and general/business aviation (about 1-2% of total CO<sub>2</sub> emissions), were modelled using simplified modelling approaches. This modelling hybrid approach was deemed fit for purpose for projections of emissions through and beyond 2050. Any inaccuracies in the resulting CO<sub>2</sub> emissions estimations are expected to be well within the level of uncertainty driven by other factors such as future aviation demand.

## Waypoint 2050 RPK forecasts 2015 – 2050<sup>32</sup>

Three scenarios were developed to address a range of potential growth options. The **central scenario** has been used for most of the analysis in this study.



Scenario	Description	RPKs in 2050	Compound annual growth rates			
			2019-2050	2019-2030	2030-2040	2040-2050
<b>L</b> Low growth	Protectionism deepens along with a reduction in mobility on top of Covid-19 impact.	15 trillion	2.3%	0.6%	2.8%	2.3%
<b>C</b> Central scenario	Continuation of historical trends, but a reduction compared with recent high-growth and taking into account the impact of Covid-19.	22 trillion	3.1%	3.1%	3.2%	3.1%
<b>H</b> High growth	Return to globalisation with a continuation of high growth trends seen in recent years, but from a revised base due to the impact of Covid-19.	25 trillion	3.3%	3.7%	3.4%	3.3%

### Exploring lower and higher scenarios

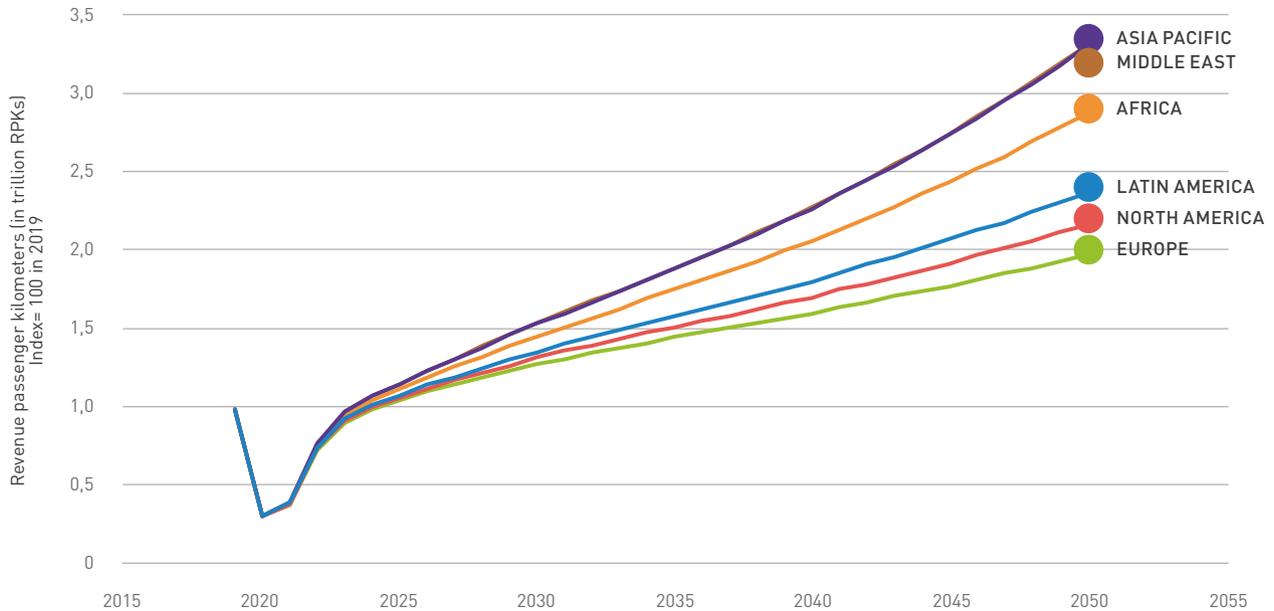
Under the Waypoint 2050 low traffic scenario (15 trillion RPKs in 2050), protectionism in trade and migration deepens with substantially lower generation of demand due to price stimulation, accompanied by a slower recovery from Covid-19 with more hesitant return to travel. Passenger numbers may increase at a greater rate than RPKs, as travellers prefer to stay closer to home.

The Waypoint 2050 high traffic scenario (25 trillion RPKs in 2050) assumes resilient growth including a “return to

globalisation”, despite challenges; a change in age structure: decline in propensity to travel in countries such as China, Germany, Italy, Russia, Japan and an increase in traffic in Mexico, Canada, India, Indonesia, US, Brazil; and substantial potential for generation of demand due to price stimulation if markets are opened. This scenario is a continuation of the high traffic growth seen in the last decade and would require a very rapid and early bounce back from the Covid-19 impact: a rapid deployment of vaccines and reduction in travel restrictions in the coming 2-3 years, but more importantly a rapid return to long-haul travel following the slowdown.

## Regional RPK forecasts 2019 – 2050 (index 2019, pre-Covid-19)<sup>33</sup>

Taking the central scenario, this graph shows which regions will demonstrate the most growth over the timeframe. Interpolated and extrapolated from regional shares in 2019 and 2039.



## Developing scenarios

To develop and investigate potential CO<sub>2</sub> emissions pathways to 2050, several sources of traffic forecasts were reviewed and consolidated into consensus scenarios by the cross-industry working group. These sources included:

- » ICAO Committee on Aviation Environmental Protection (CAEP) CO<sub>2</sub> Emissions Trends, based on ICAO traffic forecasts from 2016 and 2019<sup>34</sup>.
- » IATA 20-year Air Passenger Forecast predicts passenger demand by looking at such factors as the emerging middle class in developing countries, diverging demographic outlooks and further liberalisation of aviation markets. It assesses growth factors on 4,000 individual country pairs and forms a robust analysis on a country, region and global basis<sup>35</sup>. This was updated in 2021 to account for further evidence in the recovery from Covid-19 following initial assessments used in the first edition of Waypoint 2050.
- » ACI World Airport Traffic Forecasts 2019–2040 provides insights into the future evolution of air transport demand across the world. Using 2018 as reference year, the projections extend to 2040 and are presented on a global, regional and national level<sup>36</sup>.
- » Airbus Global Market Forecast (GMF) for 2019–2038 offers a forward-looking view of the air transport sector's evolution, accounting for factors such as demographic and economic growth, tourism trends, oil prices, development of new and existing routes<sup>37</sup>.
- » Boeing Commercial Market Outlook includes aircraft demand influenced by underlying structural changes and current market dynamics. The forecast considers detailed market specific drivers in each region<sup>38</sup>.

» IEA Energy Technology Perspectives published in June 2017<sup>39</sup>.

Each of these forecasts produced their own scenarios, with the range of aviation traffic forecasts (revenue passenger kilometres) considered in the W2050 analysis fairly wide: between 14 trillion revenue passenger kilometres in 2050 (the IEA B2DS scenario) to over 40 trillion RPKs in 2050 (the highest IATA scenario). Once the impact of Covid-19 started to be better understood, the traffic forecasting working group developed a consensus view on how these existing projections may change and adopted a revised set of forecasts which are used for this report.

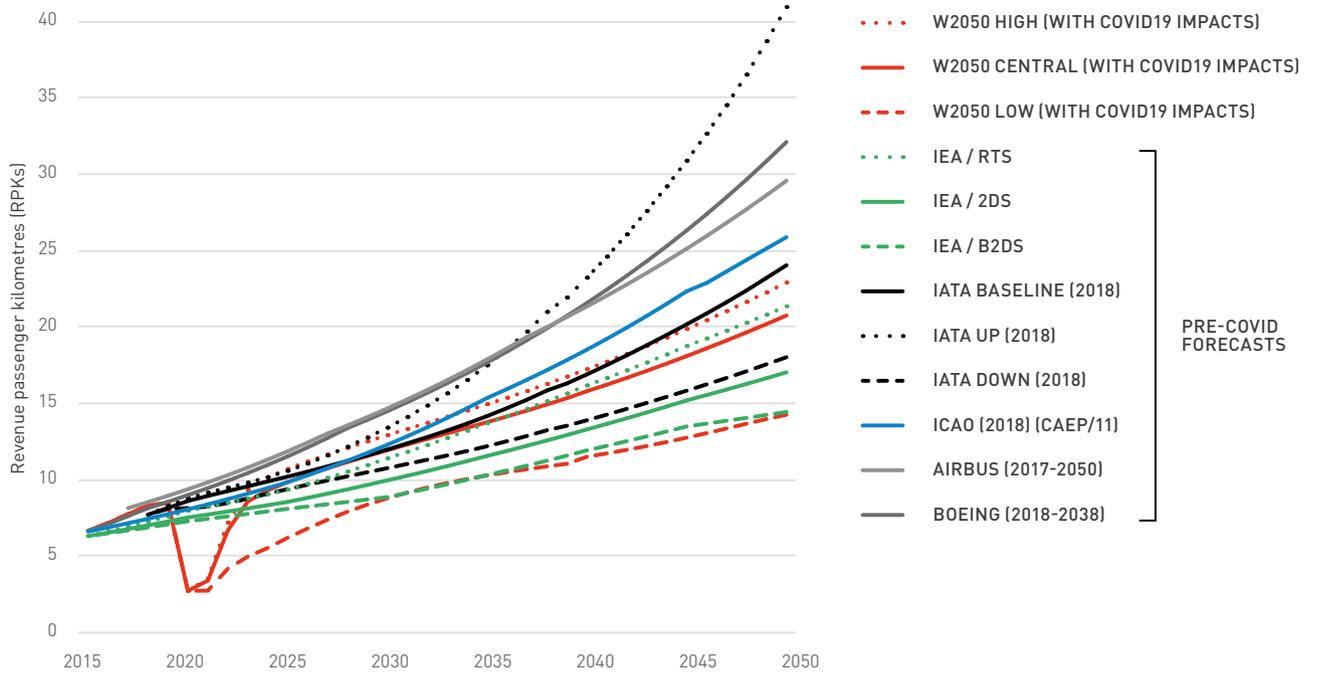
## Consideration: economic growth and underlying living conditions

One of the central challenges of forecasting air travel markets is assessing the intrinsic link between travel and living standards for different countries. There is a clear relationship between the number of trips per capita of a country each year and that country's standard of living. The size of each bubble is proportional to each country's population. The living standards (GDP per capita) drive the general relationship along with additional factors, including the cost of air travel (which is partly a function of the degree of air market liberalization in a given market), a country's geographical location and the availability of travel alternatives, as well as its inherent attractiveness as a destination. The combination of these factors explains why inhabitants of some countries on average travel more often or less often than would be expected based on their level of GDP per capita alone.



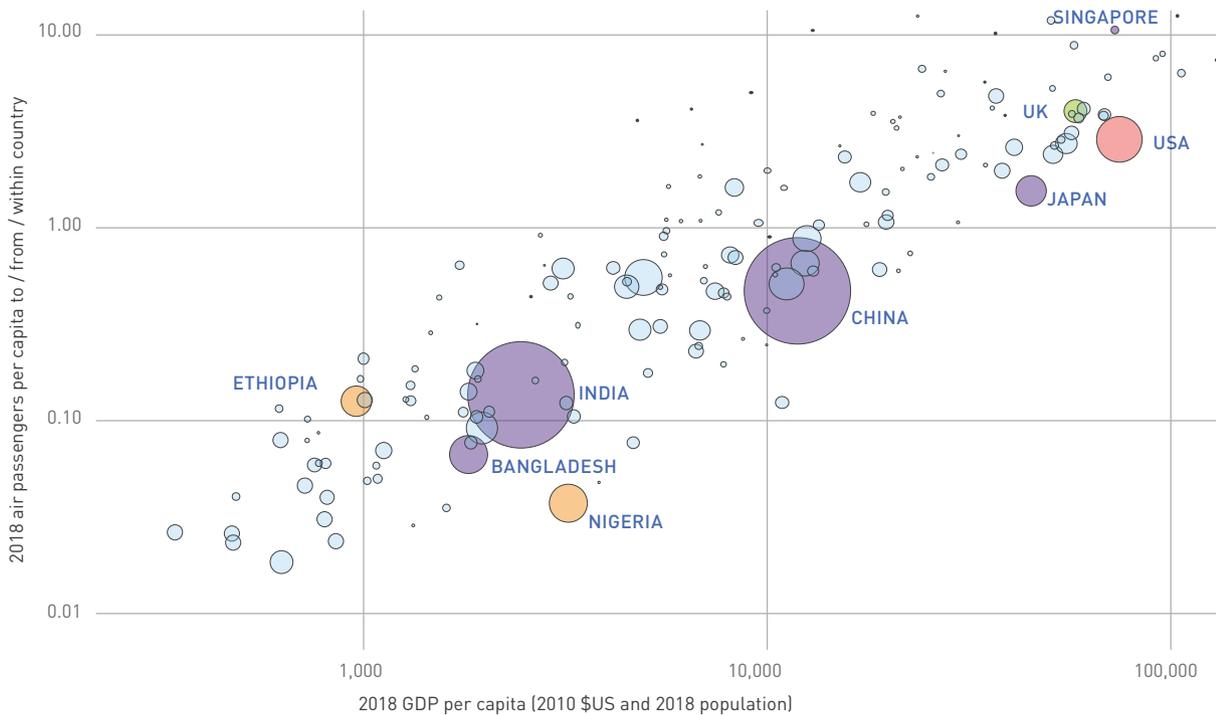
### Range of RPK forecasts 2015 – 2050<sup>40</sup>

Range of forecasts reviewed for consolidation into consensus scenarios. Existing forecasts extrapolated to 2050 if they did not include those latter years already. For illustrative purposes only.



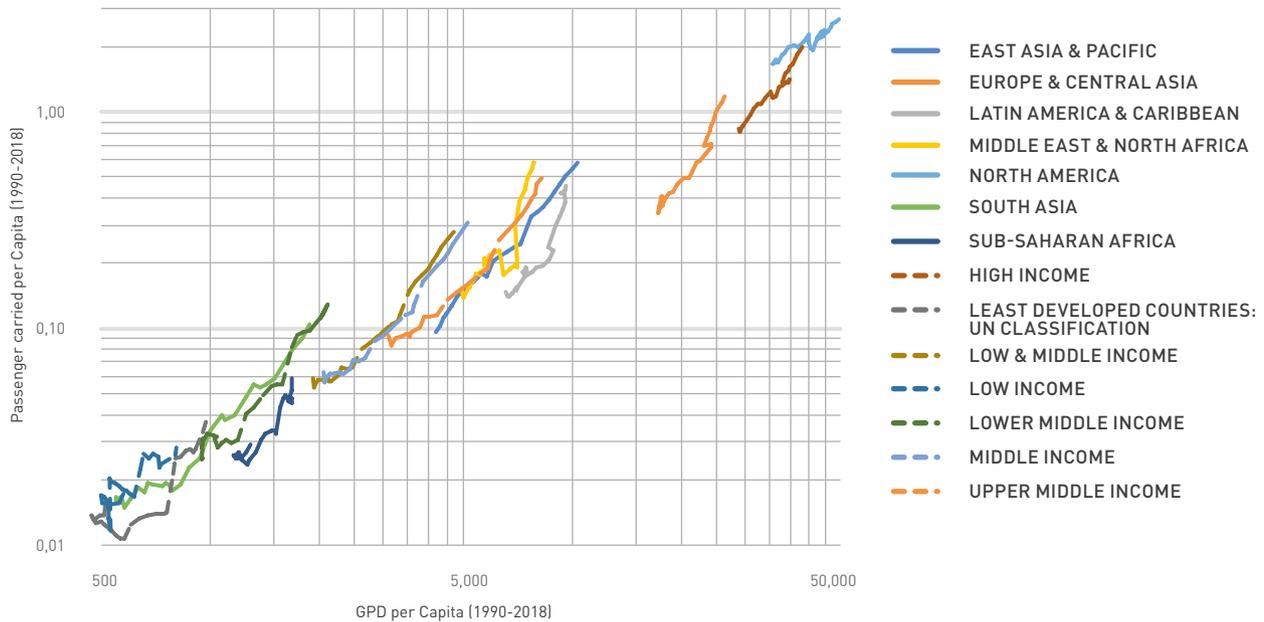
### Propensity to travel relationship to standards of living, 2018<sup>41</sup>

Analysis implies that air travel markets will grow most quickly in fast-growing but less-developed countries and will be most sluggish in slow-growing but richer countries.



## Growth in air travel comparisons, 1990-2018<sup>42</sup>

As living standards increase, aviation activity is also expected to grow. Countries with comparatively low standards of living at present, but that are forecast to improve strongly over the coming 20 years, are likely to see the most rapid increases in per capita air travel on average.



In general, countries above the trend are often islands and tourist destinations (such as the Maldives, Seychelles and Bahamas), trade hubs (such as Hong Kong and Singapore), or just a long way from anywhere (such as New Zealand). On the flip side, countries below the trend tend to be those where there is limited liberalisation / high prices in the air travel markets (such as in Africa) or other substitutes to air travel such as high-speed rail in a small number of markets.

Once a country reaches a certain level of living standards – approximately \$20,000 per capita – further gains in incomes tend not to be associated with as much increase in the number of trips taken on average by its inhabitants each year. For those countries above this income / living standard threshold, future growth in air travel will be driven less by future economic development and increases in living standards, and more by the other main drivers of air travel in the long run: population growth, including any changes to the demographic structure of the population, and future changes in the price of air travel.

For countries below the \$20,000 threshold level of living standards, however, a given increase in incomes would be expected to have a bigger effect and produce a proportionately larger rise in air travel per capita. In analysis of aviation activity per capita vs. GDP per capita as time series from 1990-2016 by regions and groups of countries. It shows that, as living standards increase, aviation activity is also expected to grow. It follows that countries with comparatively low standards of living at present, but that are forecast to improve strongly over the coming 20 years, are likely to see the most rapid increases in per capita air travel on average. While these air travel markets may be small at present, they are the growth markets of the future.

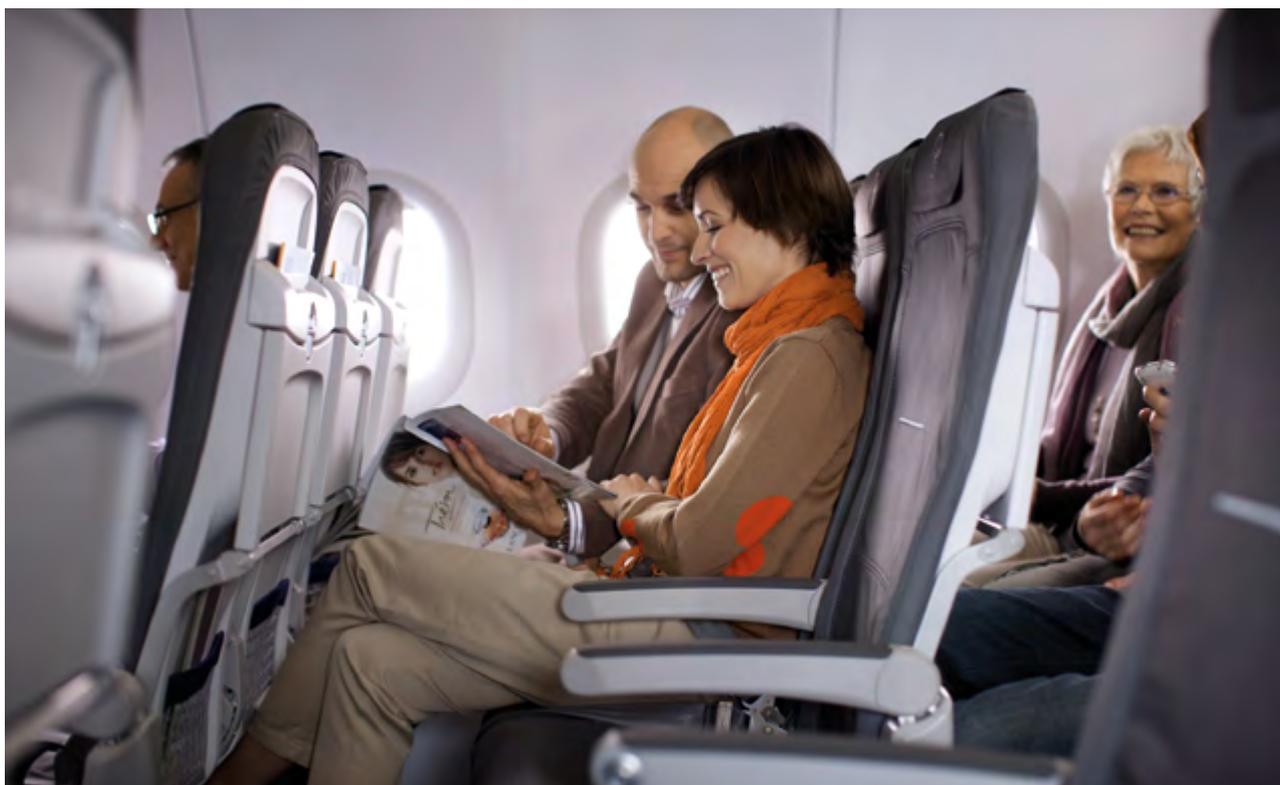
Based on these factors, it is expected that air travel markets will grow most quickly in fast-growing but less-developed countries and will be most sluggish in slow-growing but richer countries.

Despite some challenging near-term outlooks, the emerging market powerhouses of China, Mexico and Turkey are among the 26 countries forecast to join the ranks of high-income countries over the coming 20 years. Brazil and Russia were both on the cusp of the World Bank's high income threshold in 2014 but have slipped following the ongoing domestic recessions. They are expected to now surpass the threshold in the early 2020s.

As to be expected, the economies whose living standards are forecast to increase the fastest over the coming 20 years are expected to be amongst those to see their air travel markets grow the fastest too. Economic development in seven countries – notably Cambodia, Vietnam and Sri Lanka – is expected to translate into air travel market growth in excess of 5% per year over the coming 20 years.

That said, it is not all about growth rates. Levels of activity matter too, particularly when countries are starting from a very low base of living standards. Many of the less developed countries in Africa will not be mature markets in 2035. Nonetheless, sustained fast rates of growth in GDP per capita will continue to drive air demand for a long time into the future.

In terms of growth, economic development alone is expected to drive air travel to a lesser extent in the highly-developed countries. Future improvements in living standards in the G7 group of countries are estimated to translate into air travel growth of just 0.6-1.3% per year over the coming 20 years. That said, given the higher starting points of the highly-developed



countries, even reasonably modest rates of growth will correspond to sizeable increases in living standards and air travel in absolute terms. This underlines that such markets, while more mature and developed, will remain important markets for air travel expansion well into the future.

Interestingly, the number of flights taken per capita in Europe, North America, Australia and New Zealand will likely plateau in the coming years – despite modestly rising income levels, there is a limit to the number of extra flights citizens are minded to take. Growth rates in these economies tend to come from increases in population, including through migration, rather than increase in the number of flights per capita.

There is a clear distinction between advanced and emerging economies. India tops the pile of the large emerging market economies, with improvements in living standards alone expected to translate into air market growth of around 4.9% a year over the next 20 years. Indonesia and China are also towards the top, with economic development alone expected to underpin air travel growth of 3.6%-3.7% respectively each year.

Economic development in other large emerging market economies, including Vietnam (4.8% per year) and Turkey (2.2%), is expected to drive substantial air market growth over the next two decades.

### **Consideration: demographics**

Establishing the link between living standards and individual propensities to fly by country is a key piece of the puzzle. However, scaling these estimates up to country pair and global totals also requires an understanding of how population growth will affect air travel demand. It is clear that a country with population projected to expand significantly

over the next 20 years will, all else being equal, have more potential for growth in air travel than a country whose population is projected to expand less significantly, or even to decline.

Population projections produced by the United Nations (UN) shine a light on how populations are projected to change over time. Africa stands out as the region set for the biggest increase in population over the next twenty years. Most of the top 20-ranked countries by projected population increase in percentage terms between 2015 and 2035 are African. Nigeria is another notable example, with a projected population increase of 112 million (more than the present-day population of the Philippines). Altogether, Africa is expected to account for over 40% of global population growth over the next twenty years, with an increase of almost 635 million people.

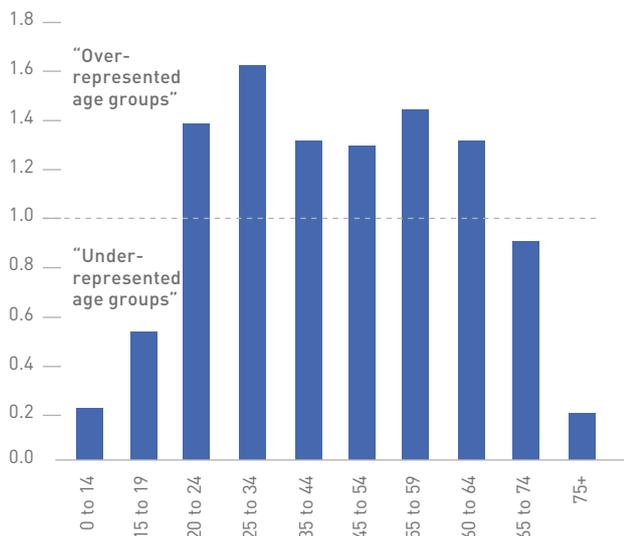
In absolute terms, India is projected to see by far the biggest change in population over the period, an increase of almost 250 million between now and 2035 (equivalent to the current population of Indonesia, which itself is the world's fourth most populous country).

With the notable exception of Japan, the most acute population challenges are in Europe, particularly in the ex-Soviet states. Four countries are projected to see double-digit percentage declines in their populations between now and 2035, including Bulgaria (-14%) and Ukraine (-12%).

The UN's projections are an obvious place to start but using them to predict how air passenger markets will evolve over time requires a further understanding of how the age structures of the populations will change. This stems from the fact that, by and large, it is people in the working-age groups (15-64) that are most likely to fly.

## Ratio of travellers by age group to population by age group, 2012<sup>43</sup>

In a UK Civil Aviation Authority survey of passengers, the 25-34 age group account for 21.5% of air passengers but only comprised 13.2% of the total population. By contrast, despite comprising around 17% of the total population, the over-65 age group only constituted around 10% of air travellers. Following Covid-19, we expect hesitation for travellers in slightly younger age groups (~55+) to continue for some time.



Global passenger surveys suggest that there is significant variation in traveller characteristics by region. However, there is a high confidence level that people in older age groups are less likely to fly. Accordingly, countries with populations projected to age considerably over the coming 20 years are likely to see corresponding reductions in the average 'propensity' to fly, which will have implications for air travel demand.

Age structures vary widely around the world. Africa stands out as having by far the lowest old-age dependency ratio (the number of people over the age of 65 compared with the number of people of working age). By virtue of the continent's young population, it is projected to remain low into the mid-2030s too. By contrast, with an old-age dependency ratio of over 26, Europe is the most top-heavy continent in terms of demographics, closely followed by North America. Both regions are projected to become increasingly top-heavy as their populations age over the coming 20 years.

Indonesia and India stand out as large economies with the lowest old-age dependency ratios. While their ratios are projected to increase in the future, they will remain low relative to other countries. At the other end of the scale, Japan is the country with the oldest population structure in the world. As this gap grows, this demographic shift will have serious implications for Japanese air travel markets. Germany's population is also projected to age significantly over the period; the largest for any major economy.

The legacy of the one-child policy contributes to China's demographic outlook. From being broadly in line with other large emerging markets at present, China's old-age

## Old-age dependency ratio<sup>44</sup>

The number of people over the age of 65 compared with the number of working age people who can support them in retirement. The current global old-age dependency ratio of 15.9 indicates that for every 100 people of working age (20-64) in the world there are 15.9 people aged over 65.

	2019	2030
Global	15.9	20.5
Africa	7.6	8.4
Asia	14.3	19.7
Europe	31.3	40.6
Latin America and Caribbean	14.8	20.1
North America	27.7	36.4
Indonesia	10.2	15.4
India	11	14.1
Japan	51	57.7
Germany	36.1	47.7
China	17.7	27.4
Kenya	5.1	6.5
Ethiopia	7.9	7.7
Australia and New Zealand	27.1	34.9
Eastern Europe	26.5	35.6
Western Europe	35.5	45.5

dependency ratio is projected to see the largest increase of any emerging market over the coming 20 years.

With these factors in mind, the Waypoint 2050 analysis uses the UN's population projections broken down by country and by age group, alongside information on the characteristics of air travellers by age group and by region, to estimate how these demographic effects will affect future air travel demand.

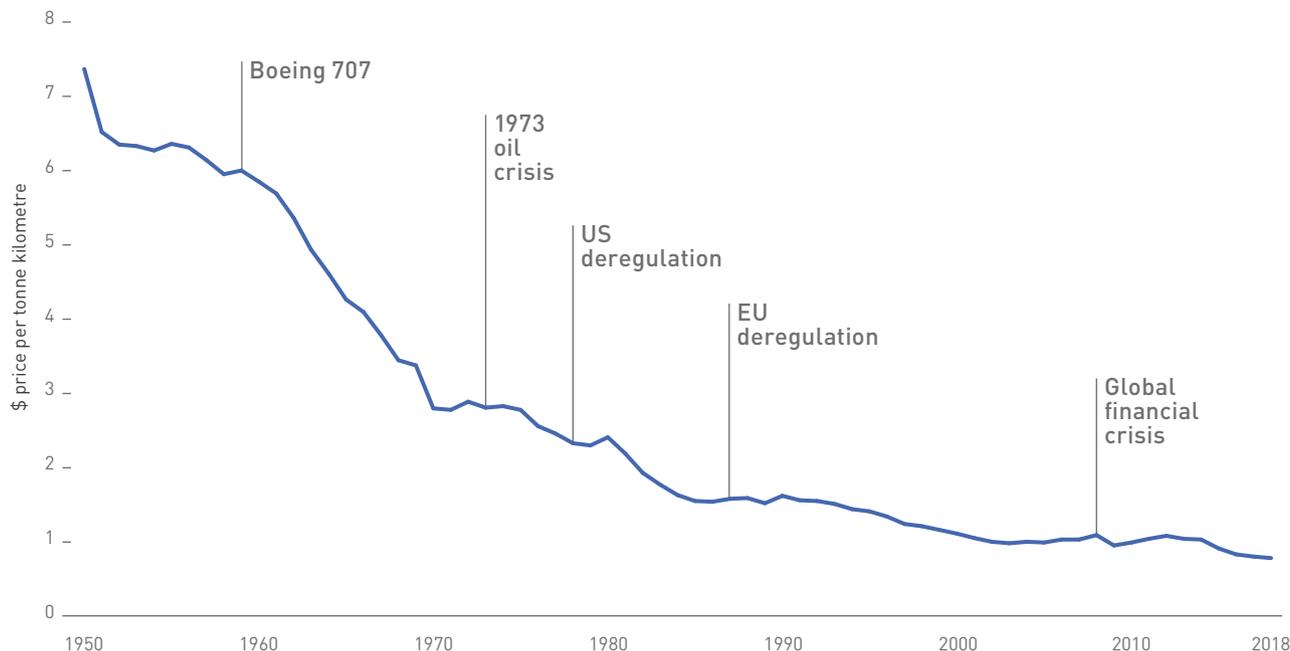
To illustrate using the example of Japan, its population is projected by the UN to decline by around 8% between 2015 and 2035. This in itself is likely to constrain future Japanese demand for air travel. However, given that Japan's population is also projected to age considerably over the same period - and older people comprise a comparatively small proportion of air travellers in the Asia Pacific region - the average 'propensity' to fly in Japan is also expected to decline over the next twenty years.

All told, it is estimated that the decline in Japan's population between now and 2035 that is relevant for purposes of forecasting air markets is more than 20%. In other words, all else equal, the combination of population and demographic pressures is expected to reduce Japanese demand for air travel by more than 1% on average each year between now and 2035. Similar situations will be faced by countries like Russia and Italy.

China is another notable example of a country that faces significant headwinds from an ageing population. To be clear, increases in living standards in China are on their own expected to underpin growth in air travel to the tune of 3.7% per year over the coming 20 years (which is equivalent to an more than 550 million additional Chinese passengers each

## Evolution of the average price of air travel 1950-2018<sup>47</sup>

There has been a steady decrease in the cost of air travel for decades, although the falling prices have levelled off in the last 20 years.



year by 2035). However, demographic pressures are estimated to reduce the overall pace of growth by around 0.6 percentage points per year.

The corollary, of course, is that countries with young populations are likely to see demographics provide a boost to air travel demand over the long term. Africa once again stands out. Demographic considerations alone will add around 100 million potential flyers in Africa over the next 20 years.

In percentage terms, population and demographics will be the strongest drivers of air markets in Africa over the coming 20 years. The two factors will on their own drive passenger growth of around 3-3.5% per year in a handful of countries, including Kenya, Tanzania, and Ethiopia (albeit from low bases in many cases).

By contrast, population and demographics will be significant headwinds to air market expansion in a number of countries, including a number of the ex-Soviet states.

Given its growing population and already large air transport market, the biggest expected change in absolute passenger numbers from population and demographics is forecast to be in the United States. The combination of population and demographics are estimated to contribute 0.3 percentage points to air market growth each year, which is equivalent to more than 40 million additional passengers per year by 2035.

However, population and demographic effects will reduce the number of potential flyers most in absolute terms in China and Japan (by 65 million and 33 million passengers respectively). Such factors will be significant constraints in Spain, Italy, Germany and Russia too.

