INSIGHT

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Introduction

The environmental impact of aviation is the single biggest challenge for the sector in the long term, but it also represents an opportunity to bring forward new technologies that deliver both environmental gains and economic returns for the UK. This INSIGHT sets out how the Aerospace Technology Institute is addressing the sustainability of air transport. The approach draws upon consultations with a wide selection of aviation industry stakeholders. The ATI intends to accelerate progress towards sustainability through its R&T investment, advancing technologies that address aviation's impact on the environment and developing environmental modelling tools to guide strategies that achieve maximum benefit.

16 SUSTAINABLE AVIATION: *ATI Framework*

EXECUTIVE SUMMARY

The ATI's technology strategy, *Accelerating Ambition*, identifies sustainability as a key priority for the air transport industry. It states: "the UK aviation industry should lead on meeting environmental imperatives and setting an ambitious sustainability agenda." This paper is a call to arms to stimulate UK and international dialogue and action to enable a sustainable future.

Sustainability is achieved through a balance that provides benefits to society and the economy without causing damage to the environment. The social and economic benefits of air transport are widely reported. However, air transport emissions including carbon dioxide (CO_2), nitrogen oxides (NO_x), and water vapour, sulphur oxides (SO_x) and smoke (carbon particulate matter - PM) which can lead to contrails contribute at least 3.5% of climate impact. This contribution is increasing with the growth of the global air transport market. Air transport also affects the environment in and around airports through NO_x, PM emissions, and noise. Aircraft manufacturing consumes raw materials, generates waste, and consumes energy. Scientific, social, and political pressure to act faster to reduce the impacts of air transport is now at unprecedented levels.

New technologies have improved the sustainability of aviation, but the growth of the sector has outpaced this improvement. And this growth is expected to resume despite the deep recession currently facing the industry caused by Covid-19. Many evaluations of the long-term potential for technology insertion agree that incremental progress will not suffice to achieve goals such as those set by the Advisory Council for Aerospace Research in Europe (ACARE) in its FlightPath 2050 report. Broader solutions incorporating alternative energy sources, operational enhancements, carbon offset, and market-based measures will be required to achieve these goals and to progress towards net zero carbon. The scale of the global climate challenge and the need to respond faster demand step changes in resolve and innovation.

The ATI is committed to enabling industry to deliver leading sustainability solutions. It will use its technology investment strategy, model development work, environmental footprint lifecycle analysis, and cross-sector influence to lead thinking and action. Our aim is to future-proof aviation by investing in a portfolio of technologies with the best chance of achieving carbon neutrality for the UK by 2050, and abating other climate change and air quality impacts, reducing noise, and delivering sustainably manufactured aerospace products.

HOW DOES AVIATION BENEFIT SOCIETY?

Air transport lets people **travel and connect**; it allows goods and services to reach market **faster** and to **access remote places**. It is made possible by a **highly-skilled workforce**

PEOPLE

There were **4.5 billion** air passengers last year - more than half of the world's population

Air transport brings people together by connecting **22,000 city pairs** with **100,000+ flights** per day (average in 2019)

SKILLS

An employee in the aviation sector contributes **4.4 times more** to the economy than the average employee in other sectors

CONNECTIVITY

50% of all international tourists reach their destination by air

Air transport enables access to remote locations for passengers, medical services, and many other essential services

HOW DOES AVIATION BENEFIT THE ECONOMY?

Air transport **supports jobs** worldwide. The sector enables **growth** for businesses, in tourism and in trade for high value, time-sensitive goods

JOBS

87.7 million jobs worldwide including direct and indirect jobs

11.3 million direct jobs with the remainder 76.4 million split between tourism, indirect and induced jobs

VALUE

If the aviation sector were a country it would be the size of the **United Kingdom** in terms of **economic value to the global economy** and the **number of people the sector employs** overall

TRADE

34.6% of global trade by value ($6 trillion in 2017)

HOW DOES AVIATION IMPACT THE ENVIRONMENT?

Eliminating its impact on the environment is the **single biggest challenge** for the aviation sector

EMISSIONS

Aviation tail-pipe emissions are estimated to contribute more than **3.5% to global human-induced climate impact** causing irreversible damage to the environment

WASTE

Manufacturing of components can generate up to 90% waste from their raw materials.

80-85% of aircraft are re-used or recycled (in weight); however widespread use of composite materials pose a challenge. And ever more aircraft are being retired

NOISE and LOCAL AIR QUALITY

Local air quality emissions and noise in the vicinity of airports **cause adverse health effects** and **affect quality of life and wellbeing**

MATERIALS

Some critical materials and processes are **hazardous** to the environment. Such materials need to be carefully managed throughout their **lifecycles**

ENVIRONMENTAL IMPACT OF AIR TRANSPORT

EMISSIONS

There is broad consensus that human activities are accelerating climate change, which, without urgent action, will have major effects on how we live. Better climate science will improve understanding of how air transport affects the environment and which technologies can help. Many global and national strategies focus on reducing carbon; air transport contributed about 2% of human-induced CO_2 emissions in 2019[1]. Essential though it is to reduce CO_2, aviation also produces emissions such as nitrogen oxides (NO_x), particulates and condensation trails that contribute to climate change. Together with CO_2, these put the estimated climate impact of aviation closer to 3.5%. Latest estimates show this could be even higher[2] as uncertainties remain about the effect of various greenhouse gases.

The airport environment is impacted by NO_x and PM emissions from aircraft, airside operations and road vehicles. Whilst these represent a small proportion of overall UK emissions (around 1% of NO_x and 0.1% of PM_{10} – particles smaller than 10 micrometres across)[3], they nevertheless cause ill health.

NOISE

Aircraft noise can affect the quality of life and wellbeing of those living under flight paths. Scientific evidence suggests that noise can affect cardiac and mental health, sleep patterns, and learning. Whilst the latest aircraft are over 70% quieter than the earliest jets, the frequency of overflight has grown substantially and is a major source of aggravation for airports and their surrounding communities.

