LIFECYCLE IMPACT

Future Work on Climate Science and Material Impacts

FLY ZERO

AEROSPACE
TECHNOLOGY
INSTITUTE

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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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Front cover 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 key 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.

This report gives a summary of the future work needed from a sustainability perspective to bring the FlyZero vision to reality. The next generation of aircraft should not only eliminate CO_2, but also address non-CO_2 emissions and material impacts. This report should be read in conjunction with 'FlyZero: Sustainability Report' [3] and / or the more detailed 'FlyZero: Sustainability Technical Report' [4], which describe the sustainability work done in the FlyZero Project.

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 emission flight for the next generation of aircraft [5]. The team went on to develop three concepts: a hydrogen fuel cell regional aircraft, a hydrogen-gas turbine narrowbody and a hydrogen-gas turbine midsize aircraft [6].

These hydrogen-powered aircraft will produce no carbon dioxide (CO_2) in flight and are expected to have reduced non-CO_2 climate impacts compared to kerosene powered aircraft – both fossil jet fuel and sustainable aviation fuel (SAF), but uncertainty is high and needs to be reduced. Better understanding of the impacts of in-flight emissions at different altitudes is needed to inform design. If navigational contrail avoidance could be implemented, it could significantly reduce the warming effect, but currently weather predictions are very uncertain.

Issues concerning the material sustainability of the concepts are largely similar to current aircraft and key areas are highlighted to improve circularity and reduce environmental impact.

The key recommendations 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
- 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
- Design for sustainability needs to be integrated into systems engineering methodology and there needs to be a significantly increased capability in life cycle assessment (LCA), backed up by sound data, to enable decision making for more sustainable solutions
- LCA studies using a consistent methodology are required on the impacts of other hydrogen production routes and SAFs, in addition to green hydrogen which has been assessed in the FlyZero project
- The use of scarce materials and those with high social and environmental impact needs to be addressed by designers and supply chains, especially carbon fibre and several high impact metals in alloys and catalysts. Manufacturing waste and energy should be reduced and substitute materials introduced where appropriate
- Improvements to recycling, decommissioning and end-of-life processes will be required, with more focus on design for disassembly and material tracking, especially for composites, batteries and fuel cells

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 and prioritised, with long term continuity and associated research infrastructure. Closer industry and academic collaboration are needed to inform design, policy and market decisions. This would require involvement from the ATI, Engineering and Physical Sciences Research Council (EPSRC) and Natural Environment Research Council (NERC).

01.
INTRODUCTION

The FlyZero team has identified 13 ‘technology bricks’ which are required to enable hydrogen flight as shown in Figure 1. Of these, hydrogen aircraft roadmaps cover six technology bricks, which are the revolutionary aerospace technology developments fundamental to realising liquid hydrogen-fuelled aircraft. The remaining seven are underpinning technology areas, which are covered by cross-cutting roadmap papers. This document is the ‘Lifecycle Impact’ cross-cutting roadmap paper.

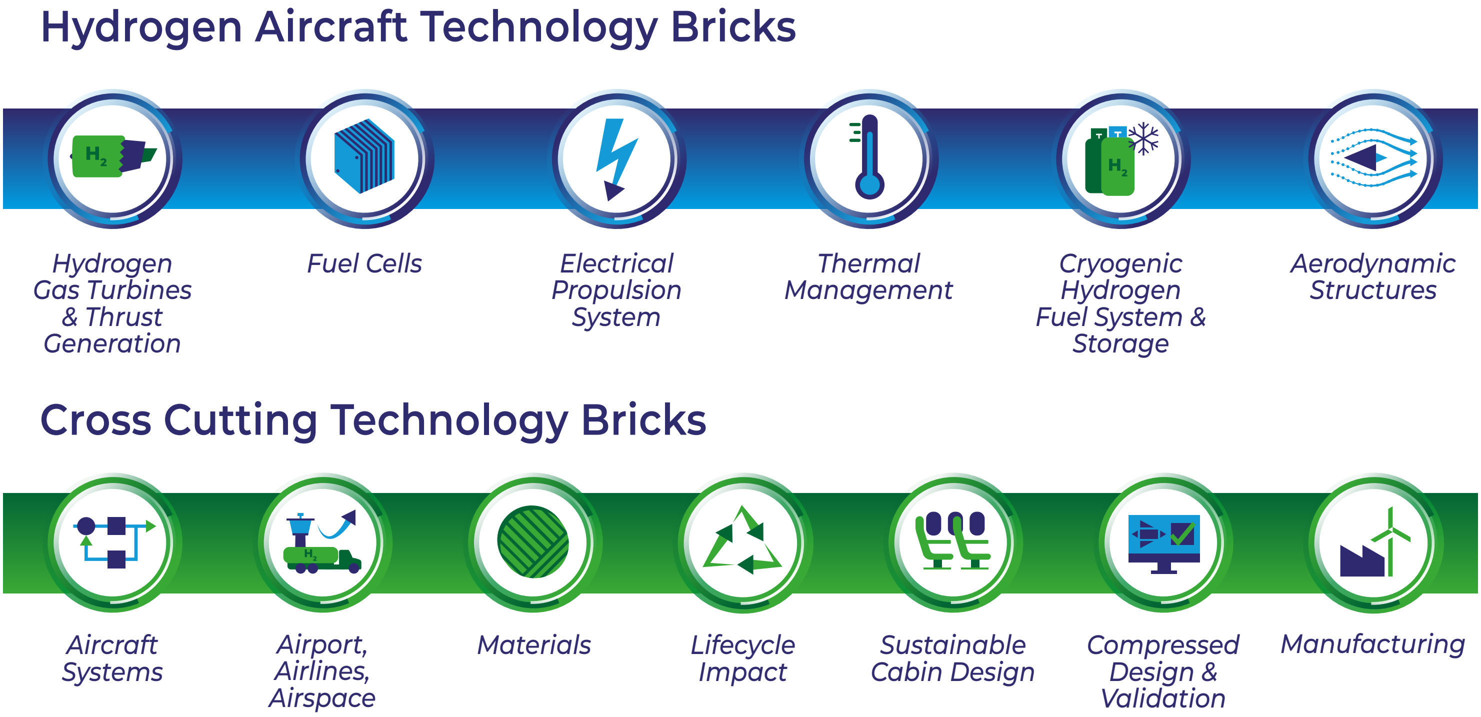


Figure 1 – Hydrogen aircraft and cross-cutting technology bricks in FlyZero

This document describes the sustainability aspects of the future work that is needed for development of a new generation of zero-carbon emission commercial aircraft powered by liquid hydrogen. It should be read in conjunction with the high-level summary ATI FlyZero ‘FlyZero: Sustainability Report’ [3] and / or the more detailed ATI FlyZero, ‘FlyZero: Sustainability Technical Report’ [4].