## Consideration: cost of travel

Developments in the price of air travel are another key factor that will dictate how air travel markets will develop in the future. The decline in the generalised price of air travel - that is the cost of air travel in both monetary terms and the value of time saved by more direct routes - has been a notable feature of the industry over the past 60 years or so.

» **Monetary costs** - on the monetary side, technological improvements, better asset utilisation and productivity gains have reduced the real costs associated with air travel by a factor of four since 1950. Competitive pressures, borne out of relatively low barriers to entry in the industry, and given increased impetus from deregulation and other factors such as the rise of low-cost carriers, have ensured that these cost reductions have been passed on to passengers. The downward trend in the price of air travel has paused in the last decade, but given that fuel prices have quadrupled, that is no surprise. It is now more affordable for more of the population to fly than ever before. By way of example, the price of a ticket from Boston to Los Angeles fell by 89% in real terms between 1941 and 2012<sup>45</sup>.

A downward trend in the real cost of air travel is expected to resume in the future, mainly reflecting new technologies and efficiencies being realised. Indeed, by making use of lighter materials and more efficient engines, the new generation of aircraft is delivering efficiencies of up to 25% compared with the previous generation. These enhancements are expected to

translate into cost savings of around 1-1.5% per year over the coming 20 years (the exact amount will depend on individual fleets and the speed at which they are replaced with newer-generation aircraft)<sup>46</sup>.

Given that oil prices account for around 25% of airlines' costs, the sharp drop in oil prices over the past year or so has had a strong impact on the price of air travel in the short run, although it is unknown how long this will last.

- » **Non-monetary costs** - non-monetary costs related to the price of air travel have also fallen significantly over time and have further stimulated growth in the industry. This mainly relates to reductions in the time that it takes to travel - time that could otherwise be spent doing a range of more productive things.

It is interesting to note that time reductions have not been driven by increases in the operational speed of aircraft. Today's aircraft are actually slower (but more efficient) than those from the beginning of the jet age, while congestion at the big airport hubs as well as enhanced security measures also need to be factored in to journey times. Meanwhile, high-speed rail and advancements in video-conferencing capabilities have both established themselves as attractive alternatives to air travel in some cases.

Time savings have instead been driven by competition in the industry and increases in the range and capability of aircraft, which have opened up new direct routings that have translated into significant time savings for passengers. The number of unique city pairs served by direct air links has more than doubled over the past 20 years alone. Coming back to the earlier example of Boston and Los Angeles, not only has the air fare fallen by 89% in real terms since 1941, the flight time is now nine hours (and 11 stops) shorter.

Over the next few years the increased adoption of Boeing 787 and Airbus A350 aircraft will make it economic to connect many more city and country pairs with direct services. The use of such aircraft will lead to considerable time savings for passengers and thus an effective fall in travel costs. These new aircraft have a range of around 8,000 nautical miles, lower seat costs, and fewer seats than existing long-haul aircraft such as the Boeing 747 and 777, and so can be viable on thinner markets. This expected fall in generalised travel costs will stimulate demand just as much as equivalent falls in monetary fares.

- » **Opportunities for liberalisation** - future potential for reductions in travel times, fuel used and therefore CO<sub>2</sub> emissions, will also be driven by changes in regulatory regimes. This reflects the fact that airline schedule planners do not work with clean sheets of paper; many airline routings are still highly influenced by where and how often air service agreements allow them to fly rather than where airlines would choose if left unhindered.

Data from the World Trade Organization (WTO) indicate that air travel markets around the world became marginally more liberal between 2005 and 2017.

However, the overarching regulatory picture remains skewed towards restrictive. The upshot is that there is plenty of potential for further beneficial gains in the form of reduced generalised costs of air travel.

An IATA study<sup>48</sup> underlines the potential benefits in this regard for air travel in Africa. Liberalisation within the continent is estimated to have the potential in some cases

to more than halve travel times between cities, as well as to reduce air fares by around 30% on average. Both effects would provide significant impetus to African air markets and economies.

There is similar potential for reductions in air fares from liberalisation within the South American and East Asian markets too. The unit price of flying a kilometre in both of these markets are around 15-30% higher than in similar length sectors operated within Europe. If air markets in these regions were to become more liberalised, unit prices in these markets would be expected to converge closer in line with those seen in Europe, which would make air travel more affordable and stimulate demand.

## Consideration: demand shift to other modes of transport

There are often calls for particularly short-haul air traffic to be replaced by alternative modes of transport such as rail. In many parts of the world, shifting to rail is not a viable option, but in Europe, Japan, China and a few other examples, there is a strong case to be made for reliable and rapid interconnectivity between long-haul flights and short-haul rail connections.

The 'Beyond 2 Degrees' scenarios developed by the International Energy Agency (IEA) in 2017<sup>49</sup> forecast a significant shift of passengers to high-speed rail as a way to 'force' emissions down to the desired result, not the result of optimisation or passenger choice modelling. It was also driven by expected limits on contribution from sustainable fuels towards the aviation sector. Additionally, lifecycle carbon assessments of high-speed rail used in this analysis do not include direct and indirect land use changes (from building the rail infrastructure to meet the shift of demand from aviation), nor the output of CO<sub>2</sub> during construction or maintenance.

There are also significant fiscal costs of rail construction, usually borne by the taxpayer (European governments provide around €50 billion per year in State aid to rail<sup>50</sup>, compared with around €0.5 billion to aviation for public service obligation routes) and noise impacts (rail noise impacts an estimated 21.9 million European citizens, whereas noise from aircraft impacts some 4.2 million)<sup>51</sup>. In addition, the considerable lead time for rail construction needs to be considered.

Aviation and rail should instead be seen as complementary options as part of a global plan to facilitate domestic and international citizen's sustainable mobility. Where opportunities exist for the shift of some short-haul air traffic to rail, there is a need for true intermodal operations to be provided, with collaborative action on inter-ticketing (using the same ticket for seamless travel on rail and aircraft); direct connections between rail stations and airports; and shared responsibility for the passenger between the different operators.

In fact, some proactive shifts to rail services for connecting passengers would be a useful way to free up runway capacity. But the construction cost (in terms of CO<sub>2</sub> emissions, noise, and fiscal considerations) in many parts of the world would prohibit extensive shifts. The reality is, the amount of CO<sub>2</sub> that would be saved, even with an aggressive shift to rail where it is possible, will likely only contribute to a small reduction in aviation emissions.

- » Just under 5% of aviation CO<sub>2</sub> emissions come from flights under 500 kilometres
- » Less than 17.5% of aviation CO<sub>2</sub> emissions come from flights under 1,000 kilometres<sup>52</sup>
  - » Of these flights, 65% take place outside of Western Europe, Japan or China (where opportunities for rail replacement is highest)<sup>53</sup>
  - » Many of these flights are between secondary or tertiary cities where construction of rail infrastructure would be prohibitively expensive, or generate too much CO<sub>2</sub> from construction, noise burdens on residents or destruction of natural habitats.
  - » Assuming even half of these flights could reasonably shift to rail (far from certain), it would reduce aviation CO<sub>2</sub> emissions by around 3% (but does not include the CO<sub>2</sub> costs of rail construction).

In addition, these are the exact types of routes where electric or hydrogen aircraft could play a useful role in the 2030s, without the sunk CO<sub>2</sub> costs of rail infrastructure development.

There are opportunities for some passengers, particularly connecting between secondary and tertiary cities and long-haul operations from hub airports, to shift on to rail. This intermodality must be built in to governmental planning of rail infrastructure.

### Consideration: using economic measures to suppress demand

Governments have sometimes turned to economic measures to reduce demand for air services, or to lower its growth. It is uncertain whether these measures have a significant dampening effect in the long term - the UK air passenger duty is the highest aviation tax in the world and yet has not stopped the growth in air travel (although it has likely slowed growth somewhat).

The main impact of increasing the cost of air travel seems to be on less affluent members of the population, reducing their access to connectivity and travel services. If the objective

### Opinion of passengers shows desire to fly and for flying to become greener, 2021<sup>54</sup>

Connectivity is important to people, but so is climate action. This puts pressure on the industry to demonstrate it can reduce emissions and continue to serve the world.

"In the future, I want to fly, but I would avoid it if I did not think airlines were reducing their carbon footprint:"

**26%** (Strongly agree) **36%** (Somewhat agree)

is to reduce CO<sub>2</sub> emissions (rather than mobility), there are more nuanced and effective forms of fiscal policy such as investment in sustainable fuels and new technology.

### Consideration: societal acceptability of air travel

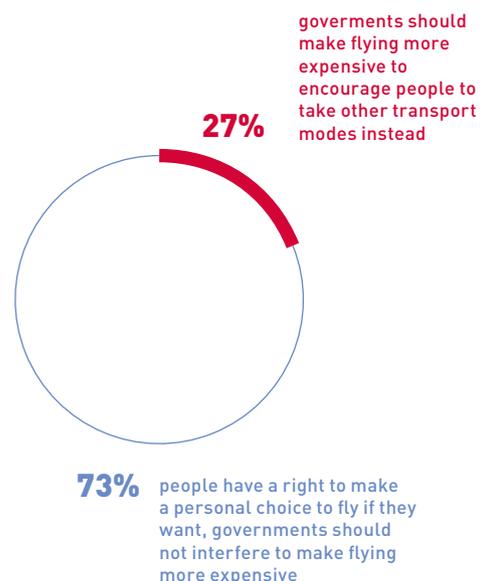
Recent observations of news reports of the avoidance and / or shift away from aviation due to climate concerns (including the "flygskam", or "flight shame" movement) were considered, including whether those were the beginning of trends or whether they will remain isolated. Potential implications on traffic scenarios were also considered.

Initial estimations of the potential effect of the flygskam scenarios exhibit some isolated reductions in aviation activity in certain markets, but appear to be marginal on the global scale given the underlying drivers of growth from emerging markets (fuelled by economic activity and population trends in the long term). Corporate customers have also announced the potential for reductions in travel.

Significantly, passenger surveys have shown that, despite concerns about the climate impact of air travel, there was a strong desire by passengers to retain the connectivity that comes with aviation, but an expectation that the industry should do everything it can to reduce its climate impact.

Passengers expect the industry and governments to concentrate on mitigation options such as sustainable aviation fuels and technology, rather than trying to limit air travel supply or demand through quotas or taxes.

Given the geographic centres of most of the industry's growth out to 2050 and beyond, as well as the work on aviation decarbonisation presented in Waypoint 2050, it is unlikely there will be a significant downward shift in aviation growth beyond the reduction in the growth forecasts presented in this report, but it does place a challenge on the industry to establish comprehensive environmental goals and demonstrate it is achieving them.



# TECHNOLOGY

**B AVIATION HAS A STRONG HISTORY OF SOLVING CHALLENGES THROUGH TECHNOLOGICAL INNOVATION. FROM THE FIRST FORAYS INTO POWERED FLIGHT, TO THE JET ENGINE, USE OF COMPOSITES AND 3D PRINTING, CONSTANT IMPROVEMENTS ARE PART OF THE SECTOR'S DNA. RESPONDING TO THE CLIMATE CHANGE CHALLENGE IS NO DIFFERENT.**

Already, today's aircraft operate incredibly efficiently, given their operating conditions and speed. Each new generation of aircraft has reduced fuel use by around 15-20% compared with the model they replace. That trend is expected to continue with new technology aircraft over the coming decades, but aerospace engineers are already exploring some radical new technologies or configurations to realise some of those savings.

## A comprehensive approach to analysing the global fleet

In order to evaluate several scenarios for how the global fleet might evolve, the Waypoint 2050 investigated the types of technology that could play a role in reducing CO<sub>2</sub> emissions and evaluated the likelihood of these entering service at a given date. Aside from their own experience, several sources were considered as input to the development of the technology scenarios, including: the IATA *Aircraft Technology Roadmap to 2050*<sup>55</sup>; publicly available supporting information from the ICAO Committee CAEP/10 and CAEP/11 cycles; the CleanSky II project; ACARE; and additional studies focused on particular technology scenarios for electric, hybrid-electric and hydrogen powered aircraft.

The resulting Waypoint 2050 scenarios were run through a fleet evolution model developed by the German Aerospace Centre (DLR)<sup>56</sup> which analysed the current global fleet of 29,000 aircraft and calculated each aircraft's current fuel burn, retirement and replacement cycle to determine when new models may replace older ones and resulted in global system level fuel burn and CO<sub>2</sub> emissions for each technology scenario. It is estimated that it takes around seven years for a new aircraft type to achieve significant penetration into the fleet and replace the production of its predecessor.

Based on this approach, each scenario was able to be run to determine what impact it may have on the CO<sub>2</sub> emissions trends.

## Exploring the scenarios

A broad scope of different technologies contributes to aircraft fuel efficiency improvement and emissions reduction, mainly from the:

- » Airframe (aerodynamics, lightweight materials and structures, equipment and systems, new configurations, energy management and electrification)
- » Propulsion systems (engine architecture, thermal and propulsive efficiency, combustor technologies, advanced materials, electrification)

In order to reduce complexities, five technology scenarios were developed to feed into the broader Waypoint 2050 scenarios work. These were based on new aircraft being developed for each of eight general sizes of aircraft, from 50 seats up to 650.

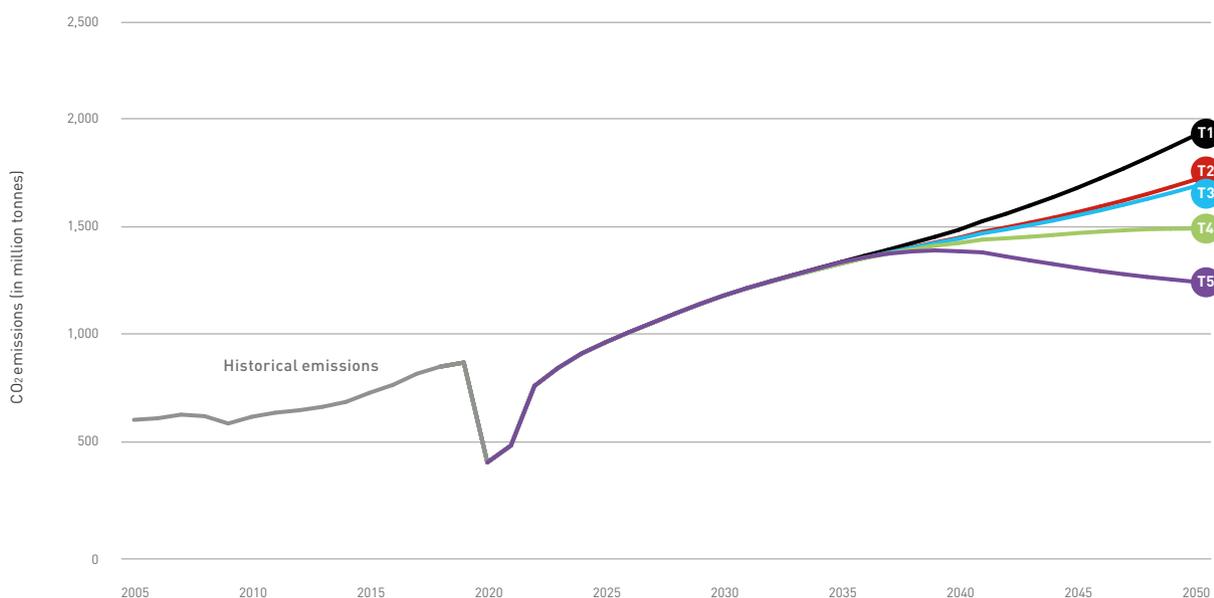
Over the next 30+ years, the industry will likely follow a number of these paths as new technologies are developed and brought to readiness before entering the market and making their way into the fleet. There is significant research taking place in the electric and hydrogen fields which may, for example, mean that some parts of the fleet can transition to those technologies sooner than currently expected – more in line with T5 scenario, for example.

For each scenario except T1: three cases (minimum, mean, max efficiency improvement) were developed and assessed. In addition, continuous technological improvement (those efficiency developments within an aircraft production cycle as performance improvement packages are released for the same aircraft type) over time of 0.2% per annum were assessed and included in the modelling.

<b>T<sub>1</sub></b>	Baseline	As older aircraft are retired, they are only replaced with aircraft that have entered service already, or are about to enter service (for example, new generation families: Airbus A220, A320 neo, A330 neo, A350; ATR 76; Boeing 737MAX, 777-X; Embraer E2; etc). Using conventional liquid jet fuel or sustainable aviation fuel. This scenario is not a realistic view of the future but sets a baseline for the fleet evolution.
<b>T<sub>2</sub></b>	Conservative: evolutionary technologies only	A new generation of aircraft follows the current models (above), but still with an evolution of the standard 'tube and wing' configuration with turbofan engine propulsion system. Using conventional liquid jet fuel or sustainable aviation fuel.
<b>T<sub>3</sub></b>	New configurations	Revolutionary configurations of aircraft incorporating new structural elements such as the strut-braced wing or blended wing body; and open rotor engine concepts. Using conventional liquid jet fuel or sustainable aviation fuel.
<b>T<sub>4</sub></b>	Towards electrification	Technology shift towards electric propulsion using battery systems (likely below 100 seats) and hybrid systems (for larger aircraft), entering the fleet from 2035-2040. Will require coordinated effort by all parts of the sector — not just manufacturers, due to new energy systems being required.
<b>T<sub>5</sub></b>	Aspirational technology	A revolutionary shift towards zero emissions aircraft (potentially hydrogen) for the narrow body segment from 100 to 200 seats. This also assumes electrification of the small aircraft segment and hybridisation of the larger aircraft segments. This shift would occur earlier (from 2030) and for larger aircraft than the T4 scenario. Will require coordinated effort by all parts of the sector — not just manufacturers, due to new energy systems being required.

## How different technology scenarios can impact growth in CO<sub>2</sub> emissions<sup>57</sup>

Each of the T1-T5 middle scenarios is mapped using the central traffic growth forecast. The T1 scenario shows where CO<sub>2</sub> emissions would be with no further improvements in aircraft efficiency and no new technology. This chart does not include reductions in emissions from the other pillars of action: operations, infrastructure, sustainable fuels or market-based measures.



## Evolutionary technologies

The T2 scenario explores some of the evolutions in aircraft design that could help cut fuel use and emissions for the next generation of traditional aircraft. Potential technologies enabling a T2 scenario (in other words, the most promising technologies for next-generation aircraft before 2035):

Introduction of these technologies early and the resulting capitalisation and penetration of the fleet will slow the impact of aviation on our climate. As more effort is put into reducing fuel burn and emissions, the associated gains become smaller. Achieving more than 30-35% reduction in fuel burn with current airframe-engine configuration only will become challenging.

## Some new technologies can be applied to existing aircraft designs

A number of the evolutionary technologies described above could also be retro-fitted onto in-service aircraft, or built into existing types as they come off the production line over the coming years. In fact, all aircraft are continuously improved throughout their production life already – so the latest aircraft that rolls out of the final assembly line will be more efficient than the same model from several years ago, around 2-3% overall improvement over 10 years of production. Performance improvement packages are also made available to airlines to increase fuel efficiency during service.

Technology	Description and benefits	Readiness level, potential for entry into use
Geared turbofan engines	Contains a gearbox between the fan and the compressor which each rotate at most efficient speed, improving the propulsive efficiency of the engine.	In operation (as an option on the A320neo, A220, Embraer E-Jet).
High pressure-ratio core engines	Engines that operate at higher pressure, reducing engine weight and improving thermal efficiency.	Will enter service with the GE9X engine on the Boeing 777X aircraft in 2022. Technology also now available for other engine designs.
Very high bypass ratio engines	A larger fan allows for the engine to exhaust more air at a lower speed, (increasing bypass ratio), improving the propulsive efficiency.	In operation (e.g. the GENx, Trent1000, LEAP, and PW1000 engines). This level of bypass ratio, or slightly higher, has become the standard for large commercial aircraft. Additional increases in bypass ratio are possible with new aircraft designs configured to accommodate larger engines – understanding there is a trade between engine efficiency (larger is good) vs. engine weight and drag (smaller is good) that limits the optimum ratio.
Composite structures for wing and fuselage	Large metal aircraft structures replaced by light-weight composite materials.	In operation on many aircraft, but with extensive use on new models such as the Boeing 787, Airbus A350. Application could be extended to even more parts of the aircraft.
Wingtip devices	Small structures mounted on the wingtips to improve aerodynamics.	In operation on most aircraft today, but improved models are continually being developed to improve efficiency further. Some older aircraft without such devices can have them retro-fitted – see the operations section.
Riblets	Small grooves on the aircraft surface which reduce the drag caused by flying through the air (inspired by shark skin).	Have been tested to be efficient, but some endurance issues remain before being able to enter into operation, could be available soon also for retrofit: at TRL8.
Active load alleviation	Gust and manoeuvre load forces are reduced by suitable flap deflection; this allows less massive wing structure.	Technology available, mass benefits can be used for a new aircraft design.

Technology	Description and benefits	Readiness level, potential for entry into use
Structural health monitoring	Sensors detecting damages in the aircraft structure; this allows less massive structures.	Technology available, mass benefits can be used for a new aircraft design.
Fuel cells for onboard power	More efficient onboard electrical power generation by fuel cells instead of engine-driven generators.	The technology has been under active development for some years, with renewed interest. Main challenge is that fuel cells can add weight and also require hydrogen (see later section on hydrogen for aviation).
Advanced fly-by-wire systems	Digital flight control systems enabling advanced flight control and navigation.	Continuous improvement.



## Revolutions in aircraft configurations

The so-called 'tube and wing' is the standard configuration of conventional aircraft, a tubular fuselage with two predominantly flat wings on either side – sometimes from the bottom of the fuselage, sometimes the top. Aircraft have

had this configuration from the very start of commercial aviation and it has been an efficient and reliable basis for all developments in aircraft design since. However, under the T3 scenario, a range of other options were explored that can bring emissions reductions beyond an evolution of the tube and wing.

Technology	Description and benefits	Readiness level, potential for entry into use
Canard	The canard configuration describes a mostly small fore plane that is placed in front of the main wing of a fixed-wing aircraft. The lifting surface of a canard is mostly used to replace the horizontal tail plane, which is the only drag-producing downward lift surface. Canard foreplanes can also be used for three-surface configurations (foreplane, central wing, horizontal tail plane). With modern flight controls even a no-vertical-tail design could be realised.	Aircraft with canard configurations are mainly found in the military area. A civil canard aircraft could be available around 2035-40, similar to other radically new configurations.
Blended wing body Hybrid wing body	A blended- or hybrid-wing body (BWB/HWB) configuration is a fixed-wing aircraft without clear differentiation between wings and fuselage. Wide airfoil-shaped bodies and efficient high-lift wings enable significant improvements of the lift-to-drag ratio compared with conventional aircraft. As the entire plane is designed to generate lift, high fuel savings are expected.	Flying BWBs exist for military purposes. Numerous research institutes are working on civil BWB designs, for a long time focusing on designs for over 400 passengers, but recently smaller designs of 100-150 seats could also be optimised, with a potential entry into service around 2035, whereas a large BWB could be expected around 2040. A KLM /TU Delft project looks at a flying V configuration and is undergoing scale model flight demonstrations.
Strut-braced wing Truss-braced wing	The strut-braced wing is a concept utilising a structural wing support to allow for larger wing spans without increases in structural weight. By increasing the span the induced drag is reduced and therefore the engine performance requirements can be reduced as well. The high wings allow for larger engine sizes, e.g. open rotors. The increased wingspan may also require a redefinition of current airport compatibility categories or the design of foldable wings.	A strut-braced design with conventional turbofan engines is not an extremely radical design change and could be realised for entry into service in 2030-35. Combination with open rotors could be envisaged for an entry into service (EIS) around 2040.
Box-wing	The box wing configuration, which was proposed first by Ludwig Prandtl in 1924, connects the tips of two offset horizontal wings. For a given lift and wingspan this configuration assures minimum induced drag and offers savings in fuel consumption compared to conventional aircraft.	This configuration has recently been revived in R&T projects and could also be available around 2035-40, similar to other radically new configurations.
Variable camber with new control surfaces	The camber (curvature) of the wing can be changed during flight to optimise lift.	Currently around TRL6, this technology would need to be applied to a new aircraft design.
Laminar flow control technology (natural and hybrid)	Maintaining the air flow over the aircraft surface turbulence-free, through suitable shaping of aircraft surface (natural) or boundary-layer suction (hybrid).	Currently sitting around TRL7, new development progress since 2017, application for new aircraft design.

## Revolutions in propulsion system

There are two main types of engine used today in commercial aviation: the turbofan and the turboprop. Each can run on traditional fossil jet fuel, or a blend of “drop-in” sustainable

aviation fuel, i.e. fuel that has almost the same properties as fossil jet fuel, but is produced from sustainable sources.

More radical aircraft concepts and new energy sources are being studied for their potential to significantly reduce emissions.

Technology	Description and benefits	Readiness level, potential for entry into use
Open rotor	Also known as unducted fan (UDF), or propfan. The fan nacelle is removed increasing the by-pass ratio beyond what is possible with turbofans. These engines offer great fuel savings compared to current turbofans, but also come with several limitations. The lack of a casing leads to higher noise emissions of the fans and necessitates airframe strengthening for safety purposes in the event of an uncontained engine failure.	While the open rotor concept itself is several decades old, its development was slowed by challenges to reduce noise (which have since been resolved), but also a reduction in the price of oil. Entry into service could take place around 2030.
Electric propulsion	Instead of combustion engines, electric motors drive conventional propellers or sets of multiple small fans. Electric energy is stored in batteries (which however have a penalising weight), alternatively, fuel cells are envisaged. CO <sub>2</sub> emissions during operations are zero for full electric aircraft. Lifecycle emissions strongly depend on the primary energy mix for electricity generation. If fully renewable sources are used, they could be close to zero as well. An additional benefit would be the eradication of non-CO <sub>2</sub> effects (such as contrails and NO <sub>x</sub> emissions). Electric motors are quieter than combustion engines, which could reduce nuisance to airport neighbours and allow increased operations from smaller city airports.	Small full electric aircraft up to 9 seats are already flying (at least for test flights). Electric aircraft up to 19 seats are planned for the later 2020s, and regional aircraft in the 2030s. Norway has the goal of operating all domestic and short-haul flights electrically by 2040.
Hybrid-electric propulsion	Hybrid-electric concepts combine the advantages of both combustion and electric engines. While the combustion and electric propulsion systems can be used in combination during take-off to provide maximum thrust, the combustion engine can be throttled back when the aircraft is in cruise flight or descending. Combustion engines could also be smaller and reduce on-board weight. Hybridisation is a necessary intermediate step for larger airplanes towards a pure electric propulsion system. Probably, the degrees of hybridisation vary with aircraft size, allowing smaller seat categories to be equipped with a higher degree of hybridisation than larger seat categories. Hybrid-electric aircraft on a new airframe body such as the Blended Wing Body can contribute to achieving CO <sub>2</sub> emissions reductions of up to 40%.	Small aircraft (15 — 20 seats) with hybrid-electric propulsion are expected during this decade, regional aircraft in the 2030s and possibly larger ones from 2040.
Hydrogen	Hydrogen is a carbon-free fuel that can be used as a propulsion fuel in two ways: a» for combustion in conventional engines, replacing jet fuel (including in large aircraft), b» in fuel cells an electrical power source. The weight of hydrogen as an three times lower than that of an amount of jet fuel with the same energy content, but its volume even in liquid (cryogenic) form is four times larger. Much larger tanks as well as fundamental changes in the aircraft fuel system are therefore needed.	One of the biggest challenges for hydrogen use in aviation is its worldwide availability at large scale, the need to produce ‘green’ hydrogen and the existence of appropriate supply infrastructure. With the global move towards renewable energy, the plans for a worldwide use of hydrogen as an energy carrier have become much more concrete, and the interest in hydrogen aircraft has risen steeply since 2019. The willingness for strong public funding has increased again in the debate about aviation support in the Covid-19 crisis. Technology programmes now envisage EIS around 2035.

## Challenges in introducing radical new technologies

Aviation is a traditionally very cautious industry, being innovative, but also taking a long time to carefully test and certify safety standards for new aircraft. Once the technologies noted above reach technical maturity and can be commercialised, there are a few other challenges before passengers will be able to fly on board:

- » Certification and testing will be much tougher for novel airframe configurations or propulsion systems, new certification procedures will have to be developed for some of them to ensure the undisputed safety level required for commercial aviation.
- » Airlines need to be able to trust in the aircraft and the technology to invest: a fleet is an expensive asset that requires very low downtime for maintenance. Airlines may be wary of completely novel technology with a range of new operating and maintenance procedures that have not been put through the rigours of commercial service.
- » There will be added infrastructure requirements to supply green electricity at high power on-airport, or green hydrogen – not only will the connections and energy sources be needed, but they may come with different ‘refuelling’ times than current aircraft, and large storage areas for battery recharge may be needed.
- » Air traffic management may need to alter procedures if the aircraft perform differently in flight (i.e. if they are slower than traditional jets, if they cannot react to emergency situations in the same way, or if they produce different wake turbulence profiles).
- » The entire human support infrastructure will need re-training, from flight crews to ground handlers, maintenance staff and airline office staff.
- » Global costs for the aviation industry to adapt to emerging energies and develop new technological solutions are likely to be considerable in the early years.
- » New aircraft types will also need to go through a process of introduction to the public to create trust – particularly those that look very different to aircraft currently flying.

None of these are insurmountable challenges, but they must be considered as the industry launches into the third era of air travel.

## Electrification

With up to 230 electric aircraft concepts in development today (although only around 30 of them for commercial-scale operation)<sup>58</sup>, electric propulsion could start entering the market in small (2 to 6 passengers) vehicles as electric personal transportation aircraft very soon (2020-2025 timeframe). Multi-rotor vertical take-off vehicles able to carry about four passengers could become a reality in the next few years, with numerous projects already in progress worldwide. While the extent of the market size is still uncertain, these aircraft could serve as a viable alternative in certain areas – like air taxis in and around our congested cities, or air ambulance/medevac platforms, taking advantage of their speed, reliability and quieter operation. Although these aircraft are not included in the scope of the Waypoint 2050 CO<sub>2</sub> analysis, they provide an important stepping-stone to commercial-sized aircraft.

Commuter aircraft (small aircraft in the 9-19-passenger class) will be next and several prototypes are in development or already flying for this size of aircraft, based on retrofits of existing models – they would likely be ready for entry into service after 2025.

Under Waypoint 2050 T4 and T5 scenarios, there may be an opportunity for electrification of aircraft in the 50-100 seat category around the 2030-35 timeframe, including some turboprop types. This would reduce their already fuel-efficient operations to virtually zero emissions and provide much-needed connectivity to regional populations.

Scaling electric technologies for short-range (up to -90 minutes), fully electric or hybrid-electric civil aircraft (in the around 100 seat size) would rely on substantial performance improvements in battery technology, or developments in hybrid systems, of well over seven times greater than today’s high-density batteries.

As a novel propulsion system and radical new technology, there are a number of challenges to scaling up electric and hybrid-electric technology.

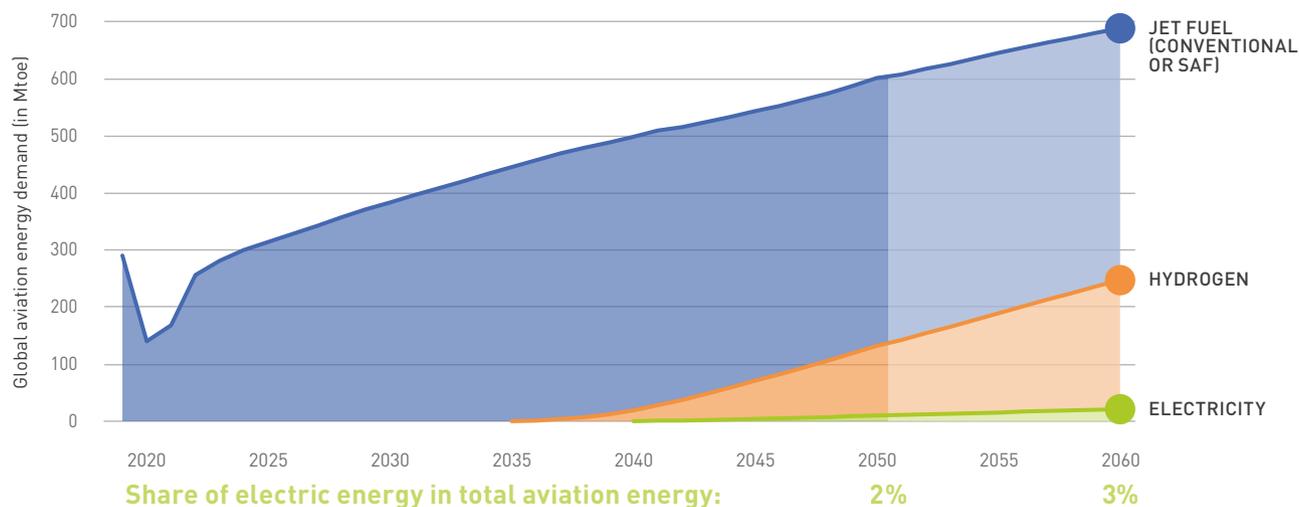
- » Key amongst them is the energy density of batteries. Whilst developments in battery technology have been rapid in recent years (driven in part by the acceleration of deployment of electric road vehicles such as Tesla), the amount of energy that can be packed into a battery is still some way off being useful in anything other than very small aircraft.
- » Aside from the density improvements, another key challenge is the fact that batteries do not get lighter as the energy is consumed, meaning that the landing weight after a flight will be the exact same as the take-off weight. With liquid fuel, the aircraft gets lighter as it flies and burns fuel. This suggests that, absent some truly exceptional leaps in battery weight / density ratio, the use of pure battery power will likely remain with very short-haul routes.
- » Fire safety of lithium batteries has been strongly improved over the last years. Nevertheless, strict testing and certification processes will be needed to ensure that electric aircraft meet the very high safety standards of commercial aviation.
- » The sustainability of battery full life cycle. Although electric flight will generate no CO<sub>2</sub> in flight, the carbon and environmental footprint of extracting the raw materials (such as lithium), manufacturing and disposal will need to be improved.
- » Storage and charging of the batteries in an airport operational sense will need to be resolved but is not complex.

