SUSTAINABILITY REPORT

The Lifecycle Impact of Hydrogen-Powered Aircraft

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

FZO-STY-REP-0005

Published March 2022

ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

To discover more and download the FlyZero reports, visit **ati.org.uk**

ACKNOWLEDGEMENTS

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FlyZero would like to acknowledge the support and expertise provided by the following individuals or organisations noting the conclusions shared in this report are those of the FlyZero project: *Ansys, University of Leeds, University of Strathclyde, Arup, Jacobs and Meggitt, Dr Alejandro Block Novelo, Dr Cristina Garcia-Duffy, Prof David Lee, Dr Jacquetta Lee and Dr Marc Stettler.*

FlyZero contributing companies: *Airbus, Belcan, Capgemini, easyJet, Eaton, GE Aviation, GKN Aerospace, High Value Manufacturing Catapult (MTC), Mott MacDonald, NATS, Reaction Engines, Rolls-Royce, Spirit AeroSystems.*

Department for Business, Energy & Industrial Strategy

FlyZero was funded by the Department for Business, Energy and Industrial Strategy.

Front cover, contents and page 6 image © ATI. Representation of air traffic for contrail assessment in FlyZero. Visualisation using Mayavi and Paraview [1] [2], and Cirium SRS Analyzer Data 2006.

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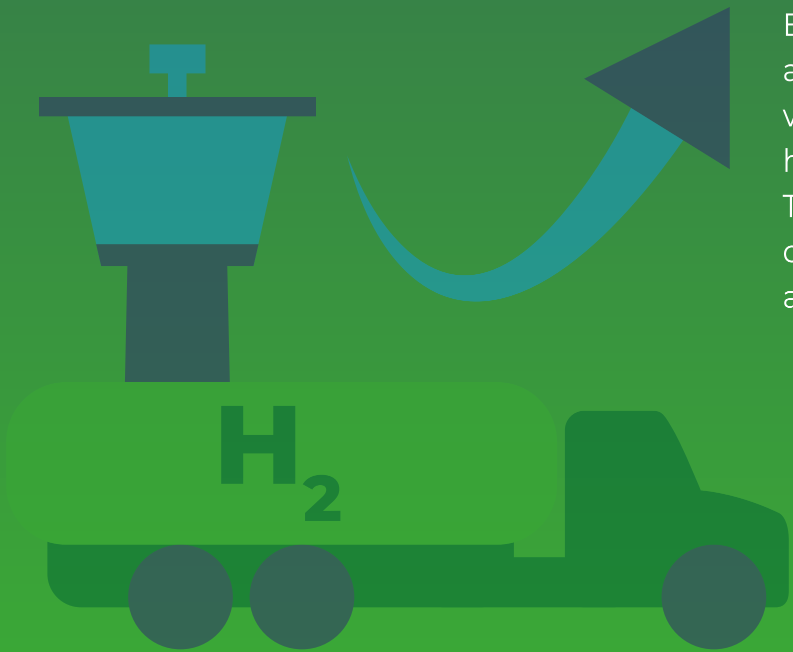
EXECUTIVE SUMMARY

FlyZero has identified key technologies that could radically decarbonise aviation. Early investment in research and development (R&D) will be essential for these concepts to be realised and deliver significant emissions reductions to contribute to the UK's Jet Zero ambitions as part of the government's ten point plan and meet its commitment to the Net Zero target by 2050.

A comprehensive assessment of primary energy sources by the FlyZero team concluded that hydrogen, stored in a liquid state, offers the best opportunity to service the future global aircraft fleet **[3]**. Using liquid hydrogen fuel would eliminate aircraft tailpipe carbon dioxide (CO_2) emissions.

In this report, the climate impact of the global fleet, including CO_2 and non-CO_2 emissions, has been estimated by bringing together the fuel production and in-flight impact including a commercial assessment for three scenarios, introducing both sustainable aviation fuel (SAF) and hydrogen-powered aircraft.

Hydrogen-powered midsize aircraft entering service in 2033, along with other variants progressively joining them over the following decade, could yield a cumulative global saving of over 4 Gt of CO_2 by 2050 and 14 Gt by 2060. This scenario would mean that no power-to-liquid (PtL) SAF would be needed by 2060. To achieve this, a substantial increase of around 12% of predicted global electricity generation for renewable or very low-carbon (nuclear) electricity would be required for use in producing and liquefying hydrogen. In comparison, producing PtL SAF to meet the same demand would require about 40% more renewable electricity, would be around 30 to 60% more expensive and have a higher environmental impact.



Emissions from the current global fleet have a complex impact on climate, with lifetimes varying from hundreds of years for CO_2, to hours, weeks or years for other pollutants. This report explains how climate metrics can reveal different perspectives on short and long-term emissions.

Current aircraft use hydrocarbon fuels as their energy source. When combusted, these produce CO_2 and water vapour, and also oxides of nitrogen (NO_x) and sulphur (SO_x).

The combustion of hydrogen fuel in a gas turbine emits no CO_2 or SO_x, though will generate 2.6 times the water emissions of fossil jet fuel aircraft. Particulate matter will largely be eliminated and it is estimated that NO_x emissions will be reduced by 50 to 70% with hydrogen gas turbines. The only emission from hydrogen fuel cell-powered aircraft is water. Elimination of particulates and reduction in NOx will help to improve air quality significantly.

As with conventional aircraft, water in the exhaust may lead to the formation of contrails, some of which could become persistent in ice super-saturated regions (ISSRs) of the atmosphere and form cirrus clouds, leading to a net warming effect. However, studies indicate that contrails from hydrogen-powered aircraft will dissipate more quickly and have lower optical density due to the absence of soot particles, so the overall impact from their contrails is expected to be less, though more research and validation is needed.

Navigational contrail avoidance (altitude or route change) has the potential to provide a rapid reduction in the overall radiative forcing, however significant research is still needed to confidently predict ISSR locations. With fuel cell-powered aircraft, it may be possible to hold water on board or condition it before release, but these concepts also require further research and investment.

Widebody and narrowbody aircraft will often fly in the stratosphere, particularly at higher latitudes. Above the tropopause – where the stratosphere meets the troposphere – the impact of contrails is dramatically reduced, but the direct impact of water vapour increases. Further research taking into account flight altitude is recommended to inform future design decisions.

Improvements in climate science through funded research and in collaboration with industry are urgently required to inform design, policy and market decisions to further reduce aviation's overall impact, regardless of the fuel being used.

Additionally, noise is a key factor that needs to be taken into consideration. Encouragingly, assessments conducted for the final FlyZero concept aircraft show them to be potentially competitive with other aircraft concepts currently under consideration.

Aviation has a good track record in managing supply chains, recycling valuable alloys and developing long lifecycle products to continuously improve on reliability and safety. However, developing a new generation of aircraft presents an opportunity to integrate sustainability into the design and manufacturing process, and further improve the circularity, the ability to reuse and recycle materials. Manufacturing waste, which is estimated to be higher than end-of-life waste, should be reduced. The carbon fibre and metals used in gas turbine alloys, fuel cell catalysts and magnetic materials are particular hotspots. Improved lifecycle assessment capability, from both a social and environmental perspective, will help to underpin specific areas of future work.

Key recommendations:

- There is an urgent need to improve the understanding of the impact of contrails, the variation in impacts of emissions with altitude and the potential for navigational contrail avoidance.
- Opportunities to achieve the significant NO_x reductions anticipated from lean-burn hydrogen combustion need verification.
- Developments in policy and regulatory frameworks are required to support initiatives to speed up decarbonisation and, where the science is sufficiently certain, to tackle non-CO_2 emissions.
- There needs to be a significantly increased capability in lifecycle impact modelling and design for sustainability methodology.
- The use of scarce materials and those with high social and environmental impact needs to be addressed by designers and supply chains.
- Improvements to recycling, decommissioning and end-of-life processes will be required.

01. INTRODUCTION

Sustainability is very much at the centre of the FlyZero project's mission to realise zero-carbon emissions in commercial aviation.

FlyZero conducted a detailed assessment of zero-carbon fuels at the start of the project and identified liquid hydrogen as offering the best option for achieving zero-carbon flight for the next generation of aircraft. The team went on to develop three concepts: a hydrogen fuel cell regional aircraft (FZR), a hydrogen-gas turbine narrowbody aircraft (FZN) and a hydrogen-gas turbine midsize aircraft (FZM).

The sustainability team was tasked with looking at the impact of these aircraft and set about examining all potential emissions including CO_2 and non-CO_2 as well as performing a life cycle assessment (LCA) for the aircraft. In FlyZero the complete life of the aircraft was considered – from materials and processing, through to manufacturing and operational life, including the impact on airport infrastructure and fuelling requirements. It also includes factoring in the effect of an aircraft's decommissioning and any related end-of-life considerations and the potential for materials recycling and reuse.