This report does not cover weight reduction, efficiency improvements and other sustainability issues directly related to the hydrogen aircraft technology bricks, as these are addressed in the roadmaps related to those technology bricks. In some cases, they may be mentioned where there are cross-cutting issues or particularly high impacts, such as sustainability of carbon fibre and certain critical minerals. A deeper look at sustainability of cabins, including materials, is covered in ATI FlyZero ‘Sustainable Cabin Design’ [7].

Noise is a key factor that needs to be taken into consideration, which is covered separately in the University of Southampton 'FlyZero Noise Report' **[8]**. Noise assessments conducted for the FlyZero concept aircraft show them to be potentially competitive with other aircraft.

In this report

Section 2 covers recommended work in climate science necessary to inform development of hydrogen aircraft. It focuses on understanding the impacts of current aircraft, as well as future aircraft fuelled by hydrogen and SAF, so that we can understand the effect of changing fuels. Very substantial uncertainties remain for non-CO_2 impacts, whereas reducing CO_2 emissions has clear and long-term benefits, and does not suffer from the same levels of scientific uncertainty. **[9]**

In **section 3**, which covers material impacts, most of the content is applicable to any aircraft, whether hydrogen powered or not. It addresses the methodology for integrating sustainability into the design process, similarly to the way manufacturability, cost, safety, etc. are considered. Materials, decommissioning and end of life are considered, with some specific examples based on interviews with decommissioning companies.

In each of **sections 2** and **3** a roadmap is presented, followed by a description of the elements of the roadmap, and then a summary of UK capability with comments on the global landscape, gaps and recommendations. In **section 4** key enablers such as policy, standards and regulations are considered, along with enabling research infrastructure. This is followed by a summary with priorities in **section 5**.

This report is not intended to be either prescriptive or exhaustive, but expresses the priorities raised in the FlyZero project. It is noted that some elements are cross-sector, so may not be led by aerospace, and may not reflect other sectors' priorities. Organisations listed in the capability sections highlight some key players for priority issues, and are not intended to list all stakeholders, particularly in the materials section where stakeholders extend across the manufacturing supply chain.

Reading the roadmaps

The roadmaps in this document differ from the technical hydrogen aircraft roadmaps in that they show a timeline of cross-cutting topics that underpin sustainable development of future aircraft and require collaboration between industry, academia, industry associations, certification bodies and other relevant organisations.

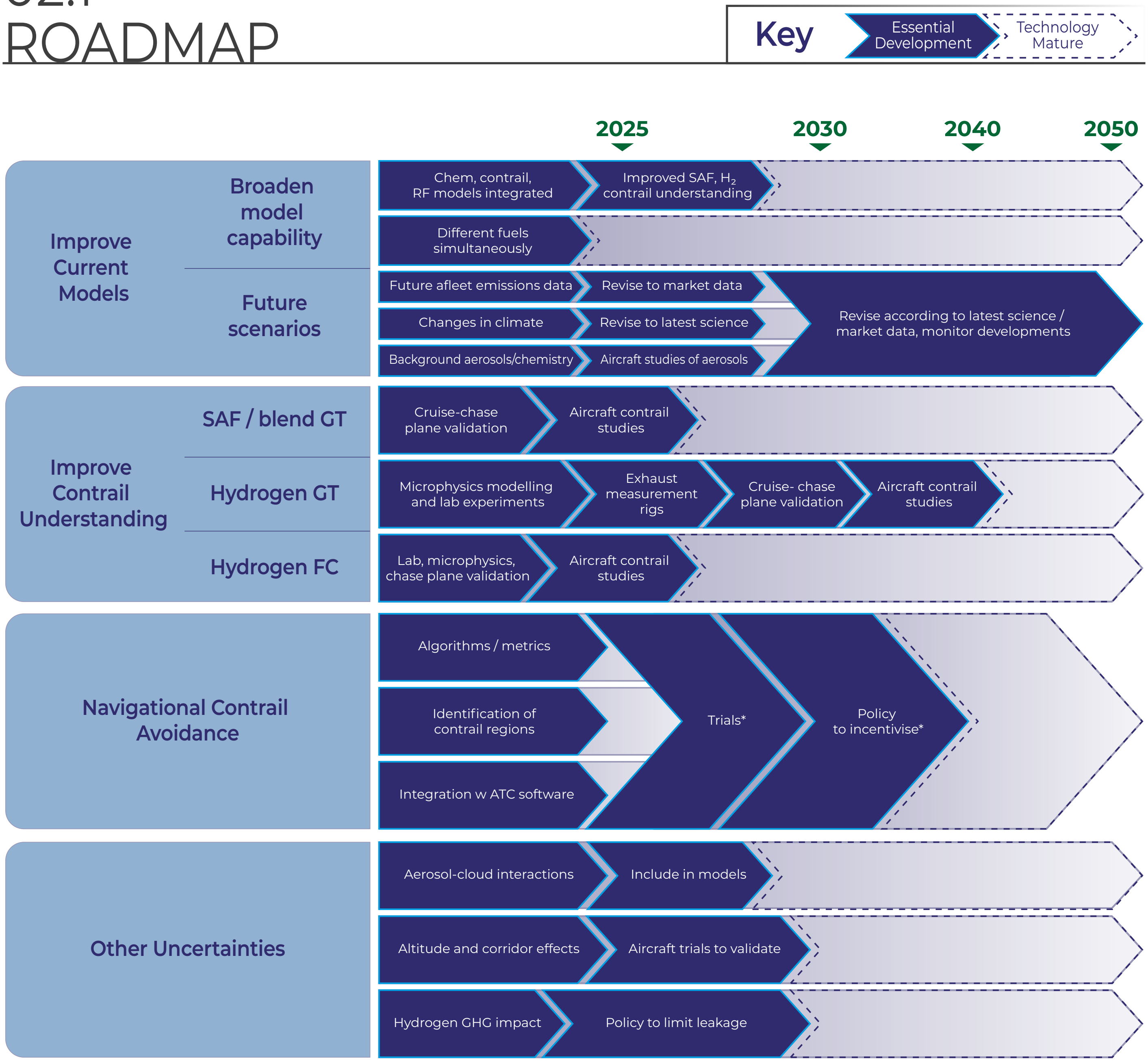
The climate impacts roadmap identifies the scientific knowledge to enable decision-making for aircraft design, markets and policy. The materials roadmap highlights the underpinning capabilities needed, such as LCA and material tracking, and material and manufacturing technologies to develop more sustainable and circular aircraft.