A transition to electric powered aviation (i.e., the operation of all-electric or plugin hybrid aircraft) would constitute a departure from the current aircraft technology, energy source, infrastructure and the operation of the global aviation system that have been optimised largely around the use of liquid jet fuel.

Analysis, based on the T5 scenario (highly ambitious, but used to illustrate an outside boundary for energy demand), shows the potential demand, requirements, and costs associated with future electric powered aircraft. As more aircraft enter the fleet to reach 100% of production (and deliveries) in 2045 and beyond, demand for electricity increases to approximately 110 TWh in 2050 and 250 TWh in 2060. This represents about 2% and 3% of global aviation energy demand in 2050 and 2060 respectively.

## Aviation energy demand evolution

The global aviation energy demand associated with the T5 scenario, where demand for direct use of electricity from the 51-100 segment starts in 2038 after the entry into service of all-electric aircraft in this segment of the fleet.



## Challenges associated with all-electric aircraft

Given current understanding of the technical feasibility of all-electric powered aircraft, it appears very speculative that all-electric aircraft of greater than around 100 seats could be technically feasible and enter service in 2045. This analysis therefore focuses on a more realistic (while still very challenging) 51-100 seat segment.

Even for the 51-100 seat segment several technical challenges remain. For example, for a 70-seat turboprop aircraft operated on a 200 nautical mile segment (around an hour's flight), the energy needed would be roughly 2.6 MWh (two motors developing 1.3 MW average power output during flight mission for an hour). Assuming an optimistic 300 Wh/kg battery energy density, the required mass of the battery would reach 8,700 kg which is greater than the design payload of the aircraft (approximately 7400 kg). Given the design challenges for a 200 NM mission, battery energy density would have to increase substantially – around seven times greater than today's highest density batteries – to enable such a scenario. Alternatively, aircraft could be designed with limited design ranges, however this would likely limit their market potential and value.

Other studies also note technical challenges associated with scaling electric powered aircraft. If the 50-100 seat segment is not able to make the shift to battery electric options, but shifts to hydrogen, this would add another 4 MtH<sub>2</sub> in 2050 (which is about +10% of that estimated in the T5 scenario for liquid hydrogen). Destination 2050<sup>59</sup> noted that currently, the battery's low specific energy (or, equivalently, high weight) would be a major constraint to the use of batteries as an aviation fuel option. The specific energy is in the range of 200

watt-hours per kilogramme, which is 60 times lower than jet fuel. Although improvements are expected, this gap is not expected to be bridged soon.

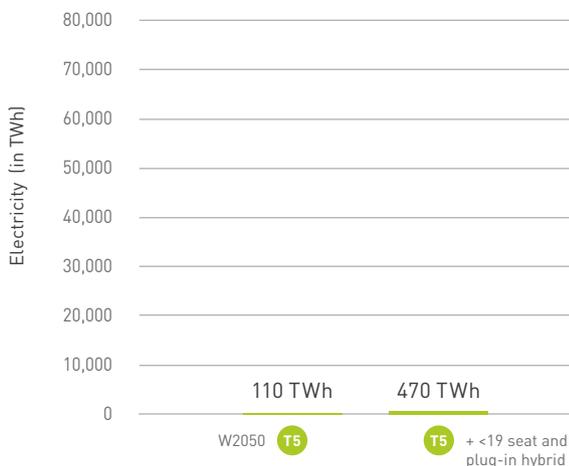
Another important constraint is the need to have specific power for a high discharge rate of the battery during certain flight phases such as take-off. It was further assessed that while all electric and hybrid-electric battery-based aircraft are likely to become technologically feasible for aircraft with an increasing number of passengers and/or growing flight range as the specific energy of batteries increases, the introduction of these technologies for the largest aircraft and longest ranges is not expected before 2050.

## Potential demand for electricity from full electric less than 19 seat segment

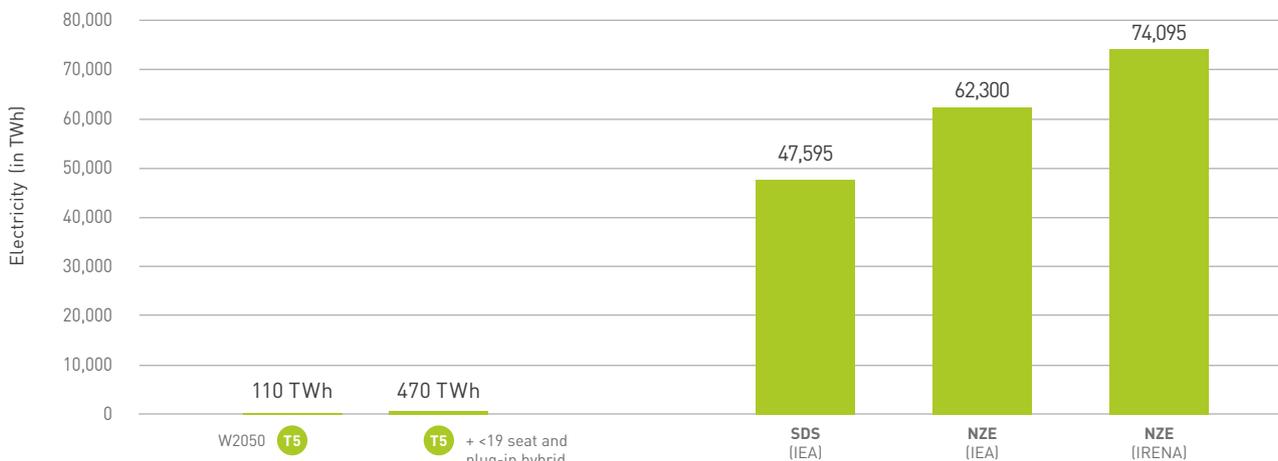
While the 51-100 seat segment is exhibiting technical challenges for full electric aircraft, activity is taking place in the less than 19-seat segment through initial aircraft research, development including the production of prototypes, demonstration, and program announcements.

This segment represents less than 1% of total fuel use (CO<sub>2</sub> emissions) from global aviation. As such, if this segment were to evolve towards all-electric aircraft, it could generate additional demand for electricity of approximately 50 TWh in 2050. Hybridisation or partial diffusion of all-electric aircraft into the fleet could result in lower demand for electricity. Demand for energy and electricity from this segment of the fleet would also be dependent on forecast of activity (traffic) in this market segment and relative growth rate of regional air mobility.

## Global aviation demand for electricity (for direct use in aircraft)



## Economy-wide production of low-carbon electricity



## Role of electric energy storage in plugin hybrid electric propulsion (HEP) aircraft

Given the significant challenges associated with developing larger all-electric aircraft, hybrid electric propulsion (HEP) aircraft may provide an intermediate technically feasible step towards full electrification. The hybridisation of hybrid-electric propulsion can be achieved by combining an internal combustion engine or fuel cell with electric motors and batteries. The advantages of HEP compared with traditional propulsion are: (a) increasing the overall aircraft efficiency; (b) increasing aircraft reliability, power distribution/quality, and flight range; (c) emissions and noise reduction; (d) capacity of extending the market to smaller airports<sup>60</sup>.

The potential demand for electric energy (uplift) depends on the power architecture of the aircraft. Only the series hybrid, parallel hybrid and series/parallel hybrid architecture have an energy storage capability (e.g., battery) which may use electricity as direct input in the case of plugin hybrid electric aircraft. In a turbo electric hybrid architecture, all the input energy into the aircraft is derived from the combustion of jet fuel.

The demand for electric energy (uplift) is largely driven by the architecture, design and operations of the aircraft. The balance or ratio of the energy stored in the batteries and total energy stored in fuel and batteries is referred to as the hybridisation factor. Several studies that have explored various hybrid electric architectures and ranges of hybridisation factors. Using the hybrid electric propulsion aircraft scenario based on T4 hybrid systems (100-500 seat), fleet diffusion scenario, and parametric hybridisation factor assumption from 1% to 15% (assuming fully charged battery at block-off), the additional demand for electricity from plugin hybrid electric aircraft could range from approximately 20 to 300 TWh in 2050.

## Overall demand for electricity

Introducing fully electric aircraft in the 50-100 seat range will require around 110 TWh in 2050. Adding to that a shift in all 9-19 seat aircraft, and a fraction of the energy demand from

plugin hybrid electric propulsion aircraft, the total demand for electricity may reach 470 TWh in 2050. This analysis does not include smaller-scale electrification for urban air mobility or other applications at the sub-9-seat scale.

In context, demand for electric energy from global aviation (110-470 TWh in 2050) could represent about 0.1 to 1% of 2050 global production of renewable electricity in context of the IEA SDS<sup>61</sup> and NZE<sup>62</sup> scenarios as well as IRENA's NZE scenario<sup>63</sup>.

## Requirements and costs (investments) associated with electric powered aviation

Requirements associated with the potential future use of electric powered aircraft on airlines/operators, airports, and OEMs were also considered and assessed.

- » **Operators: cost of electricity.** Operating costs of electric aircraft could potentially be competitive with jet fuel costs. Under the T5 scenario, the total cost from electricity in 2050 could be approximately \$8bn at today's unit cost of electricity (\$69/MWh) and drop to \$3.9bn given 2050 projected unit cost of electricity (\$34/MWh). For context, the cost of meeting that energy demand with jet fuel at today's \$635/mt<sup>64</sup> could reach \$7.6bn.
- » **Operators: aircraft (fleet) related requirements and costs.** To meet potential demand for all-electric powered aircraft, approximately 3,800 aircraft in the 51-100 seat market segment may be needed by 2050. There are also currently around 1,750 aircraft in the 9-19 seat segment in service around the world which could be the optimum use of electric aviation – this new energy source could potentially grow this market for services to and from smaller and remote communities<sup>65</sup>.
- » **Operators: turnaround time related costs.** Increased operating costs (or loss of revenues) could result from increased turnaround time during recharging. Whilst this could be mitigated due to the use of a concept such as swappable battery packs, there would be some logistical and possibly certification challenges for this option as

well. These increased operating costs may be mitigated by reduced decreased maintenance costs from electric powered systems (e.g., motors).

» **Aerospace manufacturers: battery technology.** Battery energy density would need to increase substantially to allow for future all-electric aircraft with size and range capabilities that could contribute to noticeably reducing CO<sub>2</sub> emissions. Battery energy density will be a key driver and limiting factor of future all-electric aircraft in terms of size and range capabilities. The energy density of jet fuel is about 12,000 Wh/kg. In 2018, best available li-ion battery cells had a specific energy of around 250 Wh/kg<sup>66</sup>. Short-range electric aircraft demand battery pack specific energies of 750-2,000 Wh/kg. Based upon a continuation of the historical increase in specific energy, current levels of specific energy of 250 Wh/kg for advanced Li-ion battery cells, and a packing efficiency of 80%, a battery pack specific energy of 800 Wh/kg could potentially be reached at around midcentury.

» **Aerospace manufacturers: high-temperature superconducting electric motors.** Advancements in aircraft technologies would also be required to enable all-electric powered aviation for larger aircraft (than 19 seat segment). Regional jets with about 50 seats are likely to require significantly improved mainstream technology, narrow-body aircraft with 100 seats and above may depend upon lightweight high-temperature superconducting electric motors due to the intrinsically high weight of conventional electric motors and the difficulty in providing cooling.

» **Airports: Infrastructure.** The operation of all-electric or plugin hybrid propulsion aircraft could rely on several operational concepts for battery charging:

» Battery plug-in chargers: Like fuel-refilling stations. Chargers for small aircraft through external 60 kW direct current (DC). Operations or larger aircraft (e.g., B737-800) would need amounts of battery energy in the order of 3.5 to 7 MWh, resulting in long recharging time, incompatible with current/typical turnaround times. Current 90kVA power lines could be multiplied but would require added hardware costs. Issues with peak power required from the grid resulting in additional costs.

» Battery swapping stations: Approach could address peak charging issues but would require additional spare battery packs adding to acquisition cost, increased logistic costs from transport of batteries from and to the aircraft. BSS may also require amendments to aircraft certification as battery swapping procedures could be considered a major repair or alteration.

## A renaissance for hydrogen

Hydrogen could play an increasingly important role in sustainable aviation over the coming years, with a range of uses. Importantly, it is a vital component in the production of many sustainable aviation fuels (particularly power-to-liquid) and increasing uses of these will require more hydrogen production. But hydrogen could also potentially be used as a direct energy source in aircraft as well: either through the use of hydrogen fuel cells to generate electricity for propulsion, or propulsion being delivered through direct burning of hydrogen in gaseous, or liquid form.

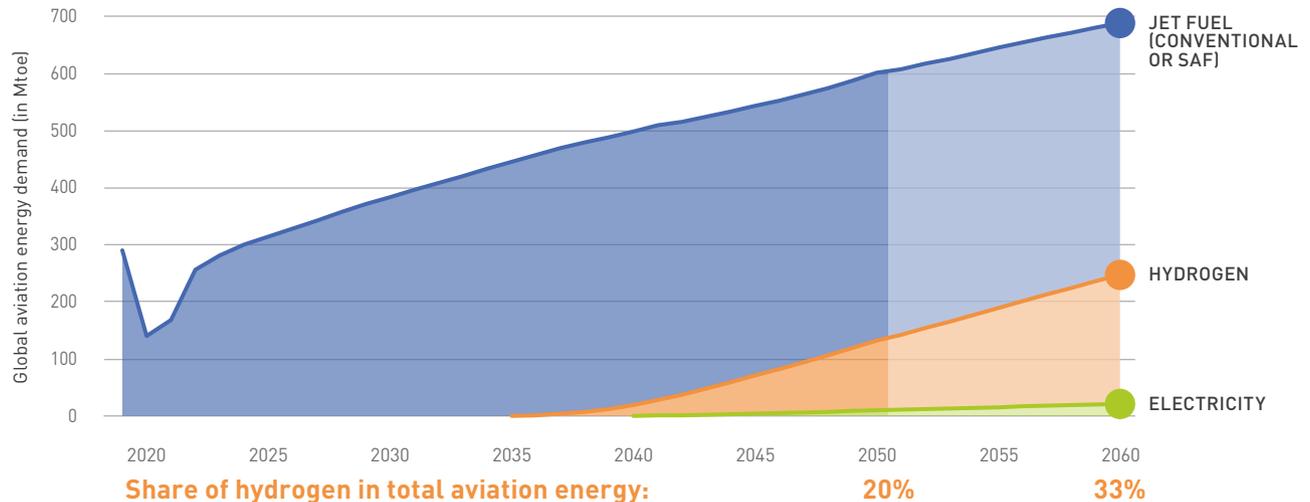
Liquid hydrogen is considered to be one major alternative energy carrier for aviation by various research projects. Flight testing and product development of hydrogen-fuelled aircraft has also advanced considerably. Synergies in technology development from the automotive industry concerning the developments of cryogenic composite tanks as well as fuel cells may be expected.

Assuming the use of so-called green hydrogen (where electrolyser production plants use low carbon electricity) or blue hydrogen (carbon emissions are captured and stored in production), the use of hydrogen can bring with it a range of environmental benefits. It is completely zero-carbon, will reduce particulate matter emissions and greatly reduces NO<sub>x</sub>. The use of hydrogen fuel cells for smaller aircraft will also significantly reduce contrail formation due to the absence of particulate matter. Depending on the system and size of aircraft, it could reduce climate impact by 70-90% compared with similar traditional aircraft. But there is a lot of work to be done if hydrogen-powered aircraft are to become a commercial reality.



## Aviation energy demand evolution<sup>70</sup>

The global aviation energy demand associated with the T5 scenario, where demand for direct use of hydrogen from the 101-200 seat segment starts in 2035.



Recent analysis by McKinsey for the European CleanSky 2 project<sup>69</sup> found that some significant challenges remain to the adoption of hydrogen by air transport:

Completely new aircraft systems would need to be developed. Liquid hydrogen requires being stored at very low temperatures (around -253°C, requiring special tanks) and has a greater volume-to-energy ratio than traditional jet fuel, although lower weight-to-energy.

A liquid hydrogen tank would need to be around four times the size of the equivalent jet fuel tank and completely different on-aircraft fuel distribution systems and engines would be required.

- » Short-haul aircraft could use hydrogen fuel cells to power distributed electric engines, with likely a very small increase in cost per passenger. This energy source would lead to a significant reduction in emissions, to almost zero.
- » For flights longer than this, special tanks (that cannot be located in the wing-like traditional fuels) require a stretched fuselage to carry the same payload, but with a range penalty. These aircraft would be equipped with hydrogen combustion engines, burning the hydrogen in the same way as jet fuel is used today. Whilst this helps with eliminating CO<sub>2</sub>, reducing NO<sub>x</sub> and other emissions, it will likely mean increases in water vapour emissions due to the nature of burning hydrogen.
- » Liquefaction of hydrogen requires an investment of energy approximately equal to a third that of the chemical energy stored in the fuel. Alternative thermodynamic cycles that capture this energy on board for mission propulsion would likely be part of the solution.
- » It is unlikely that hydrogen would be the best option for medium- and long-range aircraft before 2050, as the extra fuselage volume required and heavy tanks for

long missions would be too costly compared with using sustainable aviation fuels with conventional turbine engines. However, the reduced weight of the fuel, coupled with new technology or materials for tanks could change this assessment and there may be a potential for blended-wing style fuselages which could house larger tanks than the traditional tube-and-wing configuration.

Challenges associated with infrastructure requirements and implementation as well as the constraint of the fleet turnover should be considered in any meaningful scenario to assess the potential contribution of liquid hydrogen towards aviation's decarbonisation pathways – this is further explored below.



## Hydrogen requirements

A transition to hydrogen as a non-drop in fuel used either through fuel cells or direct combustion would constitute a departure from the current aircraft technology, energy source, infrastructure and operations that have been optimised for decades around the use of jet fuel.

The analysis, based on the T5 scenario (highly ambitious, but used to illustrate an outside boundary for energy demand), has hydrogen being considered in the 101-210 seat segment. Hydrogen powered aircraft entering this segment of the market assumed entry into service in 2035, with a ramp up to 100% share of production (new deliveries) in 2042. This assumes that all new deliveries of 101-210 seat aircraft in 2042 and in subsequent years are from hydrogen powered aircraft (i.e., from all manufacturers and that drop in fuel powered aircraft go out of production in 2042).

As more aircraft enter the fleet to reach 100% of new deliveries in 2042 and beyond, demand for hydrogen increases to approximately 43 Mth<sub>2</sub> (≈5 exajoules (EJ)) in 2050 and 79 Mth<sub>2</sub> (≈10 EJ) in 2060. This represents about 20% and 33% of global aviation energy demand in 2050 and 2060 respectively. In reality, a number of this size of aircraft may continue being delivered with conventional propulsion systems (using increasing proportions of SAF). For the purposes of this study an extreme approach was used to push to a total use of hydrogen in this segment. This represents a higher-end assessment of the likely hydrogen use by aviation in 2050.

Potential high-ambition demand for hydrogen from global aviation (43 Mth<sub>2</sub> in 2050) could represent about 8-15% of future (2050) global hydrogen production. In the IEA Sustainable Development Scenario, the global demand for hydrogen increasing sevenfold to approximately 280 Mt by 2050<sup>71</sup>. According IRENA's World Energy Transitions Outlook green hydrogen will play a major role in reducing GHG emissions and making the energy transition possible. According to the roadmap, by 2050 green hydrogen needs to have far greater supply than today, with production reaching

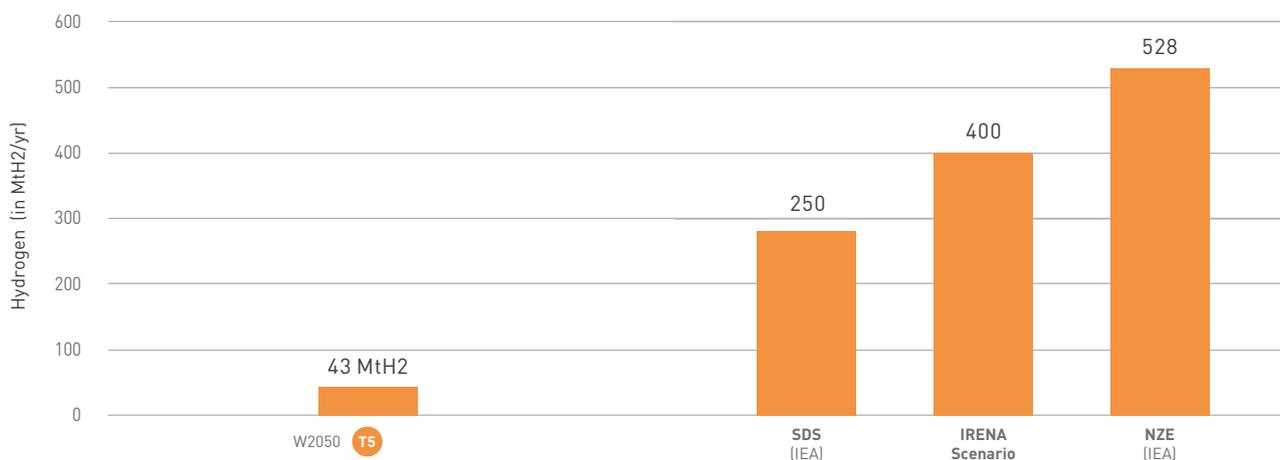
about 400 Mth<sub>2</sub>, equivalent to 49 EJ<sup>72</sup>. In the IEA Net Zero Emissions (NZE) Scenario, the global demand for hydrogen would reach 528 Mt by 2050, of which 520 Mt would be low-carbon hydrogen (broken down into 38% from fossil-based with CCUS and 62% from electrolysis)<sup>73</sup>. However, none of these scenarios predicted direct use of hydrogen in aircraft propulsion, so the global market for hydrogen production may be augmented to take into account aviation use.

Other studies have considered the potential role of hydrogen in future decarbonization scenarios for the aviation sector:

- » Destination 2050<sup>74</sup>, that focused solely on European aviation, estimated that demand for H<sub>2</sub> could reduce CO<sub>2</sub> emissions by 60 MtCO<sub>2</sub> in 2050, representing approximately 24% of the Waypoint 2050 T5 scenario. While no direct volume of hydrogen was quoted, the 24% share is in line with the share global aviation CO<sub>2</sub> emissions from Europe, and therefore makes the Waypoint 2050 and Destination 2050 scenarios comparable.
- » CleanSky 2<sup>75</sup> forecast that by 2050, aviation's demand for LH<sub>2</sub> would grow to 40 to 130 Mth<sub>2</sub> a year. While the lower bound of 40 Mth<sub>2</sub> is in line with the Waypoint 2050 estimates, the 130 Mth<sub>2</sub> appears to be based on a "maximum decarbonisation" scenario and assumptions that are far from being realistic and what appears to be internally inconsistent with the technology roadmaps and requirements contained in the same report.
- » In its Energy Technology Perspectives 2020<sup>76</sup>, in the Sustainable Development Scenario, IEA expects around 20% of the global hydrogen demand (i.e., 520 Mth<sub>2</sub> by 2070) to originate from the aviation sector, however the demand for hydrogen would be towards the production of synthetic kerosene (PtL) from hydrogen and CO<sub>2</sub> (i.e., not for hydrogen as direct source of energy by the aircraft). The use of hydrogen for direct use in aircraft was not considered in the IEA analysis, but could potentially grow the market for hydrogen.

### Potential aviation demand for hydrogen

(for direct use in aircraft)



### Economy-wide future (expected) production of hydrogen

## Requirements and costs (investments) associated with hydrogen powered aviation

Requirements associated with the potential future use of hydrogen powered aircraft on airlines/operators, airports, and OEMs were also considered and assessed. The actual requirements and impacts on the aviation sector of a transition to hydrogen powered aircraft would be dependent on opportunities and synergies that will be offered through the use of hydrogen in other sectors.

» **Operators: Cost of hydrogen.** According to the IEA NZE scenario, the average cost of producing hydrogen from renewables drops from \$3.5-7.5/kgH<sub>2</sub> today to around \$1-2.5/kgH<sub>2</sub> in 2050, essentially about the same as the cost of producing with natural gas with CCUS. With the addition of about \$1.2/kgLH<sub>2</sub> for distribution (if produced offsite), liquefaction, LH<sub>2</sub> storage and refuelling<sup>77</sup>, the unit cost of hydrogen could drop from \$4.7-8.7/kgH<sub>2</sub> today to \$2.2-3.7/kgH<sub>2</sub> in 2050. The resulting cost of hydrogen needed to meet aviation demand (under the Waypoint 2050 T5 scenario) in 2050 could be approximately \$170-370bn at today's unit cost of hydrogen and drop to \$90-160bn given 2050 projected unit cost of hydrogen. For context, cost of meeting energy demand with jet fuel at today's \$635/mt could reach \$65bn, making hydrogen costs 3x-6x with today's unit cost and 1.4x-2.4x with 2050-unit costs. Depending on the prices of carbon by 2050, the gap between hydrogen and conventional jet fuel could close. While the ATAG Waypoint 2050 study was conducted at a global level, regional differences may exist. Depending on technology developments, initiatives and governments' support, the cost of hydrogen may drop faster in some regions: there are already concerted private and government efforts to bring down the unit cost of hydrogen rapidly.

» **Operators: Aircraft (fleet) related requirements and costs.** To meet the requirements associated with the Waypoint 2050 T5 scenario, a potential of approximately 24,000 new aircraft would be required from 2035-2050 for the 100-210 seat market segment. According to the Clean Sky 2 study on hydrogen aviation<sup>78</sup>, the aircraft capital expenditure for hydrogen powered aircraft is expected to be higher than for conventional aircraft mainly due to the costs for the LH<sub>2</sub> tank structure that is integrated in the fuselage, the increased complexity of the fuel distribution, increased costs for propulsion, and the increased aircraft size. The total maintenance costs for hydrogen aircraft might rise (up to 47%) due to the larger airframe and the LH<sub>2</sub> tanks that could require more checks – especially in the first years of introducing LH<sub>2</sub> aircraft. In the long term, maintenance costs for the propulsion system might decrease<sup>79</sup>. Aircraft capital expenditure and maintenance costs may decrease as further research and development continues.

» **Operators: Turnaround time related costs.** Increased operating costs (or loss of revenues) could result from increased turnarounds due to potentially longer refuelling time for hydrogen powered aircraft (between no additional turnaround time, up to a 20% increase). Increased turnaround time could result in loss of revenue if airline capacity is reduced (given constant

fleet size) e.g., 7% fewer flight cycles<sup>80</sup> or an increase in operating costs if fleet size is increased to maintain the same capacity. However, additional research and developments are being conducted to reduce these impacts at the design stage (e.g., improvements in LH<sub>2</sub> transfer technologies such as the Universal Hydrogen 'pod' concept<sup>82</sup>). In addition, in some cases (i.e., aircraft itineraries and schedules) refuelling time is not the constraining factor in turn around time setting.

» **Airports: Infrastructure.** Before hydrogen is distributed to airports, it would have to be compressed or liquified. The delivery of hydrogen could be performed via truck trailers (liquid or compressed hydrogen) for smaller airports or through a pipeline for larger airports. When demand is low, truck trailers could be used to distribute hydrogen to airports before they are connected to pipelines as demand grows. This would require additional infrastructure costs although investments may not be aviation specific in a (regional or world) energy scenario where hydrogen generation and use are generalised for ground transport and other applications. In a scenario where hydrogen is liquefied at the airport, additional renewable electricity would be required (i.e., on the order of 300 to 570 TWh in 2050 to meet LH<sub>2</sub> needs under T5 scenario). Once distributed at the airport, hydrogen needs to be uploaded onto the aircraft via refuelling trucks or an alternative refuelling method like refuelling platforms or aircraft fuel station plots. The cost of LH<sub>2</sub> refuelling systems may be as much as five times the cost of conventional hydrant systems<sup>81</sup>, given the need to maintain high pressure and low temperature across the delivery system. Some other concepts, such as Universal Hydrogen, consider transporting hydrogen in modular capsules over the existing intermodal container freight network<sup>82</sup>. The introduction and operation of hydrogen powered aircraft may also impact airport infrastructure given the potential need to adapt airport gate box sizes to accommodate longer aircraft. The actual impacts on airport gate boxes and operations may be alleviated as potential hydrogen powered aircraft are still in the early development and design phase.

» **Airports: Infrastructure investment.** The transition from jet fuel to hydrogen powered aircraft will also require additional considerations and challenges in terms of airport infrastructure including:

- » the timing/synchronisation of investments, availability and use of infrastructure – airports will need to make decisions based on airline fleet planning and technology readiness well before aircraft enter into service in significant numbers,
- » optimisation of the air transport system i.e., infrastructure lock-in.
- » indirect infrastructure costs such as potential changes to airport layout remain highly uncertain.

There are also opportunities and synergies that will be offered through the use of hydrogen in other sectors. This could be achieved through an airport hydrogen hub concept in a stepped approach, including using hydrogen to decarbonise all airport-associated ground transport (heavy goods logistics, buses, tow trucks), paving the way to hydrogen availability for aircraft in the 2030. This will help to minimise the costs to the sector and airlines.

» **Energy suppliers: H2 production.** Low-carbon source hydrogen are needed to meet the requirements associated with aviation decarbonisation scenarios. While the current production of hydrogen is primarily from coal (black hydrogen), natural gas (grey hydrogen) or lignite (brown), hydrogen can also be produced from fossil fuels with CO<sub>2</sub> emissions reduced using CCUS (blue hydrogen). Ultimately, hydrogen is expected to be produced through electrolysis from renewable electricity (green hydrogen). Green hydrogen may eventually be produced locally at or near airports. Local electrolysis unit of 50 megawatts could serve the need for regional size airport and around 500 megawatts for larger airports<sup>83</sup>.

Meeting the demand for green hydrogen from the Waypoint 2050 T5 scenario would require approximately 2,200 TWh renewable electricity (power) in 2050. In context, this additional demand for renewable electricity is 5 to 20 times greater than the demand for electricity from all-electric and incremental demand from plugin hybrid electric aircraft (i.e., 90-400 TWh in 2050). The hydrogen powered aircraft considered in the T5 scenario (i.e., narrow body aircraft) would consume cryogenic hydrogen (as opposed to gaseous hydrogen). Between the production of hydrogen and the uplift into the aircraft, liquefaction of hydrogen will be required. The theoretical minimum energy requirement to produce liquid hydrogen ranges from 2.34-2.89 at for LH2 at 20K and 2-4 bar<sup>84</sup>. The actual energy requirement to produce liquid hydrogen is ranges from 7 to 13.4 kWh/kg at for LH2 at 20K and 2-4 bar<sup>85</sup>. At today's (actual) range of energy requirement, the demand from liquid hydrogen from aviation in 2050 would require an additional 300 to 570 TWh of renewable electricity.

» **Energy suppliers: Financing and investment.** Risks The global aviation sector is a capital intensive and long-time horizon industry. The Waypoint 2050 T5 scenario would require rapid scale up of innovation, technology development (R&D), product development, product acquisition and infrastructure building.

» **Regulatory agencies: Aircraft certification.** In addition to requirements to OEMs, airports, operators, the development, and introduction of hydrogen powered aircraft will require the certification of new technologies in a sector with very low safety risk. The certification process (including amendments to certification standards and rules) is costly and lengthy process that can only be changed without compromising safety. Certification is even more challenging with the introduction of new, disruptive technologies such as hydrogen-powered aircraft. The timing of development of certification standards would also be critical to allow for entry into service of hydrogen-powered aircraft.

Among aviation emissions, CO<sub>2</sub> is the major contributor to climate change due to its longevity in the atmosphere. Its quantification, formation and effect are very well understood. By working on reducing the fossil fuel consumption we reduce all other emissions. SAF also has the potential to reduce non-CO<sub>2</sub> emissions. However, as a complement, it is necessary to minimise the current level of scientific uncertainty over the effect of non-CO<sub>2</sub> emissions and our

industry is committed to it. Such emissions include the water vapour itself and its various forms (contrails, cirrus clouds) and the other emissions such as NO<sub>x</sub> and particulates and the combined effect of these emissions.

This is even more necessary as the hydrogen aircraft will emit a large amount of water vapour.

## THE DIFFERENT 'COLOURS' OF HYDROGEN

In order to highlight the different hydrogen production pathways, an informal colour code has started to be used. Many groups such as the International Energy Agency and International Renewable Energy Agency anticipate that green hydrogen will over time become the predominant source of hydrogen, although is starting from a very low base today. Blue hydrogen may play a transitional role as the 'hydrogen economy' builds prominence across a range of economic sectors.