MATERIALS

Turning to manufacturing, some critical materials and processes used in the air transport industry are hazardous to the environment. Such materials need to be carefully managed throughout their lifecycles: from extraction and refining, to manufacturing, operational use, and recycling and disposal. The European Union's 2016 REACh regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) has restricted the use of certain materials traditionally used for components and coatings in aerospace and required their elimination by defined dates. Consequently, many organisations have established alternative manufacturing processes to ensure compliance and reduce the sector's impact on the environment.

WASTE

Waste and effluents from aircraft manufacture, aircraft operations, and end-of-life disposal also impact the environment. Historically, aircraft manufacturing has generated large amounts of scrap, with some components generating 90% scrap from their raw materials. New near net shape technologies are improving this and reducing the energy needed for manufacturing. For retired aircraft, it is estimated that 40% to 50% of their weight is returned into the parts distribution market. A further 40% or more is either repurposed for use in other sectors or recycled[4] with the remainder 15% to 20% being disposed of or ending up in landfill. The cost of aircraft end-of-life recycling is high and in many cases is not significantly offset by the value of reclaimed materials. More work is needed to improve circularity and the recycling of difficult materials such as composites which are increasingly used in aircraft structures.

The International Civil Aviation Organisation (ICAO) has taken a global regulatory lead on the sector's environmental performance. It has set CO_2 limits for aircraft that now constitute a globally adopted certification standard[5]. In addition, it has established limits for NO_x and smoke, which have become more stringent over time, increasing pressure on aircraft and engine suppliers to develop emissions reduction technologies in response. On noise, ICAO has set limits for aircraft take-off and approach; these have also become stricter over time, similarly placing pressure on manufacturers to develop noise reduction technologies and driving the use of quieter flight paths.

As public concern about aircraft noise grows and the scientific understanding of the impact of localised pollution on health improves, aviation, like other sectors, will come under increasing pressure to introduce more technological and operational solutions. This is likely to be reflected in future ICAO rules as well as stringent local requirements set by some airports.

[1] *ATAG estimates, 2018: https://www.atag.org/facts-figures.html*
[2] *Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q.,Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J., Gettelman, A., De León, R.R., Lim, L.L., Lund, M.T., Millar, R.J., Owen, B., Penner, J.E., Pitari, G., Prather, M.J., Sausen, R., Wilcox, L.J.,*
The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment (2020), doi: https://doi.org/10.1016/j.atmosenv.2020.117834.
[3] *Sustainable Aviation UK Aviation and Air Quality Report, 2018: https://www.sustainableaviation.co.uk/wp-content/uploads/2018/06/SA-A4_UK-Aviation-and-Air-Quality_Report1.pdf*
[4] *ICAO Environmental Report, 2019: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg279-284.pdf*
[5] *https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_HI-RES_190311.pdf*

SUSTAINABILITY LIFECYCLE ANALYSIS

The ATI approach is to pursue a broad sustainability agenda. To address the overall environmental impact of air transport, a whole aircraft lifecycle approach is required encompassing development, manufacture and assembly, 20-25 years of use and end-of-life disposal. Similarly on fuels, a well-to-wake approach is needed to minimise the impact of production, distribution and use of hydrocarbons (whether fossil fuel kerosene or more sustainable alternatives), or any other alternative energy sources for aircraft, such as hydrogen or batteries. This whole lifecycle approach is outlined below.

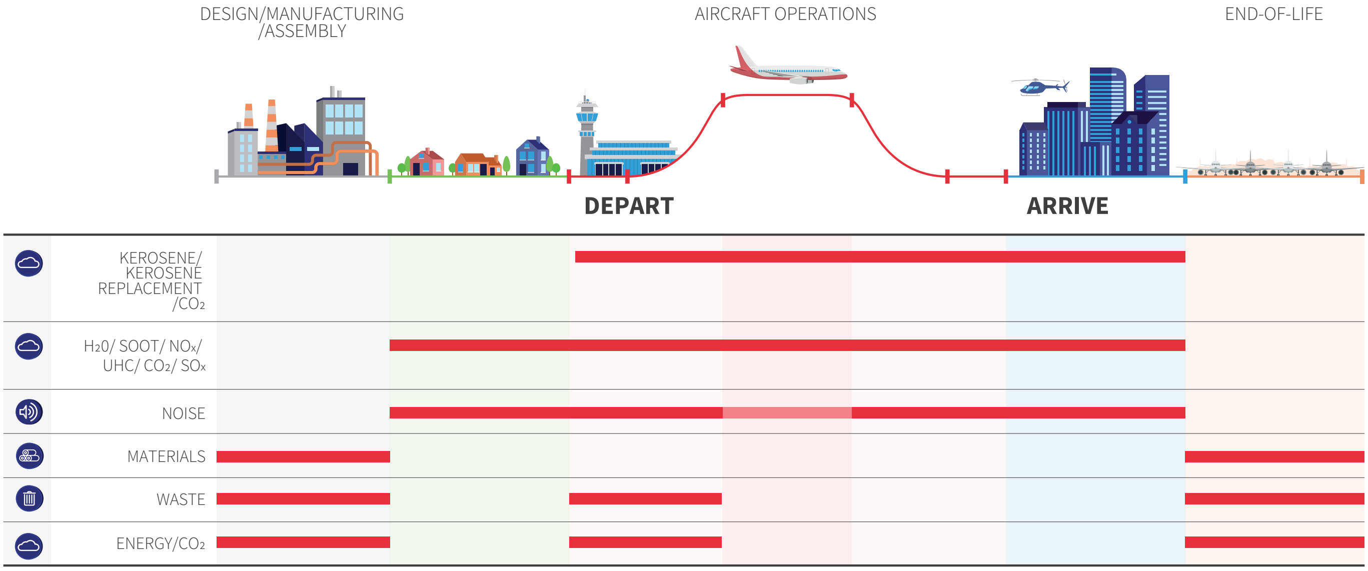


Figure 1: Lifecycle aircraft and wider aviation sources of environmental impact

THE RACE TO NET ZERO CARBON

Public concern has been growing about the increasing CO_2 emissions from human activities and their impact on the climate. As demand increases, leading to growth in global air transport and its associated CO_2 emissions, pressure has been mounting on the sector to decarbonise.