The swimlane arrows show activities for R&D, with an indicative timeline. In general where one arrow leads to another, the activities are broadly consecutive, though in some cases activities in a swimlane may occur in parallel. The dashed arrows indicate that technology or knowledge in the area covered by that swimlane is mature, though it is acknowledged that there is always room for incremental improvement.

The topic areas and swimlane activities are described in the text following the roadmaps. Goals are numbered C1, C2, C3, etc. for climate impacts and M1, M2, M3, etc. for material impacts. These goals are then prioritised at the end of the report.

02.
CLIMATE IMPACTS

02.1
ROADMAP



Key: Essential Development | Technology Mature

2025 | 2030 | 2040 | 2050

Improve Current Models

- **Broaden model capability**
  - Chem, contrail, RF models integrated → Improved SAF, H_2 contrail understanding
  - Different fuels simultaneously
- **Future scenarios**
  - Future afleet emissions data → Revise to market data
  - Changes in climate → Revise to latest science
  - Background aerosols/chemistry → Aircraft studies of aerosols
  - → Revise according to latest science / market data, monitor developments

Improve Contrail Understanding

- **SAF / blend GT**
  - Cruise-chase plane validation → Aircraft contrail studies
- **Hydrogen GT**
  - Microphysics modelling and lab experiments → Exhaust measurement rigs → Cruise- chase plane validation → Aircraft contrail studies
- **Hydrogen FC**
  - Lab, microphysics, chase plane validation → Aircraft contrail studies

Navigational Contrail Avoidance

- Algorithms / metrics
- Identification of contrail regions
- Integration w ATC software
- → Trials* → Policy to incentivise*

Other Uncertainties

- Aerosol-cloud interactions → Include in models
- Altitude and corridor effects → Aircraft trials to validate
- Hydrogen GHG impact → Policy to limit leakage

** Large scale trials and policy related to navigational contrail avoidance should only proceed if capability is sufficient to predict and avoid impacts of contrail cirrus clouds*

Hydrogen-powered aircraft will produce no CO_2 in flight and are expected to have reduced non-CO_2 climate impacts compared to kerosene powered aircraft, but uncertainty is high and needs to be reduced. Better understanding is critical to inform design, policy and market decisions.

02.1.1
IMPROVE CURRENT MODELS

Broaden model capability

Currently the UK modelling capability assesses atmospheric chemistry, contrails and radiative forcing (RF) in separate codes, with manual transfer of data between. A framework for integrating these is required, allowing a range of different models for a given phenomenon to be linked, assessed and benchmarked. The underlying models need extending to allow different propulsion approaches to be modelled simultaneously and to account for the evolution of the atmosphere with time and the impact of diurnal cycles.

- **Integrate models:** Establish framework for integrating climate chemistry, contrail formation and RF models and exchanging data. Determine which existing models to integrate and benchmark and identify gaps in capability. Identify means of accelerating computational calculations to allow more rapid turnaround of calculations. Add higher temporal resolution, e.g. diurnal cycles.
- **Different fuels in same model:** Expand contrail and climate chemistry models to allow analysis with a mix of fossil jet fuel, SAF and hydrogen gas turbines and fuel cells, that can evolve with time.

Future scenarios

In order to assess different future scenarios, modelling needs to account for an evolving global fleet, assessing alternative timescales for the roll-out of new technology in each market segment and varying regional growth. In addition, the ability to model the evolution of the atmosphere over time to account for items such as increased humidity and the location of the tropopause are required.

- **Future fleet emissions evolution:** Expand contrail and climate chemistry models to account for changes in the composition of the fleet over time, taking into account growth in different global regions, increasing cruise altitudes, as well as breakdown of current and novel fuels.
- **Background aerosol/chemistry:** Account for changes in background gaseous emissions, particulates and other aerosols, both from anthropogenic emissions and natural feedback processes. This includes aerosol dispersions and impact on contrails as well as variations in oxides of nitrogen (NO_x), methane, ozone, etc with time, including changes in methane leaked from natural gas distribution, farming and soil degradation as well as hydrogen leaked from new distribution networks.
- **Changes in Climate:** Account for changes in climate over time, including increase in temperature and humidity, potential effect on ice supersaturation and rising tropopause. Consider also changes in major air currents like jet streams.

Goal:

C1 Much improved UK modelling capability, as above, by the end of 2024. Part of this will be achieved through the TOZCA project **(see 2.2 'Capability and opportunities'),** but additional work needs to be identified and funded.

02.1.2

IMPROVE CONTRAIL UNDERSTANDING

The science behind the formation of individual contrails is established for fossil jet fuelled gas turbines. However, which contrails will become persistent, how long they persist and interact to form cirrus clouds, and their effective radiative forcing (ERF) is less clear. (ERF is a metric based on RF which is a better indicator of the eventual global mean temperature response for short-term forcings, such as cloud interactions). As well as scientific uncertainty, there is variability in contrail impact with changes in weather, altitude, latitude, time of day, season, exhaust temperature, water and particulate emissions.

Modelling currently depends on calibration with ground based and satellite measurements and emergent understanding from the reduction in flights due to the COVID-19 pandemic suggests that this needs updating. The impacts of contrails from SAF, SAF blends and hydrogen are less well understood, particularly related to the reduction in particulates emitted and the effect on ice particle size, which affects optical density, contrail lifetime and hence radiative forcing. The understanding for fuel cells is nascent, with only one paper published in 2021 giving a first approximation of the potential for contrail formation **[10]**.

Figure 2 – Rolls-Royce flying testbed (Image source © Rolls-Royce)

- **Contrail impact of SAF and gas turbine improvements:** Chase plane measurements to assess the impact of lean burn combustor technology and different SAFs and SAF blends (all of which result in reduced particulates) on contrail formation and support the reduction of uncertainty. These activities indirectly support understanding for hydrogen fuelled gas turbines through greater understanding of the impact of particulate density on contrail formation. Assess how to bridge the gap between detailed contrail formation and global impact simulations.

- **Contrail impact of hydrogen gas turbines:** Increase the understanding of how hydrogen fuelled gas turbines produce contrails in terms of the altitude and geographic spread and how the reduced particulates emitted affect the number and size of ice particles formed and consequently reduce the optical density and lifetime. This needs extending through microphysics modelling of the formation of contrails, combined with relevant laboratory scale experiments, together with chase plane measurements looking at contrail formation, optical density and longevity, including ground based and satellite observations.

  Given the need to accelerate understanding to ensure hydrogen fuelled gas turbines do not negate the benefits of not emitting CO_2, the first step is to bring a range of experts together to explore the possibilities for ground-based rig trials, followed by chase plane measurements prior to the first embodiment of a hydrogen fuelled gas turbine, including flying an engine designed for kerosene with minimal changes to enable burning hydrogen.