### Black hydrogen

Hydrogen is extracted from bituminous coal, releasing CO<sub>2</sub> and CO emissions into the air.

### Brown hydrogen

Hydrogen is extracted from lignite coal, releasing CO<sub>2</sub> and CO emissions into the air. Around 95-98% of current supply.

### Grey hydrogen

Hydrogen is extracted from natural gas, releasing CO<sub>2</sub> emissions into the air.

### Blue hydrogen

Hydrogen is extracted from fossil sources, with CO<sub>2</sub> being captured and stored permanently underground. However, between 5% and 15% of the CO<sub>2</sub> 'escapes' during the collection and distribution process.

### Pink hydrogen

Hydrogen is extracted from water using electricity generated by nuclear. The by-product, oxygen, is released into the air.

### Green hydrogen

Hydrogen is extracted from water using renewable electricity such as solar and wind power. The by-product, oxygen, is released into the air. The use of solar power is sometimes referred to as 'yellow' hydrogen. Around 0.1% of current supply

## An indicative overview of where low- and zero-carbon energy could be deployed in commercial aviation

A simplified view of which energy options might be able to contribute to the reduction in CO<sub>2</sub> emissions from air transport in which time period. This generally indicates when the technology may be commercially available, but not widespread use throughout the fleet. In addition, the potential for hybrid sources of propulsion using direct electricity or electricity generated from the aircraft engines could become a technical possibility in the regional and short-haul fleet from around 2030, medium-haul around 2035 and long-haul around 2045. Hybridisation would bring with it improvements in fuel efficiency beyond the typical evolutions in engine technology. The roll-out of these technologies depends on research advances and the distribution and supply of energy, as well as the economic case to bring these new designs and energy sources into the fleet. As new technologies evolve, these assumptions may change – denser batteries may allow greater range and larger aircraft to go electric; a strong governmental push towards a hydrogen economy may allow faster take up of that technology. Illustrative seating configuration, general flight times and share of CO<sub>2</sub> emissions for context.

	2020	2025	2030	2035	2040	2045	2050
<b>Commuter</b> » 9-19 seats » < 60 minute flights » <1% of industry CO <sub>2</sub>	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
<b>Regional</b> » 50-100 seats » 30-90 minute flights » ~3% of industry CO <sub>2</sub>	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
<b>Short haul</b> » 100-150 seats » 45-120 minute flights » ~24% of industry CO <sub>2</sub>	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
<b>Medium haul</b> » 100-250 seats » 60-150 minute flights » ~43% of industry CO <sub>2</sub>	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
<b>Long haul</b> » 250+ seats » 150 minute + flights » ~30% of industry CO <sub>2</sub>	SAF	SAF	SAF	SAF	SAF	SAF	SAF

### Regional aircraft provide useful first step

The most likely first adopters of new electric, hybrid and hydrogen opportunities in aviation are commuter and regional aircraft – those smaller than 100 seats which provide feeder services to large hub airports for onward travel, or vital connectivity between secondary, tertiary and remote communities. The current generation of these aircraft include turboprops which are more fuel efficient than current jet aircraft and could be a perfect first step for radical new technologies.

Commuter services can provide connectivity on routes that would be too time-consuming to be operated by road, or too costly to build rail links. Some smaller communities can take advantage of electric aircraft in the 9-50 seat category and there are already flying test electric aircraft today.

The next step would be to up-gauge the electric, hybrid or hydrogen technology to regional aircraft size in the 50-100 seat category (such as today’s ATR and DeHavilland aircraft) which may provide a useful and lower carbon alternative

between secondary or tertiary cities that don’t otherwise have enough traffic to justify building extensive high-speed rail infrastructure. Given the timeframes to build such infrastructure (in the range of 20 years), advances in aircraft technology could leapfrog the shift to rail for these markets, with lower carbon costs. In fact, Norway has set a goal to have domestic air travel fully electrically-powered by 2040, with the first commercial services taking off by 2030<sup>86</sup>.

### Re-thinking our energy supply

Whilst the discussion above examines the challenges and prospects for developing the new technology aircraft that will run on electricity and hydrogen, both require some shifts in the way the industry considers energy supply.

Shifting to sustainable aviation fuel will require minimal investment in on-airport distribution systems. Once the neat SAF is produced, it will only require a blending infrastructure to mix it in increasing quantities into the jet fuel supply. This will likely be done off-airport at dedicated facilities to

ensure quality control of the fuel before it enters the airport environment. It is an infrastructure investment, but due to the drop-in nature of SAF will allow a gradual ramp-up in SAF blend percentages as more supply is made available.

*Further discussion on this takes place in section d) sustainable aviation fuel.*

Hydrogen and electric battery options, on the other hand, will require a radical re-think of the energy supply system. The virtue of traditional (and drop-in SAF) fuel supply has been standardised fuel supply across the entire global system. Any flight in any commercial aircraft can land virtually anywhere in the world and pick up fuel. By having a special sub-set of the global fleet operating with entirely different energy supply, airlines will need to carefully consider how their operation will evolve to take into account the supply of hydrogen and high-voltage electricity connections.

One can imagine a special fleet of short-haul hydrogen-powered aircraft operating between, for example, Geneva and London Heathrow. It is a route with high frequency over the correct distance. An airline will need to ensure that hydrogen fuelling facilities are available at those two airports, as well as alternate diversion airports (in this case potentially Paris Charles de Gaulle, London Stansted, London Gatwick and Lyon). Additionally, having a sub-fleet of aircraft dedicated to one route is not efficient and would need to also have use on other routes, where hydrogen infrastructure would need to be established.

There will be a need to develop new hydrogen fuelling infrastructure at airports, and ideally pipelines from green hydrogen plants to airport facilities (although smaller volumes can be transported by road).

Electricity supply for electric aircraft is not nearly as novel, but it would also require new charging infrastructure and storage space for charged batteries to be available at airports (and, of course, for the high-specification electricity supply to be low-carbon).

Additionally, a range of other 'fuelling' questions will need to be answered: how long will it take to refuel / recharge a hydrogen or electric aircraft (and how will that impact turnaround times for these short-haul flights and therefore fleet utilisation)? What considerations would be needed for the size of hydrogen storage and possibly liquefaction facilities at airports, or would cryogenically-sealed pipelines be needed to deliver enough liquid hydrogen to airports? What changes will be needed to train ground crews? How will the sector overcome safety challenges that take place with the shift to different fuels? All of these are surmountable over time, but are key considerations for the industry. The current fuelling infrastructure-using fossil or SAF-is highly efficient and optimised.

A systemic approach (for the whole aviation sector as well as the wider economy) should be undertaken for all non-fossil energy carrier options (SAF, hydrogen, electricity) to properly map the potential supply limitation for the use of green primary energy as the world economy moves to carbon-free energy.

## TECHNOLOGY READINESS LEVELS

This illustrates the various stages of technology readiness level, as developed by NASA in the 1990s. The description places this in the context of a new aircraft type, but the TRLs can also apply to individual pieces of technology that go into a wider airframe make-up, or even retrofit opportunities.

ADOPTION		<b>Widespread adoption of technology in the fleet</b>	Most of the aircraft in the fleet have been replaced with the new technology models — this process can take up to seven years for wide market penetration.
		<b>Scaling up of deployment</b>	More aircraft enter the fleet across the world, replacing older (less efficient) aircraft of the same class.
DEPLOYMENT	9	<b>Actual system proven in operational environment</b>	As aircraft enter the fleet with multiple airlines, operational shake-out identifies updates or minor modifications required, ensures evolutionary improvements to systems and efficiency of product.
	8	<b>System complete and qualified</b>	Certification by relevant authorities following comprehensive test flight campaign with full production aircraft. First commercial aircraft rolls off the production line, followed by entry into service.
	7	<b>System prototype demonstrated in operational environment</b>	Full prototype has been developed and tested in normal operating environments (test flights).
DEVELOPMENT	6	<b>Technology demonstrated in relevant environment</b>	Full-sized prototypes engaged in ground testing of aircraft or engines or systems.
	5	<b>Technology validated in relevant environment</b>	Larger prototypes have been developed and tested at scale.
	4	<b>Technology validated in laboratory</b>	Early prototypes developed and tested in laboratory conditions and through computer modelling.
RESEARCH	3	<b>Experimental proof of concept</b>	Very simple experimental set up to demonstrate feasibility.
	2	<b>Technology concept formulated</b>	Taking theoretical concepts and turning them into a design concept.
	1	<b>Basic principles observed</b>	Initial idea for new technology.

## ACCELERATING TECHNOLOGY DEVELOPMENT

A range of actions will help reduce emissions. In each section, the report will explore the actions needed from policymakers, the industry and partners in other sectors to help accelerate emissions reduction across aviation.

In order to support the future development of the global aviation industry in achieving high rates of aircraft level fuel efficiency improvements, several recommendations and actions are required:

### Action items for the aviation sector

Action item	Description	Timeline	Difficulty level
Collaborate in government — industry — research institution programmes and champion their development	Industry should be an active supporter of programmes like Clean Aviation (successor to CleanSky 2) in the EU, the FAA CLEEN project in the US and other existing programmes at a national level. Where such programmes do not exist, industry can encourage governments to invest alongside industry commitments. Should be accelerated in all regions, but also in emerging economies to take advantage of new talent in the developing world.	Possible today	●○○○○○
Accelerate research into radical airframe designs, electric and hydrogen propulsion	Manufacturers: explore the potential of the emergence of new non drop-in energies for aviation. Explore new design and aircraft architecture concepts, in addition to exploring all advanced technologies. Accelerate product cycles and innovation speed with enhanced digital capabilities in order to enable sufficient market penetration of climate-friendly technologies until 2050 and beyond. Keeping affordability of new products in focus is important to ensure airlines have the ability to bring them into the fleet.	2020 — 2050	●●●○○○
Accelerate research into radical airframe designs, electric and hydrogen propulsion	Airlines: show interest and support for new technologies by participating in evaluation, making it easier for manufacturers and research establishment to drive forward the necessary developments and justify the related funding. Airlines (and similarly airports and ANSPs) are the end users of new technologies. They have a role in defining requirements for day-to-day operations and in validating if new solutions are fit-for-purpose.	2020 — 2050	●●●○○○
Form partnerships with non-aviation technology providers	Manufacturers: work with other industrial sectors (battery technology, automobiles, long-haul trucking, hydrogen sector) to form partnerships on accelerating necessary technology development.	2020-2035	●●○○○○
Provide robust incubator opportunities for new technology start-ups	Manufacturers: could fund an incubator for ideas and start-ups across the spectrum of aviation environmental efficiency. Many inventors have ideas which need to be explored and encouraged without the constraints that large global manufacturers may have.	Possible today	●●●○○○
Implement necessary infrastructure adaptations	Airports: in airport expansion plans, foresee the provision of necessary infrastructure for (clean) electricity supply, (green) hydrogen and battery recharging facilities at the time when they will be needed (small-scale soon, substantial part of regional traffic in the 2030s).	Possible today	●●○○○○
Implement necessary infrastructure adaptations	Airports: foresee ground infrastructure adaptations for radical new aircraft concepts, e.g. blended wing bodies, hydrogen.	2025-2035	●●○○○○

## Action items and policy proposals for governments

Action item	Description	Timeline	Difficulty level
Continue to fund research programmes where they exist and develop projects where they do not	In the coming years, government must ensure that access by aerospace industry to ongoing funding for high-value collaborative R&D, essential for delivering highly efficient future aircraft and propulsion systems, remains in place. Examples include the Clean Aviation Partnership project in the EU.	2020-2030	●●○○○○
Provide strong guidance to green aviation research	Execute a national or supra-national research agenda that places the highest priority on; advances in environmentally friendly aviation, including radical new aircraft concepts, new sustainable propulsion energies, such as electricity and hydrogen, and highly efficient operations and infrastructure.	Possible today	●●○○○○
Research into non-CO <sub>2</sub> impacts also vital	Expand the focus from 'CO <sub>2</sub> emissions reduction' to 'climate impact mitigation', considering also the impact of non-CO <sub>2</sub> effects and how technology and adapted flight operations can reduce these effects. Some research is already ongoing in this space and while there is better understanding, the work has so far not provided conclusive operational or technology fixes and answers for the industry.	Already underway, can be expanded immediately	●●●○○○
If putting in place a market-based measure, invest a portion in R&D	As global and regional market based measures are adopted, Governments should invest a portion of any funds collected in aircraft and propulsion technology that accelerates the sector's path to reducing CO <sub>2</sub> .	Available today	●○○○○○
Implement ICAO aircraft CO <sub>2</sub> Standard	The ICAO CO <sub>2</sub> Standard should be implemented in national legislation.	Required today	●○○○○○
Develop a wider hydrogen economy strategy for all potential users of hydrogen	Build a coalition of potential users and providers of green hydrogen in your country / region to start planning for a significant increase in hydrogen use by transport, including aviation. More generally, the changing energy needs of the aviation sector should be included in national energy strategies.	Possible today	●●●●○○
Ensure sufficient infrastructure for low-carbon electricity across your economy	Support the introduction of hybrid-electric and full-electric propulsion, as key enablers to reach medium-and long-term CO <sub>2</sub> emissions reduction goals.	2020-2050	●●●●○○

## Action items and areas for research institutions

Action item	Description	Timeline	Difficulty level
Ensure that research programmes take into account real-world requirements	The organisations in charge of defining aviation research and technology policy and strategy, such as ACARE in Europe, are giving special emphasis to the innovation and integration aspect, with stronger participation of end users, namely airlines, airports and air navigation service providers; this is also reflected in ACARE's name change from 'Advisory Council for Aeronautic Research in Europe' to "Advisory Council for Aviation Research and Innovation in Europe".	Possible today	●○○○○○
Help facilitate clean energy and technology collaborations between industry sectors	Research programmes should support closer R&D cooperation between different sectors (such as aviation and energy) to create synergies.	Possible today	●○○○○○
Provide a platform for visionary thinking and radical departures from standard research	The strategic research organisations have extended their goal-setting timeframe further into the future, with ACARE's vision document 'Flightpath 2050' and NASA's strategic planning including an additional generation of long-term future ultra-green aircraft concepts. More room is thus given to radically new ideas for the air vehicles and air transport concepts of the future, which rely on out-of-the-box thinking and leaving the classical concepts of tube-and-wing aircraft as well as today's forms of airports and airspace organisation.	Possible today	●●○○○○
Ensure sustainability is part of any aviation-related curriculum at specialist universities	Educate aviation students on aviation's potential for green growth and willingness to decarbonise to ensure they are ready to innovate to support this technological challenge.	Possible today (and already happening in many cases)	●○○○○○

## Action items for the energy industry

Action item	Description	Timeline	Difficulty level
Plan strategic energy needs	Include aviation as a future customer of large amounts of clean electricity and hydrogen.	Required today	●○○○○○
Develop worldwide hydrogen supply structure	Develop a worldwide hydrogen supply network, in collaboration with the aviation industry, ensuring that hydrogen is available at the majority of airports in the world — this is a prerequisite for the development of a hydrogen-powered aircraft programme, as manufacturers normally develop for a world market rather than a regional one.	2025-2040	●●●○○○
Development of new SAF pathways and maturation of existing ones	The energy industry should prioritise and contribute to the development of new SAF pathways and push the maturity of already existing pathway-feedstock combinations and newer technologies like power-to-liquid.	Possible today	●●●○○○

## Action items for the finance community

Action item	Description	Timeline	Difficulty level
Focus funding on new efficient aircraft acquisition	Regional and multilateral development banks can play a proactive role in supporting the fleet replacement with new efficient aircraft.	Possible today	●●●○○
Sustainable finance opportunities	Aviation should be able to access sustainable finance, green bonds etc to support decarbonisation projects through technology, SAF, infrastructure improvements etc.	Possible today	●○○○○
Development of new SAF pathways and maturation of existing ones	The energy industry should prioritise and contribute to the development of new SAF pathways and to push the maturity of already existing pathway-feedstock combinations and newer technologies like power-to-liquid.	Possible today	●●●○○

## Action items for other stakeholders

Action item	Description	Timeline	Difficulty level
Develop synergies with the automotive sector	Automotive sector: this industry is fairly advanced in building vehicles using new clean propulsion energies (electricity, hydrogen). Collaboration between the automotive and aviation sectors is needed to benefit from synergies in the development and implementation of clean energy solutions.	2020 - 2050	●○○○○
Develop synergies with the hydrogen sector	Hydrogen sector: ensure potential aviation demand for hydrogen is included in green hydrogen scale-up planning: for traditional SAF production, power-to-liquid production and also direct hydrogen use. Included in planning should be an exploration of the potential need to deliver large quantities of hydrogen to airport sites (storage, liquefaction, pipelines, etc).	2020- 2050+	●●●○○

# IMPROVEMENTS IN OPERATIONS AND INFRASTRUCTURE

**HOW AIRCRAFT ARE FLOWN THROUGH THE SKIES CAN MAKE A GREAT IMPACT ON THE EFFICIENCY OF EACH INDIVIDUAL FLIGHT. WHILST IMPROVEMENTS IN OPERATIONS (THE WAY AIRCRAFT ARE FLOWN AND IMPROVEMENTS THAT CAN BE MADE ON BOARD) AND INFRASTRUCTURE (THE EFFICIENCIES FROM THE AIRSPACE AND AIRPORT SYSTEM) WILL NOT PROVIDE THE LARGEST CONTRIBUTIONS TO LONG-TERM CO<sub>2</sub> REDUCTION, THEIR IMPACT CAN BE SIGNIFICANT.**

Operations and infrastructure efficiency improvements have the potential to contribute to reducing CO<sub>2</sub> emissions and help meet the 2050 carbon goal. While the overall emissions reductions from operations and infrastructure efficiency improvements will – by themselves – not be sufficient to meet the goal, these measures can often be implemented at scale faster than aircraft-level technologies (that are constrained by the rate of entry of aircraft into the fleet) and therefore the impacts from operations and infrastructure efficiency improvements can be significant contributors, particularly in the near term.

Aircraft operations (airline and aircraft operator focus) include measures such as: reduction of weight, improvements in aerodynamics of in-service aircraft and use of systems to improve efficiency during the operation of aircraft. In the short-term, these elements will play a crucial role to bring down emissions, but this only has a limited impact on longer-term emissions trajectories, as opportunities for these efficiency measures are fully exploited in the early years. Infrastructure improvements (air traffic management and to a lesser extent airport operations) include measures such as: structural changes in air traffic management (ATM) operations, energy savings at the airport such as limitations on the use of auxiliary power units, single engine taxi, and reduced taxi times.

Optimising fuel consumption is a challenge for many groups in commercial aviation. Motivation to deal with the subject

comes not only from the desire to minimise fuel expenditure, but to increase overall efficiency and also to address environmental concerns.

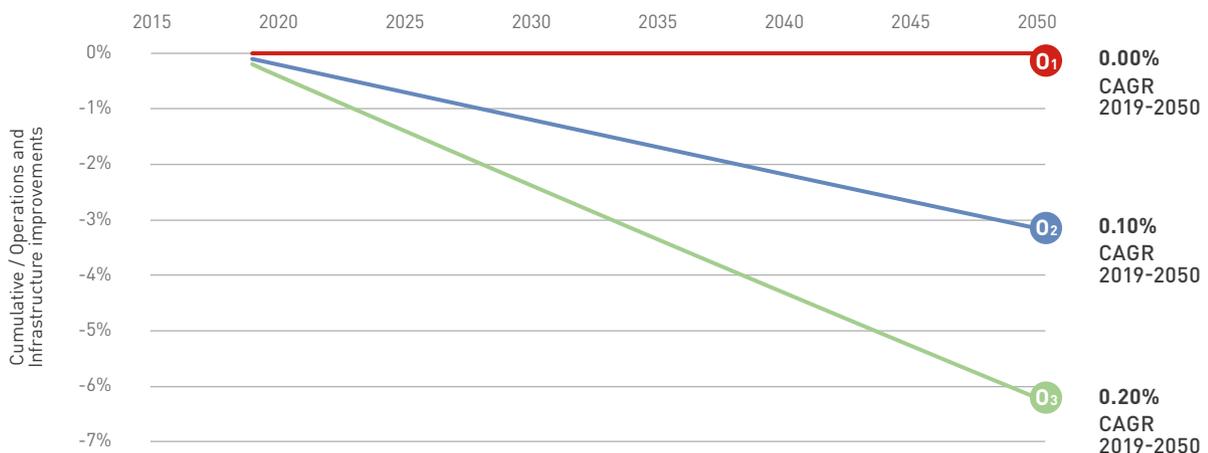
Reducing fuel burn is the first way to reduce emissions and hence the environmental impact and associated costs. The market expects aircraft manufacturers, in cooperation with their suppliers, to design and deliver the most economically efficient aircraft with the best environmental performance possible. Manufacturers are committed to improving the fuel burn and emissions performance of their aircraft through the implementation of new technologies but also through operational measures during the in-service life of the aircraft.

Airframers, infrastructure providers, airports, aviation authorities and air navigation service providers can all participate by providing airlines with the means to operate their aircraft in the most efficient way possible.

To investigate the potential contribution from operations and infrastructure efficiency improvements and to build on the expertise of the participants, sources were reviewed within the Waypoint 2050 project and considered as the basis for the development of a range of potential scenarios for CO<sub>2</sub> emissions reductions resulting from operations and infrastructure efficiency improvements. These include the ICAO CAEP/10 and CAEP/11 reports, the IATA Technology Roadmap, the CANSO Efficiency 2050 Goal and the UK Sustainable Aviation Road-Map (2016).

## Operational efficiency scenarios for Waypoint 2050<sup>88</sup>

Three simple scenarios were developed to illustrate potential pathways for operational and infrastructure efficiencies on a per-annum basis.



## O<sub>1</sub> Low improvement

Investments in operations and infrastructure are counterbalanced by degraded ATM performance due to congestion from traffic increases.

While difficult to estimate given the complex counteracting feedback loops of (1) investments in operations and infrastructure resulting in fuel burn reductions and (2) increased congestion resulting in increased operational inefficiencies and fuel burn, this scenario of (net) zero percent improvement in fuel efficiency is meant to illustrate this situation.

Despite what looks like no improvement in this scenario, maintaining current efficiency despite traffic growth will require investment in ATM improvements in order to avoid a degradation in the performance of the system and reduction in efficiency.

## O<sub>2</sub> Mid improvement

Substantial investments in operations and infrastructure result in (net) CO<sub>2</sub> reductions of 0.10% per annum, a 3+% overall contribution in 2050.

## O<sub>3</sub> High improvement

Substantial investments in operations and infrastructure result in (net) CO<sub>2</sub> reductions of 0.20% per annum, a 6+% overall contribution in 2050.

## Developing scenarios

Trying to develop high-level scenarios in this space is challenging, as there are so many individual initiatives taking place all over the world, with different opportunities for efficiency improvements. Necessarily, a broad estimate needs to be developed in order to feed into the Waypoint 2050 overall scenarios. The delivery of improvements is further challenged by congestion in parts of the system – trying to put more flights into a finite airspace will reduce the effectiveness of operational efficiency measures.

As described in the scenarios above, the net improvement from aircraft operations and infrastructure is dependent on the underlying growth in traffic measured in terms of number of flights or movements.

- » In the central traffic forecast, the increase in number of movements will be around 2.3.
- » Under high traffic forecast, the number of movements could increase by a factor of around 2.6.
- » The low traffic forecast will see less than a doubling of movements (1.6 times).

Scenarios that would result in a more than two times increase in number of movements could result in substantial levels of congestion in some parts of the global airspace system depending on the rate at which capacity is added to the system.

What is clear is that substantial investment will be needed to help keep up with the increase in connectivity being generated by this growth in traffic.

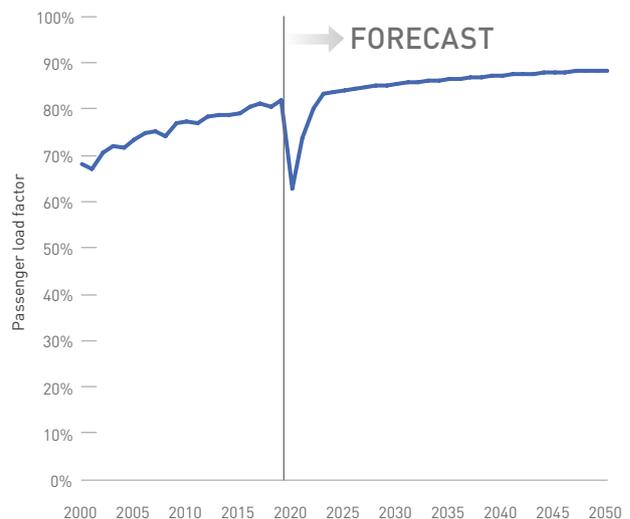
## Airline-based operational improvements

Load factors can make a significant impact on the fuel efficient utilisation of aircraft and have been improving substantially in recent years (the impacts of Covid-19 are causing a number of unusual impacts, but the industry expects to revert to typical load factor conditions as traffic returns to normal).

Efficient aircraft operations also require the careful integration of many factors, including: regulatory restrictions, en-route and airport traffic management requirements, maintenance, crew scheduling and fuel costs. Effective flight planning, careful operation and maintenance of the aircraft and its engines are essential to ensure that the aircraft is consistently being used in the most efficient way possible and addressing all requirements. The aircraft will experience performance degradation through its operational life. Careful operation and maintenance can limit it and thus reduce cost, safety risks and optimise efficiency.

## Historic and projected average load factor<sup>89</sup>

The scenario modelling projected a continued increase in airline load factors.



## Practical opportunities for operational improvements

Measure	Explanation, how it reduces CO <sub>2</sub>
Retro-fitting winglets	Several manufacturers have developed variations of wingtip devices that reduce the wake vortex created by the movement of air around the wingtip. These aerodynamic modifications, using advanced computational fluid dynamics, enable airlines to save more than 4% in fuel, reduce aircraft noise and as much as 8% in NO <sub>x</sub> emissions. Over 9,000 aircraft have been retrofitted, saving over 100 million tonnes of CO <sub>2</sub> since 2000.
Light-weight aircraft cabin equipment	New catering trolleys can be up to one-third lighter than their predecessors, saving nearly 28,000 tonnes of CO <sub>2</sub> annually in one airline's operation by using lightweight composite materials. Further weight reductions of 30-40% have been achieved through the introduction of lighter inflight entertainment systems.
Light-weight seating	By replacing standard seats with lightweight, slimline models, airlines can cut weight by 30%, with one airline saving more than 21,000 tonnes in CO <sub>2</sub> emissions a year.
Light-weight cargo containers	Airlines have developed high-tech, fire-resistant containers by using composite materials such as MACROLite and Kevlar that have proven to be more durable and lightweight. This has allowed one airline to avoid over 3,000 tonnes of CO <sub>2</sub> emissions annually, reduce maintenance time and carry more cargo.
Electronic flight bags / tablet computers	Using a tablet computer instead of heavy paper flight crew manuals, weighs half a kilogramme as opposed to 20 kilos in printed material. One airline has avoided nearly 3,500 tonnes in CO <sub>2</sub> annually, with other airlines experiencing similar effects.
Last-minute fuel and water uplift	Rather than refuelling by simply filling the tanks each time (or filling potable water tanks), airlines are increasingly working to match fuel and water requirements more precisely to passenger loading and weather conditions en route. This reduces fuel uplift and saves weight and CO <sub>2</sub> emissions.
Electric or assisted taxiing	There are a range of solutions available that minimise the use of jet engines during aircraft taxiing. Options that utilise electric motors fitted to landing gears and guide the aircraft from the terminal gate without the need to run the engines can cut CO <sub>2</sub> emissions and unburned hydrocarbons by over 60% and NO <sub>x</sub> emissions from the taxiing phase by over 50%. An example of a solution is proposed with a special tug that tows the aircraft to the runway and is remotely steered by the pilot. Only the APU needs to run during this phase, which can lead to emissions reductions of up to 85% on airports with long taxi distances. Solutions exist but further research and development are needed for full application and usefulness of electric-taxiing.
Using thinner paint for aircraft liveries	Thinner chrome-free paint has the potential to reduce the weight of paint by 15%, while also eliminating the need for additional solvent chemicals that are detrimental to the environment. With paint on an aircraft weighing as much as 250 kilograms, these modifications have enabled one airline to save 60,000 tonnes of CO <sub>2</sub> without compromising the paint quality (which can have aerodynamic benefits as the aircraft flies).
Maintaining exterior paint conditions	Deterioration of the aircraft's exterior surface is to be expected on any aircraft in service, the loss of paint in critical areas of the airframe will upset the local airflow to an extent that overall drag can be increased.