This report acts as a summary of this work and provides the FlyZero project team's conclusions on the potential sustainability impact of next generation aircraft. It also outlines future work that will be needed to accelerate the sustainable introduction of zero-carbon emission aviation.

For more details on the sustainability work, methodology, assumptions and detailed analysis of results, please see the ATI FlyZero 'Sustainability Technical Report' **[4]**. For more details on recommendations for future work, see the ATI FlyZero 'Lifecycle Impact' cross-cutting roadmap **[5]**.

02. APPROACH AND METHODOLOGY

In FlyZero, impacts were assessed for the aircraft materials, manufacturing and maintenance (MMM), fuel supply and aircraft infrastructure, and in-flight emissions. The fuel supply and in flight emissions were then brought together with commercial and policy analysis scenarios to provide assessments for the whole fleet. An outline of assessments and how they link together is indicated in **Figure 1**.

Airport infrastructure requirements and hydrogen fuel production were assessed using the SimaPro life cycle assessment tool. Assumptions made include that hydrogen would be produced via water electrolysis using renewable electricity and the team consulted with Arup, Meggitt and Jacobs to inform its approach.

FlyZero took its impact data for SAF and fossil jet fuel from the International Civil Aviation Organisation (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) publications. Indirect land use change was also factored in, along with core production values for bio-based SAFs where appropriate **[6] [7]**.

The overall impact is expressed in global warming potential (GWP) values - these were reduced to account for projected increases in the availability of renewable energy between 2030 and 2060. The impact of power-to-liquid (PtL) SAF was assessed using the SimaPro values for hydrogen, along with a dedicated tool developed by Meggitt for use within the project.

The FlyZero engineering teams assessed fuel efficiency for the hydrogen concepts against a baseline of SAF and fossil jet-fuelled aircraft. Atmospheric climate impacts for emissions and contrails were estimated in collaboration with the University of Leeds based on FlyZero fuel parameters and data **[8]**.

The commercial and policy analysis scenarios in **section 4** include fuel production and in-flight impact assessments for the future fleet from 2030 to 2060. For further details, please see the ATI FlyZero 'Sustainability Technical Report' **[4]**.

To conduct LCAs for the aircraft, details of each concept aircraft design were collated in terms of materials, manufacturing and maintenance using simplified bills of materials (BOMs). These were compared against baseline aircraft as may be expected for entry into service in the 2030s, capable of being powered by SAF. The parameters under consideration include:

- Material mass
- Estimated process scrap
- Manufacturing processes
- Estimates of replacement parts needed through the life of the aircraft

These were assessed by Ansys using the Granta Materials Intelligence tools, drawing on lifecycle impact data from sources such as the ecoinvent database. Ansys also assessed the BOMs in relation to restricted substances and hotspots for social impact in upstream material supply chains.

Aircraft end-of-life (EOL) impacts were assessed qualitatively by The University of Strathclyde, with researchers conducting interviews with companies to identify areas that needed to change. EOL impact was not included in the quantitative LCA as the research team expects this to be small and current predictions on the impact of decommissioning activities to be conducted in 35+ years' time would be potentially unreliable.

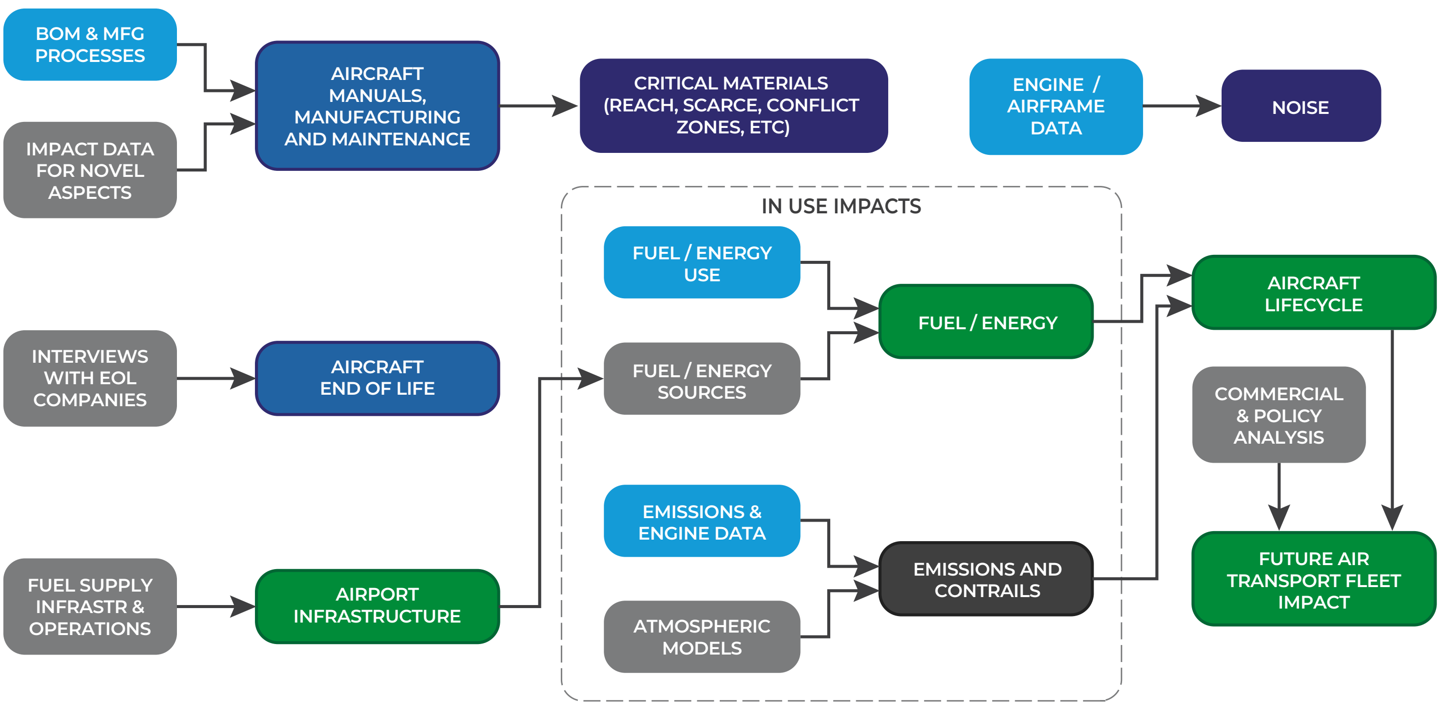


Figure 1 – FlyZero Sustainability impact model block diagram

02.1 CLIMATE METRICS

The challenge when applying climate metrics is that emissions have different lifetimes in the atmosphere. So, while CO_2 lasts for hundreds of years, methane will be present for around 10 years and water vapour can remain for weeks in the stratosphere, while even persistent contrails may last only a few hours. The climate impact of NO_x is a complex interaction of chemical processes with different lifetimes affecting methane and ozone.

This means that there is no one metric to adequately compare the climate impact of emissions, and different ones are required to reveal their effect from different perspectives. The impact of an emission at any given time is expressed as radiative forcing (RF), which is energy flux per unit area. To understand how this affects climate over a timescale, this can be converted to other metrics.

In this report, we have used global warming potential (GWP) and global temperature change potential (GTP), which are both ways of expressing radiative forcing, usually expressed as the mass of CO_2 which would have the same impact:

- GWP is well known, and is the RF integrated (summed up) over a defined timescale (100 years for GWP_{100}).
- GTP is the temperature change due to the emission at a given future time (in 100 years' time for GTP_{100}) and is seen by some climate scientists as a better metric for climate policy.

03. CLIMATE IMPACT AND ENERGY DEMAND

03.1 FUEL PRODUCTION

To move aviation away from the use of fossil fuels, new energy carriers, capable of storing renewable energy produced on the ground, will need to be developed.

Electrofuels, like hydrogen or PtL SAF, will require electrical energy for the electrolysers and (in the case of PtL) the direct air carbon capture plant and refinery. For bio-SAF the energy required is that associated with the agricultural processes, collection, processing and refinement of the bio-feedstocks.

A substantial increase in renewable or very low-carbon (nuclear) electricity will be required for the production and liquefaction of green hydrogen to meet the future demands of aviation. The most optimistic FlyZero scenario ('Scenario 1: Midsize first, high ambition', as described in **section 4**) would require about 8% of predicted global electricity generation in 2050, and possibly as much as 12% in 2060 (global electricity projections do not yet extend to 2060) **[9]**. In comparison, the production of power-to-liquid SAF to meet the same demand would require around 40% more renewable electricity than liquid hydrogen.

Hydrogen production requires about 10 litres of de-ionised water for every kilogramme of hydrogen, or about 20 litres of tap water, which, for UK fuel demand, would equate to less than 1% of the UK water supply, and a much lower proportion in countries where large amounts of water are used for agriculture. While water use for PtL SAF would be similar or slightly higher, water requirements for bio-SAF from crops would be an order of magnitude higher.