- **Contrail impact of hydrogen fuel cells:** The understanding is very sparse, with the only assessments of the potential of fuel cells to produce contrails assuming that the water is emitted as a vapour [10]. Given that the water emitted by fuel cells can be conditioned or held on board for limited periods, research into understanding the key variables in minimising contrail formation and impact is required. This should include laboratory studies on falling droplets (released in liquid phase) to measure water vapour in wake and ice nucleation, studies of microphysics modelling of water released in atmosphere and chase plane studies where water droplets of defined temperature and size are injected into the atmosphere and the resulting contrail is studied.

Goals:

C2 Improve 5–95% confidence intervals for contrail cirrus ERF from approximately +/- 70% [9] to +/- 25% by 2027. This would benefit from international collaboration.

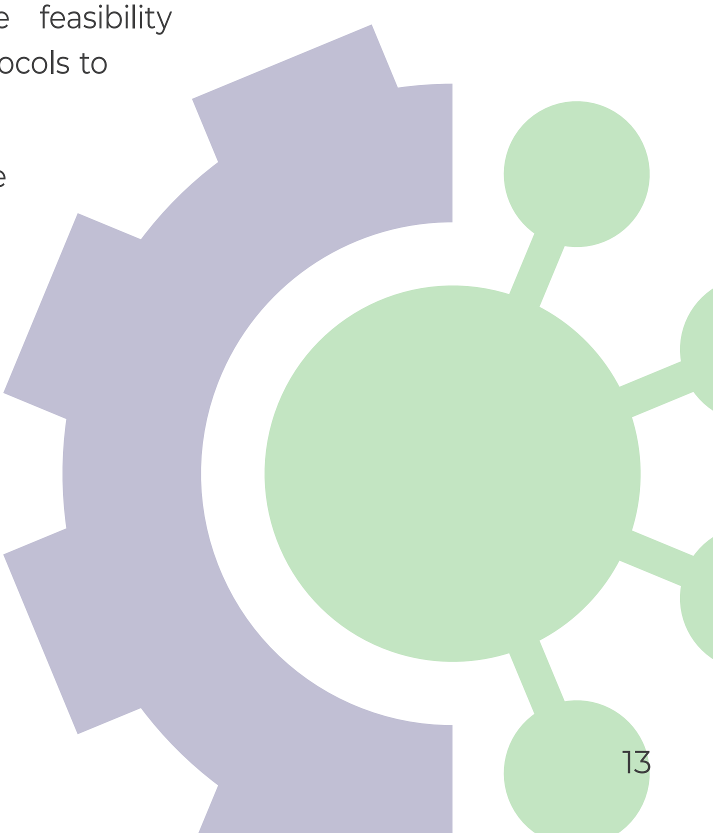
C3 Engage industry and funding bodies to establish the research infrastructure (laboratory experiments, gas turbine ground rigs, modelling and chase planes) needed to accelerate understanding of contrail impacts from SAF, hydrogen fuel cell and hydrogen combustion aircraft. This will need a costed plan by September 2022 to have research infrastructure in place to align with gas turbine development. **See 4.3 Research infrastructure.**

02.1.3
NAVIGATIONAL CONTRAIL AVOIDANCE

If it can be validated, navigational contrail avoidance could provide a rapid route to reducing the ERF of aviation and is already a subject of research for the current fleet. This is reliant on the ability to predict regions where persistent contrails will form (ice super-saturated regions, ISSRs). Methodologies to predict ISSRs in real time are very uncertain and need further developing and validating.

It is also necessary to clearly understand and balance the impact of increased fuel burn from diverting aircraft. Environmentally, this risk is much smaller for hydrogen aircraft where no CO_2 and less NO_x will likely be emitted compared to fossil jet fuelled aircraft, but can be considerable for CO_2 emitting aircraft, where the extra CO_2 would remain and accumulate in the atmosphere for hundreds or even thousands of years. If confidence becomes sufficient in both prediction of ISSRs and in the impact of contrails generally (previous section), then further trials will be needed, along with integration into air traffic management (ATM) procedures and policies to incentivise.

- **Algorithms and metrics:** Understand the implications of increased fuel burn versus contrail reduction with appropriate metrics to compare. Combine state of the art ERF estimates with avoidance algorithms to explore uncertainties and assess temperature and time varying scenarios.
- **Identification of contrail forming regions:** Improve meteorological weather prediction including relative humidity for ice. Develop optimised statistical approach to identify and avoid regions with very high probability of forming warming contrails accounting for both existing uncertainties and future improvements. Investigate regional effects.
- **Integration with ATM software:** Demonstrate feasibility of integration with ATM, including data sharing protocols to enable integration with flight planning software.
- **Trials:** If confidence in prediction is sufficient, more widespread operational trials and evaluation are required.
- **Policy:** Develop policy measures that can incentivise appropriate navigational avoidance, including establishing appropriate metrics to quantify benefits.



Target:

C4 Confidence to decide whether navigational contrail avoidance is feasible by 2025 in terms of meteorology, economics, ATM, policy and environmental impact. Followed by trials and policy development if positive, to be in place in time for introduction of FlyZero concept aircraft in early 2030s.

Figure 3 – Contrails, showing how some have spread to form cirrus clouds (Image source © Stella Job)

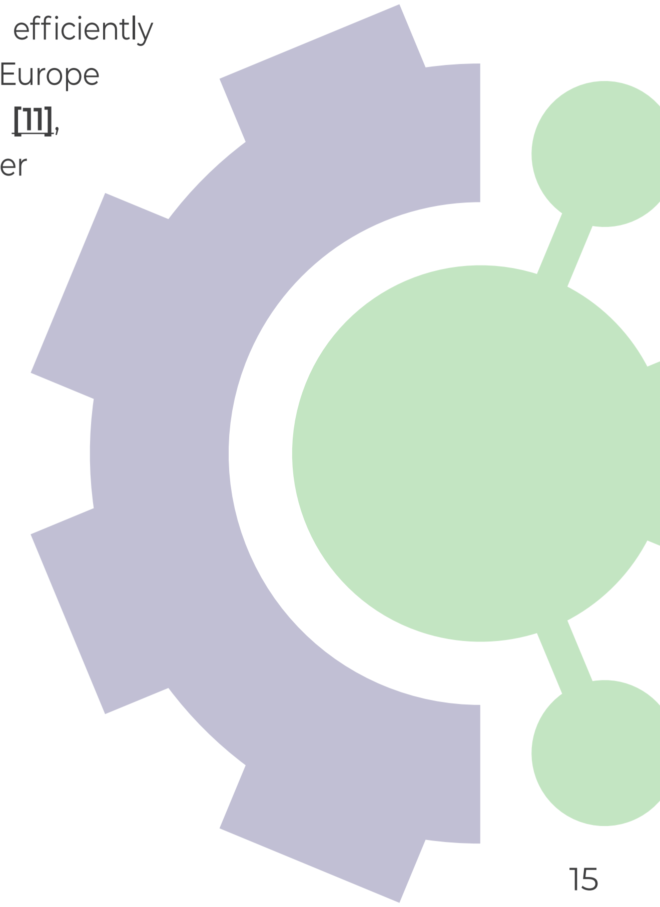
02.1.4
OTHER UNCERTAINTIES

The uncertainty bands around the climate impact of some of the phenomena are considerable. This is most noticeable for contrails, where uncertainty is of the same order of magnitude as the most likely impact. Understanding this uncertainty - whether resulting from inaccuracy in modelling or variations in conditions - is paramount to ensure that the most important phenomena are addressed with future designs and remove the risk that technology changes lead to a worsening output for the climate.