Measure	Explanation, how it reduces CO <sub>2</sub>
Exterior cleaning	The natural accumulation of dirt on the external surface will introduce a slight roughness that, overall, can induce significant additional drag.
Performance improvement packages for in-service aircraft	The implementation of performance enhancements and fuel burn improvements to existing aircraft can reduce fuel consumption and emissions by 2% - can come in the form of software updates, operational measures and small technology retrofits. These performance improvement packages can reduce drag, improve propulsion efficiency and streamline aerodynamic surfaces, in addition to further improvements that enhance airflow and save up to 6.4% in fuel consumption.
Fuel efficiency management systems	Enhanced fuel efficiency systems that apply to flight and ground operations enable airlines to cut fuel use and CO <sub>2</sub> across their operation by analysing flight patterns and suggesting small improvements that can add up to a big difference across the fleet, throughout the year.
Reduced engine taxiing	Reduced engine taxiing, where pilots taxi on a reduced number of engines and then start the rest nearer the runway, has saved one airline 4,100 tonnes of fuel per year at its hub airport.
Engine wash / fuselage wash	To ensure the long-term health of aircraft engines, modern engine wash systems have been developed to remove airborne contaminants that would otherwise cause the engine to operate at higher temperatures and burn more fuel. This closed-loop system reuses deionised, heated and atomised water to remove contaminants from compressor blade surfaces and restore engine performance, leading to a 1.5% fuel reduction and saving up to 500,000 tonnes of CO <sub>2</sub> per year across the fleet.
Aircraft interior cleaning	Keeping the passenger and crew areas clean will have the added benefit of minimising weight increase through dirt accumulation. Regular cleaning of cargo compartments should also be considered. Cleaning can also reduce maintenance costs associated with repairs due to foreign objects causing damage to cargo compartment panels (broken suitcase handles or wheels).
Condensation	Aircraft are designed to minimise the generation of condensation, but studies suggest that an aircraft can accumulate in excess of 200 kg of water. Condensation is affected by seating density, load factor and utilisation. Short turnaround times may not allow full evaporation or drainage of the condensed water. Careful maintenance of insulation blankets and correct functioning of the piston type drain valves on the lower fuselage shell should be periodically checked. Additionally, several providers produce zonal dryers which can be used to cut down on condensation formation.
Raise awareness and train crews	<p>The way air crews and engineers operate aircraft can have a significant impact on fuel consumption and emissions.</p> <ul style="list-style-type: none"> <li>» Ensure regular training sessions, promote application of green procedures</li> <li>» Deploy consulting activities to review the whole ecosystem involved in the fuel efficiency procedures</li> <li>» Develop sustainable engagement programmes between airlines and manufacturers</li> <li>» Participate in networking activities to share experience within the community (Forums, webinars...)</li> </ul>

## Practical opportunities for infrastructure improvements

Measure	Explanation, how it reduces CO <sub>2</sub>
Fixed electrical ground power at gate	Fixed electrical ground power and pre-conditioned air powered by local electrical grids or solar power enables airlines to turn on auxiliary power units nearer to the departure time. At one major hub airport, the use of this gate power lowered CO <sub>2</sub> emissions by over 100,000 tonnes per year and reduced aircraft noise.
Airport collaborative decision making	<p>Airport collaborative decision-making (A-CDM) facilitates the exchange of information between the aircraft, ground handler, and air traffic control provider by enhancing information sharing. This provides more accurate turn-around information for airlines and allows for the effective use of slots, which can minimise delays and fuel burn. When A-CDM was implemented at 17 airports in Europe, over 102,700 tonnes of CO<sub>2</sub> per annum was saved, on top of over 2.2 million minutes of taxiing time and €26.7 million in fuel<sup>90</sup>.</p> <p>Currently, 29 European airports are fully A-CDM “compliant”. In Asia Pacific, 50 airports are operating A-CDM procedures to a varying degree. The US is working to implement Surface-CDM at 27 airports by 2024. Airports in the Middle East, South America and Africa are beginning to adopt A-CDM. Challenges include: a lack of automation platforms for information exchange; lack of integration between airports and ANSP (insufficient cooperation between stakeholders); and limited knowledge of A-CDM.</p>
Surface congestion management (reducing taxiing delays)	New software and hardware tools used to generate virtual airport departure queues, assist in managing an airport’s surface congestion. The tool builds 15-minute departure blocks, that minimise the amount of time airlines spend on the taxiway waiting for their departure slot. By determining the number of aircraft permitted to taxi, and considering possible weather events, time of day, and regional air traffic congestion, airlines spend more time waiting at the gate with engines switched off, which saved 48,000 tonnes of CO <sub>2</sub> each year at one major airport.
Performance-based navigation	<p>Performance-based Navigation (PBN) flight procedures use GPS and satellite technology for navigating aircraft using enhanced trajectories, improves airspace capacity, safety and environmental performance. This provides additional flexibility in the design of flight paths over the use of traditional ground based navigational aids. Using advanced navigational equipage, aircraft arrivals occur in pre-determined arcs that allow for more predictable approaches from both tricky terrain and airspace congestion. This not only reduces noise, but can also save a tonne of CO<sub>2</sub> per landing. PBN technologies offer a significant opportunity to design more efficient flight paths to reduce fuel burn and even reduce community noise.</p> <p>Being introduced today. Many ANSPs are implementing these procedures as part of airspace modernisation projects. ICAO has required all States to develop a national PBN implementation plan setting out timelines and targets. Those plans were updated in 2018. ANSPs continue to advance those plans in the modernisation of their airspace and to apply new standards as they become available. EU regulatory provisions establish a gradual migration to a full PBN environment with satellites as the main positioning source for PBN by 2030.</p>

Measure	Explanation, how it reduces CO <sub>2</sub>
Required navigation performance (RNP)	<p>Required navigation performance (RNP) is a navigation specification PBN which permits the operation of aircraft along a precise flight path with a high level of accuracy and integrity. RNP offers safety benefits by means of its precision and accuracy and facilitates more efficient continuous descent approaches by aircraft. A study undertaken by GE Aviation calculated the impact of standardised RNP approaches at just 46 regional airports in the USA and found that it would save 39,000 tonnes of fuel and 124,556 tonnes of CO<sub>2</sub> per annum.</p> <p>Many ANSPs are progressively implementing RNP as part of airspace modernisation efforts and airlines are increasingly equipping their aircraft and training pilots. New navigation separation standards such as “Established on RNP” provide additional opportunity to further enhance the utilisation of these procedures without a decrease in airport efficiency.</p>
Space-based navigation	<p>Air traffic controllers use surveillance technologies like radar and ADS-B to track and control flights. Ground-based surveillance technologies are limited to line-of-sight and are not available in all areas (particularly over water and in very remote regions). Newly available space-based surveillance technology provides full global tracking of appropriately equipped aircraft and enables air traffic controllers to safely reduce separation requirements in non radar-controlled airspace, improving the capacity of the airspace and enabling more fuel efficient routings.</p> <p>Available as of early 2019, space-based ADS-B surveillance is being adopted by many agencies to provide surveillance data in airspace where they do not have coverage with conventional radar or ground based ADS-B. In 2021 this technology was used to support a trial removing the Organized Track System (OTS) in the airspace over the North Atlantic and enabling aircraft to flight plan to take better advantage of winds.</p>
Continuous descent / climb	<p>Continuous climb and descent operations (CCOs and CDOs) are aircraft operating techniques enabled by airspace design, instrument procedure design and facilitated by air traffic control. Studies suggest that the benefits of improving CDO in particular may be significant (&gt;40 kgs of fuel per flight). CCO and CDO allow aircraft to follow a flexible, optimum flight path that delivers major environmental and economic benefits - reduced fuel burn, emissions, noise and fuel costs. ANSPs have been implementing and improving these operations for a number of years. RNP technologies are further improving opportunities for CCO and CDO. There are still limitations with the application of CCO/CDO at busy airports and during busy periods due to the need for tactical intervention by air traffic controllers to safely manage arrival and departure flows.</p>
Expansion of ‘perfect flight’ partnerships	<p>So-called ‘perfect flights’ are single, optimised, commercial flights used to set an optimum standard for efficiency of a flight. It can be an effective tool to demonstrate optimisation opportunities (over several flight phases): fuel consumption, operating cost, CO<sub>2</sub> and other gaseous emissions and noise. The programme can also provide a catalyst for airlines and wider industry stakeholders to demonstrate feasibility of achieving CO<sub>2</sub> emission reductions. The collaborative exercise involves: airline, aircraft manufacturer, departure and destination airports and service providers, en-route and terminal area ATM providers and government aviation authorities. The techniques and lessons learnt while undertaking perfect flights can be brought into every day operations in order to improve system-wide performance.</p>



Measure	Explanation, how it reduces CO <sub>2</sub>
4D Trajectory-based Operations (TBO)	<p>The implementation of 4D trajectory management is being researched by SESAR in the EU, NextGen in the USA, NLR in the Netherlands, IATA and others. The 4D trajectory concept is based on the integration of a time element into the 3D aircraft trajectory. It aims to ensure flight on an unrestricted, optimum trajectory for as long as possible in exchange for the aircraft obligation to meet accurate arrival times over designated points. The concept is still in development with some initial trials underway. The ICAO Global Air Navigation Plan forecasts use by 2030, and implementation is dependent on next generation air traffic management and aircraft automation systems.</p>
Flexible tracks / free-route airspace	<p>Taking advantage of improved navigational capabilities such as RNP, ANSPs are able to provide and accept requests for flexible routes allowing flight crews to react to changing weather patterns and fly more efficient direct routes. The systems will analyse current weather conditions and a flight's trajectory to re-route flights along a more efficient path, subject to approval from flight crew and air traffic control. Up to 500,000 tonnes of CO<sub>2</sub> a year could be saved when fully implemented over Europe alone.</p> <p>Dynamic airborne reroute procedures are currently available to be applied to user preferred routes over the North and South Pacific region. Mandatory requirements for flexible routing (including aircraft equipment capabilities), as well as pilot/dispatcher and pilot/air traffic controller workload need to be taken into account when implementing these measures.</p>
Flexible use of military airspace	<p>Large blocks of airspace are controlled by military and are often unavailable for civil operations requiring civil aircraft to be routed around this airspace. A number of States have successfully implemented flexible use of this airspace — handing it over to civil air traffic management when not in use by military and allowing much more direct routing of aircraft. Such initiatives could reduce emissions significantly in a number of States: in just one example, the opening of a single piece of airspace allowed every flight to save 6 minutes of flight time and 5,000 tonnes of CO<sub>2</sub><sup>91</sup>. In order for implementation, good civil / military cooperation is required. Political sensitivity surrounding the confidentiality of military exercises and military restricted areas can require complex negotiations.</p>
Formation flight	<p>There are benefits to the wake of a leading aircraft to provide efficiency improvements on following aircraft. Airbus has a project called fello'fly which looks at how software can make this a reality. Flight tests demonstrated that significant fuel savings could be achieved when two aircraft fly approximately 3 kilometres apart, without compromising passenger comfort. If the fuel-reduction technology proves viable, the aviation industry will benefit from a collaborative activity that demonstrates a clear commitment between manufacturers, airlines, air navigation service providers, regulators and authorities to reduce fuel consumption and CO<sub>2</sub> emissions. This collaborative activity could make a significant impact on aircraft's environmental performance: fuel savings are expected to reach 5-10% per trip.</p>

In addition, there are a number of large programmes being implemented across wide areas of airspace which can also bring efficiencies:

#### Single European Sky

The Single European Sky initiative aims to increase the efficiency of air traffic management and air navigation services by reducing the fragmentation of European airspace. By its nature, this ongoing initiative is pan-European and open to neighbouring countries. Its purpose is to modernise Europe's airspace structure and air traffic management technologies so as to ensure forecast growth in air traffic can be met, safely and sustainably, whilst reducing costs and improving environmental performance. Many of the benefits of SES are being delivered through technological, safety, and operational improvements. It aims to create a more integrated and digital European airspace for sustained traffic growth. The delivery of seamless air traffic services is built on optimised airspace organisation, supported by progressively higher levels of automation, common ATM data services and an improved role of the Eurocontrol Network Manager to optimise the ATM network.

#### SESAR (Europe)

The Single European Sky Air Traffic Management Research, SESAR, is the European Union's air traffic management modernisation programme. It combines technological, economic and regulatory aspects and will use the Single European Sky legislation to synchronise the plans and actions of the different stakeholders and bring together resources for the development and implementation of the required improvements throughout Europe, in both airborne and ground systems.

#### NextGen (United States)

NextGen is a wide-ranging transformation of the entire US air traffic management system. It involves replacing ground-based technologies with new and more dynamic satellite-based technology and implementing advanced ATM technologies and capabilities. It is a collaborative effort between the Federal Aviation Administration and partners from the airports, airlines, manufacturers, government agencies, state, local and foreign governments, universities and associations.

## Interdependencies affecting the potential for operational and infrastructure improvements

The W2050 operations and infrastructure scenarios are interdependent with several factors which can introduce inefficiencies compared with ideal flightpath conditions. These can include:

- » **Safety considerations** – aircraft will deviate from the optimal route in order to ensure adequate separation between other aircraft.
- » **Weather** – to ensure safe and smooth flight, adverse weather systems may need to be avoided.
- » **Capacity**<sup>92</sup> – to accommodate capacity limitations either at the airport or within airspace, aircraft may be required to hold prior to arrival, or wait on the ground prior to departure. When traffic demand approaches available capacity, congestion increases, reducing efficiency as discussed above. However, with measures such as airport collaborative decision making, air traffic flow management and better use of data throughout the system, sometimes these measures can be brought in earlier in each flight. For example, delaying aircraft on the ground until capacity throughout the journey is available. Or slowing down aircraft en route to avoid bunching of flights close to congested airports.
- » **Capacity** – another area of potential capacity constraints in the future is the emergence and proliferation of other airspace users, such as unmanned aerial vehicles
- » **Noise** – to reduce noise impact on the ground, aircraft operations around the airfield are subject to noise abatement procedures that may reduce noise for a certain neighbourhood but may cause the aircraft to fly an approach or departure that is a less efficient route or accept sub-optimal altitudes.
- » **Airline practices** – flight planning systems need to have the flexibility to benefit from more optimal routes that may be available.
- » **Military** – civil aircraft generally must route around military airspace zones and other types of restricted airspace increasing fuel burn. ANSPs can actively seek cooperation from the military to implement and optimise the Flexible Use of Airspace.
- » **Institutional** – aircraft may take less than optimal routes due to fragmented airspace. Different regions / countries may have different operating procedures, charging mechanisms and require specific hand-over protocols that may lead to less than optimum fuel-efficient routing. These may be resolved by political will.

## ACCELERATING OPERATIONAL AND INFRASTRUCTURE EFFICIENCY

In order to support future emissions reductions from operations and infrastructure, several recommendations and actions are proposed:

### Action items for the aviation sector

Action item	Description	Timeline	Difficulty level
Work in partnership to re-build air traffic volumes based on perfect flight principles	Air traffic management (with partners): as air traffic volumes recover following the Covid-19 shutdown, the industry should prioritise perfect flight principles to optimise flight trajectories and make operations as efficient as possible, rather than implementing these elements as an add-on to normal traffic growth.	2020-2024	●●○○○
Full implementation of fixed electric ground power	Airports: introduce fixed electrical ground power and pre-conditioned air at all remaining appropriate aircraft stands.	Possible today	●○○○○
Full implementation of fixed electric ground power	Airlines: put in place procedures for flight crews to always use fixed electrical ground power when parked at equipped stands.	Possible today	●○○○○
Work in partnership to implement assisted taxiing opportunities	Airlines / aircraft manufacturers / suppliers / airports / ground handlers / air traffic management: should investigate opportunities for assisted taxiing (electric taxiing systems, remote taxiing systems and taxiing to runway) to reduce the use of engines for ground movements. Work in partnership to ensure certification and successful deployment in operations.	2020-2025	●●●○○
Full implementation of weight-based efficiency measures	Airlines: make use of all available weight-based efficiency measures: » Tablet computers for flight deck use » Lighter cabin equipment » Lighter seating	Possible today	●●○○○
Full implementation of weight-based efficiency measures	Component suppliers: continue to invest in R&D to develop new cabin equipment which reduces weight and increases efficiency.	2020-2050	●●○○○
Acceleration of full implementation of A-CDM	Airlines / airports / ground handlers / air traffic management: ensure complete use of A-CDM to improve efficiency of airport-based operations.	2020-2030	●●●○○
Full implementation of continuous approach and departure	Air traffic management: where operationally possible, implement more efficient approach and climb-out procedures.	2020-2025	●●●○○
Investigate new approach technologies and procedures at all applicable airports	Air traffic management: performance-based navigation (PBN) and its next step required navigation performance (RNP) provide precise and efficient flightpaths into airports, particularly those in challenging environments. Investigate the opportunities for using these systems to improve the performance of flights at airports (if the investment in technology is warranted by the unique situations at the airports), whilst ensuring engagement with local communities if traditional flightpaths shift.	Possible today	●●●○○

Action item	Description	Timeline	Difficulty level
Full implementation of aerodynamic efficiency opportunities	Airlines: ensure remaining applicable fleet have winglet and other aerodynamic efficiency devices retro-fitted, where appropriate (not all aircraft are eligible, or already have devices included).	Possible today	●●○○○○
Support the implementation of trajectory-based operations	Air traffic management: the establishment of enhanced data sharing will be necessary to enable improved fuel-efficiency management through trajectory based operations (TBO). TBO will unlock harmonised gate-to-gate management of airborne and ground operations (through airport collaborative decision making and air traffic flow management), while maintaining a balance of demand and capacity through the use of new technology and artificial intelligence.	2025-2030	●●●○○○
Work with local communities on new airspace design	Airports / air traffic management: some new airspace design and technology implementation may change the traditional aircraft approach paths to airports and increase or change the impact of air traffic on some communities (whilst decreasing it on others). Whilst these are being implemented to improve climate efficiency, sometimes they lead to changed noise impacts on the residents living around the airport. Working with communities to develop metrics may help prioritise these competing objectives. Community opposition to airspace changes is a difficult road block to implementation.	Possible today	●●○○○○
Collaborate to speed up investigating, testing and certification of new efficiency measures	Whole industry: develop enhanced and faster protocols for evaluating new aviation-specific procedures or technologies. Most new systems, operational procedures or pieces of technology require extensive airworthiness safety testing before being certified for use in real world operations. The challenge of certifying this new capability cost-effectively however, requires closer up-front collaboration with OEMs, avionics suppliers, regulators and operators to seek process improvements wherever possible.	Possible today	●●○○○○
Encourage efficiency action throughout the system	Whole industry: work with employees, crews, engineers and external parties to develop concepts for new efficiency measures in each company.	Possible today	●○○○○○
Increase use of rail for connecting passengers	Airlines: investigate opportunities for increased intermodal operations with rail operators, including through-ticketing options, where opportunities exist (mainly in Europe and parts of East Asia). Airports: work with rail operators and governments to improve connections between terminals and rail stations (preferably step-free and in the same building or under cover connections)	Possible today	●●○○○○
Increase share of passengers reaching the airport by public transport	Airports: work with local authorities and transport providers for simple and seamless connections between public transport and airport facilities.	Possible today	●○○○○○

## Action items and policy proposals for governments

Action item	Description	Timeline	Difficulty level
Make military air space flexible use	Large blocks of airspace are controlled by military and are often unavailable for civil operations. A number of States have successfully implemented flexible use of this airspace — handing it over to civil air traffic management when not in use by military and allowing much more direct routing of aircraft. Could reduce emissions significantly over a number of States.	Available immediately	●●○○○
Implement the ICAO Aviation System Block Upgrades	The ICAO Global Air Navigation Plan (GANP) sets out a series of Aviation System Block Upgrades or technology modernisation projects focused on four performance improvement areas: airport operations; global interoperable systems and data; optimum capacity and flexible flights; and efficient flight paths. The initiatives reflect consensus around the series of technologies, procedures, and operational concepts needed to meet future capacity and ATM challenges. An analysis by ICAO found that if implemented Block 0 and 1 elements would deliver global fuel and CO <sub>2</sub> savings of between 1.6 — 3.0% in 2025 <sup>93</sup> . Governments must carry through implementation plans for this vital project.	Already underway, block 1 technologies are scheduled for 2019-2025	●●●○○
Develop new systems for regulators to progress on national, regional and global harmonisation of standards	Regulators need to accelerate the change process without sacrificing safety. With closer aircraft manufacturer, regulator and ANSP focused collaboration, the development of guidance material, criteria, and policies for new operational capabilities could likely be reduced from 5-10 years to 3-5 years. Having regulator participation supports the assurance that new investments will be returned in the form of cost savings, capacity enhancements, and other direct benefits.	Possible today	●●○○○
Encourage and fund comprehensive intermodal planning	Bringing together particularly rail and aviation operations for seamless mobility between transport modes. To be effective, long-haul air passengers should be able to transfer to appropriate rail connections to nearby cities with ease of access (ideally connections in the airport terminal) and on a single ticket. Rail infrastructure expansion should be seamless with airport facilities, where possible, to ensure the greatest uptake by passengers.	Possible today	●○○○○
Ensure balanced comparison of transport modes	Designing the solutions for the future sustainable mobility of citizens requires a thorough assessment of all environmental aspects for those transport modes which can be complimentary. There is a need to avoid policy decisions made by only looking at one environmental aspect.	Possible today	●●○○○

## Action items and areas for research institutions

Action item	Description	Timeline	Difficulty level
Focus on operational procedure improvements for aviation system	There could be a range of further improvements to airspace utilisation and aircraft ground movements which could be the focus of continuing research efforts: improved efficiency with ATC spacing tools is one example.	From today	●○○○○

## Action items for the energy industry

Action item	Description	Timeline	Difficulty level
Work in partnership with airports to ensure low carbon energy supply	Need to adapt airports and infrastructure for new aircraft designs and new energy requirements (low carbon electricity and/or hydrogen). When the technology is further developed, aircraft manufacturers would have to work closely with airports and other stakeholders to advance the required changes.	From today	● ○ ○ ○ ○ ○

## Action items for other stakeholders

Action item	Description	Timeline	Difficulty level
Community and aviation system engagement	Communities in the vicinity of airports are sensitive to noise and emissions from operations at any nearby airports. Their cooperation is essential to enabling growth and enabling new operations at the airport. Local communities need to find representatives that can express community concerns while also appreciating the economic role played by the airport and the aviation industry and recognise the industry goal for reducing CO <sub>2</sub> and noise.	Possible today	● ● ● ○ ○ ○



# DEPLOYING SUSTAINABLE AVIATION FUEL

**SINCE JET AIRCRAFT FIRST STARTED FLYING IN THE 1950s, COMMERCIAL AVIATION HAS RELIED ON NEARLY A SINGLE SOURCE OF ENERGY. THIS CHANGED IN JANUARY 2008, WHEN A COMMERCIAL AIRCRAFT WAS OPERATED ON AN ALTERNATIVE FUEL FOR THE FIRST TIME. BY 2011, FOLLOWING YEARS OF SAFETY TESTS AND MUCH CAREFUL SCRUTINY, AIRLINES WERE APPROVED TO FLY PASSENGERS ON A NEW SUSTAINABLE AVIATION FUEL (SAF).**

By 2015, the first regular supply of SAF was being delivered to airports and since then a number of new production facilities have been in development or construction. Despite this progress, it is estimated that by 2025, with a rapid and significant policy push only around 2% of total jet fuel use will be with sustainable aviation fuels<sup>94</sup>. To begin the energy transition towards a complete replacement of fossil fuel with alternative sources in aviation, an acceleration is needed to ensure that the 2% is achieved and rapidly scaled-up.

Whilst the technology exists today and over 365,000 commercial flights have been operated on SAF since certification was granted in 2011, the ability for SAF to contribute to the industry's decarbonisation roadmap is dependent on both the production scale-up of existing certified pathways that now needs to take place and also on new forms of feedstock being developed. There is no question the industry can entirely meet its energy needs in 2050 from a range of renewable sources, but the core challenge is how to completely transition an industry in under 30 years - both economically and practically.

## What is sustainable aviation fuel?

Sustainable aviation fuel, a term that generally refers to non-fossil derived aviation fuel, will play a key role in aviation's ability to meet the 2050 carbon goal. Sustainable aviation fuel is characterised by three key elements:

- » Sustainable – Sustainability in this context is defined as something that can be continually and repeatedly resourced in a manner consistent with economic, social and environmental aims, and conserves an ecological balance by avoiding depletion of natural resources.
- » Alternate feedstock to crude oil – It is a fuel for aviation with an alternative feedstock to crude oil. In this case non-conventional or advanced fuels and includes

any materials or substances that can be used as fuels, other than conventional, fossil-sources (such as oil, coal, and natural gas). It is also processed to jet fuel in an alternative manner. Feedstocks for SAF are varied; ranging from cooking oil, plant oils, municipal waste, waste gases, and agricultural residues – to name a few.

- » Fuel – Fuel means jet fuel that meets the technical and certification requirements for use in commercial aircraft.

Sustainable aviation fuels are certified like any other jet fuel before they can be used for regular service. They can be safely mixed with the latter to varying degrees, use the same supply infrastructure and do not require the adaptation of aircraft or engines. Fuels with these properties are called “drop-in fuels” (i.e., fuels that can be automatically incorporated into existing airport fuelling systems).

Moreover, to validly use the term ‘sustainable’ they must meet sustainability criteria such as lifecycle carbon emissions reductions, limited fresh water requirements, no competition with needed food production and no deforestation.

Sustainability criteria are defined at international level through ICAO, by bodies such as the Roundtable for Sustainable Biomaterials, or regionally and locally through schemes such as the European Union's RED II and California's LCFS.

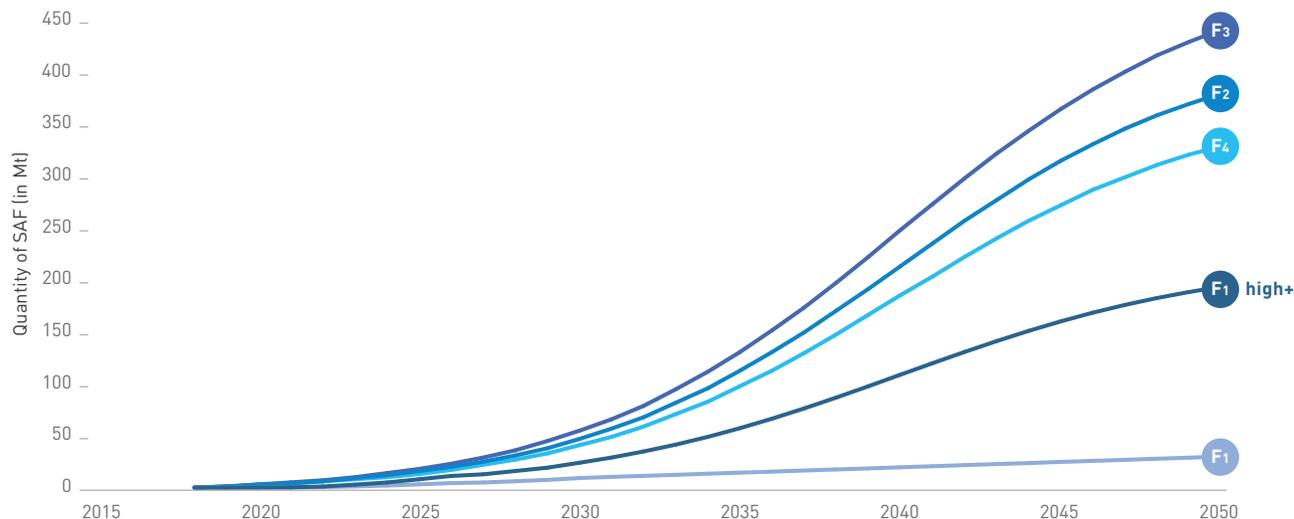
## Developing scenarios

A set of scenarios were generated based on two methods. The first took the current expected supply ramp-up trajectory and plotted this out to 2050. The second used a ‘backcast’ analysis from each of the consolidated scenarios to determine the magnitude of the SAF needed to ‘close the gap’ with the goal.

Scenario	Description	SAF volumes (To meet net-zero in 2050 [90% fuel replaced at 100% ERF])	Emissions reduction factor average (2050)	CO <sub>2</sub> reduction	% of fuel supply	Production facilities (2020-2050)	Investment cost (2020-2050)
2020 situation	Nascent industry starting to ramp up new energy source.	0.05 Mt (0.063 bn litres)	~70% <sup>95</sup>	0.11 Mt CO <sub>2</sub>	0.03%		
2025 forecast	Series of new production facilities come on stream in the 2020-2025 timeframe, beginning of scale-up process	3-8 Mt (3.8-10 bn litres)	80% <sup>96</sup>	8-20 Mt CO <sub>2</sub>	~2%		
<b>F<sub>1</sub></b> Current trends — baseline	A continuation of the current growth of SAF development, extrapolated to 2050. A low scenario represents a linear continuation of average rates of SAF deployment and a high scenario includes an s-curve extrapolation, based off current levels of ramp-up.	30-195 Mt (40-240 bn litres)	100%	95-615 Mt CO <sub>2</sub>	6-39% of fuel use in 2050 (depending on fuel volume scenario)		
<b>F<sub>2</sub></b> Pushing technology and SAF	A backcast which would see a ramp-up of SAF production	380 Mt (475 bn litres)	100%	1,200 Mt CO <sub>2</sub>	90% of fuel use in 2050	5,904	\$1.25 trillion
<b>F<sub>3</sub></b> Aggressive SAF	A backcast which prioritises SAF deployment over spending on technology	445 Mt (550 bn litres)	100%	1,400 Mt CO <sub>2</sub>	90% of fuel use in 2050	7,026	\$1.45 trillion
<b>F<sub>4</sub></b> Aspirational technology-driven	A backcast which fills in the gap following significant radical technology deployment	330 Mt (410 bn litres)	100%	1,040 Mt CO <sub>2</sub>	90% of fuel use in 2050	4,964	\$1.1 trillion

### Sustainable aviation fuel ramp-up long-term

Simple analysis of ramp-up required for several scenarios and expected volumes of SAF required in 2050, assuming a 100% emissions reduction factor in 2050.



## Current status

Since 2011, when SAF was approved for use in commercial flight, there has been a slow but steady increase in the production of SAF. In 2015, the first regular supply of SAF started being delivered to airports. Given the timeline for

financing, offtake agreement negotiations, building consents and construction, the next few years are likely to see a raft of new production facilities come on stream. But despite this ramp-up in supply, it will need to be doubled for the industry to reach 2% of jet fuel use in 2025.

## SAF in the next years<sup>97</sup>

Current production will follow the F1 trajectory, but the expected policy environment in the next 2-4 years will shift towards the F1 high trajectory at a global level. The F1 high+ trajectory is very feasible, but extra policy initiatives are needed to reach that point: recent announcements suggest this could be a possibility towards the 2030 timeframe. Practicalities of financing, construction and production timelines around the world mean getting above F1 high+ is unlikely before 2030.

Year		2020	2021E	2022F	2023F	2024F	2025F	2026F	2027F	2028F	2029F	2030F
F1	000 tonnes	50.4	80	376	1,092	1,877	3,071	4,299	4,914	6,142	7,370	9,213
	m litres	63	100	470	1,365	2,346	3,839	5,374	6,142	7,677	9,212	11,516
	% of fuel	0.03%	0.04%	0.15%	0.4%	0.6%	1%	1.3%	1.5%	1.8%	2.1%	2.5%
F1 high	000 tonnes	50.4	95	562	1,632	2,806	4,591	6,427	7,346	9,182	11,018	13,773
	m litres	63	119	703	2,040	3,507	5,739	8,034	9,182	11,477	13,773	17,216
	% of fuel	0.03%	0.05%	0.22%	0.6%	0.9%	1.5%	2.0%	2.2%	2.6%	3.1%	3.7%
F1 high+	000 tonnes		166	978	2,838	4,879	7,984	11,178	12,774	15,968	19,162	23,952
	m litres		208	1,222	3,548	6,099	9,980	13,972	15,968	19,960	23,952	29,940
	% of fuel		0.09%	0.4%	1%	1.6%	2.6%	3.5%	3.8%	4.6%	5.3%	6.5%
<b>Production facilities</b> (expected date to start producing)		Fulcrum (US)	World Energy (US exp)	SkyNRG (NL)	Velocys (UK)	At least 30 additional facilities (or expansions) anticipated in the 2025-2030 timeframe						
			LanzaTech (Nth Asia / EU)	Red Rock (US)	Eni (IT)							
				UPM (US)	Gevo (US)							
				Neste (SG exp)	ECB (PY)							
				Marathon (US)	Total (FR)							
				Repsol (CO)	Preem (SE)							
				ST1 (SE)	Phillips 66 (US)							

## How switching to SAF reduces emissions

There are different approaches to measuring lifecycle reductions of CO<sub>2</sub> emissions in SAF, but all come from the basic premise of either using a fuel based on feedstocks that draw in CO<sub>2</sub> as they are produced, recycling CO<sub>2</sub> emissions from waste sources or CO<sub>2</sub> captured directly from the air. The CO<sub>2</sub> emissions from the burning of the fuel in an aircraft engine are not fundamentally different to fossil fuels, but the production of the feedstock takes CO<sub>2</sub> out of the atmosphere, creating a 'loop'. In addition, the use of SAF has sometimes shown to have a small improvement in fuel performance (the slightly higher energy density of SAF had resulted in a smaller fuel burn), as well as benefits in reducing particulate matter emissions, leading to greater air quality performance and possibly even lower contrail formation.

Lifecycle emissions reductions are not generally 100% by themselves, given the energy needs to process the raw feedstock into sustainable aviation fuel and transport it to the airport. However, if the production facilities are run on renewable energy and transport is through pipelines or using alternative

energy vehicles, the emissions reduction factor can be improved significantly: even beyond 100% with the addition of carbon capture and storage (CCS) of CO<sub>2</sub> or methane from the production processes.

The CO<sub>2</sub> reductions possible through a shift to SAF can be accounted for two ways: by the volumes of SAF deployed (the percentage of SAF blended with traditional fuel across the system); and the emissions reduction factor (the lifecycle reduction in CO<sub>2</sub> emissions when compared with fossil jet fuel). For example, one could replace 100% of the fuel needed with SAF that has an emissions reduction factor (ERF) of 10% and you would have a 10% saving in CO<sub>2</sub>. Or replacing 10% of the fuel with SAF that has a 100% ERF has the same result. This 'trade space' can be altered over time to give an idea of the volumes of SAF required or the lifecycle CO<sub>2</sub> emissions requirements to meet the same overall CO<sub>2</sub> emissions reductions.

Today's best performing SAF sources have around a 90% ERF, although others are less: the average ERF is likely around 70% today. Over time, the emissions reduction factors will likely improve and some feedstocks in experimental conditions are

even displaying a greater than 100% ERF. These are particularly rotational crops that help sequester CO<sub>2</sub> in the soil as they grow. Additionally, as technologies such as CCS mature, the small production inefficiencies of SAF can be further reduced, improving the ERF. Even today, some production processes with CCS additions are showing emissions reductions of over 150% and even 200%<sup>98</sup>.

*For the purposes of the Waypoint 2050 analysis, it was decided to limit the ERF in 2050 to 100% reduction in CO<sub>2</sub>, despite the probability that it could be higher at that point. This was to maintain a conservative outlook and not rely too heavily on CCS, but leave room for further improvement.*

## Availability of feedstock

One of the key questions about the use of SAF at scale is whether there is enough source material to generate the required quantities, given the growth in the industry's demand for fuel. Several independent assessments<sup>99</sup> have found that, yes, there is enough feedstock from sustainable sources to more than meet the needs of the industry in 2050 and beyond.

Outlined in the table over the next pages, including detailed work carried out in 2021 for Waypoint 2050<sup>107</sup>, the central case for a range of different sources (with appropriate sustainability filters added) shows that around 200 Mt of SAF annually could be produced through 'traditional' SAF pathways alone. Power-to-liquid (PtL), has an unlimited potential, although comes with challenges to scaling up. The highest need for SAF in the Waypoint 2050 scenarios (outlined in Scenario 2: aggressive SAF deployment) is around 445Mt of SAF in 2050.

## SAF availability from various feedstocks, Mt<sup>107</sup>

Change from 2020 to 2050 is because the assumed product slate is increasingly optimised for SAF as road markets electrify. Only industrial waste gases reduce as the steel industry decarbonises. Central case.

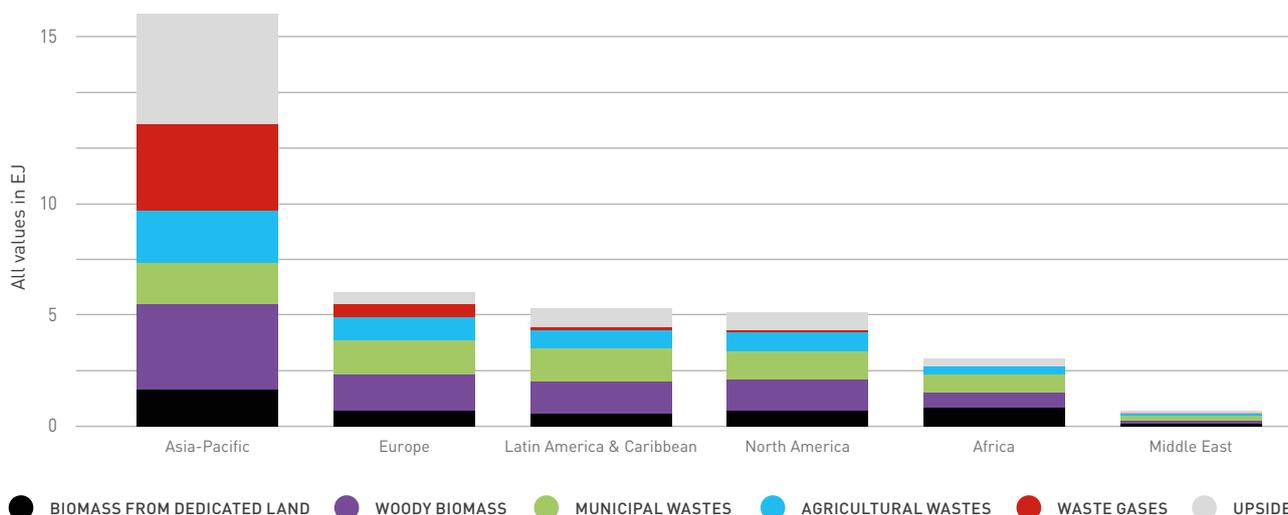
SAF Availability (Mt)	2020	2050
Waste and residue lipids	11.6	13.9
Oil crops and trees	13.4	16.1
Cellulosic cover crops	24.8	27.4
Agricultural residues	52.5	57.9
Woody biomass	51.7	51.7
Municipal solid waste	22.0	22.0
Industrial waste gases	28.6	9.5
<b>Total</b>	<b>205</b>	<b>198</b>

## Sources of SAF

One important aspect of the search for alternative sources of fuel for aviation has been the need to take a 'portfolio' approach to the development of the sector. There is no one single solution, but opportunities exist across different types of feedstock and can be tailored to locally appropriate feedstocks. Some parts of the world may have large amounts of agricultural waste. Others might have municipal waste landfill problems. The next pages outline several potential SAF feedstock assessments.