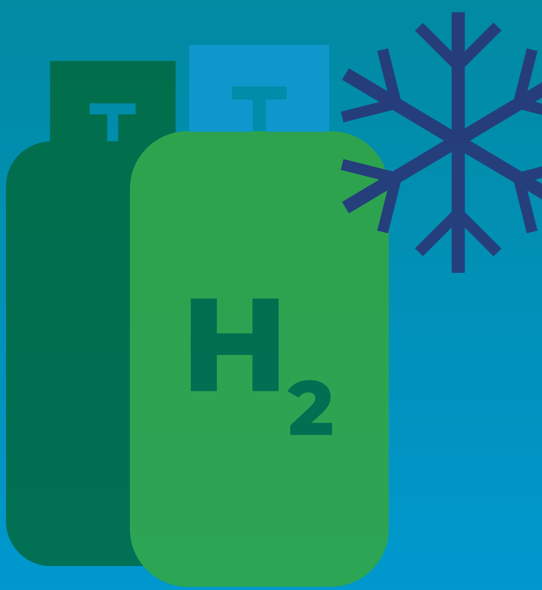


Figure 2 compares the climate impact of a representative selection of fuels in 2030, using the global warming potential (GWP) metric. This shows how the impact of different biofuels varies widely depending on the feedstocks and the production pathway. Some biofuel SAFs produced from cover crops have very low, possibly even carbon-negative impacts due to their ability to trap and store carbon in the soil, but fuels derived from dedicated oil crops have a much higher impact. Fuels from municipal solid waste are likely to contain some fossil-based plastics so a non-bio carbon content of 10% has been assumed here.

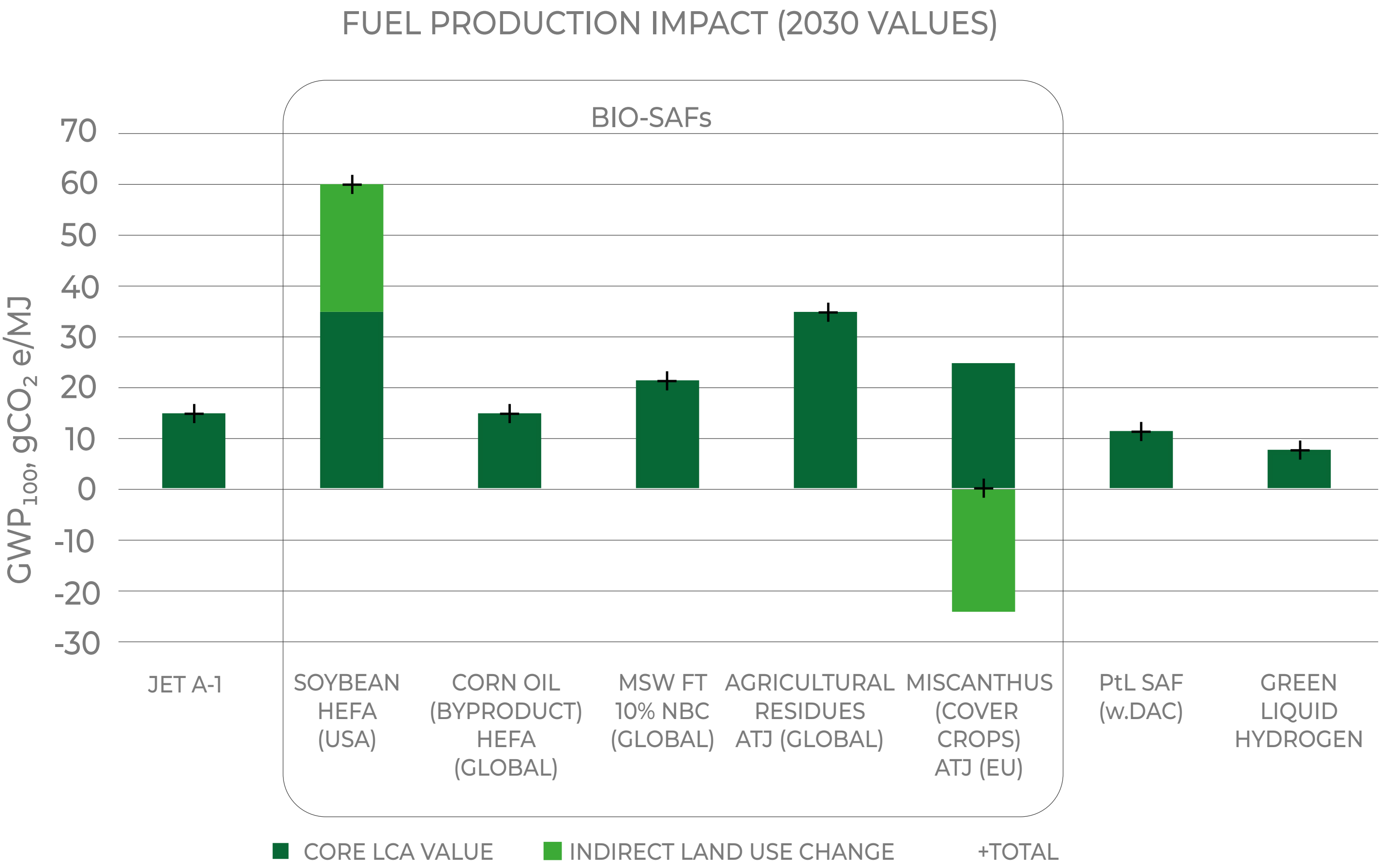


Figure 2 – Fuel production impacts. Estimated 2030 values

Fossil jet fuel and biofuel data from CORSIA, with values reduced based on increasingly renewable energy content according to International Energy Agency Announced Pledges Scenario. Power-to-liquid and green hydrogen calculated within FlyZero. A range of biofuels has been selected to indicate the wide variation in impacts, and represent realistic biofuel SAFs in the future ***[6] [7] [10]****.*

Hydrogen has an indirect greenhouse gas effect, so it is important to limit leakage in the hydrogen production supply chain. Future work on infrastructure will need to address this, though current early research indicates that it would be significantly lower than the impact of current leakage from natural gas infrastructure **[11]**.

03.2
IN-FLIGHT IMPACTS

Hydrogen has the potential to significantly reduce aviation's environmental impact by eliminating CO_2 emissions which is a top priority for the aviation sector. CO_2 can remain in the atmosphere for hundreds of years, meaning that continued emissions are contributing to an exponential increase in climate warming. However, eliminating CO_2 does not fully solve the problem of climate impact, non-CO_2 impacts must also be addressed.

The impact of the aviation emissions results from various physical and chemical processes which involve CO_2, NO_x, soot, sulphur and water vapour. A useful overview for current aircraft is provided by 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018', Lee, et al **[12]**. Nevertheless, there are still areas where uncertainty is very high, and there is a dearth of scientific literature about the impact of aviation in relation to novel fuels, such as SAFs and hydrogen.

FlyZero has examined the key impacts of non-CO_2 emissions including novel research undertaken by the University of Leeds to simulate the impact of contrails and NO_x, based on fuel parameters and emissions data from FlyZero **[8]**. Further work is urgently required to build on the findings from these studies.

Water vapour and contrails

Water vapour has a small direct greenhouse gas effect, but its main effect is much larger if it forms contrails which, under certain circumstances in ice super-saturated regions (ISSRs), may last a long time and turn into cirrus clouds that trap heat in the earth's atmosphere. Although these persistent contrails also create a small cooling effect by reflecting solar radiation during the day, their net result is warming.

Higher water emissions will result in the formation of more contrails. More contrails will form as average exhaust gas temperatures reduce in pursuit of higher bypass ratio engines. Burning SAF produces more water vapour than fossil jet fuel (due to the higher hydrogen to carbon ratio) so tends to form slightly more contrails. Hydrogen combustion generates 2.6 times as much water as fossil jet fuel, so it will give even more contrails, at lower altitude and at higher ambient temperatures. Hydrogen fuel cells will form contrails most of the time due to their much lower exhaust temperatures. Only a few of these will become persistent, if they form in ISSRs.

Just as water vapour condenses on the inside of a car's windscreen on a cold day, ice particles in contrails form much more easily if they have a solid surface on which to nucleate. With conventional aircraft, the water vapour condenses on the particulates present at the exhaust. However, hydrogen aircraft exhaust contains no particulates, though there may be some background particulate matter in the atmosphere, which means they will form fewer, larger ice particles with lower optical density, and so less radiative forcing, or climate impact. Larger particles will fall faster, so contrails may not be as persistent as those from aircraft powered by kerosene (fossil or SAF). Similarly, as SAF produces fewer soot particles than fossil jet fuel, contrails from SAF may also have lower impact.