Aircraft designers want to know the effect of changing the design cruise altitude on climate impacts. The impact of contrails, NO_x and water vapour emissions are known to vary at different altitudes, but there is considerable research to be done to effectively inform design.

- **Aerosol-cloud interactions:** Currently there are no best estimates of ERF of aerosol-cloud interactions (ACI) from sulphate and soot in aviation fuel emissions [9]. Existing literature suggests a cooling effect, counteracting other aviation effects, though there is very low confidence in the magnitude of the ERF and whether it is positive or negative. While there are no (or minimal) aerosol emissions from hydrogen aviation, this is important to understand in order to compare the impacts of fossil jet fuel, SAF and hydrogen. New work is needed to quantify the ERF of ACI for current aircraft.

- **Altitude effects:** Newer aircraft are built to cruise efficiently at higher levels and an estimated 40% of aircraft in Europe now fly at or above FL360 (approx. 36,000 ft or 11 km) [11], which would usually be in the stratosphere. Water vapour emissions in the stratosphere impact climate more as altitude increases, but contrail formation in the stratosphere is rare. Impacts of NO_x emissions can also vary with altitude and geography. Further research is needed to develop understanding and integrate it into a form that is directly useful for aircraft designers.



- **Corridor effects:** Early stage research has identified that once NO_x reaches a saturation level in a particular region, the mechanisms to affect atmospheric chemistry change, leading to lower climate impact. So it is possible that impacts could be reduced if aircraft could be confined to strict routes. Likewise, overlapping of contrails in flight corridors will influence and confine the radiative forcing of contrail cloudiness. Further research is needed to identify whether corridor effects are potentially beneficial or not, and if so, whether it is feasible both from atmospheric science and ATM perspectives to reduce overall climate impacts in highly trafficked regions.

- **Hydrogen as indirect greenhouse gas (GHG):** Hydrogen has an indirect impact on climate via interactions with hydroxyls, methane and stratospheric water vapour. Aspects of this have been researched and the impact of hydrogen leakage in the production and distribution supply chain has been estimated. The GWP100 (global warming potential integrated over 100 years) impact of hydrogen has been estimated to be 5 ± 1 kg CO_2 e/kg (i.e. 1 kg hydrogen has the equivalent impact of 5 ± 1 kg CO_2.) [12]. However, climate scientists are investigating further mechanisms which may increase the expected warming impact. Confidence is needed to inform policy on restricting leakage of hydrogen in supply chains.

Goals:

C5 (Most urgent for design) Computational study of altitude effects (especially water vapour and contrails) to clearly inform design completed by 2024. This will build on FlyZero work to develop new models of global fleet mission profiles and understand the impact in climate models.

C6 Develop understanding of soot and sulphur ACIs to establish whether hydrogen aircraft will lose a significant cooling effect by 2025. This will use the UK Earth System Modelling simulations, building on previous work by University of Leeds [13].

C7 Improved simulations of hydrogen GHG impact published by end of 2022 to inform policy on leakage to atmosphere.

02.2
CAPABILITY AND OPPORTUNITIES

02.2.1
UK CAPABILITY

Key UK organisations active in climate science related to aviation include:

Imperial College London, Transport & Environment Laboratory: Aerosol science, pollution, navigational contrail avoidance

Manchester Metropolitan University (MMU), Centre for Aviation, Transport and the Environment: Climate science, leading large collaborative projects

University of Manchester, Dept for Mechanical, Aerospace & Civil Engineering: Exhaust emissions, acoustic emissions, high-altitude effects of flight

University of Bristol, School of Chemistry: Corridor effects for NO$_x$

University of Cambridge, Whittle Laboratory & Centre for Atmospheric Science: Aviation Impact Accelerator (see below)

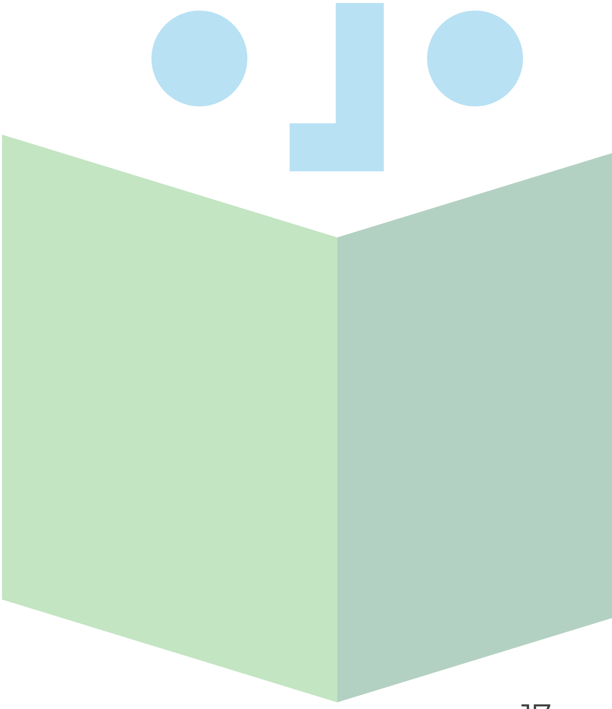
University College London (UCL), Energy Institute: Techno-economic assessments and integrated modelling of the global air transportation system

University of Leeds (UoL), School of Earth and Environment / Priestly International Centre for Climate: Radiative forcing, contrails, atmospheric chemistry, ice nucleation, aerosols

University of Oxford, Environmental Change Institute: Climate change (inc. in context of aviation)

University of Reading, National Centre for Atmospheric Science: Meteorology

SATAVIA: Software for navigational contrail avoidance, and condition monitoring



02.2.2

MAJOR CURRENT UK PROJECTS

TOZCA - Towards Zero Carbon Aviation, Nov 2021 to Oct 2024, UCL, UoL, University of Southampton and MIT: Techno-economic analysis for zero carbon aviation targets. Includes developing contrail and chemistry models for novel fuels