## Feedstock availability by region exajoules (EJ)<sup>107</sup>

SAF feedstock availability is not uniform across the world. Some regions have a higher availability of land for (non-food) crop-based feedstocks, others have large volumes of household waste or the conditions for renewable electricity supply. Asia-Pacific shows the highest potential for feedstock out of all regions, as well as the most air traffic growth over the coming decades.



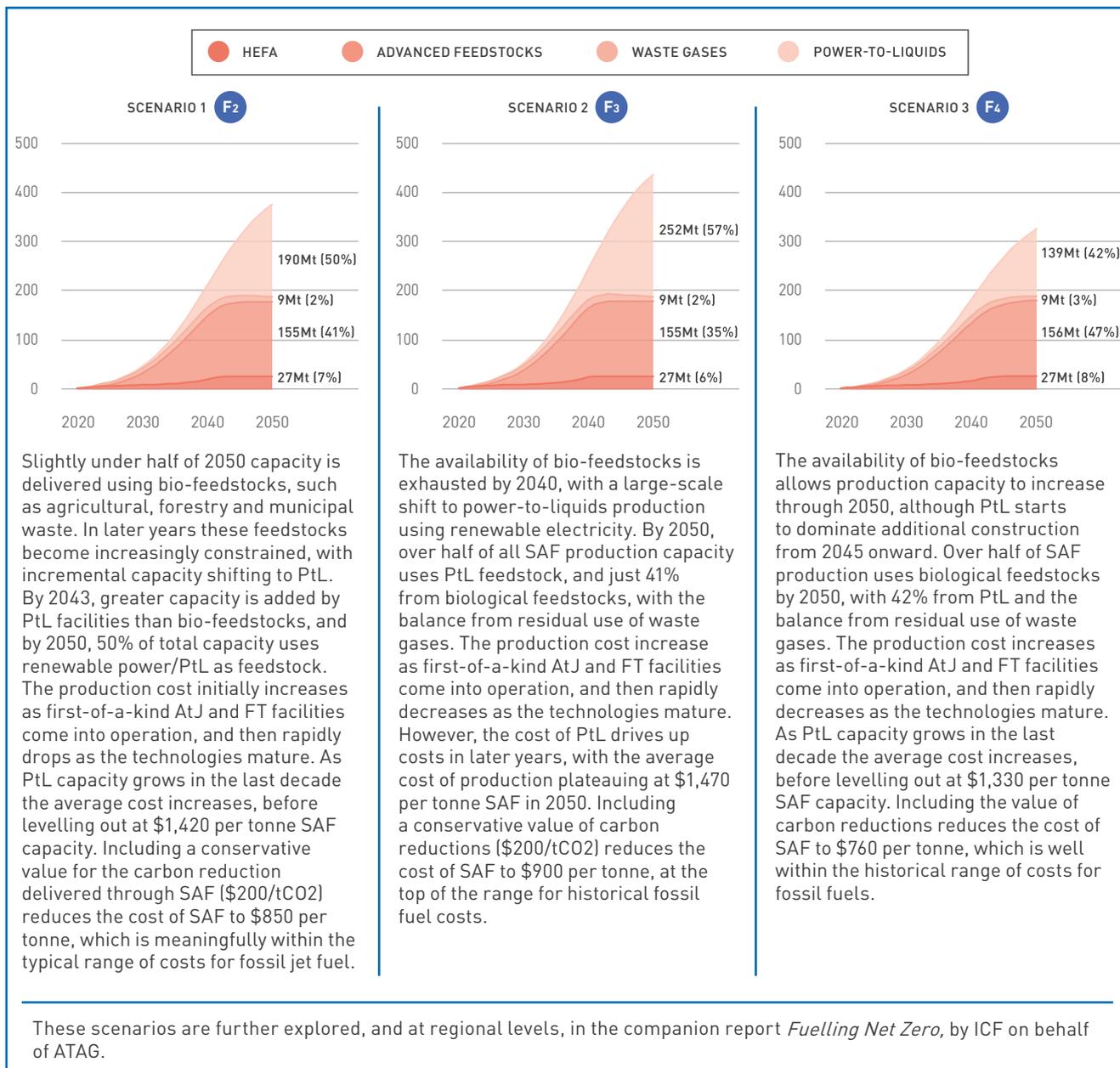
	State of development	Global SAF potential per year by 2050	Opportunities and challenges
<p><b>Municipal solid waste (MSW)</b></p> <p>Following sorting to remove any recyclable components, typical organic MSW can be processed into SAF.</p>	Substantial quantities of MSW exist globally which are not used for energy production and nearly all end up in landfills. A number of MSW feedstock plants are under construction, with the first major facility close to completion.	22 Mt	MSW opportunities are heavily influenced by whether a waste disposal fee exists for depositing MSW into a landfill site. A significant opportunity appears to be imposing MSW disposal costs in countries (often developing) that don't have this.
<p><b>Woody biomass</b></p>	Opportunities are substantial but tend to be linked to specific regions (such as the Nordics) that have an existing timber or paper industry.	52 Mt	There is a limit to how much forestry residue can be collected based on existing paper or forestry industry economics of collection of material and distance from collection points.
<p><b>Agricultural waste residues</b></p> <p>The cellulosic waste left over from agricultural production, for example the stalks and stems of sugarcane.</p>	Agricultural residues represent a significant feedstock opportunity, including in developing nations where they are often burned (creating dangerous air quality issues), but still need to be demonstrated economically at scale.	58 Mt	Challenges are the economic aggregation of residues, or ensuring that residues do not go to other markets, such as feed.
<p><b>Waste oils and lipids</b></p>	Used cooking oil and tallow are reasonably simple feedstocks, being used in continuous production today.	14 Mt	The major limiting challenge is the supply of used cooking oil and tallow. Aggregation and collection of used cooking oil is efficient. Tallow collection less of an issue as it is concentrated in major meat processing plants, however the potential supply will be limited to match that of meat production.
<p><b>Industrial off gases</b></p> <p>Recycling the off gases from steel and other industrial production processes into SAF.</p>	Carbon monoxide (industrial off gas) is used to produce ethanol, which can be converted into SAF. While the technology is proven, economics result in mostly ethanol being produced at present.	9.5 Mt	Significant quantities of industrial off gases exist, globally, but especially in countries like China and India that have large steel industries — there is very real potential for scale up of this production pathway.

	State of development	Global SAF potential per year by 2050	Opportunities and challenges
<p>Oil crops:</p> <p><b>Carinata</b></p> <p>Carinata is an oil seed grass that is grown in marginal conditions and can be used as a rotational cover crop in winter.</p>	<p>Carinata appears to be well suited to parts of South America, Australia, and Europe as a rotation crop. It has been used as a HEFA feedstock to power flights already.</p>	16 Mt	<p>An improvement in life cycle potential is possible, as significant biomass is returned to the soil, potentially allowing for emissions reduction factors greater than 100%. Carinata is well suited to arid land, however the challenge can be the economics of low-density production.</p>
<p>Oil crops:</p> <p><b>Camelina</b></p> <p>Mostly produced in Europe and Asia, Camelina is a short-season crop that takes 85-100 days to mature and requires ~10 inches of rain to produce a crop, which can be grown in a wide variety of soil types and conditions.</p>	<p>Camelina has been used to produce SAF and was a key focus of the European FlightPath project.</p>		<p>Well suited to non-productive land, which improves sustainability credentials, but adds an economic challenge for cultivation.</p>
<p>Oil crops:</p> <p><b>Jatropha</b></p> <p>Oil crop which grows reasonably well in dry areas on degraded soils that are marginally suited for agriculture, producing countries include Indonesia, Ghana, Madagascar and Brazil.</p>	<p>Trials have taken place in parts of Europe</p>		<p>Well suited to non-productive land, which improves sustainability credentials, but adds an economic challenge for cultivation.</p>
<p>Oil crops:</p> <p>The above is a small selection of the many non-food oil crops that could be explored, with research ongoing into crops such as Pennycress, Macaruba, Agave and Pongamia. The Solaris project in South Africa has been exploring the use of a no nicotine tobacco plant to create sustainable aviation fuel with a 70% emissions reduction factor whilst creating opportunities for traditional tobacco farmers to diversify.</p>			
<p>Oil 'crop':</p> <p><b>Algae</b></p>	<p>Micro- and macro-algae has been extensively studied and has great potential, although this feedstock is yet to be developed into commercial-scale facilities. Of particular interest is the ability to grow large amounts of algae with a limited footprint.</p>		<p>More progress needs to be made in the energy consumption of algae cultivation and drying before this becomes a commercially viable source.</p>
<p>Oil 'crop':</p> <p><b>Halophytes</b></p> <p>A salt-tolerant plant that grows in soil or waters of high salinity, such as in saline semi-deserts, mangrove swamps, marshes and sloughs and seashores.</p>	<p>Has been proven in test flights to work in aviation at a small scale with a clear opportunity being the lack of requirement for fresh water, implying significant opportunity to use desert land in places like the Middle East.</p>		<p>A limitation will be the potential to scale up into very large production. Could remain a niche supplier.</p>

	State of development	Global SAF potential per year by 2050	Opportunities and challenges
<p>Cellulosic crops: <b>Miscanthus</b></p> <p>High yielding energy crop that grows over 3 metres tall, resembles bamboo and produces a crop every year without the need for replanting. Flourishes in subtropical and tropical regions of Africa and southern Asia, grows throughout most of China, Japan and Korea, also common in US.</p>	<p>Potentially a big opportunity, with yields potential of 500 kgs of SAF per hectare of crop but has not been progressed outside of academic modelling.</p>	27 Mt	<ul style="list-style-type: none"> <li>» Requires further analysis and real-world trials</li> <li>» Could develop growing programmes in ideal terrains as pilot projects</li> <li>» Opportunity to improve the collection and distribution of this feedstock</li> </ul>
<p>Cellulosic crops: <b>Switchgrass</b></p> <p>Native to the United States and suitable energy crop because of its perennial growth habit, high yield potential on a wide variety of soil conditions and types, compatibility with conventional farming practices, and value in improving soil and water conservation and quality.</p>	<p>Has mainly been a theoretical opportunity so far, but with yield potential of 800kg of SAF per hectare.</p>		<ul style="list-style-type: none"> <li>» Requires further analysis and real-world trials</li> <li>» Could develop growing programmes in ideal terrains as pilot projects</li> <li>» Opportunity to improve the collection and distribution of this feedstock</li> </ul>
<p>Cellulosic crops: <b>Reed Canarygrass</b></p> <p>Perennial wetland grass, native to parts of the US, Europe, and Asia. It is a cool-season grass that is less productive than warm-season grasses.</p>	<p>Potential SAF yield of 400kg per hectare of crop grown.</p>		<ul style="list-style-type: none"> <li>» Requires further analysis and real-world trials</li> <li>» Could develop growing programmes in ideal terrains as pilot projects</li> <li>» Opportunity to improve the collection and distribution of this feedstock</li> </ul>
<p>Cellulosic crops: The above is a small selection of the many non-food cellulosic crops that could be explored, with research ongoing into a range of other crops.</p>			
<p><b>Power-to-liquid</b></p> <p>Using renewable electricity to convert CO<sub>2</sub> (either captured from industrial processes or direct from the air) into SAF. Could be deployed anywhere in the world. Initially likely to be near existing industrial facilities or close to sources of renewable energy.</p>	<p>Early stages of development with lab-scale tests showing the technology works but needs to be further developed. Some parts of the technology process (i.e. Fischer-Tropsch processing) are very mature and in common use.</p>	<p>Potentially unlimited supply Expected ERF: 95%</p>	<p>Significant potential for scale-up and production of nearly 100% emissions reduction when compared to fossil jet fuel. Three major challenges: the maturity of the technology; the availability of hydrogen in sufficient quantities; and most significantly the need for large quantities of low carbon electricity.</p>

## Sources of sustainable aviation fuel, global 2020-2050<sup>107</sup>

Production capacity by feedstock, Mt per year



Slightly under half of 2050 capacity is delivered using bio-feedstocks, such as agricultural, forestry and municipal waste. In later years these feedstocks become increasingly constrained, with incremental capacity shifting to PtL. By 2043, greater capacity is added by PtL facilities than bio-feedstocks, and by 2050, 50% of total capacity uses renewable power/PtL as feedstock. The production cost initially increases as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly drops as the technologies mature. As PtL capacity grows in the last decade the average cost increases, before levelling out at \$1,420 per tonne SAF capacity. Including a conservative value for the carbon reduction delivered through SAF (\$200/tCO<sub>2</sub>) reduces the cost of SAF to \$850 per tonne, which is meaningfully within the typical range of costs for fossil jet fuel.

The availability of bio-feedstocks is exhausted by 2040, with a large-scale shift to power-to-liquids production using renewable electricity. By 2050, over half of all SAF production capacity uses PtL feedstock, and just 41% from biological feedstocks, with the balance from residual use of waste gases. The production cost increase as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly decreases as the technologies mature. However, the cost of PtL drives up costs in later years, with the average cost of production plateauing at \$1,470 per tonne SAF in 2050. Including a conservative value of carbon reductions (\$200/tCO<sub>2</sub>) reduces the cost of SAF to \$900 per tonne, at the top of the range for historical fossil fuel costs.

The availability of bio-feedstocks allows production capacity to increase through 2050, although PtL starts to dominate additional construction from 2045 onward. Over half of SAF production uses biological feedstocks by 2050, with 42% from PtL and the balance from residual use of waste gases. The production cost increases as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly decreases as the technologies mature. As PtL capacity grows in the last decade the average cost increases, before levelling out at \$1,330 per tonne SAF capacity. Including the value of carbon reductions reduces the cost of SAF to \$760 per tonne, which is well within the historical range of costs for fossil fuels.

## Rotational cover crops

A number of options exist for use of so-called rotational cover crops. These crops can be grown in fields normally planted with food crops, but during winter or in years when fields are normally left fallow. This ensures that arable land can continue to grow food and actually benefits the soil – leading to increased yields in the seasons where food crops are grown. These rotational crops help to restore nitrogen in the soils, can sequester carbon dioxide, improve water absorption and reduce erosion and runoff, amongst other benefits.

## What was excluded from the analysis?

The analysis on pages 76-78, undertaken by ICF using data from the Energy Transitions Commission<sup>108</sup>, takes a very conservative approach to assessing the likely availability of feedstocks and the demand from sectors other than aviation. It does not, for example, make use of significant quantities of arable land, reserving them for production of food and limits the expectations from early-stage technologies such as algae.

This analysis considers three key constraints, covering sustainability, fairness, and economic limitations. The sustainability constraint reflects the environmental and social limitations on the feedstock availability, such as the constraints on land that can sustainably be used for energy crop growth, or the fraction of agricultural residues that must be left on the land to maintain the soil quality. The fairness constraint reflects the balance of feedstocks that can be used for SAF production, compared to use by other sectors. Many of these feedstocks are used today for heating, animal bedding or feed, soaps, lubricants, and as raw material for oleochemicals industry. As other industries also decarbonise, there will likely be increasing demand for feedstocks to produce heat and energy, and for material uses such as bioplastics. Aviation is a fraction of global emissions and the decarbonisation of aviation must be matched by decarbonisation across all sectors, so the demand from other sectors must be considered. The final constraint is the volume of feedstock that can be economically used to produce fuels and enable flights at economically sustainable socially acceptable prices.

### Choices, use by other sectors

The ability for aviation to complete an energy transition to sustainable aviation fuels relies on a number of factors: the cost of the fuel to airlines is a key consideration, as is the logistical ability for the energy system to make the transition in 30 years. Key to this is the enabling environment: the access for new energy suppliers to capital markets for the construction of production facilities; and policy choices by governments to ensure that aviation is seen as a priority for the use of these feed sources.

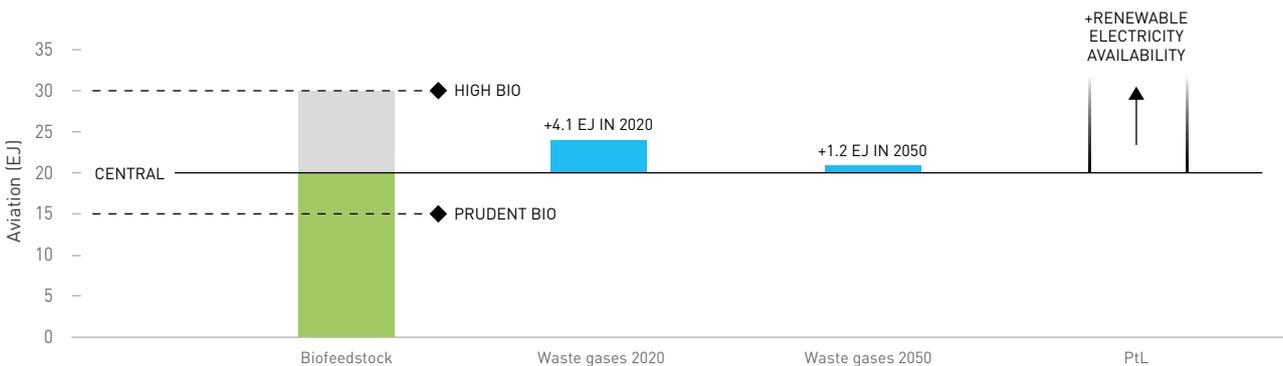
Analysis by the Energy Transitions Commission<sup>109</sup>, International Energy Agency<sup>110</sup> and World Economic Forum<sup>111</sup> has shown that between 30 and 110 EJ of bio-feedstock is available per year, with higher levels of availability if technological or societal changes (such as reduced meat consumption) create new opportunities for land use. However, there are other potential users for these feedstocks other than aviation.

Aviation is rightly seen as a 'hard to abate' sector, one of the few parts of the economy which does not have readily accessible low carbon energy options (alongside shipping, heavy duty land transport, steel, plastic and cement production). All other transport has the ability to transfer to electricity or has the ability to turn to alternative energy carriers such as LNG, methanol, DME or hydrogen. Whilst both electricity and hydrogen could be excellent options for short-haul air transport by 2035-2040, long-haul aviation will rely on liquid fuel for many decades and should be seen as a priority user of the feedstock and production potential.

The choice lies with governments to set the right policy framework for the use of these sources. Given those choices, for the Waypoint 2050 analysis, a conservative 20 EJ of biomass was made available to aviation (with the rest going to other industrial sectors). This forms the basis for assumptions across each of the scenarios, being augmented by waste gases and PtL pathways. Detailed modelling across 48 different feedstock / production processes / regional availability generated the model which was used to identify the most suitable opportunities at the right cost and emissions reduction.

### Bio-feedstocks provide around 20EJ per year<sup>112</sup>

Additional energy from waste gases and low-carbon electricity (PtL) being used to fulfil demand.



## Current approved pathways

Following the first test flight on alternative fuels in January 2008, a collaborative effort was made by engineers, chemists and aviation fuel experts to go through rigorous safety and certification processes to approve the use of SAF in passenger flights across the system. Each pathway needs to undergo a rigorous testing and analysis procedure before being approved by a panel of technical experts from the industry including airframe and engine manufacturers. This process is part of ASTM International, the global standards setting agency for fuels. Once approved, each pathway can be used to generate sustainable aviation fuel which can be blended with fossil fuel and used in flight.

As of publication, there are seven approved pathways, with a further eight in the pipeline for testing and approval over the coming years. Each pathway widens the opportunities for more SAF to be supplied over time. Currently, there is a blending limit of 50% SAF mixed with fossil fuel (some of the processes have a lower blending limit). This is primarily due to a lack of aromatics in sustainable aviation fuel. These

particulates help seals to swell inside older aircraft engines and prevent fuel leaks. Newer engines do not have this concern, and SAF has been performance tested at 100% in newer aircraft. While SAF production volumes remain low, a blend limit does not hamper the use of SAF, however, it is expected that the blend limit will eventually increase to 100%.

## Ensuring sustainability

From the very first steps towards a new energy source, the aviation sector has agreed that sustainability must be at the core of the transition. Aviation has been able to learn from the mistakes made in first-generation biofuels used in road transport, building systems to avoid these pitfalls. From the beginning, the Sustainable Aviation Fuels Users Group, a committee of airlines, has determined key criteria to ensure best practice in this area. Coupled with the Roundtable on Sustainable Biomaterials (a multi-stakeholder organisation founded by environmental groups and experts in assessing sustainability certification for the bio economy); and the development of standards at ICAO, there is a robust framework for sustainably scaling up SAF.

Pathways and processes	Feedstock options	Producers using the pathway	Date of ATSM approval	Current blending limit
FT-SPK Fischer-Tropsch Synthetic Paraffinic Kerosene	biomass (forestry residues, grasses, municipal solid waste)		2009	up to 50%
HEFA-SPK Hydroprocessed Esters and Fatty Acids	used cooking oil, waste animal fats, distillers corn oil, tall oil, algae, jatropha, camelina	World Energy / Neste / SkyNRG / Phillips 66 / Marathon / Gron, Diamond Green / AIC / +	2011	up to 50%
HFS-SIP Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	microbial conversion of sugars to hydrocarbon	Amyris / Total	2014	up to 10%
FT-SPK/A Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics	renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops	Fulcrum / Velocys / Red Rock	2015	up to 50%
ATJ-SPK Alcohol-to-Jet Synthetic Paraffinic Kerosene [isobutanol]	agricultural waste products (stover, grasses, forestry slash, crop straws)	Gevo	2016	up to 50%
ATJ-SPK Alcohol-to-Jet Synthetic Paraffinic Kerosene [ethanol]	Industrial waste gases, agricultural waste products (stover, grasses, forestry slash, crop straws)	LanzaTech	2018	up to 50%
CHJ Catalytic hydrothermolysis synthetic jet fue	Triglyceride-based feedstocks (plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil)	ARA / Euglena	2020	up to 50%
HHC-SPK High Hydrogen Content Synthetic Paraffinic Kerosene	Biologically-derived hydrocarbons such as algae	IHI World	2020	up to 10%

Sustainability is not just a matter of the choice of feedstocks – it is also how they are collected, cultivated, harvested, processed and transported. Some key sustainability criteria for aviation fuels include the following elements:

- » Will not displace, or compete with, food crops or cause deforestation
- » Minimise impact on biodiversity
- » Produce substantially lower life-cycle greenhouse gas emissions than conventional fossil fuels
- » Will be certified sustainable with respect to land, water and energy use
- » Deliver positive socio-economic impact

As a global transportation sector, aviation needs a harmonised standard to ensure that sustainability criteria are equally applied across the industry. A patchwork of standards would inhibit the development of a commercially viable market. While there are myriad standards in place, both regulatory and voluntary, a critical element will be for aviation fuel stakeholders to enable greater cooperation between standards to increase transparency, decrease the cost of compliance, increase end-user visibility to the biomass, and increase the incentives for next-generation fuel pathways. It is also vital that a unified accounting structure be established to verify the origin and sustainability credentials of these new fuels for aviation. The ICAO CORSIA is expected to be a driver to achieve this.

The development of an accepted set of globally harmonised standards will help ensure that investment is directed at fuels that meet clearly defined and internationally-agreed sustainability criteria, thus minimising this form of risk. Criteria need to be mutually recognised around the world. For aviation, global standards are needed wherever possible, due to operational routing of aircraft, common global equipment and worldwide fuel purchasing requirements.

### Can it be scaled-up?

Given unlimited resources, the analysis shows that there will be enough feedstock available to completely shift to SAF for aviation<sup>13</sup>, however, can that be achieved in the next 30 years? It is instructive to look at other forms of renewable energy to see what trajectories have been observed.

Ethanol is one such illustration, with production increases in Brazil and the United States (which together produce 85% of the first-generation biofuel) having been driven by policy incentives in both countries: the Pró-Álcool programme and Renewable Fuel Standard which both required minimum blending into transportation fuels. Over 100 billion litres of ethanol was produced globally in 2016.

Biodiesel production in the United States increased substantially between 2001 and 2016, with over 8 billion litres being produced per year at its peak.

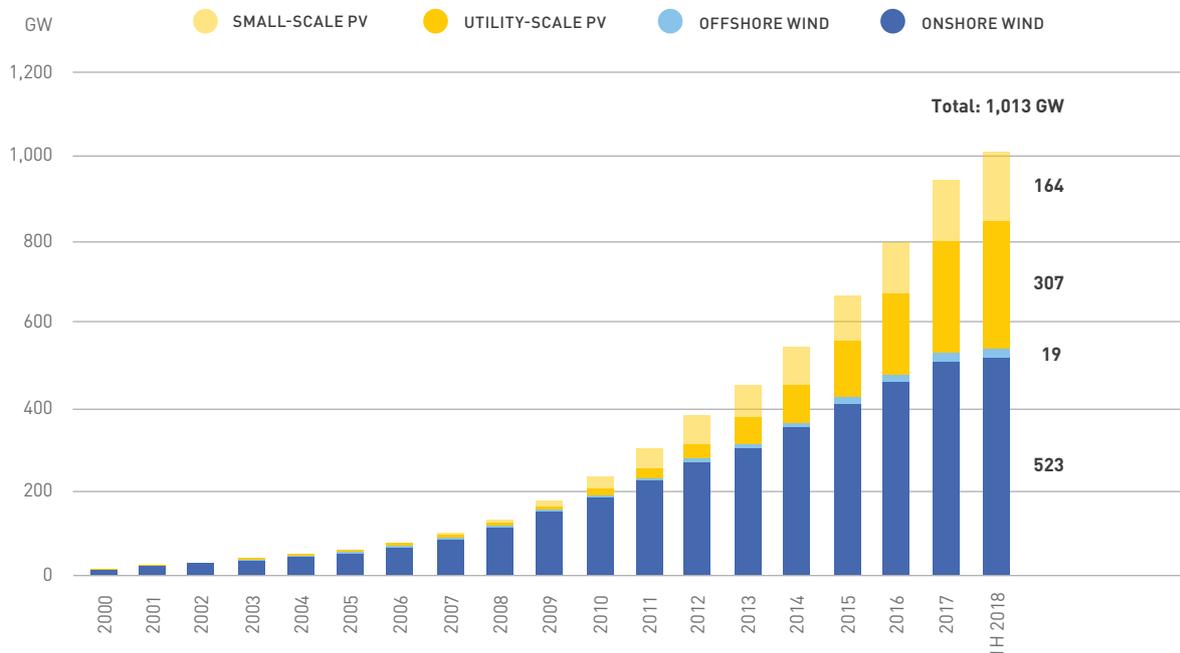
Since 2000, wind and solar capacity has increased 65-fold, with advances taking place at a speed which has defied forecasts<sup>14</sup>. Whereas the first 1,000 gigawatts of wind and solar required an estimated \$2.3 trillion of capital spend, BloombergNEF estimates reaching 2,000 gigawatts will only cost \$1.23 trillion, set to take place before 2024.

Analysis shows the comparison of the expected and/or required trajectories of quantities of SAF under the W2050 project along with;

- » the global ethanol production where the 1980 year shifted/matched to 2025 for aviation SAF forecast levels.
- » US biodiesel with the production in 2012 shifted/matched to 2025 for aviation SAF forecast levels.

Historical trends for alternative fuels from other sectors (e.g., ethanol and biodiesel) are in line with low W2050 scenario for SAF based on a linear extrapolation of current SAF production forecast through 2025. It is also important to consider the

### Global wind and solar installations, cumulative to June 30, 2018



steepness of the slopes (i.e., growth rate) of quantities of alternative fuels. Between 2010 and 2016 when market conditions were strong, US biodiesel grew at an average CAGR of more than 40%. US ethanol had CAGR of 18% between 2001 and 2010. In comparison, under a mid-scenario, the growth rate of quantity of SAF from 2025 to 2035 is in the order of 22% per annum. It is also important to consider the geographical scope of these markets where the W2050 scenarios envision global mobilisation of multiple pathways, rather than just a few nations and one technology as illustrated with the ethanol and biodiesel precedents.

### Scaling up power-to-liquid

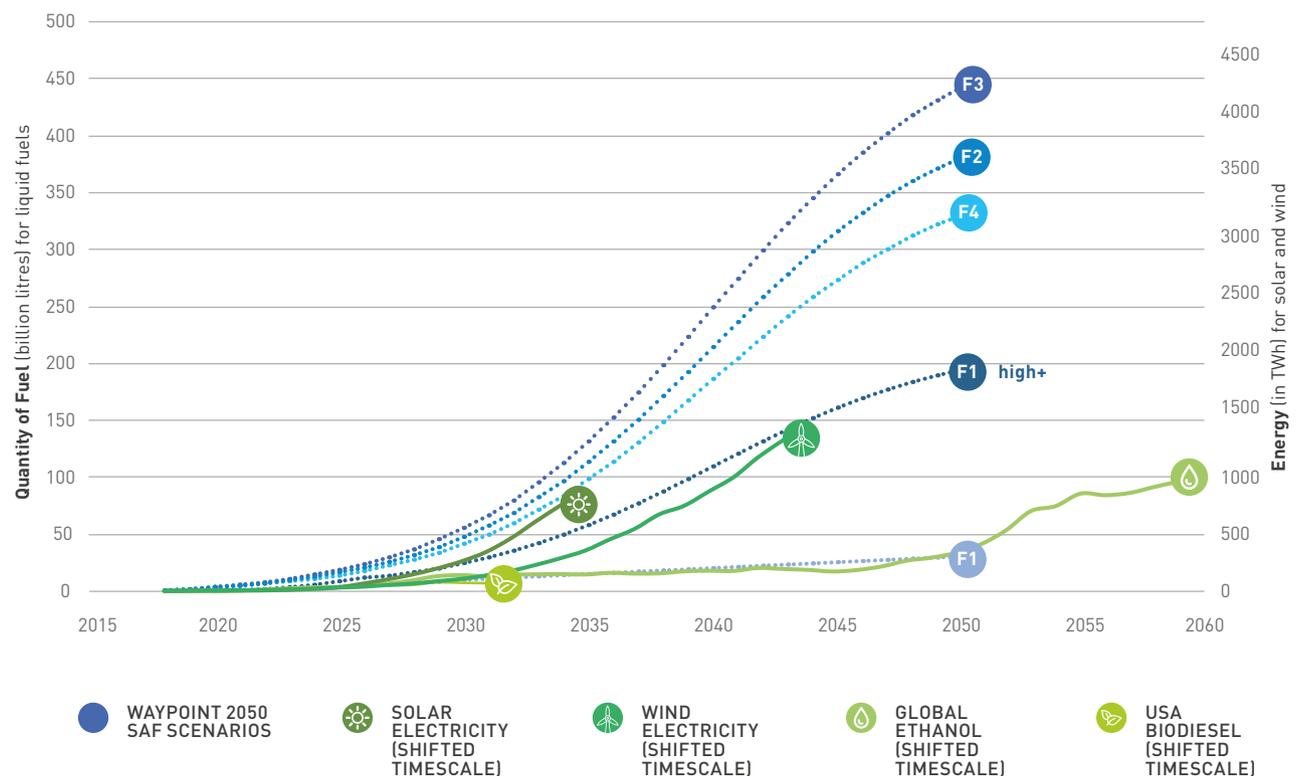
There is a considerable opportunity in the development of the power-to-liquid option for SAF development. Assuming the technology is progressed and the cost significantly reduced, PtL could make a significant contribution to the portfolio of different pathways for SAF production and its scalability is theoretically unlimited. The cost of the resulting fuel will be a core driver of airline demand, but perhaps the biggest challenge is the requirement for renewable energy supply.

Scaling up renewable energy to provide for the production of aviation fuel will require significant investment in solar, wind and possibly nuclear capacity. At the same time, the world needs to shift existing electricity to renewable or low carbon sources (currently, just 36% of global electricity is produced from low carbon sources<sup>119</sup>). The cost of electricity from these sources is rapidly declining – particularly solar and wind – and the share of electricity supply from these sources is increasing<sup>120</sup>, but not currently fast enough to meet the climate goals set by the Paris Agreement. Some estimates suggest these low carbon sources will generate around 50% of global electricity in the latter years of the 2020s<sup>121</sup>.

The push to develop PtL as an option for aviation will need to take place in this environment and could either be seen as an additional driver for increased acceleration in renewable and low carbon electricity supply throughout the economy, or a less important user of the resource than other transport modes and users. However, as the rest of the economy shifts to low carbon electricity, liquid fuels for aviation could be a longer-term user of this energy supply. Given current trajectories<sup>122</sup>, there do not appear to be concerns with capacity constraints for renewable electricity by 2050.