The University of Leeds ran simulations using an established model to estimate the impact of contrails from both hydrogen combustion and fuel cells, as well as fossil jet fuel and SAF for comparison. This is a novel area with very limited prior literature regarding the formation and persistence of contrails from hydrogen combustion, and there is no measured data. Results from the modelling will need to be validated via further work on characterising contrails.

Aircraft flight altitude is also a factor regarding emissions from aviation. Widebody and narrowbody aircraft will often fly in the stratosphere, particularly at higher latitudes **[13]**. Above the tropopause, contrail impacts dramatically reduce, however the direct impact of water vapour emissions will increase. Further research taking into account flight altitudes is recommended to inform design decisions. Contrail avoidance is addressed in **section 3.4**.

NO_x and air quality

While future lean burn technology can considerably reduce NO_x emissions from the combustion of hydrocarbon fuels, the use of hydrogen could offer significant additional reductions as it has different combustion characteristics. This is described in ATI FlyZero 'Hydrogen Gas Turbines Technical Report' [14]. Compared to current regulations, hydrogen gas turbines could reduce NO_x emissions by 50-70%, which has benefits for both climate impact and air quality around airports. Hydrogen fuel cells are better still as they do not produce NO_x at all. Air quality at airports will also be improved by much reduced particulate emissions, though some will remain from brakes and tyres, as well as from lubrication oil.

Combined climate effects

Bringing together the fuel production emissions for different fuel / propulsion systems with the CO_2 and non-CO_2 effects, **Figure 3** shows the climate effect as GWP_{100} - global warming potential over 100 years - averaged for mission profiles across the aircraft fleet, with comparative technology levels.

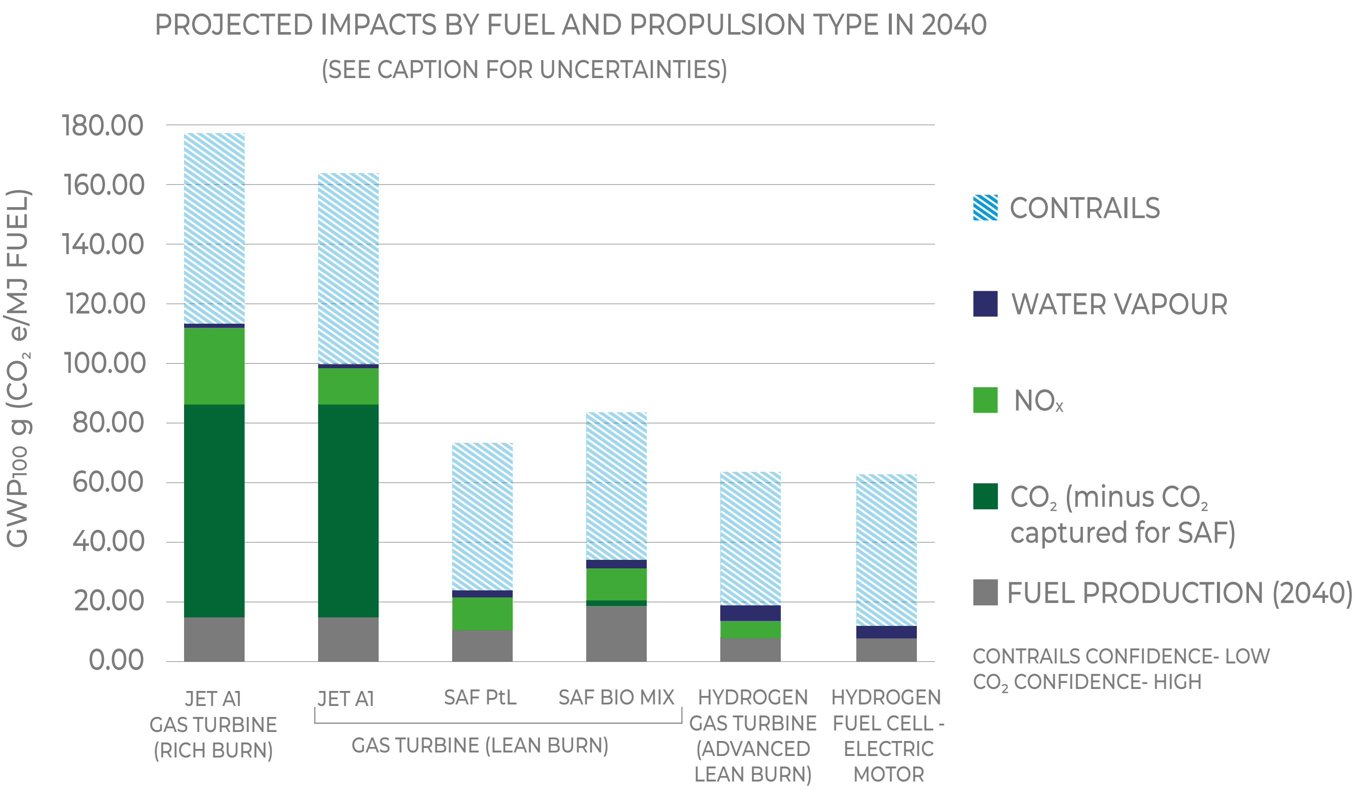


Figure 3 – Projected impacts by fuel and propulsion type in 2040

Fuel production impacts for 2040; Aerosol impacts not included; PtL SAF assumes direct air capture of CO_2; PtL and liquid hydrogen assume renewable power generation; SAF bio mix selected to represent realistic future biofuel SAFs; CO_2 is assumed captured for SAFs, except for an assumption of 10% non-biogenic carbon content from municipal solid waste, which forms part of the SAF bio mix.

Confidence levels are high for CO_2, medium for water vapour, low for NO_x and fossil jet fuel contrails, very low for SAF and hydrogen contrails.

While battery electric aircraft have no emissions and form no contrails, the weight of the batteries limits the range to well below the requirements set in FlyZero, so this was not pursued **[3]**. From an environmental perspective, battery electric aircraft technology should be exploited by the sub-regional and regional market sectors, with ranges potentially extended using multi-hop flights. The challenges of battery use, such as the scarcity of the materials required and recycling at end of life, are covered in detail in the ATI FlyZero 'Sustainability Technical Report' **[4]**.

03.3 OVERVIEW OF IMPACT CATEGORIES AND CONFIDENCE

Impact category	*Comments on impact*	*Confidence level for climate impact of category*
Fuel production	*Renewable energy use of PtL SAF (with direct air capture) is around 40% higher than green hydrogen (by electrolysis). Biofuel impacts vary widely.*	*Medium*
CO_2 emissions	*Eliminated by SAF and hydrogen, though SAFs from municipal waste may contain some fossil carbon, in which case not all CO_2 would be deemed captured.*	*High*
NO_x emissions	*Estimated to be 50 to 70% lower for hydrogen than kerosene fuels (fossil or SAF)*	*Low*
Water vapour emissions	*2.6 times more emissions from hydrogen than from fossil jet fuel, 2.4 times more than SAF* *(SAF has a higher hydrogen to carbon ratio than fossil jet fuel).*	*Medium*
Contrails	*Confidence in contrail impacts for current aircraft is low. SAF contrails are expected to be less warming than those from fossil jet fuel, due to reduced particulates seeding ice formation. Hydrogen is expected to have even less impact, despite more water, though more research is needed to confirm this.*	*Low for Jet-A1 contrails* *Very low for SAF / hydrogen contrails*
Soot and sulphur emissions	*Eliminated with hydrogen (apart from small amounts of soot from lubrication oil burn), Reduced with SAF compared to fossil jet fuel. Impacts are very uncertain and could be net cooling.*	*Very low*

Table 1 – Comments on impact and confidence levels for fuel production and in-flight emissions

03.4 CONTRAIL AVOIDANCE

Contrails are mostly short-lived, and a relatively small proportion of flights cause the majority of persistent, warming contrails. A proportion of these persistent contrails could be avoided by rerouting aircraft away from ISSRs (usually above or below) via air traffic management, with a small fuel penalty. However, the ability to confidently predict whether contrails will be or have been avoided is still in its infancy, meaning that there is a risk of extra fuel burn, and the associated cost and emissions, possibly without avoiding the contrails. The risk for hydrogen-powered aircraft, where no CO_2 and less NO_x will be emitted, is much less compared to fossil jet-fuelled aircraft.

Navigational contrail avoidance technology is currently being trialled by several organisations to assess the viability of contrail prediction and feasibility of integrating into air traffic control procedures. If it is demonstrated to be feasible, it could enable the short-term warming effect of some contrails to be removed. In the case of hydrogen fuel cells, it may be possible to store water on board while going through ISSRs, or condition it to reduce the potential to form persistent contrails.

This is an important area for future research. The charts in **section 4** show an indicative 50% contrail reduction with 1% fuel penalty. This is not a statement about what is achievable but is included to illustrate the potential.

04. IMPACT OF THE GLOBAL FLEET

A key factor under consideration needs to be the annual impact of the global aircraft fleet.