Why is air transport so difficult to decarbonise?

Air vehicles require a lot of energy to propel them and accelerate to a high enough speed for the wings to generate enough lift to take-off, and to maintain sufficient airspeed to stay aloft. The higher the take-off weight of the aircraft, the more energy required. The larger the aircraft, the higher the frictional forces from the air (drag), requiring more energy to overcome them. Except for some military aircraft, all air vehicles must carry the energy required to propel them and power their onboard systems. The best energy sources for aircraft therefore offer the highest energy per unit mass and per unit volume. Kerosene has by far the best combination of these characteristics of any known energy source suitable for air vehicles. Kerosene has a range of other useful characteristics: relatively low volatility and flammability, making it easier to handle; it remains liquid over the wide range of external air temperatures that air vehicles will encounter; it serves as a coolant, lubricant and hydraulic fluid; and it is relatively low-cost. Furthermore, its stored chemical energy can be efficiently released and converted into propulsive thrust by burning it in a lightweight, highly reliable jet engine. But for every tonne of kerosene burnt, around three tonnes of CO_2 emissions are generated. Globally in 2019, flights emitted over 900 million tonnes of CO_2 from burning some 300 million tonnes of kerosene[6].

Carbon abatement strategies

A range of carbon abatement measures have been identified for reducing aviation tail-pipe emissions (see figure 2)[7]. In the UK, the Sustainable Aviation coalition's carbon report[8] includes a roadmap for decarbonising UK aviation tail-pipe emissions.

Carbon abatement will be achieved via a combination of the following measures:

- Improvements in ***aircraft technology;***
- Aircraft ***operational improvements;***
- Increased use of ***sustainable aviation fuels (SAF);***
- Implementation of various ***market-based measures*** such as taxation, incentives, carbon pricing and offsetting carbon in other areas of the economy for those CO_2 emissions that cannot be abated through the above mechanisms.

Contribution of measures for reducing international aviation net CO_2 emissions

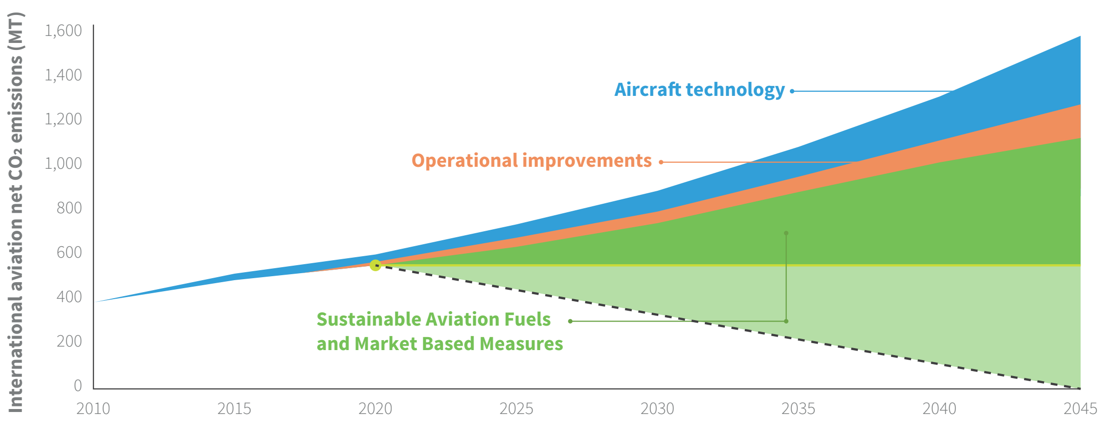
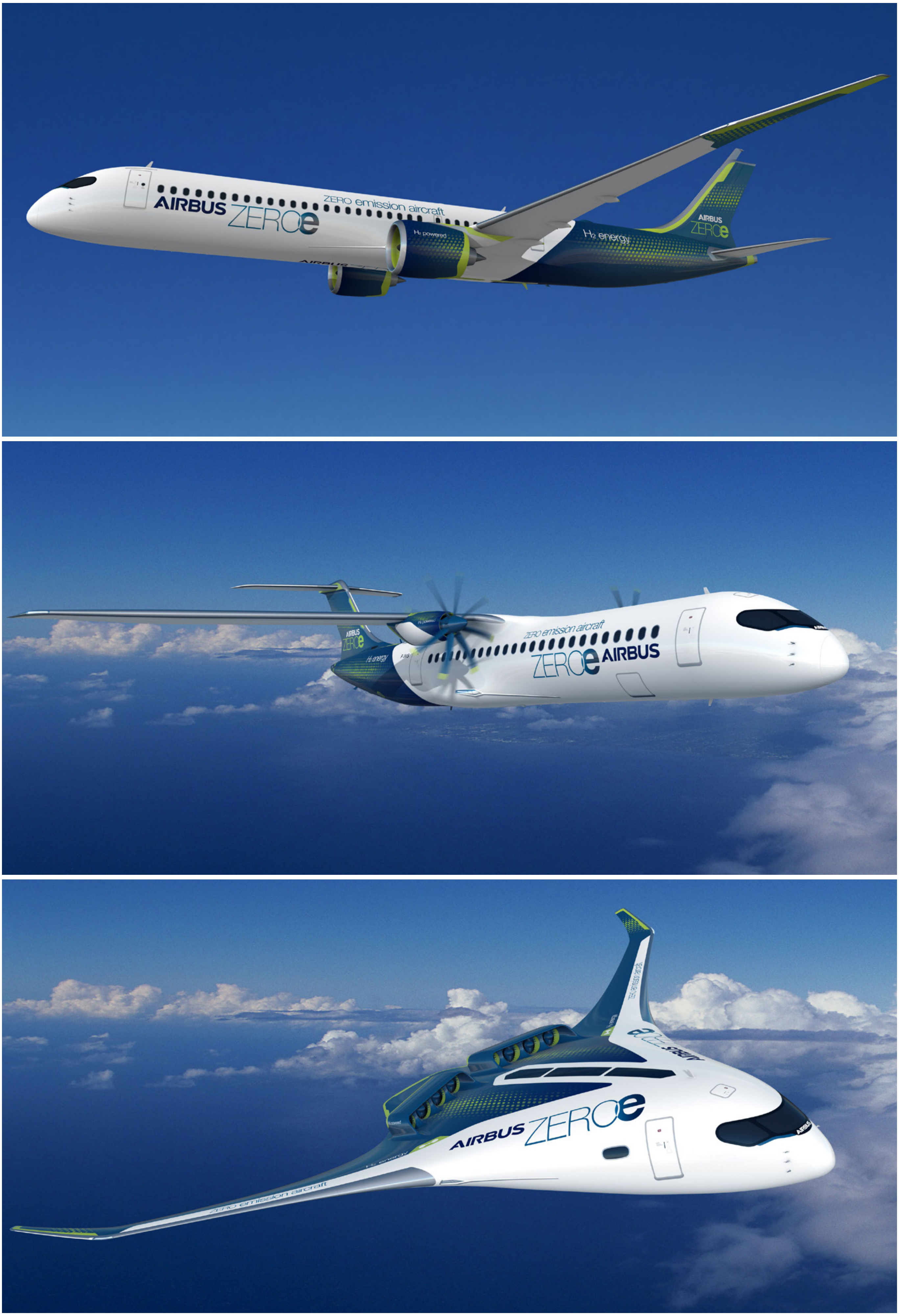