NAPKIN - New Aviation Propulsion Knowledge and Innovation Network, Nov 2019 to Apr 2022, Heathrow & nine partners: Modelling the introduction of low or zero emissions aircraft into regional and short-haul aviation

Aviation Impact Accelerator (AIA) - Jun 2020 ongoing – Whittle Lab & partners: Aircraft climate impact simulator

02.2.3

OVERSEAS LANDSCAPE

International collaboration will be of benefit in several areas. Some key centres include:

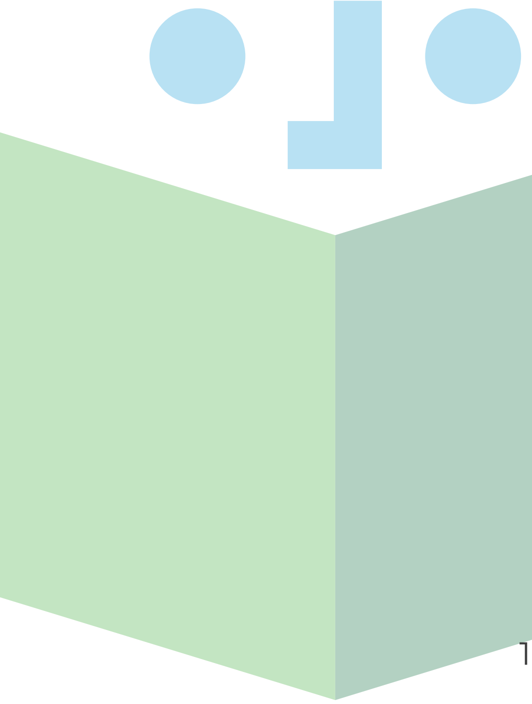
Deutsches Zentrum für Luft- und Raumfahrt (DLR - German Aerospace Center), Germany: Established expertise in atmospheric physics and chemistry and energy flow, formation and understanding of contrails, both measurements and predictions. A current project of particular relevance is 'H_2Contrail'

Centre National de la Recherche Scientifique (CNRS - National Centre for Scientific Research), France: Measurements in the environment, inc. instrumented aircraft, models to capture the behaviour

Massachusetts Institute of Technology (MIT), Laboratory for Aviation and the Environment, USA: Inc. low emissions technologies, atmospheric impacts of aircraft pollution

National Center for Atmospheric Research (NCAR), USA: Climate research including atmospheric chemistry and contrails

NASA, USA: Extensive capability covering all aspects of climate change, including experimental and predictive capability



02.2.4

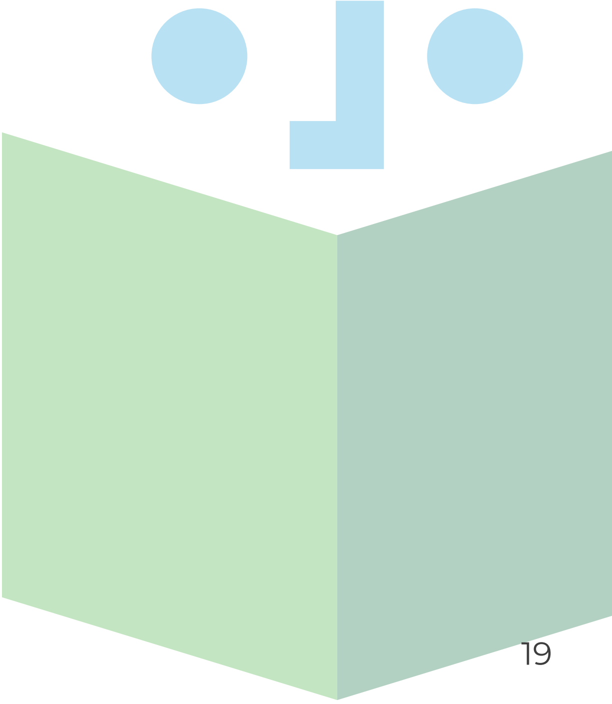
GAPS AND RECOMMENDATIONS

The UK universities have historically operated with piecemeal funding and insufficient interaction with aerospace companies. FlyZero has found bridging the gap between academia and industry has accelerated learning. It is critical to further develop UK capability, whilst recognising the importance of continued overseas collaboration. There is much value in having several global centres of excellence which reveal different perspectives and can be compared, particularly where the results have a strong influence on decision making.

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, EPSRC and NERC. A 'sandpit' could be arranged to determine a suitable path.

Aspects of the proposed work needed for design decisions, e.g. altitude effects, need to be accelerated, so should augment projects like TOZCA and AIA, rather than waiting for the outcome of these projects before progressing.