This has been estimated by bringing together the fuel and in-flight impacts described above, along with a commercial assessment for the introduction of both SAF and hydrogen aircraft. This is displayed below in Figure 4, 5 and 6 for the following scenarios:

- **Scenario 1: Midsize first - high ambition:** beginning with a hydrogen midsize aircraft with an entry into service in 2033, followed by the narrowbody in the late 2030s, and finally the regional entering service in the early 2040s. This scenario has the most potential to reduce emissions.
- **Scenario 2: Regional first - high ambition:** beginning with a hydrogen regional aircraft entering service in 2033, followed by the narrowbody in the late 2030s, with the midsize joining the fleet in the mid-2040s. This represents previous expectations for the introduction of hydrogen aircraft before FlyZero.
- **Scenario 4: Regional first - unaccelerated:** with a limited performance regional hydrogen aircraft entering service in 2035, followed by a much slower introduction of narrowbody in the mid-2040s and the midsize in the mid-2050s.

For more details on the scenarios, see the ATI FlyZero 'Market Forecasts and Strategy' **[15]**. *Scenario 3 is not included here as results are similar to scenario 2.*

These scenarios assume that biofuels will reach limits based on sustainable feedstock availability. The uptake of SAF begins with oil-based biofuels, which are already commercially available, then other biofuels such as alcohol-to-jet and fuels from waste **[16]**. PtL SAF is then predicted to ramp up, but later reduce as it is displaced by the cheaper hydrogen fuel. The CO_2 is deemed captured for bio-based and PtL SAF.

Figure 4 shows the annual global impact by fuel in GWP_{100} for each scenario, alongside the corresponding fuel use in exajoules. This indicates how the overall climate impact starts to reduce, despite commercial growth, as SAF and hydrogen replace fossil jet fuel. The impact curves plateau as CO_2 reduces and only non-CO_2 emissions, mainly from contrail cirrus, are left. The reduction in non-CO_2 impacts due to moving to SAF or hydrogen is partly offset by the predicted increase in aircraft traffic.

Figure 5 shows the combined annual global impact of all fuels by category as GWP_{100}, revealing the integrated warming effect over a period of 100 years from the year of emission. The dashed line indicates the potential saving if 50% of contrails were avoided with a 1% fuel penalty.

In **Figure 6**, the annual in-flight emission impacts (not including fuel production) are presented by category as GTP_{100}, indicating the effect on temperature 100 years from the year of emission. The potential saving if 50% of contrails were avoided with a 1% fuel penalty is again indicated.

These charts show how CO_2 has by far the greatest effect in the long term, and its removal would dramatically cut the warming impact of aviation.

Error bars are not included for clarity, but these charts should be read alongside **Table 1** as the confidence levels for impacts of several emissions are low. See **section 2.1** Climate Metrics for more explanation of the different metrics.

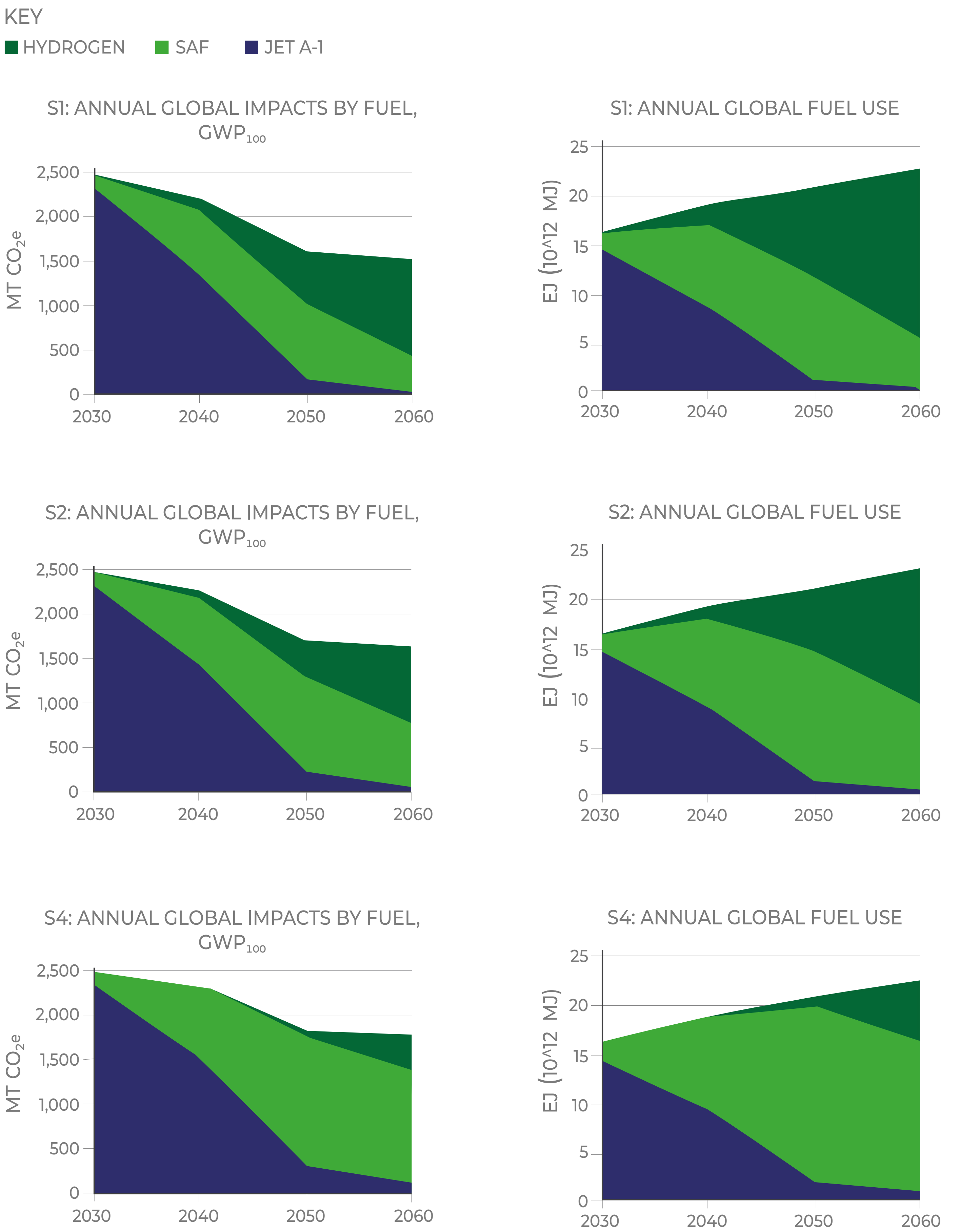
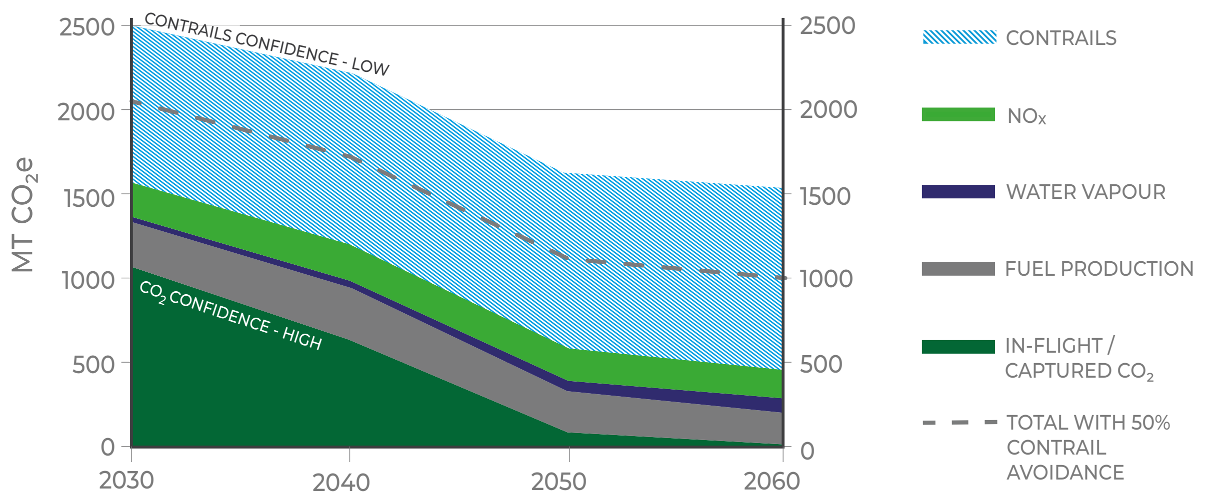