Figure 2: Modified carbon roadmap based on original ICAO Global Environmental Trends on CO_2 Emissions and Contribution of Measures for Reducing International Aviation Net CO_2 Emissions (Source: ICAO 2019 Environmental Report[9])

The ATI's technology programme invests around 50% of its funding towards technologies that directly reduce aviation emissions. Most of the remaining 50% will also contribute either directly or indirectly to improving the broader sustainability of the industry.

[6] *ICCT data 2019: https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf*
[7] *ICAO Global Environmental Trends on CO_2 Emissions and Contribution of Measures for Reducing International Aviation Net CO_2 Emissions:https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20(1).pdf*
[8] *UK Sustainable aviation carbon roadmap: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf*
[9] *ICAO 2019 Environmental Report: https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20(1).pdf*



Airbus ZEROe hybrid-hydrogen concept aircraft

AVIATION TARGETS AND GOALS

Setting targets and goals has been very effective for aviation, driving ambitious action by industry, research organisations, and governments. It is essential to track the impact of technologies on progress towards cleaner aviation to steer efforts and shape future targets.

ATAG AIR TRANSPORT ACTION GROUP

2008 ATAG Declaration

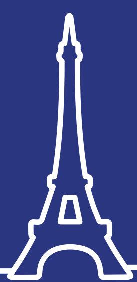
The Air Transport Action Group, a global coalition of member organisations and companies in aviation, committed to progressive global fleet CO_2 reductions through an annual 1.5% fuel efficiency improvement between 2009 and 2020, stabilising aviation net CO_2 emissions at 2020 levels, and reducing net CO_2 emissions to 50% of those in 2005 by the year 2050.

ACARE

2011 ACARE Flightpath 2050

The European Union committed to technology goals to reduce emissions in the air and on the ground, and to increase aircraft recyclability, all by 2050. These targets are relative to a typical new aircraft in the year 2000.

- CO_2 ⬇75%
- NO_x ⬇90%
- Noise ⬇65%
- Designed to be recycled
- Zero on ground



DASSAULT AVIATION · BOEING · ROLLS ROYCE · GE Aviation · AIRBUS · SAFRAN · United Technologies

2019 Paris Airshow CTO Statement

The 2019 Paris Airshow saw CTOs from seven of the world's largest civil aerospace companies declaring their continued commitment to environmental targets and goals set out by ATAG and ACARE.

2020 ICAO Carbon Neutral Growth

ICAO established a goal for carbon neutral growth from 2020, which is broadly similar to ATAG. This will be largely delivered through offsetting via the CORSIA[10] scheme which enters its pilot phase in 2021.

CORSIA

2020 UK Net Zero Carbon

The UK's Sustainable Aviation coalition, including airlines, airports and aircraft manufacturers, committed to working towards zero net carbon emissions for UK aviation by 2050[11]. They have produced strategies and roadmaps for carbon abatement, noise and alternative low carbon fuels.

SUSTAINABLE AVIATION

2020 European Green Deal

The European Green Deal proposed by the European Commission includes a law to implement the 2050 climate-neutrality objective.

The European Green Deal

2022 ICAO Long Term Aspirational CO_2 Goal

Working groups established by ICAO are exploring a long-term global goal for CO_2 emissions. A decision is expected at the 41st ICAO Assembly in 2022

ICAO

Although many of the industry goals and approaches have been aspirational and voluntary, it is likely that ICAO and national authorities will consider them when setting enforceable emissions limits.

Since its formation, the ATI as an organisation and through individuals in our advisory network, has been active in defining future targets, goals and strategies in the UK, including through Sustainable Aviation and in Europe as a member of ACARE and its working groups.

PROGRESS TO DATE AGAINST TARGETS AND GOALS

The aviation industry has consistently delivered aircraft fuel efficiency improvements of at least 1.5% per year for the past decade, in line with the ATAG[12] climate targets. In Europe in 2017, average fuel consumption per flight for commercial flights had decreased by 24% since 2005[13]. In the same timeframe, the total CO_2 and NO_x contributions from all European flights had increased by 16% and 25% respectively[14]. The steady growth in passenger demand has outpaced the improvements from better technologies. Covid-19 apart, this trend is likely to continue unless faster progress can be made on technology and other measures.

Between 2005 and 2017 the average noise per flight reduced by 14%[15]; however, the number of people living in close proximity to major European airports (and therefore exposed to noise) increased in the same proportion.

The following sections cover progress towards CO_2, NO_x, and noise targets that have been achieved and future necessary improvements to achieve ACARE Flightpath 2050 goals. The analysis focuses on aircraft and propulsion technologies. Improvements from operations have yet to be quantified.