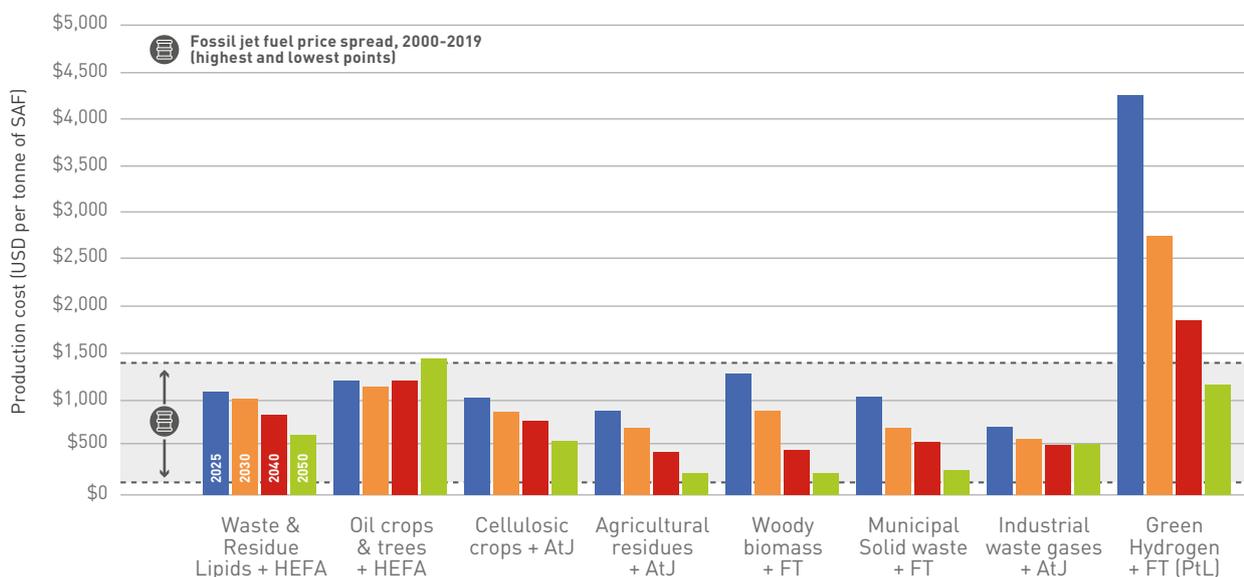
### Scaling up the production of SAF is going to be a challenge, but not insurmountable

Waypoint 2050 sustainable aviation fuel scenarios are placed in context of the historical evolution and ramp-up of other alternative sources of energy (global ethanol production<sup>83</sup>, USA biodiesel production<sup>84</sup>, solar electricity generating capacity<sup>85</sup>, wind electricity generating capacity<sup>86</sup>). Given that the SAF scenarios represent forecasts from 2019-2050 and the alternative sources of energy are based on historical data, timescales for the alternative sources of energy were shifted to align to an arbitrary year (2025) for the purpose of analysis and illustration. The historical evolution of quantities of global ethanol production and USA biodiesel represented in terms of volumes (in litres in a given year) without conversion to equivalent energy. Global solar electricity and wind electricity are represented on the right-hand scale (in TWh in a given year) aligned with the equivalent energy from jet fuel. The SAF volume of 3.5 billion litres in 2025 corresponds to approximately 1980 production levels of global ethanol, 2012 production levels of USA biodiesel, 2010 energy level from solar and 2000 energy level from wind. The industry believes that it can reasonably reach twice this level of SAF production in 2025 (i.e. around 6-7 billion litres).



### SAF costs will come down (carbon cost included)<sup>125</sup>

Indicative analysis for a selection of SAF pathways at a global level shows that costs will be able to reduce, mainly driven by economies of scale and some feedstock input reductions. There are a range of costs displayed showing a spread for different feedstock types. Production cost shown includes the value of the carbon reduction, i.e. the net production cost. This allows it to be compared to fossil fuel costs on a level basis. By adding in the cost of carbon (\$100 per tonne in 2030, rising to \$200 per tonne by 2050), it is likely that there will be a levelling in the differential between SAF and fossil jet fuel, but it is clear that government support in the next decade can make all the difference to the long-term availability and uptake of SAF. This should also be seen in the context of historical jet fuel costs, which have fluctuated significantly in the past 20 years. Future oil prices are unknown.



SAF pathway	Feedstock types	Projections	Share of jet in product output
HEFA	<ul style="list-style-type: none"> <li>» Rapeseed oil</li> <li>» Oil cover crops</li> <li>» Soybean oil</li> <li>» Crops on degraded land</li> <li>» Used cooking oil</li> <li>» Tallows and fats</li> </ul>	A reduction in costs of around 3% from 2025-2050, as current hydrogen is replaced with more expensive (but lower CO <sub>2</sub> ) green hydrogen. Assumption that most HEFA capacity is retrofitted from current fossil uses. Feedstocks cost stays steady throughout period (except for oil crops where supply / demand dynamics play out), but a decline in operating and capital expenditures comes with economies of scale.	46% Could go up to 90% if maximised, but unlikely to rise above ~60%
ATJ	<ul style="list-style-type: none"> <li>» Cover crops</li> <li>» Forest residues</li> <li>» Agricultural residues</li> <li>» Municipal solid waste</li> </ul>	A reduction in costs of 26% from 2025-2050, driven by feedstock cost reductions, operating and capital expenditure improvements.	77% Can go up to 90% if using ethanol as intermediary
FT-SPK	<ul style="list-style-type: none"> <li>» Cover crops</li> <li>» Forest residues</li> <li>» Agricultural residues</li> <li>» Municipal solid waste</li> </ul>	A reduction in costs of 41% from 2025-2050, driven by expected strong capital expenditure between 2025 and 2030 when technology is fully proven and starts to commercialise. Addition of carbon capture and storage to the process would reduce CO <sub>2</sub> emissions significantly (including to negative emissions) but increase the fuel cost by around 6%.	60%
PtL	<ul style="list-style-type: none"> <li>» Electricity, carbon captured from the air</li> </ul>	A reduction in costs of 61% from 2025-2050, driven by cost of hydrogen coming down and the cost / availability of low carbon electricity.	60% Can be maximised to 80-90%

Addition of carbon capture and storage to these processes would reduce CO<sub>2</sub> emissions significantly (including to negative emissions) but increase the fuel cost slightly.

## What will be the cost of the energy transition?

Despite the current cost of SAF being around 2-3 times that of fossil jet fuel, analysis shows that, over time, the cost of sustainable aviation fuel from a variety of sources has the opportunity to reduce significantly. When the cost of carbon is included, this could come within an acceptable margin of fossil jet fuel. However, it is clear that government support will be needed in the 2020-2030 period to set up the basis for the long-term energy transition for air transport.

## Building a new industry: investment in a SAF future

Sustainable aviation fuel not only brings environmental benefits for aviation, but it can also foster the development of a new industry. Given the diversity of feedstocks that aviation is considering, there are few places that could not support some development of a new, sustainable, energy industry. These can range from collection of agricultural waste in the most appropriate environments, to establishment of algae farms on land or off-shore, to biofuel facilities in cities utilising municipal waste.

The complete transformation of an energy system that has been in operation for a century will require significant investment and construction. Analysis for Waypoint 2050 estimates that up to 5,000 - 7,000 facilities may be required to produce sufficient SAF to achieve the climate targets of the aviation industry<sup>126</sup>. In 2050, the capacity of an average facility is estimated to be -120 million litres (32m gallons, 100,000 tonnes), producing 83 million litres (22m gallons, 65,000 tonnes) of SAF per annum.

The number of facilities required could be lower if the energy industry develops a hub-and-spoke model for the AtJ and PtL approaches, with regional production of alcohols and hydrogen respectively, which are then converted into SAF at central hubs.

Totalled across all feedstocks and regions, this analysis estimates that an investment of approximately \$1 - \$1.45trn will be necessary to build sufficient SAF capacity. Annualised, this is equivalent to around 6% of yearly oil and gas capital expenditure. As a point of comparison, global energy companies spent around \$500 billion in 2019 on capital expenditure<sup>127</sup> with historical capex of around \$770bn per

year. And Governments provide \$317 billion in fossil fuel consumption subsidies (around \$4.4 trillion in subsidies over the last decade)<sup>129</sup>.

Each of these facilities will produce and monetise fuels and co-products additional to SAF, so revenues from aviation will only support a portion of this investment.

While over 90% of oil and gas production is located in just 22 countries<sup>130</sup>, the SAF industry will need to leverage feedstocks across almost every country, improving energy security, independence, and resilience for many nations. By bringing the aviation industry, government, energy, agriculture and academic expertise in a country or region together, as it is already successfully done in multi-stakeholder initiatives, industry can analyse the optimal opportunities that exist in each country for aviation biofuel production, including the most effective feedstock sources and infrastructure requirements.

The development of a new energy industry will also bring with it jobs: both new opportunities and as a way to re-purpose existing fossil fuel based jobs and facilities. Investments in bioenergy are highly effective to create jobs, with labour required to gather, process and transport feedstock, to design, construct and operate facilities, and to support the wider supply chain.

Such a transformation of the aviation energy system will provide opportunities to generate additional jobs and energy industries closer to the source of feedstocks, as well as the airports at which airlines will be fuelled. Estimates suggest this shift could generate up to 14 million jobs in SAF production worldwide, with around 1.4 million people employed in the production facilities themselves and up to 12.6 million in the construction of facilities, collecting feedstocks (such as used cooking oil and agricultural waste) and the supply chain and logistics<sup>131</sup>.

## Required number of facilities, globally and by region.

Assumes small production close to the source of feedstock - consolidation (and a smaller number of larger facilities) possible, particularly for some feedstock types.

Scenario		Global	Africa	Asia - Pacific	Europe	Latin America & Caribbean	Middle East	North America
1	Pushing technology and operations	5,904	410	2,270	1,256	726	217	1,025
2	Aggressive SAF deployment	7,026	464	2,661	1,525	843	279	1,254
3	Aspirational and aggressive technology perspectives	4,964	355	1,940	1,027	623	172	847



### Total infrastructure investment required (Billion USD).

Scenario	Global	Africa	Asia - Pacific	Europe	Latin America & Caribbean	Middle East	North America
1 Pushing technology and operations	\$1,250	\$90	\$481	\$259	\$161	\$44	\$212
2 Aggressive SAF deployment	\$1,450	\$101	\$554	\$306	\$183	\$55	\$252
3 Aspirational and aggressive technology perspectives	\$1,100	\$80	\$421	\$219	\$142	\$36	\$180

### Indicative job creation potentials for SAF production worldwide.

Scenario	Global	Africa	Asia - Pacific	Europe	Latin America & Caribbean	Middle East	North America
1 Pushing technology and operations	13.5 m	1.2 m	5.6 m	2.4 m	1.9 m	0.4 m	2.0 m
2 Aggressive SAF deployment	14.1 m	1.2 m	5.9 m	2.5 m	2.0 m	0.4 m	2.1 m
3 Aspirational and aggressive technology perspectives	13.0 m	1.2 m	5.4 m	2.3 m	1.9 m	0.3 m	1.9 m

## Re-thinking our energy supply

Explorations of the different pathways for aviation’s energy future as part of Waypoint 2050 work have identified that the sector will need access to low-carbon electricity and green hydrogen both to produce power-to-liquid SAF and potentially for primary use in aircraft propulsion (see the discussion in b) technology).

Analysis for Waypoint 2050 shows that this could consume between 8% and 18% of the currently planned low-carbon electricity production and 23-56% of the currently planned green hydrogen supply in 2050, depending on the scale-up of PtL in particular. However, this depends on the Waypoint 2050 scenario that is able to be pursued and these represent the maximum cases as a comparison. The likelihood is that aviation will need lower quantities of both electricity and hydrogen.

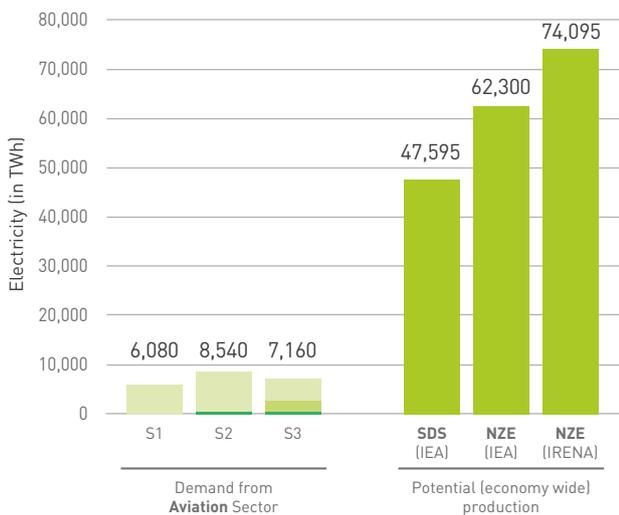
Any shift to these forms of energy for aviation will likely bring with them an increase in generation of both low-carbon electricity and green hydrogen to meet the needs of air transport, as the IEA and IRENA analysis of production does not include hydrogen for direct use in aviation.



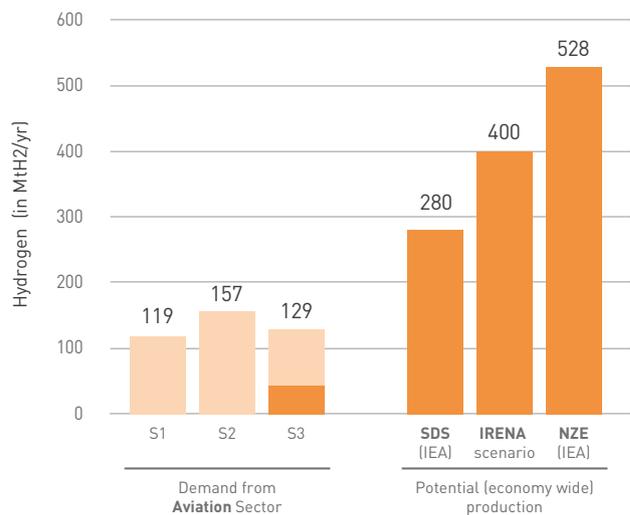
## Combined air transport demand for electricity and hydrogen, 2050<sup>132</sup>

Whether for use as direct energy for aircraft, or as part of the process to produce hydrogen or PtL SAF, this illustrates the total possible demand aviation may have for low-carbon electricity and green hydrogen in 2050 across each of the three Waypoint 2050 scenarios. These represent upper-bound estimations for illustrative purposes: it is likely that requirements will be lower than this. The IEA and IRENA scenarios also don’t account for the full use of hydrogen or electricity in aviation, so aviation may boost investment (and supply) in these energy sources above the current scenarios.

### Total electricity



### Total hydrogen



## ACCELERATING THE ENERGY TRANSITION

Progress has been made in the development and deployment of SAF over the past ten years. However, to reach levels of SAF required, both further technological development and improved economics are needed, quickly.

There is a key role for policy frameworks at this crucial early phase of SAF industry development. Without a supportive policy landscape, the aviation industry is unlikely to scale up biofuel consumption to levels where costs fall and SAF becomes self-sustaining.

Few industries are as competitive as aviation. This produces excellent outcomes for state economies and consumers. Producer surplus has historically trended below the weighted average cost of capital meaning both consumers and national economies receive the benefits of aviation below the true cost. The impact of this situation is the aviation sector is often cautious when making a business decision involving unquantified risk or potentially subjecting an airline to a competitive disadvantage. Hence, airlines need encouragement to use SAF from an early stage.

Such incentives are necessary at this early stage of development to close a production cost gap and allow the capacity of SAF production to increase. But incentives are not expected to be a permanent feature of this energy sector, as learning-by-doing and economies of scale bring production costs lower and remove the gap between SAF and fossil fuels. Policy is a temporary gap-filler to assist the economics of SAF production reach self-sustaining profitability and scalability.

The aviation industry has committed to ambitious goals for reducing emissions. SAF is an important part of the plan to reach these goals and the industry and its partners have made significant progress. There is confidence that SAF can be a very significant part of every airline's future. From policymakers, the industry is looking for the right set of legal, fiscal and policy responses to ensure this new energy stream can be incorporated into business as usual as quickly as possible.

### Action items for the aviation sector

Action item	Description	Timeline	Difficulty level
Get started by doing a first test flight	Airlines should begin with taking part in test flights and getting used to the process to deliver and use SAF, before looking into long-term agreements. Whilst doing a single flight on SAF will not change the world in a macro sense, getting the experience from a logistical and internal coordination perspective is a valuable stepping-stone to larger involvement.	Possible today	●●●○○
Make substantial and bold SAF offtake agreements at an early stage	Airlines must be willing to take a long-term view and invest in SAF offtake agreements at an early stage. Several airlines have made important investments in this area, but a lot more will be needed.	Will take a 2-3 years	●●●●○
Show leadership to set up the policy infrastructure needed for SAF acceleration	Provide industry leadership on best practice concerning: sustainability standards, accounting procedures, logistics, communication, effective policy and business case development.	Possible today	●●○○○
Make the case to governments and the finance community for SAF	Ensure aviation can opt-in to existing ground transport policies and build understanding for the importance of directing feedstock towards hard to abate sectors such as aviation.	Possible today	●●○○○

## Action items for the aviation sector

Action item	Description	Timeline	Difficulty level
Provide support to airlines for SAF projects in local areas	Airports: whilst most airports are not involved first-hand in fuel purchasing (or distribution), the support of airports in helping to develop local SAF opportunities for airline partners and promote smart government policy can be invaluable.	Possible today	●●○○○
Join SAFUG or the RSB	The Sustainable Aviation Fuel Users Group and / or the Round Table on Sustainable Biomaterials are key fora to ensure that the energy transition takes place in a robust and sustainable way.	Possible today	●○○○○
Bring passengers and major customers on board	Allow passengers and corporate customers to take part in direct SAF purchases through your booking engine — paying the difference between the cost of SAF and fossil jet. This has proven to be a popular option for a couple of airlines that offer it, allowing passengers to ensure they are making a difference in a robust way.	Could take 2-3 years	●●●○○
Foster research to explore the feasibility of augmenting the maximum blend rate usable during regular service	While the maximum blend rate is today set at 50%, it may be technically feasible to augment it to allow flying with 100% SAF.	By 2025	●●●○○

## Action items and policy proposals for governments<sup>133</sup>

Action item	Description	Timeline	Difficulty level
Clean energy transition push across government	Commit to supporting an energy transition through significant investment in sustainable aviation fuels. This can help drive new energy industries and re-use refining and other infrastructure.	Required from today	●●●●○
Pursue partnerships for SAF scale-up	Launch SAF partnership and cooperative projects bringing together local aviation industry stakeholders, energy suppliers, research institutions and potential feedstock suppliers.	Possible today	●●○○○
Pursue partnerships for SAF scale-up	Engage in public-private partnerships for sustainable aviation fuel production and supply.	2020-2025	●●○○○
If putting in place a market-based measure, invest a portion in SAF	As global and regional market-based measures are adopted, Governments should invest a portion of the funds collected in SAF and SAF R&D that accelerates the sector's path to reducing CO <sub>2</sub> .	Available today	●○○○○
Prioritise aviation (and other hard-to-abate sectors) as a user of alternative fuel	Set priorities for the sustainable energy mix in your country to ensure that the right type of low carbon energy is developed for each sector — aviation does not have alternatives at this time, particularly for long-haul operations and so should be seen as a priority user of feedstocks for liquid fuels.	Possible today	●●○○○

## Action items and policy proposals for governments<sup>133</sup>

Action item	Description	Timeline	Difficulty level
Prioritise aviation (and other hard-to-abate sectors) as a user of alternative fuel	Road transport has historically had more advantages for feedstock use, making aviation use of these resources uneconomical — this situation should be reversed.	Possible today	●●○○○○
Explore potential for SAF development at a national or regional level	Undertake local supply opportunity audits to investigate where potential SAF could be developed.	2020-2025	●●●○○○
Support innovation into new energy alternatives	Support sustainable aviation fuel R&D and demonstration plants with academic and research organisations across the range of feedstock sources.	2020-2040	●●○○○○
Support development of SAF production	Attract capital to expand SAF capacity through loan guarantee programmes for construction of SAF production facilities (de-risking the early investment anxiety for new technologies).	2020-2035+	●●●○○○
Support development of SAF industry	Direct research and development activities for local SAF production pathways and new energy industries.	2020-2025	●●●○○○
Support development of SAF industry	Commit to policy certainty, or, at a minimum, policy timeframes that match investment timeframes.	2020-2030	●●○○○○
Demonstrate leadership	Commitment for government travel to be undertaken on SAF, either directly or through book-and-claim options initially.	Possible today	●●○○○○
Demonstrate leadership	Adopt globally-recognised sustainability standards and work to harmonise global standards.	2020-2025	●●○○○○
Demonstrate leadership	Encourage user-friendly sustainable aviation fuel accounting methods and work to harmonise global standards.	2020-2025	●●○○○○
Provide incentives for airline use of SAF	Make SAF zero-rated under carbon taxation or other market-based measures, if they are being developed.	2020+	●●●○○○
Blending or production incentives for SAF producers or suppliers.	Ensure existing policy incentive frameworks, often designed for ground transport, also include aviation and evaluate higher incentives for aviation over ground transport which has other energy alternatives.	2025+	●●○○○○
Take a global leadership role in managing the aviation energy transition.	Showcase Government action at a regional and global level by championing SAF opportunities with other governments and at ICAO.	2020-2030	●●○○○○

## Action items and areas for research institutions

Action item	Description	Timeline	Difficulty level
Implement SAF research programmes	<p>Research needs to accelerate in several areas:</p> <ul style="list-style-type: none"> <li>» Technology pathways (for example, power-to-liquid fuel opportunities)</li> <li>» Feedstock yields for crop feedstocks</li> <li>» Lifecycle improvements for all feedstock types</li> <li>» Completely new sources of liquid SAF</li> <li>» Production pathway efficiency improvements</li> </ul>	2020-2040	●●●○○

## Action items for the energy industry

Action item	Description	Timeline	Difficulty level
Demonstrate commitment to SAF at an early stage	Divert funding to sustainable aviation fuel production and deployment from fossil fuel extraction and capital expenditure	Required today	●●●●●

## Action items for the finance community

Action item	Description	Timeline	Difficulty level
Focus funding on SAF opportunities worldwide	Regional and multilateral development banks can play a proactive role in developing a SAF industry, helping to finance production and bring costs down. Of particular importance to the multilateral development banks is the job creation opportunities that exist in new energy economies, alongside the climate upside.	Possible today	●●○○○

## Action items for other stakeholders

Action item	Description	Timeline	Difficulty level
Other transport modes should prioritise best available energy options	Other transport modes which have existing alternative energy sources should focus efforts on shifting to sources like electricity and hydrogen, leaving liquid alternative fuel sources for harder-to-abate sectors (such as aviation).	2020-2035	●●●●○

# OUT-OF-SECTOR CARBON REDUCTION MARKET MECHANISMS

**ALTHOUGH THE CONTRIBUTION FROM TECHNOLOGY, OPERATIONS AND INFRASTRUCTURE IMPROVEMENTS AND SUSTAINABLE AVIATION FUEL WILL PROVIDE A VAST MAJORITY OF THE 2050 EMISSIONS REDUCTIONS, THERE WILL BE A NEED TO INVEST IN OUT-OF-SECTOR CARBON REDUCTION MEASURES TO DEAL WITH REMAINING EMISSIONS.**



This section provides some background on the status of carbon markets and potential evolutions, including considerations of sources of offsets by 2050 that may be different from today's. The use of offsetting, a market-based measure or out-of-sector carbon reductions can be used as part of the method to meet the industry goals, depending on the availability of sustainable aviation fuels. In each of scenarios 1-3, Waypoint 2050 has identified the need for a particular quantity of sustainable aviation fuel to meet 90% of the sector's liquid fuel requirements, however the remaining emissions reductions to net-zero would need to come from some form of out-of-sector carbon reduction. The CO2 reduction from SAF could also be fulfilled with offsetting, depending on the cost of available offsets at the time, vs the cost differential of SAF and fossil jet fuel.

There are very few forecasts for the types of offsets that will be available in 2050. The offset markets that exist today through global instruments such as the United Nations Clean Development Mechanism (CDM) are enabling funding of carbon reduction projects across the world. This 'low-hanging fruit' should, in theory, have all been funded before 2050 and will no longer be available. However, there are a number of mechanisms that will still be available, or will likely come to maturity over the coming decades. In this section they are broadly referred to as 'offsetting', meaning they offset the remaining emissions generated by air transport through 'out-of-sector' projects to compensate for unavoidable CO2 emissions in aviation.

## International carbon pricing mechanisms under the Paris Agreement

Article 6 of the Paris Agreement provides for voluntary cooperation among countries for the implementation of NDCs to allow for higher climate ambition, promote sustainable development, and promote environmental integrity:

- » Article 6.2 covers cooperative approaches, where Parties could opt to meet their NDCs by using internationally transferred mitigation outcomes (ITMOs).
- » Article 6.4 establishes a mechanism for countries to contribute to GHG emissions mitigation and sustainable development. The emission reductions can be used to meet the NDC of either the host country or another country.

Several key questions remain, for example there is a lack of clarity on key issues related to Article 6 and the transition of existing CDM projects and associated methodologies. These were due to be decided over the last several United Nations Framework Convention on Climate Change (UNFCCC) Conferences of the Parties (COPs), but there has been little progress in these international negotiations and the delay of COP26 has pushed resolution back further.

Carbon pricing policies are sometimes considered to be effective to incentivise carbon reduction roadmaps, to foster the entry into service of new technologies and allow the development of sustainable aviation fuels for example. Carbon pricing mechanisms already exist for the aviation sector. This is why the sector supports a rapid implementation of the ICAO CORSIA, the first global market-based measures that apply to an entire sector.

But it is important that a balance is struck between incentivisation policies on one hand and the inability of airlines to have sufficient funding to invest in more efficient aircraft and sustainable fuels on the other.

Scenario	Description	2050 out-of-sector emissions reductions
M <sub>0</sub>	Out-of-sector market-based measures are used as a substantial contribution to aviation's decarbonisation in 2050	970-1,500 Mt
M <sub>1</sub>	Out-of-sector market-based measures are used to remove residual CO <sub>2</sub> emissions.	135 Mt
M <sub>2</sub>	Out-of-sector market-based measures are used to remove residual CO <sub>2</sub> emissions.	155 Mt
M <sub>3</sub>	Out-of-sector market-based measures are used to remove residual CO <sub>2</sub> emissions.	115 Mt

## Current sources of offsets

Over the last few years an array of CO<sub>2</sub> products has become available. Carbon credit products are also evolving and developing especially under the Paris Agreement. An important distinction is between projects in the voluntary (or nonregulated) market, which generate offsets called VERs (Verified – or Voluntary – Emission Reductions), and projects in the Kyoto (or regulated) market, which generate offsets called CERs (Certified Emission Reductions). A key difference is that VERs rely on third party verification while CERs are formally certified under Kyoto rules. Different quality standards can apply to VERs and CERs.

Current sources of offsets or type of projects cover a wide range of sources;

- » Energy efficiency including offsets from more efficient stoves, more efficient power generation, light bulb replacement, use of ‘waste’ energy in co-generation.
- » Renewable energy such as wind turbines, hydroelectricity and solar, thermal and photovoltaic systems.
- » LULUCF (Land Use, Land Use Change and Forestry), including avoided deforestation, reforestation of former forest areas, afforestation of new areas, other types of land use projects.
- » Industrial greenhouse gas offsets, including reduction of emissions and/or destruction of hydrofluorocarbon, compounds (HFCs), reduction of emissions and/or destruction of nitrous oxide (N<sub>2</sub>O),
- » Methane (CH<sub>4</sub>) capture and use in energy generation e.g., from landfills, from mines and from anaerobic digestion of, for example, livestock wastes.

## ICAO’s CORSIA

In 2016, governments meeting at ICAO agreed to establish the world’s first climate pricing mechanism for any single global sector. The Carbon Offsetting and Reduction Scheme for

International Aviation (CORSIA) will offset about 80% of the growth in international aviation CO<sub>2</sub> emissions from the end of 2020. CORSIA is intended to offset the growth in emissions from international aviation, which is not covered under the Paris Agreement. Like the Paris Agreement, CORSIA is initially a voluntary scheme, with States deciding if their country will be included. In later years, it is mandatory for all but small and developing countries.

CORSIA does not cover domestic air transport services, as these are subject to national action under the ‘nationally determined contributions’ outlined in the Paris Agreement. However, if countries are wishing to implement market-based measures for domestic aviation, the industry strongly urges them to use the CORSIA template to design their systems.

In order to address the concerns of developing States and to take into account the special circumstances and respective capabilities of States, CORSIA will be implemented in phases, illustrated above. From 2021 until 2026, only flights between volunteering states will be subject to offsetting requirements.

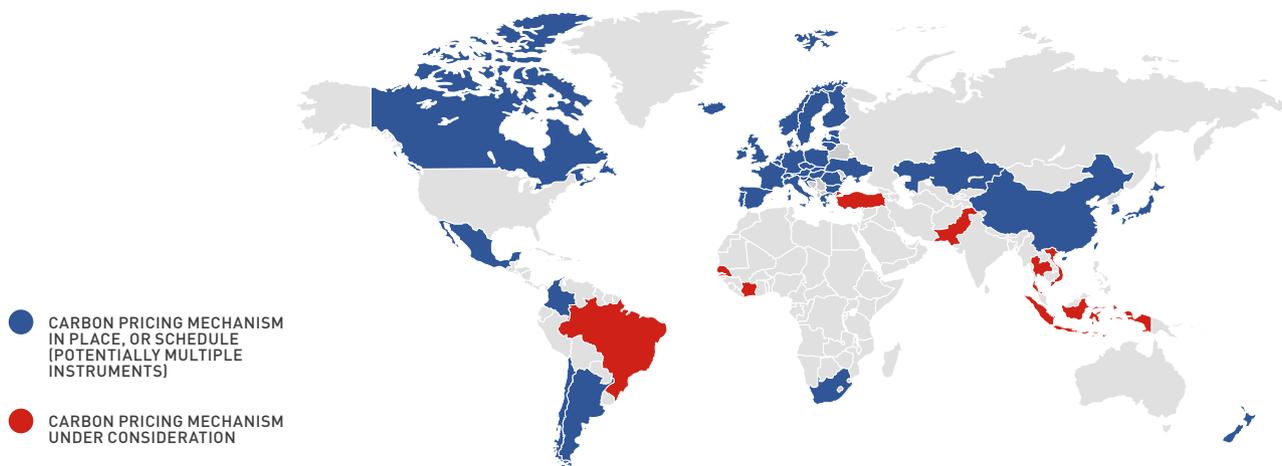
From 2027, all flights will be subject to offsetting, with the exception of flights to/from Least Developed Countries (LDCs), Small Island Developing States (SIDS), Landlocked Developing Countries (LLDCs) and small aviation markets, unless they volunteer to participate.

The ICAO process also includes a robust mechanism to ensure the offsets used in CORSIA bring about real reductions in CO<sub>2</sub> emissions. In the past, a number of questionable offset schemes have not delivered on the emissions reductions they promised. The emissions units that can be used by airlines under CORSIA will be decided by a group of government-appointed technical experts based on several criteria that have been approved by the ICAO Council. The criteria for emissions unit integrity include:

- » Are additional
- » Are based on a realistic and credible baseline
- » Are quantified, monitored, reported and verified
- » Have a clear and transparent chain of custody

## Simplified map showing countries where carbon pricing mechanisms have been introduced<sup>135</sup>

In some of these States, multiple instruments have been (or are scheduled to be) implemented – on a regional level or city level. These include predominantly taxes and emissions trading schemes. In addition, for international aviation, CORSIA has been implemented at a global level.



- » Represent permanent emissions reductions
- » Assess and mitigate against potential increase in emissions elsewhere
- » Are only counted once towards a mitigation obligation
- » Do no net harm

Criteria for emissions unit programme design:

- » Clear methodologies and protocols and their development process
- » Scope considerations
- » Offset credit issuance and retirement procedures
- » Identification and tracking
- » Legal nature and transfer of units
- » Programme governance
- » Transparency and public participation provisions
- » Safeguards system
- » Sustainable development criteria
- » Avoidance of double counting, issuance and claiming

Currently, CORSIA is expected to last until around 2035, with regular reviews of the performance of the system during this lifespan. As emissions reduction opportunities are deployed across the sector to bring down emissions, they may be complemented by an appropriate global market-based measure from 2035 forward.

## Existing carbon pricing mechanisms at a regional, national and sub-national level

A total of 64 carbon pricing initiatives (taxes and emissions trading schemes being the most common) have been implemented with a further three scheduled for implementation around the world, covering 48 national jurisdictions and 32 subnational jurisdictions. These initiatives cover 21.5% of global GHG emissions. They collectively raised \$53 billion in carbon pricing revenues in 2020<sup>134</sup>. Offsetting's evolution

While the projects described in the section above cover a wide range of current sources, the sources of offsets could change significantly in the future. Historically, offsets were based on avoidance of emissions compared to a 'business as usual' or baseline scenario. In the future and given the emissions levels required to meet climate change mitigation goals or ambitions, sources of offsets would need to change dramatically. The Task Force on Scaling Voluntary Carbon Markets aims to make the carbon market more efficient and robust to meet future global demand as many companies around the world look to take early climate action.