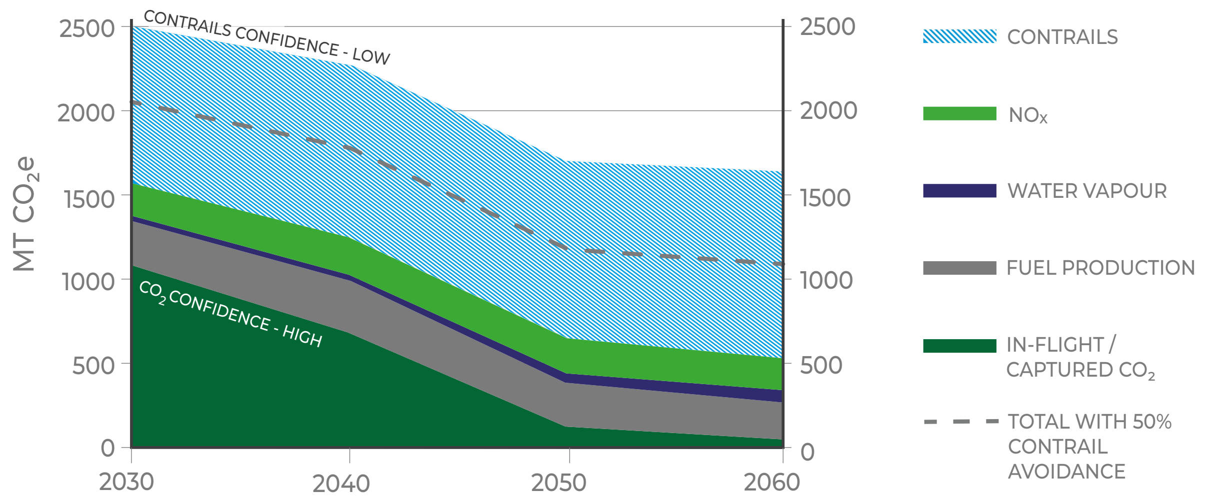
Figure 4 – Annual global impacts by fuel (GWP_{100}) alongside annual fuel use

This indicates how overall impacts reduce despite commercial growth as SAF and hydrogen progressively replace fossil jet fuel. Please see text for confidence levels for impact data, which is low for several emissions.

S1: ANNUAL GLOBAL IMPACTS BY CATEGORY, GWP_{100}



S2: ANNUAL GLOBAL IMPACTS BY CATEGORY, GWP_{100}



S4: ANNUAL GLOBAL IMPACTS BY CATEGORY, GWP_{100}

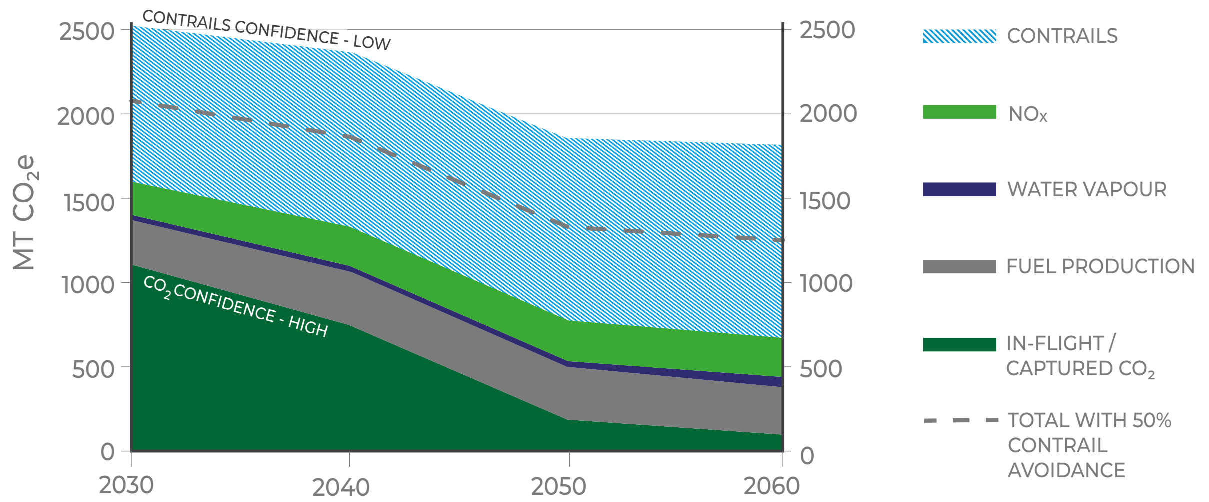


Figure 5 – Annual global impacts by category (GWP_{100})

***Metric**: GWP_{100}, indicating the warming that would be caused over 100 years from the year of emission. Confidence levels are high for CO_2, medium for water vapour, low for NO_x and Jet-A1 contrails, very low for SAF and hydrogen contrails.*

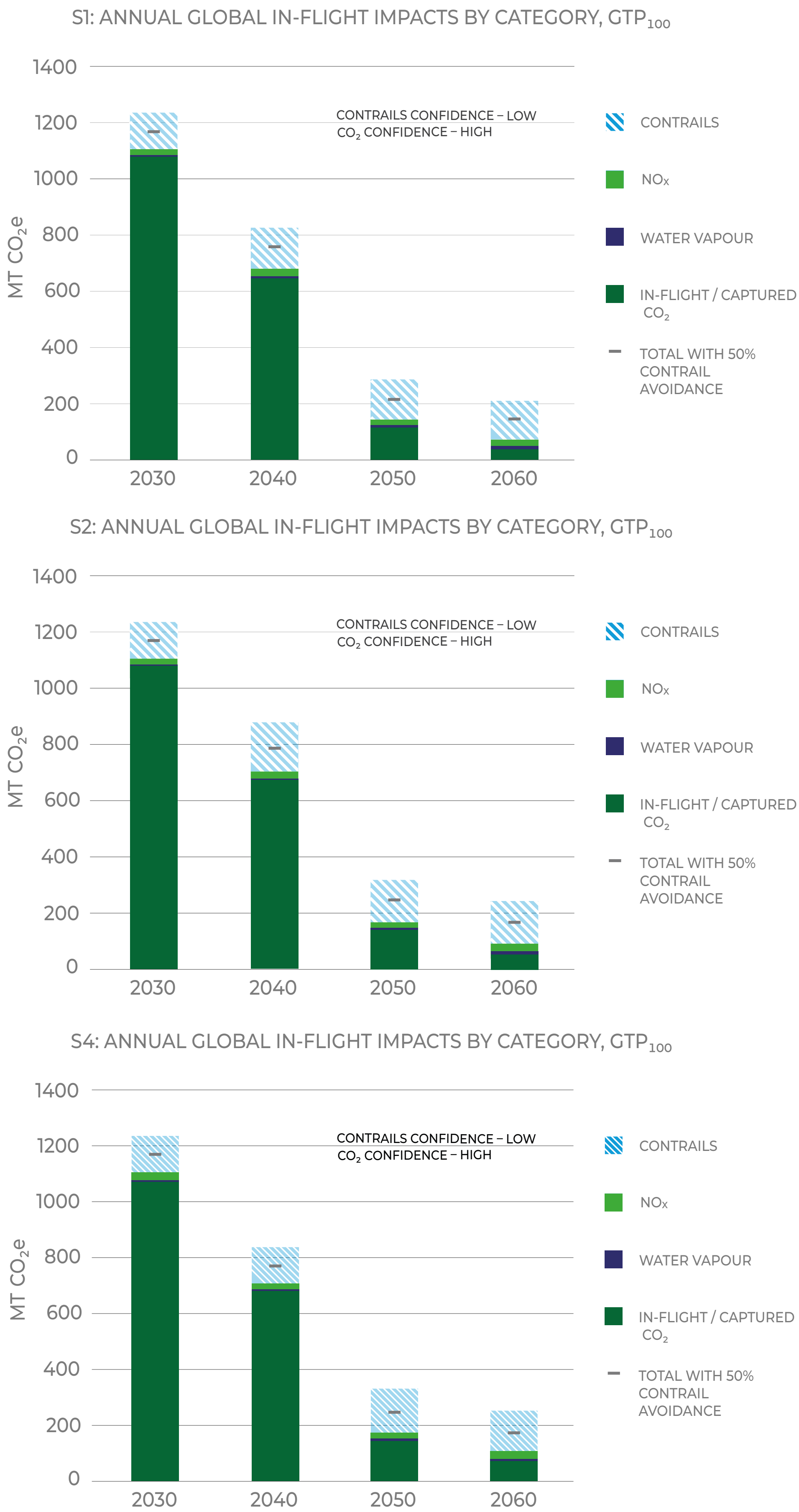


Figure 6 – Annual in-flight impacts by category (GTP_{100})

***Metric**: GTP_{100} indicating the effect on temperature 100 years on from the year of emission. Confidence levels are high for CO_2, medium for water vapour, low for NO_x and Jet-A1 contrails, very low for SAF and hydrogen contrails. Fuel production is not included.*

05. DESIGN FOR SUSTAINABILITY

The development of a new generation of aircraft provides a golden opportunity to better integrate sustainability into design and manufacturing processes as well as tackling any issues around their circularity.