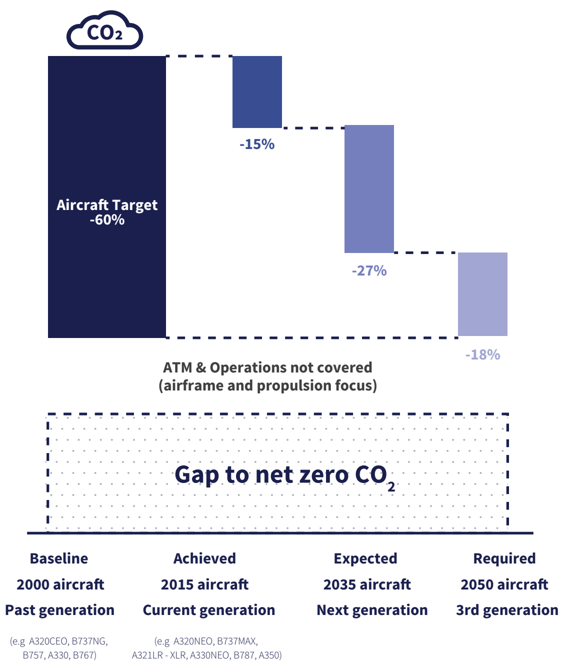
The ACARE Flightpath 2050 targets are set relative to the baseline performance of typical new aircraft in the year 2000. They envisage performance improvements through successive aircraft generations, as follows:

- the ***current generation*** of aircraft, with a technology standard dated around 2015, which is now replacing the 2000 aircraft generation;
- the ***next generation*** of aircraft is expected to enter into service in around 2035, with technologies developed up to that time; and
- the ***third generation*** of aircraft with technologies developed between 2040 and 2050.

Progress on aircraft CO_2 reduction

The ACARE Flightpath 2050 goal for CO_2 is a 75% reduction by 2050 relative to 2000, with 60% coming from improved aircraft and operational improvements making up the remainder.

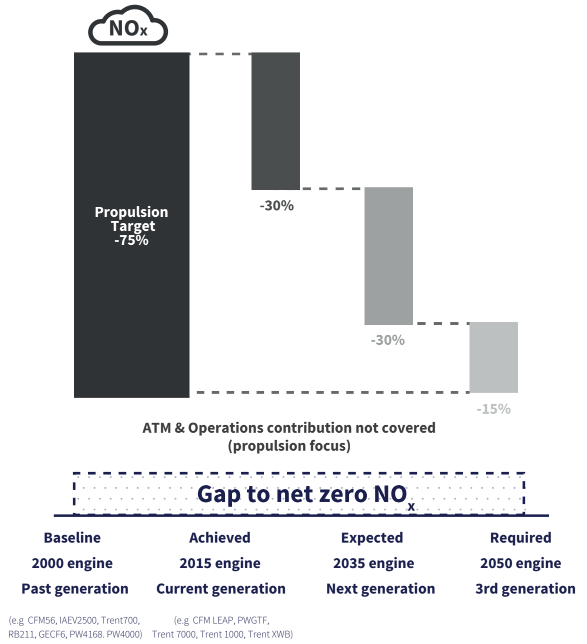
ATI's own aircraft models for a notional 4,000 nm[16] mission show that current aircraft are around 15% better than those in 2000, which is consistent with the Sustainable Aviation carbon report[17].



Next generation aircraft should target a further CO_2 reduction of about 30% (relative to 2015) to be in line with ACARE's 2050 target. However, analysis by the Clean Sky 2 Joint Undertaking[18] indicates the most likely reduction to be only around 20%, showing the level of the challenge.

Lower CO_2 emissions can come from better aerodynamics, such as higher aspect ratio wings, better engine nacelle integration, and the use of wingtip devices; and from lighter structures and materials such as low-weight high-strength alloys and composite materials. Engines will play a major role by improving fuel efficiency. Engine manufacturers have increased the pressure ratios in engines, from 30-40 in 2000 up to 50 today, for better thermodynamic efficiency; and they have increased engine bypass ratios from around 6:1 up to 12:1 for better propulsive efficiency. The next step will be increasing pressure ratios to around 70 and introducing ultrahigh bypass ratio (more than 15:1) technologies, to yield an additional 10% improvement in fuel efficiency.

[10] *https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx*
[11] *https://www.sustainableaviation.co.uk/news/uk-aviation-commits-to-net-zero-carbon-emissions-by-2050*
[12] *ATAG climate targets (https://www.atag.org/facts-figures.html)*
[13] *European Aviation Environmental Report (EAER) 2019 (https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_HI-RES_190311.pdf*
[14] *Ibid*
[15] *Ibid*
[16] *Nautical miles*
[17] *UK Sustainable aviation carbon roadmap: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf*[25] *ATAG climate targets (https://www.atag.org/facts-figures.html)*
[18] *2019 Aviation and the Environment Conference, Cranfield University: https://www.cranfield.ac.uk/events/events-2019/aviation-and-the-environment-conference-2019/aviation-and-the-environment-2019-presentations*

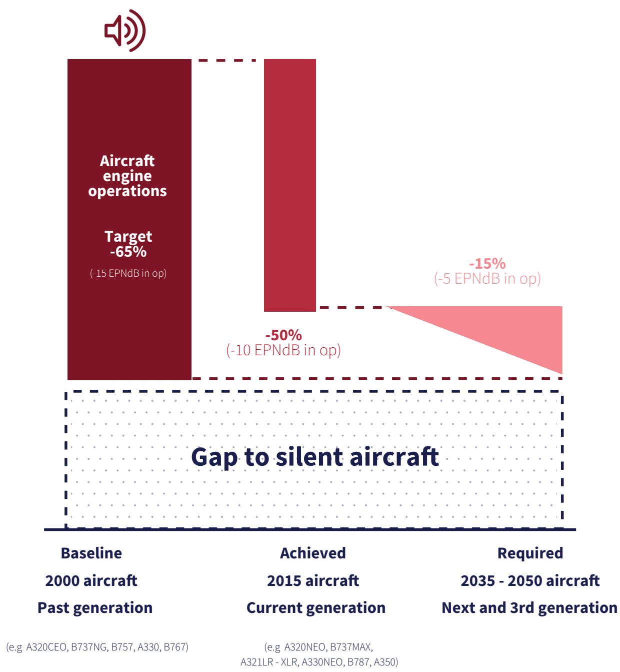


Progress on engine NOx reduction

The ACARE Flightpath goal for NOx is a 90% reduction by 2050 relative to 2000, with 75% coming from improved propulsion systems and the remainder from operational improvements.