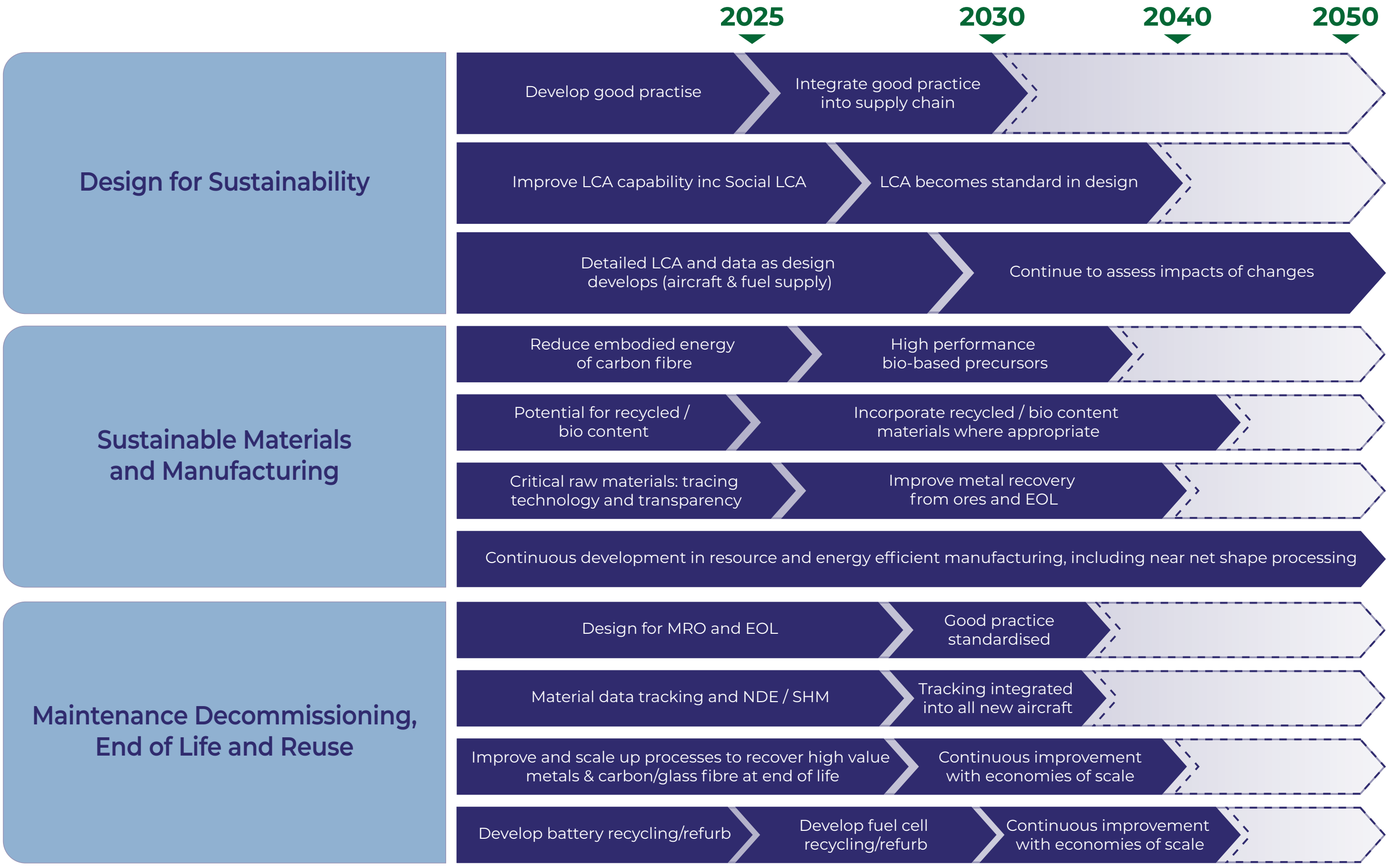
An audit should be carried out of the current capabilities in laboratory-scale experiments, modelling and chase plane capability to identify gaps. **See Section 4.3 'Research infrastructure'.**



03.
MATERIAL IMPACTS

03.1
ROADMAP

Key
Essential Development
Technology Mature



2025
2030
2040
2050

Design for Sustainability

Develop good practise → Integrate good practice into supply chain

Improve LCA capability inc Social LCA → LCA becomes standard in design

Detailed LCA and data as design develops (aircraft & fuel supply) → Continue to assess impacts of changes

Sustainable Materials and Manufacturing

Reduce embodied energy of carbon fibre → High performance bio-based precursors

Potential for recycled / bio content → Incorporate recycled / bio content materials where appropriate

Critical raw materials: tracing technology and transparency → Improve metal recovery from ores and EOL

Continuous development in resource and energy efficient manufacturing, including near net shape processing

Maintenance Decommissioning, End of Life and Reuse

Design for MRO and EOL → Good practice standardised

Material data tracking and NDE / SHM → Tracking integrated into all new aircraft

Improve and scale up processes to recover high value metals & carbon/glass fibre at end of life → Continuous improvement with economies of scale

Develop battery recycling/refurb → Develop fuel cell recycling/refurb → Continuous improvement with economies of scale

Sustainable methodology needs to be integrated into design, materials, decommissioning and end of life to set the aerospace industry on course to develop a new generation of more sustainable and circular aircraft.

03.1.1
DESIGN FOR SUSTAINABILITY

There is a strong need for robust methodology for assessing sustainability throughout the design process alongside other factors. This may include:

- Environmental life cycle assessment (LCA)
- Social LCA
- Restricted substances
- Critical raw materials
- Impact of design on end-of-life treatment and maintenance, repair and overhaul (MRO)
- Finance and business models which incentivise sustainable practice.

Collaboration and sharing of good practice are needed across the supply chain, alongside training, both through higher education and in the workplace. Leadership of this activity needs to be established.

- **Design for Sustainability (D4S) good practice:** Tools are needed to integrate D4S into systems engineering methodology to be assessed within technical gate reviews, as is done for safety, cost, design for manufacture, etc.

  Existing initiatives led by industry associations, e.g. the ADS Design for Environment group, should be complemented by development of good practice across the aerospace supply chain. It is recommended that workshops are undertaken to share and learn from methods used which are appropriate to different stages of design. This could lead to development of good practice guidance, working with the International Aerospace Environment Group (IAEG). It is recommended that ATI work with the Aerospace Growth Partnership (AGP), primes and tier 1s to support this work.

- **LCA capability:** LCA is a very powerful tool to highlight priorities in reducing environmental impact, but expertise in understanding LCA methodologies and applying them to products is lacking. Better capability to undertake LCA and more reliable data, especially from further up supply chains, are needed. Simplified LCA can be effective, as full LCA is complex and expensive, but some simplified LCA tools can bring a risk of use with limited understanding and poor data, so should be treated with caution.

  Social LCA is an emerging discipline which highlights the importance of understanding the human related impacts associated with upstream supply chains. Several materials that are vital to aircraft efficiency, such as cobalt, have high social impacts. Social LCA still needs significant development to provide suitable frameworks.

  Further training is needed in higher education and the workplace. It is recommended that ATI and other funding bodies promote the use of LCA in research projects at an appropriate level, to improve capability and gather data, as we move towards LCA becoming a standard part of design.

- **Detailed LCA and data for aircraft and fuel supply:** FlyZero has conducted a simplified LCA for the concept and baseline aircraft using Ansys tools. This should be taken to a more detailed level as design progresses and more detailed bills of materials are available.

  Further LCA studies are required on alternative pathways for producing hydrogen, including blue and turquoise routes as well as green, and bio and power to liquid SAFs, using a consistent methodology. This will enable more reliable through life impact assessments. (For an explanation of the hydrogen production pathways, see National Grid 'The hydrogen colour spectrum' **[14]**.)

Goals:

M1 Integrate D4S good practice and LCA capability (social and environmental), comparable to current capability for assessing design for manufacturing and cost, by 2025 for the design of new hydrogen aircraft, and by 2030, with associated good practice guidance / standards, for the rest of the aerospace supply chain.

M2 Improved understanding of comparative LCA impacts of fuels by end of 2023

03.1.2
SUSTAINABLE MATERIALS AND MANUFACTURING

In aviation it is always a priority to develop materials to reduce weight and enable efficiency improvements throughout the aircraft, to reduce fuel use. Specific technologies related to these are not covered here, but are addressed in the ATI FlyZero hydrogen aircraft roadmaps, especially the ATI FlyZero 'Aerodynamic Structures Technical Report' [15].