FlyZero began embedding sustainability into its designs from the start, with workshops that reviewed each team's work against a dedicated checklist, using a risk assessment format. These workshops were revisited later in the project once more information was available from internal work and external contracts. This captured key areas to address for each technology brick.

This approach should be further developed to ensure that sustainability is incorporated early into the systems engineering methodology and technical gate reviews, alongside factors like design for manufacturing, cost and assembly.

Sustainability checklist areas in aircraft design process:

- Efficient design
- Raw materials
- Efficient manufacture
- Use phase
- End of life

06. MATERIALS, MANUFACTURING AND MAINTENANCE IMPACT

Figure 7 shows the results of the Ansys MMM study [17] into the impact of each FlyZero concept and the baseline comparison aircraft. This includes materials and manufacturing for the initial aircraft, along with replacement and repair of parts during its operational life. The FlyZero concepts are shown to have a slightly higher impact, which reflects their higher weight due to the fuel systems and associated structure required for liquid hydrogen. In the case of FZR, the propulsion impact is significantly higher, due to the presence of a platinum catalyst in the fuel cells.

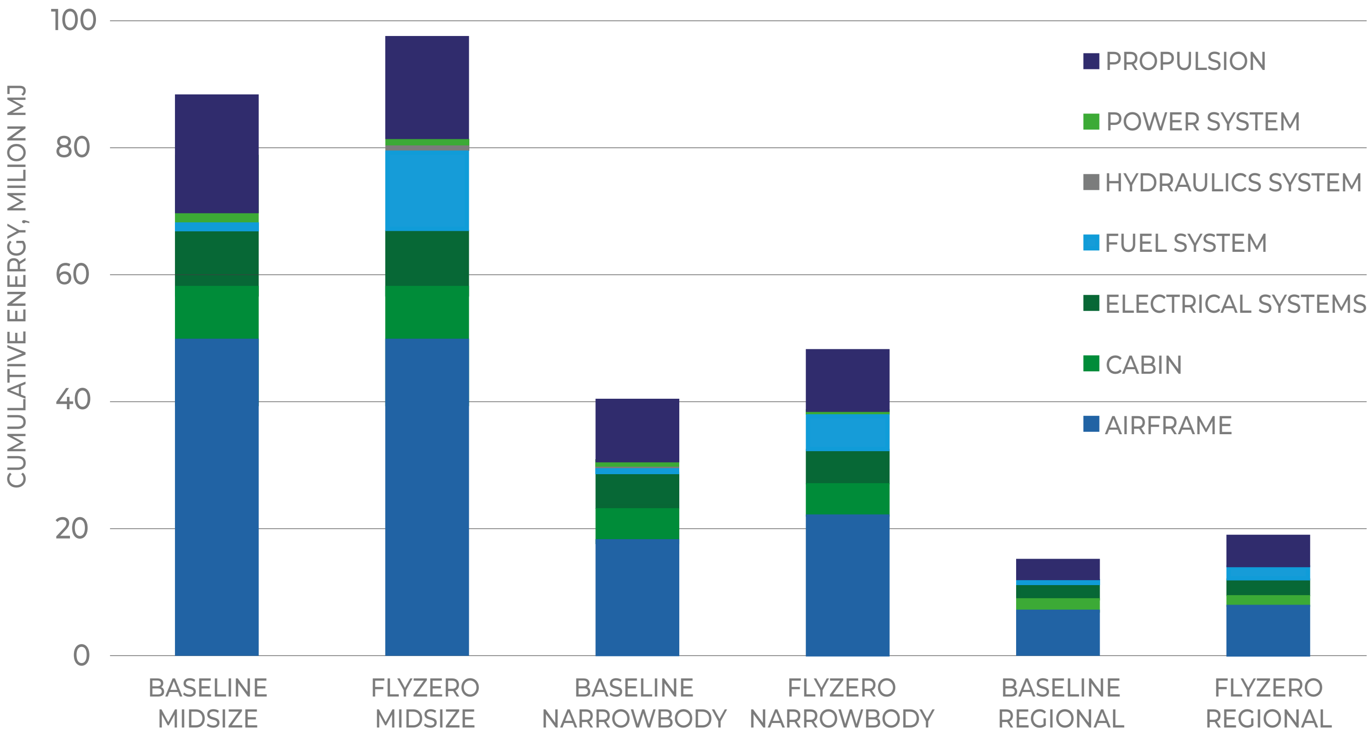


Figure 7 – Energy use for materials, manufacturing, maintenance and repair by module

Data based on bill of materials generated by FlyZero and environmental impact data from Ansys.

The bill of materials analysis revealed some key points on the impact of raw materials commonly being used for structures and systems. Carbon fibre is the material with the highest environmental impact in the aircraft. Its use has clear benefits in weight reduction with consequent fuel savings, however it is recommended that research on reducing the energy required for its manufacture should be prioritised, as well as looking to locate carbon fibre-related activities where renewable energy is available.

Aluminium in structures and seating along with the metals used in gas turbine alloys, fuel cell catalysts (platinum) and magnetic materials also have a high impact, as does electronic equipment.

The extra weight of liquid hydrogen fuel systems and tanks also has a considerable impact. This will be multiplied if they need replacing every few years, as has been assumed at this stage in FlyZero. Accelerated research and design will be needed to determine the best fatigue-resistant materials for these systems.

The estimates made in FlyZero for scrap material may be low, as they account only for process waste and do not include the potential for human or machine error and incorrect orders. Nevertheless, around 1.5 to two times as much material will be thrown away as is used in the aircraft, with more material being disposed of throughout its operational life as parts are replaced during repair and maintenance activities.

Despite the high material impact of manufacturing, FlyZero's estimate of the MMM impact, using a 2030 energy mix, is that this is only around 1% of the impacts of fuel and emissions over the FlyZero concepts' lifetime (as GWP_{100}). This compares to about 0.3% for a fossil jet-fuelled aircraft because of its higher operating emissions. This will reduce over time as the energy used in manufacturing and raw material production becomes more renewable. In the UK this is likely to reduce significantly by 2050. However, reducing energy use must remain a priority to reduce costs and because availability of renewable energy is set to limit the path to decarbonisation for many decades to come.

While the simplified LCA approach conducted with Ansys for FlyZero was far less resource intensive than a full LCA, it did reveal a great deal of useful information. The related LCA should become more detailed as the aircraft design progresses. Improvements to life cycle assessment capability, both social and environmental, are needed across the industry to appropriately assess key areas as aircraft designs develop, especially where their impact is critical to improving efficiency and reducing weight.

07. DECOMMISSIONING AND CIRCULARITY

When considering end of life issues, there is very little difference between the FZN and FZM concepts in terms of end-of-life (EOL) management compared to baseline aircraft. The fuel cells in the FZR concept represent a new challenge, with the main economic driver being platinum recovery. However, this will potentially be addressed by the automotive sector for use in decommissioning trucks and buses before it becomes a significant challenge for aviation.

Commissioned by the FlyZero project, the University of Strathclyde produced a report summarising the decommissioning process, including any economic and operational factors [18]. In addition, they interviewed asset owners, maintenance, repair and overhaul companies (MROs), decommissioning organisations and recyclers, to recommend improvements on circularity and EOL value of aircraft [19]. Key points from their research include:

- Composite volumes are increasing but handling and recycling is still challenging. Carbon fibre recyclers take production scrap, but it is not economical yet to take EOL waste.
- Batteries are not considered a problem as recycling capability has developed for the electric vehicle sector. Lithium has only recently started to be recovered, which is important due to limited global supply. More information about battery life and use history would improve value for potential reuse.
- More information from major aerospace companies would be valuable in relation to manuals and training for MROs and materials identification for EOL activities, especially as new elements are introduced.
- Design to enable longer life through maintenance, repair and refurbishment, and then to allow cost-effective disassembly will improve circularity. Improvements in recycling processes for composites must be a priority.