Improving engine fuel efficiency via higher engine pressure ratios tends to increase NOx levels, requiring additional mitigation through better combustion technologies including rich-burn, quick-mix and lean-burn (RQL) combustors. These technologies have delivered improvements of around 30% in NOx for current engines, relative to 2000.

By 2035, ultra-high bypass propulsion systems will incorporate variable pitch fans and variable cycles for further efficiency, and additional combustion technology improvements are expected to deliver a further 30% improvement in NOx, totalling a 60% improvement against 2000.



Progress on aircraft noise reduction

Noise is generated by an aircraft from various sources including from its propulsion system, the airframe itself and from the landing gear particularly when approaching to land. Reducing perceived noise efficiently is achieved by improving the signature at whole aircraft level, not only via reduction of individual noise sources. Great attention must also be paid to how noise is experienced so that adoption of better, person-friendly metrics can guide those setting the direction of technology strategy. The ACARE Flightpath goal for noise is a 65% reduction (-15 EPNdB per op) relative to 2000, to be achieved via a combination of engine, operational improvements, and aircraft design. ATI analysis using data from EASA shows a reduction in aircraft noise of more than 50% (-10 EPNdB per op) over the past two decades. A further 15% reduction (-5 EPNdB per op) is required to achieve the ACARE FP2050 target.

Image from Airbus

Operational improvements

Air traffic management (ATM) has also delivered reductions in CO_2 emissions by enabling aircraft to fly closer to optimum routes for efficiency and reducing diversion hold. Improvements in perceived noise have been delivered through the implementation of steeper approaches. Further work is underway on how to avoid contrail formation. The ATI is reviewing data on all of these and further projections will be released in future.

ACHIEVING SUSTAINABILITY TARGETS

The industry is still some way from hitting sustainability targets and must move faster to outpace the effects of the growing market and fulfil public expectations to achieve net zero carbon.

Accelerating Ambition calls for UK aviation to lead on responding to environmental imperatives and to prioritise sustainability. To focus efforts, the ATI has created a sustainability technology framework defining the technology priorities to achieve this. A wide range of technologies and approaches need to be pursued and integrated to cover the spectrum of commercial aviation.

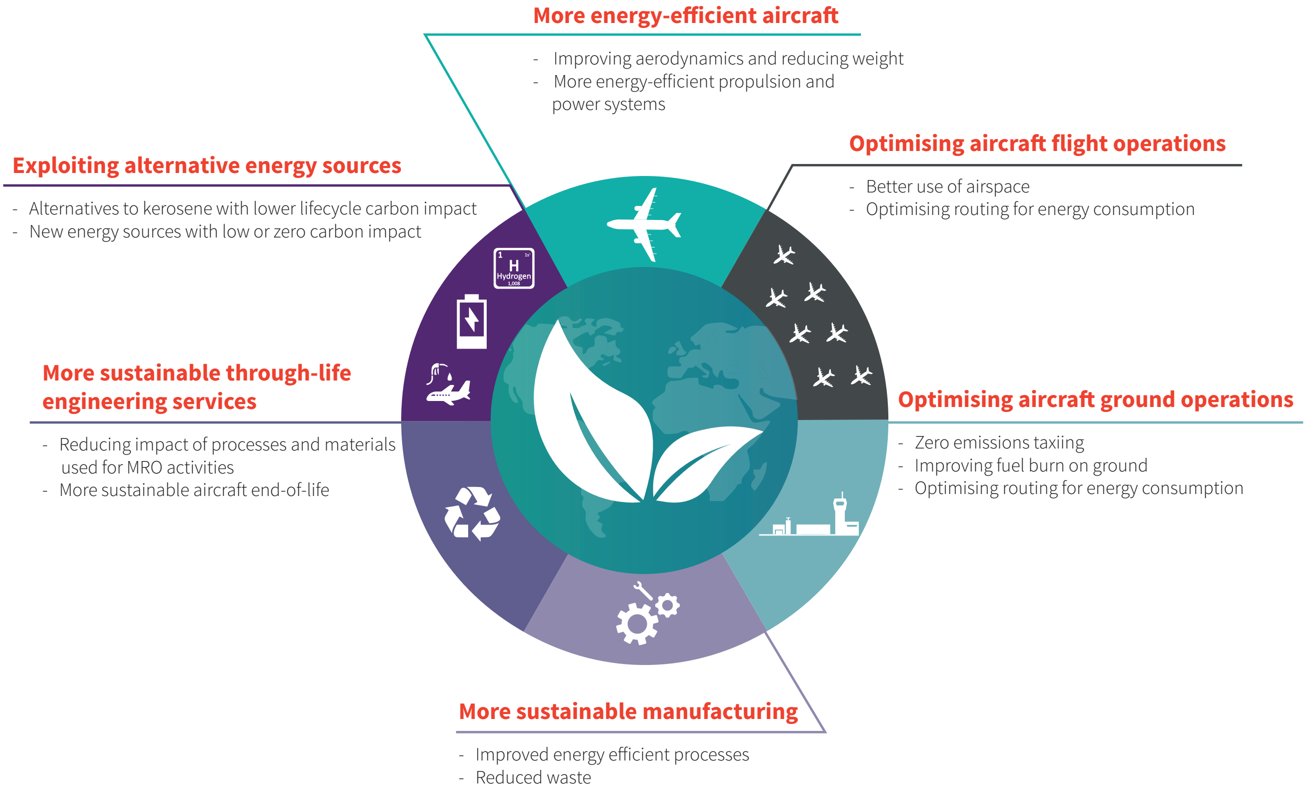


Figure 4: Aerospace Technology Institute sustainability technology framework

Optimising aircraft flight operations

Operational improvements benefit all air traffic, rather than individual aircraft. However, large investments are required to modernise airspace and air traffic management systems and to realise improved weather prediction and atmospheric data capabilities. In some cases, implementation also depends on new systems and software within aircraft.