This section describes a non-exhaustive range of potential technologies that could form the basis for offsets in the 2040+ time frame (if needed).

It is worth noting that in the Intergovernmental Panel on Climate Change SR15 Report on meeting the 1.5°C challenge, three of the four pathways include CCS and bioenergy with CCS (BECCS) as necessary mitigation technologies. The Paris Agreement calls for a balance between anthropogenic sources and removals by natural carbon sinks. Put another way, in order to meet the 1.5°C stretch goal of the Paris Agreement, there will need to be some type of carbon sink if CO<sub>2</sub> emissions across the economy continue to grow until around 2030. These can be through a range of measures that will still be available in 2050 to offset emissions that have not been able to be reduced.

## 2050 offsets: direct air carbon capture and sequestration

Direct air capture (DAC) is a nascent technique in which CO<sub>2</sub> (and potentially other greenhouse gases) are removed directly from the atmosphere. The current technique uses large fans that move ambient air through a filter, using a chemical adsorbent to produce a pure CO<sub>2</sub> stream that could be stored or re-used. Significantly, unlike traditional carbon capture technologies, it removes CO<sub>2</sub> from the atmosphere, rather than being attached to a power station or other source of emissions. This means it would remove emissions from diverse sources, including air travel.

A DAC facility developed by Climeworks<sup>136</sup> can reduce CO<sub>2</sub> by 90% from the CO<sub>2</sub> captured in the machine. To have any significant effect on global CO<sub>2</sub> concentrations, DAC would need to be rolled out on a vast scale - perhaps up to 30,000 large DACs facilities would capture some 30Gt of CO<sub>2</sub> per year (or up to 30 million small scale plants by the end of the century)<sup>137</sup>. This scale-up would require:

- » significant renewable energy resources to power the plants;
- » a production and then disposal system for the chemicals used in the process;
- » storage sites for the CO<sub>2</sub> removed from the atmosphere (either in geological formations such as empty oil reserve voids where it turns into stone through natural processes); or
- » re-use as a product – as a feedstock for new fuels (see the SAF section on power-to-liquid), or as part of enhanced oil recovery in the fossil fuel industry.

Currently, there is one demonstration facility near Zurich owned by Climeworks, and another by the same company in Iceland. Carbon Engineering<sup>138</sup> also operates a pilot plant in British Columbia. In addition, there are several companies that have developed small-scale capture units, with numerous research projects also underway.

The costs of removing CO<sub>2</sub> from the atmosphere using direct air capture is currently priced at around \$600 per tonne of CO<sub>2</sub>. With improvement in technology expected to decrease this cost to \$100-\$200 per tonne of CO<sub>2</sub> in 2025-2030 and perhaps further after that. Direct air capture, although a nascent technology, could provide a valuable way to reduce and perhaps even reverse current global CO<sub>2</sub> emissions pathways, but it needs to be proved at scale if it is to be available to hard-to-abate sectors such as aviation as an offsetting option.

DAC, should it work at scale and be able to be deployed across the world, could be an important part of the global effort to tackle climate change.

## 2050 offsets: forestry and natural climate solutions

It is estimated some 15-20% of the world's greenhouse gas emissions come from deforestation - often undertaken for economic development reasons (such as logging or farming). The move to use forestry as a source of carbon credits - in effect paying the opportunity cost for nations or communities which would otherwise profit accrue economic benefits from the deforestation - has been investigated for many years and is under discussions at the UN as part of the Paris Agreement. Already, forestry projects have made up 42%

of all credits issued in the last five years<sup>139</sup> and the price of forestry credits has been rising in the last year, but there are challenges: ensuring that the forestry protection is permanent and looking after indigenous communities rights are just two areas that must be considered. The accounting framework for the international transfer of credits must also be decided on. But protecting existing tropical and other forests is a key component of international efforts to prevent climate change and, if developed with consideration, this could be a significant source of carbon credits in the coming years.

Moreover, there is increasing pursuit of other natural (or nature-based) climate solutions which could not only prevent CO<sub>2</sub> emissions, but actually remove CO<sub>2</sub> from the atmosphere. Reforestation (planting trees) is tried and tested – although must also come with safeguards to ensure that trees planted do grow to maturity and this process also takes a long time. Rehabilitation of peatlands, for example, which cover 3% of the earth's surface, could provide significant carbon sinks. Around 15% of the world's peatland has been drained, a process which emits some 1.3 Gt of CO<sub>2</sub> per year<sup>140</sup>. By rehabilitating these natural carbon sinks, CO<sub>2</sub> in the atmosphere will also be reduced.

At this stage, the scale of the 2050 potential from these natural climate solutions is unknown, although estimates suggest up to 11.3 billion tonnes of carbon could be reduced annually through such measures<sup>141</sup>.

## 2050 offsets: carbon capture and storage

Carbon capture and storage (CCS) is a technology that can capture up to 90% of the CO<sub>2</sub> emissions produced from the use of fossil fuels in electricity generation and industrial processes, preventing the carbon dioxide from entering the atmosphere. Furthermore, the use of CCS with renewable biomass is one of the few carbon abatement technologies that can be used in a 'carbon-negative' mode – actually taking carbon dioxide out of the atmosphere.

The CCS chain consists of three parts:

- » capturing the carbon dioxide,
- » transporting the carbon dioxide, and
- » securely storing the carbon dioxide emissions, underground in depleted oil and gas fields or deep saline aquifer formations.

Despite CCS being a technology available for many years, there has not so far been widespread use of the method and there is scepticism from some policy groups as to its ability to be a major part of the world's climate response. One of the key arguments against the use of CCS technology is that it could facilitate a prolonged use of fossil energy, rather than pushing investment towards low carbon and renewable energy.

However, alongside mitigation of emissions, it is now being seen as a core part of any economy-wide strategy to tackle emissions by the IPCC, IEA, UK Committee on Climate Change and the Energy Transition Commission.

CCS can significantly reduce emissions in energy-intensive industries including cement, petrochemicals and steel and a number of countries in Europe are looking at ways to ensure CCS is included in next generation bioenergy clusters to reduce lifecycle emissions from those facilities. These include facilities in Norway, the Netherlands and the UK. Worldwide, plans for 30 facilities have been announced since 2017, doubling to 40 million tonnes the amount of carbon sequestered<sup>142</sup>.

There is widespread confidence that a next generation of plants would not have a high cost (around \$45/t of CO<sub>2</sub>)<sup>143</sup>.

In the long term, and with anticipated technology advancements and associated reduction in costs for removal of CO<sub>2</sub>, there are opportunities for the CCS sector to issue CO<sub>2</sub> reduction certificates, or carbon credits, that could be freely traded in the carbon market. The inclusion of CCS certificates in the carbon market could potentially complement the choice of available emissions reductions used by the airline sector as part of their mandatory offset requirements, i.e. under CORSIA, provided all of the environmental integrity criteria will be met. The availability of carbon credits linked to CCS could represent a viable alternative and act as an additional source to ensure a balanced supply of carbon credits, in particular when different industry sectors start to compete for the same type of carbon credits, resulting in scarcity and an expected sharp increase in the price of carbon credits.

## Competition for opportunities

Whilst these are valuable opportunities for reduction in CO<sub>2</sub> emissions from sectors that have not been able to eliminate emissions entirely, there will likely be a large amount of residual CO<sub>2</sub> emissions still being generated across the economy in 2050, despite best efforts to reduce these. In that case, there could be competition to secure these remaining offset opportunities.

The first order of action should be to reduce emissions from in-sector opportunities (including, in aviation's case, the use of alternative fuels), but a realistic assessment of likely CO<sub>2</sub> reduction actions by all sectors of the economy (based on UNFCCC nationally determined contributions by governments, and action by international aviation and shipping) will need to be compared with advances in the offsets mentioned above to determine the best allocation of offset use by sector.



## PURSUING OUT-OF-SECTOR CARBON REDUCTIONS

Whilst the aviation industry's primary focus needs to be on how it can reduce CO<sub>2</sub> emissions within the sector, there may remain some need for offsets or out-of-sector carbon reductions to be accessible out to 2050 and perhaps a little beyond. There are some key building blocks to ensure these are available to aviation and other hard-to-abate sectors, as they are needed to help with overarching climate objectives.

### Action items for the aviation sector

Action item	Description	Timeline	Difficulty level
Investigate partnership opportunities with future offset providers	Airlines: there will be a restricted market for next-generation offsets in the 2035+ timeframe, with many sectors looking to forestry, natural carbon sinks and carbon capture opportunities. Airlines should instigate partnerships with these providers at an early stage, helping to accelerate early action in these areas and lock-in long-term offset agreements.	2020-2050+	●●○○○

### Action items and policy proposals for governments

Action item	Description	Timeline	Difficulty level
Support CORSIA	Volunteer for the early stages of CORSIA (as of publication, 106 countries have done so) and take part in capacity building to ensure CORSIA is successful. For those States exempted from the mandatory phase from 2027, commit to participation in CORSIA anyway.	2020-2035	●○○○○
Ensure CORSIA continues to evolve	Work with other States at ICAO to ensure CORSIA meets the intended environmental ambition and remains fit for purpose. Ensure CORSIA's standards are maintained and new offset opportunities are evaluated (based on rigorous sustainability criteria) on a regular basis.	2020-2035	●●●○○
Set a long-term CO <sub>2</sub> goal	Through ICAO, set a long-term CO <sub>2</sub> goal for international aviation at the 2022 ICAO Assembly compatible with the most recent scientific evidence from the Intergovernmental Panel on Climate Change.	2020-2022	●●●○○
Do not duplicate market mechanisms, base any domestic measures on CORSIA principles	CORSIA should be the single robust market mechanism on international flights, to avoid duplication and danger of market distortions. If States wish to deploy market-based measures on domestic flights for climate reasons, the industry encourages the use of the CORSIA framework to ensure ease of compliance and a reduction in duplication of systems and monitoring.		●○○○○
If putting in place a market-based measure, invest in in-sector CO <sub>2</sub> reductions	As global and regional market-based measures are adopted, Governments should invest a portion of the funds collected in SAF, SAF R&D and technology R&D (among other opportunities) that accelerate the sector's path to reducing CO <sub>2</sub> .	Available today	●○○○○

Action item	Description	Timeline	Difficulty level
Work with fellow governments to conclude UNFCCC Article 6 discussions	Whilst CORSIA is a standalone scheme, it will rely on carbon credits traded across international jurisdictions. The establishment of global standards for such transactions is vital and Article 6 of the Paris Agreement needs to be agreed for this to really thrive.	2020	●●●○○
Promote development of carbon capture opportunities	Carbon capture — particularly direct air capture — is a vital component of long-term carbon removal and is a key component for allowing the world to meet the Paris Agreement goals.	2020-2050	●●●●○
Develop robust forestry accounting standards with other States and promote forestry offset development	Cooperation is needed between private sector and government-led forestry programmes, e.g. jurisdictional-level approaches and nested REDD+ projects, within national or subnational accounting systems.	2020-2025	●●●○○

## Action items and areas for research institutions

Action item	Description	Timeline	Difficulty level
Accelerate development of carbon capture and direct air capture efficiency	Efficiency of the operation and electricity use of direct air capture systems must evolve to bring the cost of this technology down.	2020-2050	●●●●○

## Action items for the finance community

Action item	Description	Timeline	Difficulty level
Pursue carbon removal opportunities	Support the development of direct air capture, carbon capture and storage and natural climate solutions as a priority and make credits available to sectors such as aviation.	2020-2050+	●●○○○

## Action items for other stakeholders

Action item	Description	Timeline	Difficulty level
Develop additional carbon credit products	Carbon markets: Development of carbon products that are tailored to airlines financial situation and need. Explore the feasibility of derivative products, e.g. carry-trades, futures and tailor-made contracts.	2021-2023	●●○○○
Establishment of a carbon reference price	Carbon markets: the development of standardised reference price for carbon triggering a pricing signal backed by emissions reductions projects that are impacted by supply and demand.	2021	●●○○○



# METHODOLOGY, GLOSSARY AND REFERENCES



# METHODOLOGY OF WAYPOINT 2050 ANALYSIS

Attempting to predict the future is challenging at the best of times, but with so many variables, the challenge becomes even greater. In order to assess the likely forecasts for traffic growth, technology deployment, operational and infrastructure efficiency gains and sustainable aviation fuel ramp-up, a set of working groups was established with over 70 experts from across the sector.

A literature review of existing publications and research helped to set a baseline for the CO<sub>2</sub> emissions forecasting process used as the basis for this W2050 Project. This approach is consistent with the general approaches and methodologies from forecasts and sources that were analysed (ICAO's CAEP, IEA, IATA, Boeing, Airbus and their associated sources).

The first step comprises economic modelling and traffic forecasting. A global economic model is generally used to transform fundamental attributes and trends such as population, gross domestic product, propensity to travel into aviation traffic generally measured in number of passengers, revenue passenger kilometres (RPKs), revenue tonne kilometres (RTKs), available tonne kilometres (ATKs), etc.

Aviation traffic is then used as input to a fuel burn forecasting process that uses data of baseline fleet and operations. The baseline fleet and operations are generally based on the reference year of the forecasts and the future evolution of the

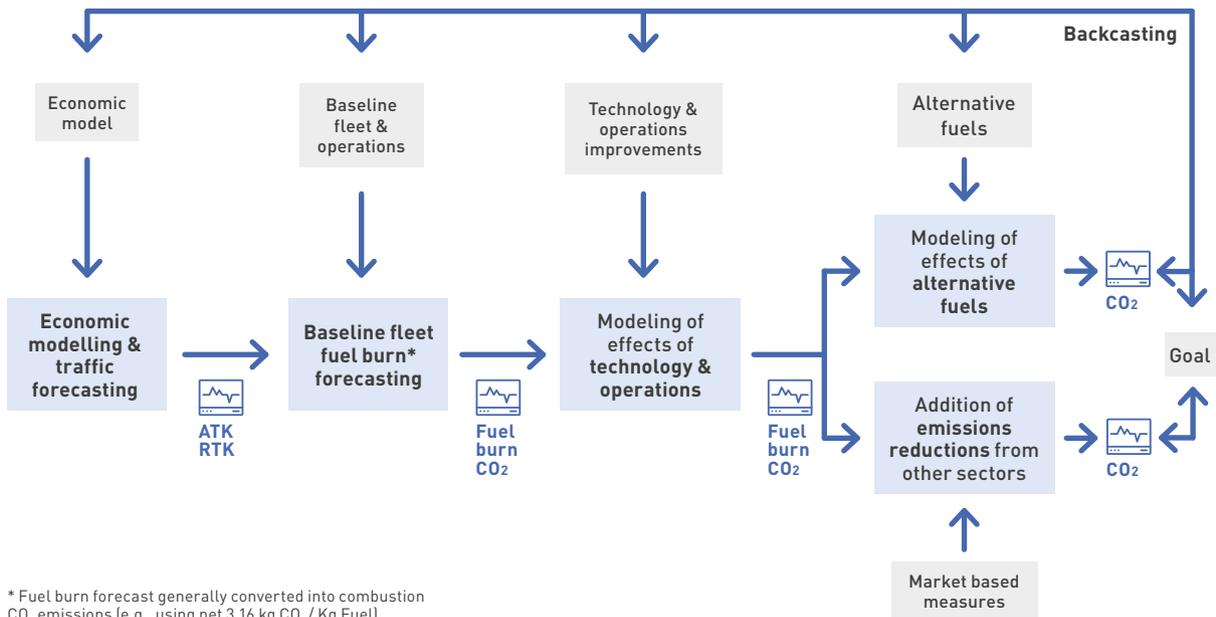
fleet and aviation system assumes that the technology and operations remain at the level of performance observed in the reference year. This was augmented in July 2021 with an update to the traffic forecasts based on the impact Covid-19 will have on traffic (included in an updated traffic forecast from 2020-2040) and on load factor.

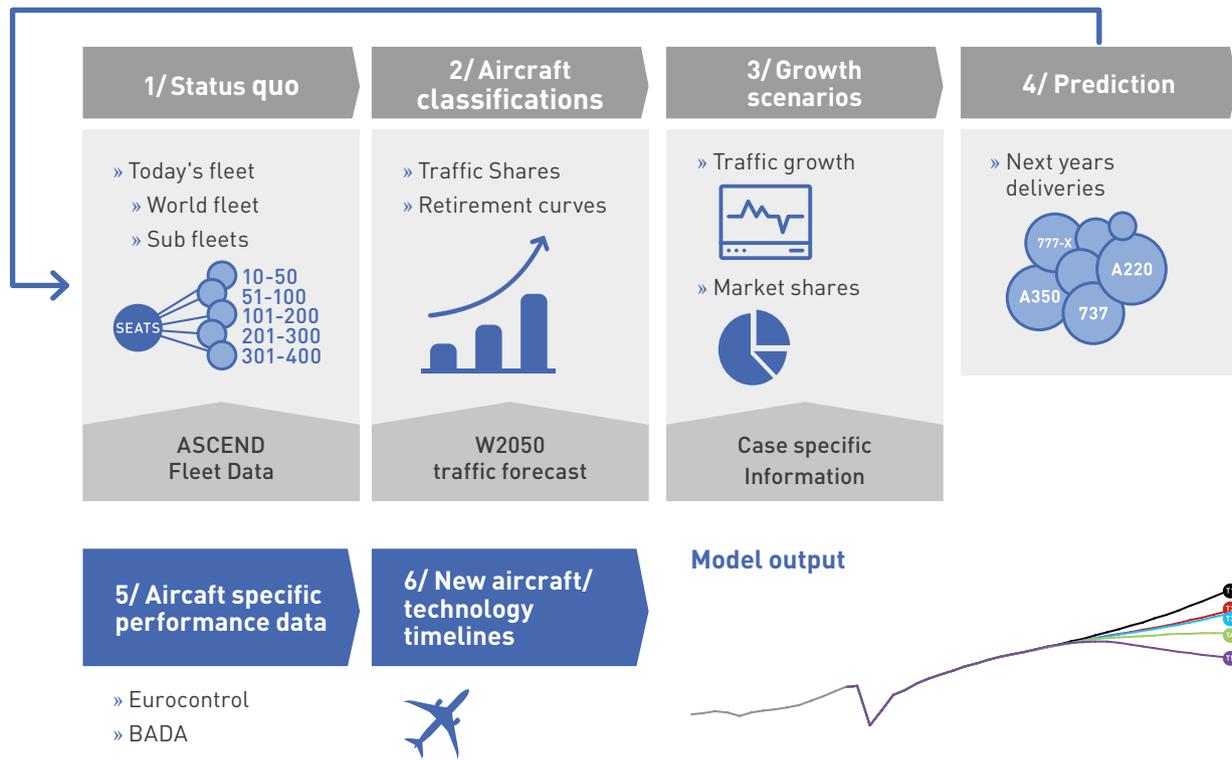
Subsequently, technology and operational improvements are used to develop scenarios where the performance of the fleet (e.g., newly delivered aircraft or in-production aircraft) evolve at various rates of improvement.

The effect of alternative fuels are then modelled downstream to technology and operations scenarios. This generally requires a range of assumptions, including; (1) jet fuel replacement rate and (2) lifecycle emissions of alternative fuels.

Finally, the inclusion of emissions reductions from other sectors through market-based measures were considered and evaluated.

The steps described above constitute the CO<sub>2</sub> emissions forecasting process. As described in the report, some W2050 SAF scenarios were developed using a 'backcasting' approach where the modelling assumptions are adjusted such that the resulting emissions forecast meet 90% of the fuel replacement in 2050.





## Fleet evolution methodology and fuel burn modelling

A methodology developed by the German Aerospace Centre (DLR)<sup>44</sup> is used to model the introduction of novel aircraft configurations into the world fleet and to assess their impacts on global CO<sub>2</sub> emissions of air transport. It consists of two separate modules:

- » Evolution of the world fleet of commercial passenger aircraft (steps 1-4).

Forecast of the evolution of fuel and CO<sub>2</sub> efficiency based on fuel consumption and performance information of each aircraft model, and global CO<sub>2</sub> emissions and traffic calculated by aggregating the single aircraft estimates (steps 5-6).

The fleet forecast used here is a bottom up forecast based on year-to-year dynamics.

- » The first step is to identify today's fleet of aircraft from the Cirium Fleets Analyzer
- » From the detailed information provided by Cirium Fleets Analyzer, the following year's retirements are then projected for each make and model in the world fleet, based on the specific age of each active aircraft. The retirement process is driven by retirement curves based on ICAO-CAEP/9 version. These curves are estimated through a survival analysis from historical data.
- » The next step is estimating the number of additional aircraft needed to satisfy the selected traffic growth scenario.

- » The sum of aircraft needed for replacement and growth constitutes the next year's aircraft demand = new aircraft deliveries. The original aircraft that are forecasted to remain active (i.e. are not retired) plus the new aircraft deliveries (including yet unfixed make and model) make up the new world fleet. This process of simulating yearly fleet changes is repeated until the final year of the forecast period is reached.

The number of seats is individual for each aircraft and is taken from the Cirium Fleets Analyzer database. New aircraft configurations enter the world fleet through projected deliveries of 'fixed demand' (order backlog) and 'unfixed demand' (future generic aircraft to satisfy the projected demand, but that are not ordered yet).

It is not aimed to detail the realisation of unfixed demand by forecasting market shares for specific makes and models. Instead, the demand in each seat category is represented by a 'generic aircraft'. This generic aircraft stands for the average delivered aircraft of a specific forecast year. A higher share of more efficient aircraft is represented by a gradually improving fuel efficiency of the generic aircraft over the years. This modelling method thus accounts for the combined impact of a fleet of multiple aircraft models. All assumptions regarding the impact of new aircraft projects, market shares, ramp-up times and technology on aircraft fuel efficiency in a specific size category can be reflected by adjusting a single parameter: the technology factor (fuel function multiplier) of the generic aircraft in the respective size category.

## Assumptions on aircraft types (i.e., seat category) available for growth and replacement

While the technology scenarios were developed for large aircraft categories i.e., with seats above 500, the absence of a proposed replacement for the A380 (i.e., A380neo) or any other market announcement required the consideration of how to address potential demand for such aircraft types. The default (base case) analyses presented in the report assume the absence of such future aircraft where traffic for 501+ seat categories was shifted i.e., serviced by the 401-500 seat category.

While assumptions on particular products – especially given the long time frame of forecasting required by the 2050 Waypoint project – were not made, a sensitivity analysis was conducted between the default (base case) scenario described above and a scenario where hypothetical aircraft could fulfill traffic in the 501+ seat category. It was observed that this assumption has very little impact on the overall CO<sub>2</sub> emissions trajectory, where differences between both scenarios are on the order of 0.2% in 2050.

## Developing new energies pathways: hydrogen and electricity

To assess the potential demand, requirements, and costs (investments) associated with electric and hydrogen powered aviation, a working group of industry experts was formed. The group collected and conducted a review of publicly available documents and reports on hydrogen and electricity as energy sources for direct use by global aviation in the coming decades. Using the first edition of the Waypoint 2050 scenarios and analyses as a starting point, potential aggregate demand for electricity and hydrogen was estimated for the T4 and T5 scenarios. Scenarios were complemented with additional information available since the publication of the first edition of the Waypoint 2050 study, including technical assessments and studies from members of the Working Group. Finally, the group conducted a first order assessment of the potential requirements and costs associated with hydrogen and electricity associated with relevant W2050 scenarios.

## Sustainable aviation fuel deployment

A host of factors drive the decisions made in the market today, including national and international regulations, technologies, local feedstock availabilities, the availability of infrastructure to re-use and the available demand. The analysis undertaken as part of the Waypoint 2050 process by ICF (and outlined in full in the report *Fuelling Net Zero*) assumes that the complex reality can be distilled into two key factors that drive the macro trends: The cost of the fuel, and limitations on the availability of feedstocks.

The cost of SAF is simplified to the feedstock cost, plus the allocated facility cost, minus the environmental value. Extensive analysis has been conducted to estimate the cost for each feedstock, and a detailed model has been built to calculate the infrastructure costs. Regulation drives the market today, and this model simplifies the complex patchwork of policies, mandates, and incentives to a single environmental value for the carbon reduction delivered by the SAF, built from an analysis from the current and potential

carbon reduction for each pathway and forecasts for the value of carbon reductions over the next three decades.

Each region has a different set of feedstocks available, imposing a varied set of constraints to the development of the local SAF industry. This report investigates these limitations to show the opportunity for the different feedstocks and technologies in each region.

SAF demand is an input to this method. The required volume is based on analysis developed by the extensive Waypoint 2050 process.

The analysis estimates the most economic use of feedstocks and technologies in each region to achieve this demand, with allowance made for both in-year costs, and investments in more expensive current production methods to mature the technologies for future widespread deployment. The analysis calculates the annual combined feedstocks and facility costs, accounts for the carbon value and then uses a merit ranking approach to distribute the incremental capacity. This process is repeated for each year of the analysis, with a variety of mechanisms and adjustments to help the model better reflect reality.

# GLOSSARY

## Terms

### Net-zero emissions

Also known as climate neutrality (although the terms have different technical connotations), net zero emissions is reducing emissions to as close as possible to nothing, with the remaining emissions compensated for through offsets or technologies such as carbon capture to remove CO<sub>2</sub> from the atmosphere.

### Offsets

In many parts of this report, 'offsets' is used as shorthand for out-of-sector carbon removal: the process to pay for removal of CO<sub>2</sub> from the atmosphere (or avoid CO<sub>2</sub> emissions) through traded carbon credits. Currently, these include traditional carbon offsets such as renewable energy schemes, but in the future these sources should be exhausted and sectors will rely on afforestation, natural carbon sinks and technologies such as carbon capture and direct air capture to remove CO<sub>2</sub> from the atmosphere.

## Abbreviations

### 2DS

Two degree scenario (of the International Energy Agency)

### ACI

Airports Council International

### ATAG

Air Transport Action Group

### ATK

Available tonne kilometres: a measure of aviation's total passenger and cargo capacity, calculated as capacity in tonnes x kilometres flown

### ATM

Air traffic management

### ASTM International

The global agency which manages the certification process for fuels, including sustainable aviation fuel

### B2DS

Beyond two degree scenario (of the International Energy Agency)

### BECCS

Bio-energy with carbon capture and sequestration

### BWB

Blended wing body

### CAEP

Committee on Aviation Environmental Protection

### CAGR

Compound annual growth rate

### CANSO

Civil Air Navigation Services Organisation

### CCS

Carbon capture and sequestration

### CNG

Carbon-neutral growth: where activities of an industry (traffic, in aviation's case) continues to grow, but the CO<sub>2</sub> emissions are reduced or compensated for to stabilise at a given level.

### CORSIA

Carbon Offsetting and Reduction Scheme for International Aviation

### ETP

Energy technology perspectives (of the International Energy Agency)

### ERF

Emissions reduction factor: the lifecycle CO<sub>2</sub> benefit of sustainable aviation fuel, once CO<sub>2</sub> reduced through the production or growth of the feedstock, and production CO<sub>2</sub> has been accounted for.

### DACCS

Direct air capture and carbon sequestration

### IATA

International Air Transport Association

### ICAO

International Civil Aviation Organization

### ICCAIA

International Coordinating Council of Aerospace Industries Associations

### IEA

International Energy Agency

### LCFS

California's Low Carbon Fuels Standard

### O&I

Operations and infrastructure

### PtW

Pump to Wake

### RPK

Revenue passenger kilometres: a metric which multiplies each passenger carried one kilometre. This is the metric used throughout this report to identify traffic trends

### RED II

European Union's second Renewable Energy Directive

### RTK

Revenue tonne kilometres: a metric tonne of revenue load – passengers and cargo – carried one kilometre

### RTS

Reference technology scenario (of the International Energy Agency)

### SAF

Sustainable aviation fuel

### UNFCCC

United Nations Framework Convention on Climate Change

### WtW

Well to wake

## Units

### Gt

Gigatonne (1 billion tonnes)

### Mt

Megatonne (1 million tonnes)

### TWh

Terrawatt hour (unit of energy equal to outputting one trillion watts for one hour)

### MWh

Megawatt hour (unit of energy equal to outputting one million watts for one hour)

### MW

A million watts

### EJ

Exajoule (unit is used in discussing energy budgets. The global primary energy production in 2019 was 581 EJ)

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- <sup>117</sup> IEA <https://bit.ly/32xSbZX>
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- <sup>119</sup> International Energy Agency *Electricity Information*, September 2019: low carbon sources include: biofuels and waste (2%); solar (2%); wind (4%); geothermal, tidal, other (1%); hydro (16%); nuclear (10%). Fossil electricity sources include natural gas (23%); oil (3%); and coal (38%). [www.iea.org/reports/electricity-information-2019](http://www.iea.org/reports/electricity-information-2019)
- <sup>120</sup> International Energy Agency OECD gross electricity production by source, 1974-2018 <https://bit.ly/3hsA1gh> and electricity from renewables are expected to grow by 50% between 2019 and 2024 alone: [www.iea.org/reports/renewables-2019](http://www.iea.org/reports/renewables-2019)
- <sup>121</sup> BloombergNEF *New Energy Outlook 2019*: [www.bloomberg.com/graphics/2019-can-renewable-energy-power-the-world/](http://www.bloomberg.com/graphics/2019-can-renewable-energy-power-the-world/). Low carbon includes nuclear, but the report suggests renewables will provide 50% of the global electricity supply by 2037 and will cross the 50% mark at different rates in these countries: Japan (2036), China (2036), UK (2025), Germany (2022), France (2036 - although if you include nuclear, France is nearly 100% low carbon already).
- <sup>122</sup> IEA analysis, electricity from renewables are expected to grow by 50% between 2019 and 2024 alone <https://bit.ly/33vlqf9>

<sup>125</sup> Data from ICF *Fuelling Net Zero* analysis for Waypoint 2050, augmented with analysis from ATAG / IATA Environment and IATA Economics. Jet fuel shown with a range of 2000-2020 high of \$180 per barrel (\$1,415 a tonne) in July 2008 and a low of \$40 per barrel (\$314 a tonne) in 2016.

<sup>126</sup> ICF Analysis in *Fuelling Net Zero*, commissioned by ATAG for Waypoint 2050, September 2021.

<sup>127</sup> International Energy Agency *Oil 2020*, 2020:  
[www.iea.org/reports/oil-2020](http://www.iea.org/reports/oil-2020)

<sup>128</sup> International Energy Agency capital expenditure by oil and gas companies <https://bit.ly/2ZGIBDj>

<sup>129</sup> International Energy Agency *Energy Subsidies Database*  
<https://bit.ly/32whYlp>

<sup>130</sup> Energy Information Administration:  
[www.eia.gov/international/overview/world](http://www.eia.gov/international/overview/world)

<sup>131</sup> ICF Analysis in *Fuelling Net Zero*, commissioned by ATAG for Waypoint 2050, September 2021.

<sup>132</sup> Waypoint 2050, using data from IEA and IRENA

<sup>133</sup> Policy suggestions include items generated by The Atlantic Council *SAF Policy in the United States*, April 2020 by Fred Ghatal <https://bit.ly/3iznk19>

<sup>134</sup> World Bank, *State and Trends of Carbon Pricing 2021*, May 2021:  
<https://openknowledge.worldbank.org/handle/10986/35620>

<sup>135</sup> World Bank, *State and Trends of Carbon Pricing 2021*, May 2021.

<sup>136</sup> Climeworks: [www.climeworks.com](http://www.climeworks.com)

<sup>137</sup> Nature Communications *An inter-model assessment of the role of direct air capture in deep mitigation pathways*, July 2019:  
[www.nature.com/articles/s41467-019-10842-5](http://www.nature.com/articles/s41467-019-10842-5)

<sup>138</sup> Carbon Engineering: [www.carbonengineering.com](http://www.carbonengineering.com)

<sup>139</sup> World Bank, *State and Trends of Carbon Pricing 2020*, May 2020.

<sup>140</sup> Fires in Indonesian peat swamp forests in 2015, for example, emitted nearly 16 million tonnes of CO<sub>2</sub> a day. This is more than the daily emissions from the entire US economy. At the same time, peatlands are the largest natural terrestrial carbon store. Worldwide, the remaining area of near natural peatland (~3 million km<sup>2</sup>) contains more than 550 gigatonnes of carbon, representing 42% of all soil carbon and exceeds the carbon stored in all other vegetation types, including the world's forests. This area sequesters 0.37 gigatonnes of CO<sub>2</sub> a year. International Union for the Conservation of Nature, 2020 <https://bit.ly/3kkeqZy>

<sup>141</sup> World Resources Institute, 2017 <https://bit.ly/32y1wUd>

<sup>142</sup> International Energy Agency, *Energy Technology Perspectives 2020*

<sup>143</sup> Energy Strategy Reviews, *An assessment of CCS costs, barriers and potential*, Sara Budinis, Samuel Krevor, Niall Mac, Dowell Nigel, Brandon Adam Hawkes

<sup>144</sup> Nolte, 2012

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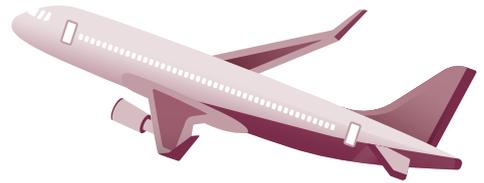
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