Figure 8 – Aircraft scrap. Photo by Stella Job

08. NOISE

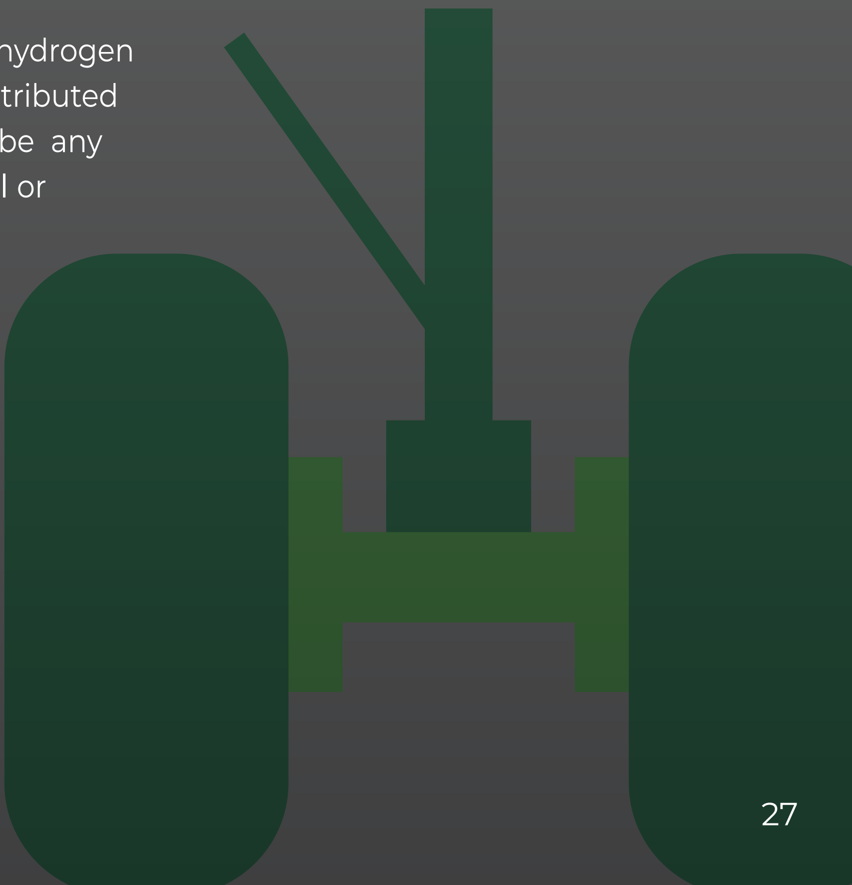
Noise has a significant environmental impact. It has a particularly high profile in relation to airport operations and supporting good community relationships with those living close to airport runways.

Noise is regulated both internationally by the ICAO and locally by individual airports. It was therefore considered early on during the conceptual design stages of the FlyZero project through a collaborative study with experts from the University of Southampton's Institute of Sound and Vibration Research **[20]**.

This preliminary study identified the key technological and operational factors that should influence the design of the FlyZero concepts with regard to noise targets for a potential entry into service in the 2030s. The assessment shows that all three concepts have the potential to exceed the noise targets set by the project's top level aircraft requirements (TLARs) and are competitive with other worldwide conceptual studies.

Significant noise reduction opportunities for a hydrogen aircraft arise from its lower take-off weight and take-off thrust compared to a current-day kerosene aircraft performing a comparable mission. Additionally, optimising the aircraft's operation can potentially maximise its performance, including noise. There is clearly a need for more studies to explore aircraft design and engine cycles, with the study of different climb gradients (at take-off) and descent gradients (at approach) representing a prime optimisation opportunity.

The acoustic risks from the introduction of hydrogen combustion, hydrogen fuel cells and distributed electric propulsion are not considered to be any higher than future conventional fossil jet fuel or SAF-powered aircraft. Therefore, the FlyZero team believes that its concept aircraft are just as likely to achieve the very low noise attributes being estimated for future kerosene-powered aircraft concepts.



09. KEY FINDINGS

One of the greatest challenges the world faces is climate change due to anthropogenic emissions, of which aviation currently contributes about 3.5% [12]. The most significant warming emission from aviation is CO_2, and the results of FlyZero indicate that using liquid hydrogen as a fuel for the future fleet is the most cost-effective way to tackle this.

The use of liquid hydrogen would also be the most energy-efficient route to clean aircraft propulsion, only outperformed by batteries which can only be used by very short-range aircraft. While it is apparent that some biofuels have low or negative climate warming impact in production when indirect land use change is accounted for, feedstocks are limited. This means that a sustainable kerosene-based future for aviation would depend on producing PtL SAF with direct air capture. This would use about 40% more electrical energy than hydrogen production, would cost around 30 to 60% more and is predicted to have a higher non-CO_2 impact. Having eliminated CO_2, hydrogen combustion is estimated to reduce NO_x by 50-70%, while fuel cells emit only water.

While the exact figures on contrail impacts remain very uncertain for all fuels, it is expected that they will be reduced by using SAF compared to fossil jet fuel. And it is believed that they will be further reduced with the introduction of hydrogen. This is because of the different characteristics of contrail cirrus clouds where particulate matter is reduced. Particulate matter is almost eliminated with hydrogen combustion and is not produced by hydrogen fuel cells.

The estimated reduction in NO_x levels and elimination of particulates would also lead to improvements in air quality in and around airports.

A lack of scientific certainty on the impact of non-CO_2 aviation emissions, including potential variations in their impacts at different altitudes, is a major barrier to decision-making in design, markets and policy. There is an urgent need for accelerated academic research in close collaboration with industry.

For the wider aviation industry, introducing liquid hydrogen would be a significant challenge, requiring a completely disruptive approach to current aircraft technology, airport infrastructure and fuel production. It may require as much as 10-12% of global electricity generation in the second half of this century, but this is much less than would be needed for full-scale adoption of PtL SAF. However, other sectors will be driving the development of hydrogen infrastructure forward before aviation (as opposed to SAF), so the aviation sector would not be carrying all the costs involved.

In terms of materials and manufacturing, hydrogen aircraft would have a slightly higher embodied energy than baseline equivalents. This is due to the need for new structures such as cryogenic fuel tanks and systems, plus fuel cells and thermal management in the case of the FZR concept. Manufacturing waste is predicted to be high and material impact increases if fuel tanks and systems need to be replaced several times throughout an aircraft's life. However, these represent only about 1% of the total impact of through-life emissions with a 2030 energy mix and will be reduced to a fraction of that as the energy mix becomes more renewable.

When considering specific materials, carbon fibre contributes the highest impact, followed by aluminium and high-performance alloys, as well as magnetic materials, catalysts and electronics.

Overall, hydrogen aircraft represent the most sustainable long-term option for all but very short-range aircraft, which could be powered by batteries.

10. RECOMMENDATIONS

During the project, FlyZero identified key technologies that could radically decarbonise aviation. Early investment in R&D will be essential for these concepts to be realised. They have the potential to deliver significant emissions reductions, contributing to the UK's commitment to achieving Net Zero by 2050 to mitigate global warming. From a sustainability perspective the key recommendations, detailed separately in the ATI FlyZero 'Lifecycle Impact' cross-cutting roadmap [5] include:

- There is an urgent need to improve the understanding of the impact of contrails, the variation in impacts of emissions with altitude and the potential for navigational contrail avoidance.
- Opportunities to achieve the significant NO_x reductions anticipated from lean-burn hydrogen combustion need verification.
- Developments in policy and regulatory frameworks are required to support current initiatives to speed up decarbonisation and, where the science is sufficiently certain, to tackle non-CO_2 emissions.
- There needs to be a significantly increased capability in lifecycle impact modelling and design for sustainability methodology.
- The use of scarce materials and those with high social and environmental impact needs to be addressed by designers and supply chains.
- Improvements to recycling, decommissioning and end-of-life processes will be required.

It is recommended that a strategic, coordinated initiative is taken to accelerate climate research related to aviation. Funding in this area should be significantly increased, with long term continuity. Closer industry and academic collaboration is needed to answer the questions to inform design, policy and market decisions. This would require involvement from the ATI, Engineering and Physical Sciences Research Council and Natural Environment Research Council.

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11.1 TABLE OF FIGURES

11.2 LIST OF ABBREVIATIONS

AtJ	*Alcohol-to-jet (SAF production process)*
BOM	*Bill of materials*
CO_2	*Carbon dioxide*
CORSIA	*Carbon Offsetting and Reduction Scheme for International Aviation*
DAC	*Direct air capture (of carbon dioxide)*
EIS	*Entry into service*
EOL	*End-of-life (adjective) or end of life (noun)*
FT	*Fischer Tropsch (SAF production process)*
FZR	*The FlyZero hydrogen fuel cell regional aircraft concept*
FZN	*The FlyZero hydrogen-gas turbine narrowbody aircraft concept*
FZM	*The FlyZero hydrogen-gas turbine midsize aircraft concept*
GTP	*Global temperature change potential*
GWP	*Global warming potential*
HEFA	*Hydro-processed esters and fatty acids (SAF production process)*
ICAO	*International Civil Aviation Organization*
ISSRs	*Ice super-saturated regions (where persistent contrails form)*
LCA	*Life cycle assessment*
LH_2	*Liquid hydrogen*
MMM	*Materials, manufacturing and maintenance*
MRO	*Maintenance, repair and overhaul (also used to refer to organisations carrying out these activities)*
MSW	*Municipal solid waste*
NO_X	*Oxides of nitrogen*
PtL	*Power-to-liquid, sometimes referred to as e-fuel or electrofuel*
RF	*Radiative forcing*
SAF	*Sustainable aviation fuel*
TLARs	*Top level aircraft requirements*

SUSTAINABILITY REPORT

The Lifecycle Impact of
Hydrogen-Powered Aircraft

FLY ZERO

AEROSPACE
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