The Institute is working with interested groups, such as the UK Future Flight Challenge[19], on how operational improvements can be taken forward.

Airspace management is fragmented, mostly following national borders, leading to inefficiencies in flightpath optimisation. Enabling optimum routing would bring considerable benefits. Initiatives such as the European Union's Single European Sky[20] could bring an estimated 3-5% reduction in CO_2 depending on aircraft type and route[21].

The lack of accurate data on flight positioning, scheduling and the weather leads to conservatism and inefficiencies in the system. Improvements over the next decade could reduce fuel burn by an average of 1.5%[22] per aircraft and flight by optimising cruise climb and continuous descent and reducing contingency and diversion hold. They could also help reduce noise in heavily populated areas and enable pilots to avoid regions where contrail formation is likely.

More energy-efficient aircraft

For the next generation of aircraft, improved aerodynamics should reduce CO_2 through developments such as higher wing aspect ratios and aeroelastic tailoring, folding wingtips, highly integrated high-lift systems, and improved engine integration. Some of these will also reduce noise on landing. Further structural integration and utilising additive manufacturing will save additional weight and emissions. Automated high-speed production processes will allow composite wings to be deployed on single aisle aircraft. These topics are all part of the ATI's investment in future wing technologies.

Approaching 2050, novel architectures such as flying wings or blended wing bodies could be introduced, possibly lowering CO_2 emissions by up to 30%[23] and reducing noise by placing their propulsion systems within or above the fuselage. However, they would necessitate substantial airport infrastructure investment. The ATI's FlyZero project will allow the UK community to explore these subjects in detail and develop technology projects.

For larger single aisle and widebody airliners, the next step will be the introduction of ultra-high bypass ratio turbofan engines. These will have optimised cores and increased pressure ratios, saving fuel and reducing noise. Lean burn combustion systems will deliver dramatic reductions in NO_x. Ultra-high bypass turbo fan technology is currently the largest element of the ATI programme; it is expected to be demonstrated in the next five years and be available towards the end of this decade. Future evolution will bring variable pitch fans and variable cycles for further efficiency.

For more radical aircraft, new propulsion and power systems employing batteries and hydrogen are being investigated, with some already flight-tested. Electrifying propulsion could allow more distributed systems (rotors, propellers, or tilt-rotor configurations) to deliver higher aerodynamic and fuel efficiency.

Optimising aircraft ground operations

ACARE Flightpath 2050 targets zero emission taxiing by 2050. Short term improvements can be made through procedures such as single engine taxiing, reducing start-up times, optimising ground track operations, and eliminating ground hold.

More efficient aircraft scheduling and electric taxiing would minimise the use of ground vehicles, further reducing carbon emissions and noise. Some aircraft ground operations will be investigated under the FlyZero programme, and the ATI portfolio includes technologies for more efficient and electric taxiing.

More sustainable manufacturing

Aerospace manufacturing is extremely challenging. Processing high-performance materials and complex structures can be difficult and energy intensive. More energy efficient processes and greater automation will reduce energy consumption and emissions.

Digital twins - digital replicas of physical components, parts, assemblies and their processes - will help to save energy by optimising processes, reducing scrappage and minimising re-manufacturing.

Aircraft manufacture can also generate much waste, with some components generating up to 90% scrap. Near-net shape (NNS) manufacturing, including forging, forming, casting, additive manufacturing and others, aims to produce parts as near as possible to their final shape to reduce machining and scrap.

Manufacturing and assembly technologies represent around 40% of the ATI portfolio, in conjunction with many companies and centres of excellence such as the High Value Manufacturing Catapult.

[19] *https://www.ukri.org/our-work/delivering-economic-impact/industrial-strategy-challenge-fund/future-of-mobility/*
[20] *European Commission Single European Sky initiative: https://ec.europa.eu/transport/modes/air/ses_en*
[21] *Understanding the potential and costs for reducing UK aviation emissions, Report to the Committee on Climate Change and the Department for Transport, November 2018*
[22] *Ibid*
[23] *Understanding the potential and costs for reducing UK aviation emissions, Report to the Committee on Climate Change and the Department for Transport, November 2018: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785685/ata-potential-and-costs-reducting-emissions.pdf*

Alternative energy sources

Batteries can produce carbon-free energy, provided the electricity used to charge them is green. However, their potential in aviation is limited as they have very low power and energy densities, severely compromising the endurance of all-battery powered aircraft. This is unlikely to change for some time. Thus battery-powered aircraft will suit only short-range applications such as general aviation and the anticipated new markets for personal air vehicles and air taxis. These represent a small proportion of CO_2 and NO_x emissions, and the new markets should in any case be served by net zero carbon aircraft from their outset. As many prospective battery-powered aircraft are intended for urban operation, they will need to be very low noise, posing a further tough challenge. The ATI programme is funding some battery all-electric and hybrid-electric projects. Batteries are freely available, but optimised for automotive applications. The ATI sees a big opportunity for aero-optimised batteries and is working to launch a dedicated aerospace battery project.

Green hydrogen in aircraft could eliminate carbon emissions. Hydrogen can power turbofan or turbo-prop engines, or fuel cells. This has potential in the next 10-15 years; the technology is ready, but production, distribution, and storage infrastructure would require high investment. Hydrogen has a higher energy per unit mass than kerosene, but its energy per unit volume is much lower. Even for liquid hydrogen, which must be stored at -253°C, fuel tanks would be several times the size of the kerosene equivalent. It follows that if it were possible to use hydrogen in existing aircraft, with the same tank volume, the range would be considerably less than that from kerosene. Despite its limitations and challenges, global interest in hydrogen as a medium-term net zero carbon possibility is increasing rapidly. The ATI programme is currently funding a project to develop a hydrogen fuel cell-powered aircraft; more projects will follow. There could be a market for hydrogen-powered regional and sub-regional aircraft (20-130 seats). The feasibility of hydrogen for longer ranges falls away because the increased storage requirement compromises the aircraft design. For example, a transatlantic hydrogen-powered airliner would be around 50% larger than an equivalent kerosene-powered aircraft, with accompanying increases in cost and overall energy usage. Increased energy efficiency would be key to minimising fuel tank capacity and aircraft cost.

Synthetic drop-in fuels will be essential for decarbonisation. These divide into synthetic biofuels, derived from for example biomass or waste; and synthetic electrofuels derived from combining green hydrogen and sustainably sourced CO_2[24]. The ATI is engaging with SAF experts on opportunities for projects. SAF are compatible with kerosene-powered aircraft, and would retain the same distribution and storage architecture as today.

The use of synthetic biofuels in aviation is still in its infancy. Although they provide significant CO_2 savings and other benefits, their uptake has been very modest and will remain so until their costs are reduced.

Synthetic electrofuels could offer benefits[25]. They are a much longer-term prospect, requiring high investment in R&T, process infrastructure, and green hydrogen. Producing them is energy intensive, requiring a combination of hydrogen and CO_2. It is estimated that the cost of e-fuel will be several times that of hydrogen. Clearly, with the high potential fuel cost, energy efficiency will gain even higher priority, capitalising on any improvements that hybrid power systems might bring.

[24] *The Royal Society, Sustainable synthetic carbon based fuels for transport: https://royalsociety.org/-/media/policy/projects/synthetic-fuels/synthetic-fuels-briefing.pdf*
[25] *UK Sustainable Aviation Fuels Report, February 2020: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf*

More sustainable through-life engineering services

Aircraft maintenance, repair and overhaul (MRO) uses scarce or hazardous materials, and is energy-intensive. Non-destructive inspection technologies help by providing data to improve utilisation, reduce scrappage, and save energy and materials. Other technologies include integrated vehicle health monitoring and management, which can reduce unplanned maintenance and optimise MRO scheduling.

The ATI has released a strategy for through-life engineering services, available on the website. It has also supported R&D projects to promote sustainable testing and inspection.

ACARE Flightpath 2050 includes a target for 100% aircraft recyclability by 2050. Some manufacturers have set voluntary targets of 100% by 2025[26]. Current aircraft are about 80-85% recyclable by weight[27], thus 15-20% cannot be re-used. Future aircraft will have recyclability built into their design, manufacturing, and assembly.

Best practices for decommissioning exist but are not widely adopted. Understanding where waste and inefficiency occurs will improve EOL activities. The ATI is working with UK organisations to incentivise better techniques.

Newer aircraft use more composite materials. Recycling these, or developing them from sustainable materials, will be key for the sector to meet its targets. Recycling batteries and fuel cells, likely to be used in general aviation and personal air vehicles, is also a challenge with more work needed to adopt best practice. The ATI is working with others on approaches to more sustainable composites, while the Faraday[28] and Driving the Electric Revolution[29] challenges (which include the ATI) are working towards sustainable electric propulsion systems, including batteries and wider power systems.

ASSESSING ATI DELIVERY ON SUSTAINABILITY

The ATI must focus more on sustainability if it is to deliver the necessary impact. Consequently, it is developing further environmental and whole aircraft modelling tools to help assess the sustainability benefits of its R&D investment decisions. The Institute will initially concentrate on lifecycle CO_2 and deliver different scenarios with detailed technology roadmaps to achieve maximum carbon abatement by 2050. These scenarios will explore different levels of technology effectiveness, fleet mixes, and introduction times for technologies into existing and new aircraft. Modelling and analysis capabilities for water, NO_x, noise, and contrail formation will also be taken forward.

Work is also underway with partners to model wider sustainability aims such as materials usage, waste, and recyclability. Data will be provided by demonstrator projects that will feed into future aircraft programmes.

All of this will be delivered with the aim of incentivising R&D that will:

- ***Accelerate*** developments with the most potential
- ***Tackle*** areas where the current activity is low – for example finding solutions for flight and ground operations, where the Institute will need to engage with players in the wider air transport arena.
- ***Fast-track*** exploitation of alternative energy sources such as bio and fully synthetic fuels, and hydrogen (for sustainable aviation fuel, in fuel cells or directly as a fuel for gas turbines).
- ***Deliver*** larger-scale, more ambitious, UK-based, low or zero carbon demonstrators.

[26] *Bombardier C-Series EPD: https://gryphon4.environdec.com/system/data/files/6/12107/epd921_Bombardier_C_SERIES100.pdf*
[27] *Airbus PAMELA-LIFE: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=ACADEMY_PAMELA.pdf*
[28] *https://www.ukri.org/our-work/delivering-economic-impact/industrial-strategy-challenge-fund/future-of-mobility/*
[29] *Ibid*

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GLOSSARY

ACARE	Advisory Council for Aerospace Research in Europe
ATAG	Air Transport Action Group
ATI	Aerospace Technology Institute
ATM	Air Traffic Management
CNG	Carbon Neutral Growth
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EOL	End-of-Life
EPNdB	Effective Perceived Noise in decibels
EU ETS	EU Emissions Trading Scheme
FP2050	FlightPath 2050
GDP	Gross Domestic Product
H_2O	Water Vapour
ICAO	International Civil Aviation Organisation
LAQ	Local air quality
MRO	Maintenance, repair, and overhaul
NNS	Near Net Shape
NO_x	Nitrogen oxides (NO and NO_2)
PM	Particulate Matter
RQL	Rich-burn, Quick-mix, Lean-burn
R&T	Research and Technology
REACh	Registration, Evaluation, Authorisation and Restriction of Chemicals
SAF	Sustainable Aviation Fuel
SO_x	Sulphur Oxides
SRIA	Strategic Research and Innovation Agenda
UHBPR	Ultra High Bypass Ratio

WHO WE ARE

The **Aerospace Technology Institute** (ATI) is an independent not-for-profit company at the heart of aerospace research and development in the UK. Our mission is to raise UK ambitions and lead technology in air transport to maximise the UK's full economic potential. We do this by providing objective technical and strategic insight, maintaining a UK aerospace technology strategy, and together with Industry and Government, direct match-funded research investments – set to total £3.9bn between 2013 and 2026.

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[35] *ICCT report on aviation emissions: https://theicct.org/publications/co2-emissions-commercial-aviation-2018*