Some materials which provide optimal properties can also consume very high energy in production, deplete scarce resources, or have social impacts which may be a cause for concern. Ongoing work should continue to consider material substitutions, but where these materials are still the best choice, harmful impacts need to be addressed.

- **Reducing impact of carbon fibre:** Carbon fibre (CF) is highlighted as the material with the highest embodied energy impact (specific embodied energy x mass) in future aircraft, though its contribution to weight reduction and thus aircraft operational emissions savings validates its use. Both the precursor production and conversion to CF are very energy intensive. R&D to reduce energy and develop bio-based precursors is recommended, as well as siting production where renewable energy and/or waste heat can be used to reduce impact. See recommendations for CF pilot lines in section 4.3 Research infrastructure

- **Recycled and bio-based content (RBBC):** RBBC is already being introduced in cabin furnishings [7]. Further work should assess parts across the airframe which could use RBBC without significant penalties to weight or efficiency. Recycled CF could replace glass fibre or virgin CF in some applications. Fire resistant polyfurfuryl alcohol (PFA) resins from sugar cane waste now have applications in aircraft interiors and battery boxes with potential for jet engine components [16]. Work is needed to: Develop parts with RBBC; introduce bio-sourced chemicals for high performance resins; review standards and certification to enable sustainable materials; design for uncertainty / short fibres; scale up alignment processes for recycled CF.

Figure 4 – Battery box manufactured with PS200 prepreg, using fire retardant, bio-based PFA resin. Undergoing fire test. (Image source © SHD Composite Materials Ltd)

- **Critical raw materials (CRMs) and sustainable value chains:** CRMs are those with both high economic importance and high supply risk. These comprise some of the key building blocks of aerospace. Production of cobalt, a key component in superalloys and batteries, is increasing, and has potentially negative social and environmental impacts. Future work needed includes: Use of blockchain and other traceability technologies for raw materials to ensure provenance; transparency in prices and trading; technology to improve metal recovery from ores and recyclate. **(See also comments on Social LCA in 3.1.1.)**

- **Continuous development:** Resource and energy efficient manufacturing should continue to be prioritised across the aircraft and monitored through LCA. This includes developing near net shape processes such as additive manufacturing, casting, reducing energy in composite curing **[17]**, improving closed loop recycling of alloys such as the Rolls-Royce 'Revert' programme **[18]** and moving away from machine from billet processes with poor buy-to-fly ratios.

Goals:

M3 Reduce energy use in carbon fibre manufacturing significantly by 2030. Introduce high performance bio-based precursors by 2035.

M4 ATI work with stakeholders to undertake a full review of opportunities for RBBC in 2022-3, identifying target products and associated barriers, such as standards and design methodology, followed by funding for product and process development.

M5 Internationally accepted procedures in place by 2030 for transparency and traceability for critical materials and those with high social impact. This should link to the work of the Critical Minerals Association and the Responsible Minerals Initiative.

03.1.3

MAINTENANCE, DECOMMISSIONING, END OF LIFE AND REUSE

As part of FlyZero, the University of Strathclyde interviewed asset owners, MROs, decommissioning organisations and recyclers, to understand their perspective on how to improve circularity and end-of-life (EOL) value of aircraft. Their recommendations are included in the points below.

Except for very high value materials, recycling processes are not often developed until waste quantities reach substantial amounts, e.g. thousands of tonnes per annum, which for some materials, the aviation sector will never reach. Most aircraft scrap materials have commonality with other sectors, e.g. battery and fuel cell recycling will reach larger volumes more quickly in automotive, there is much more glass fibre composite scrap from wind energy and construction. So there is a need for producer responsibility to be worked out in cross-sector collaboration.

- **Design for MRO and EOL:** Processes are needed to ensure that design for disassembly / EOL is considered at appropriate stages, enabling maintenance and repair or higher value recycling, rather than disposal. More interaction between design teams and dismantlers / MROs would highlight areas for improvement. This relates to D4S in **section 3.1.1.** Important examples of this include:

    One way assembly, which reduces complexity with assembly and disassembly and also reduces materials used on the structure by eliminating shims and additional fixing plates.

    Fastenerless assembly, which could facilitate recycling as well as reducing weight. See ATI FlyZero 'Aerodynamic Structures Roadmap Report' [19]

- **Tracking for material data and diagnostics:** Lack of material data, exacerbated by intellectual property issues, inhibits high value EOL recovery and refurbishment. Material data 'passports', or digital twins, are needed, including onboard diagnostics (e.g. loading / cycling information), as seen in automotive, and recording material replacements at MRO. Tracking technologies can be integrated with systems for informing design and validation and optimising through life support. Non-destructive evaluation (NDE) and structural health monitoring (SHM) can also help to extend lifetimes and enable refurbishment.
- **High value metal recycling:** Improving circularity is also important for metals such as aluminium used widely in aerospace. In future, industry should look increase the use of secondary metals from end-of-life scrap. A wider framework is required to process end-of-life aerospace metals to avoid contamination and degradation. Also further research is required to develop greater understanding of the impact of impurities on material performance. The long-term objective should be no primary material use.

- **High value composite recycling:** CF recycling is active using pyrolysis for manufacturing waste, but very limited for EOL material. Fluidised bed CF recycling is developed to pilot scale, and may accept more EOL scrap due to its tolerance to metals / contaminants. Solvent-based methods for fibre recovery and fibre alignment processes are at TRL 6-7. Commercialisation is limited by low volumes and market acceptance of short fibre products. Scale up of more contamination tolerant processes for EOL scrap is needed, along with alignment technologies to gain higher value from the fibres and development of applications for recycled CF intermediate materials in cabins and other products would provide markets.

  Glass fibre composite recycling is progressing, led by the wind energy and construction industries, which may enable cabin interiors to be recycled **[20].**

- **Battery and fuel cell recycling and refurbishment:** Li-ion battery recycling in UK is very limited, and as yet, does not recover lithium, though cobalt and nickel are recovered. There is currently no recycling of fuel cells in the UK, though there is interest in recovering the platinum.

  Battery recycling should be expanded to prevent export. Fuel cell recycling needs to be developed, and novel fuel cell architectures need to consider material recovery. Modular battery and fuel cell design with through life diagnostics will facilitate refurbishment. These are likely to be led by the automotive industry.

Goals:

M6 Standards development and accepted good practice for material data and diagnostics to be routinely integrated in data passports / digital twins by the time FlyZero concept aircraft come into service in the early 2030s. Standards should be addressed alongside technology development.

The target for RBBC in **3.1.2** would identify markets for recycled CF and support growth in CF recycling supply chains. Recycling of glass fibre composites, batteries and fuel cells are likely to be led by other sectors, but the aerospace sector should support these.

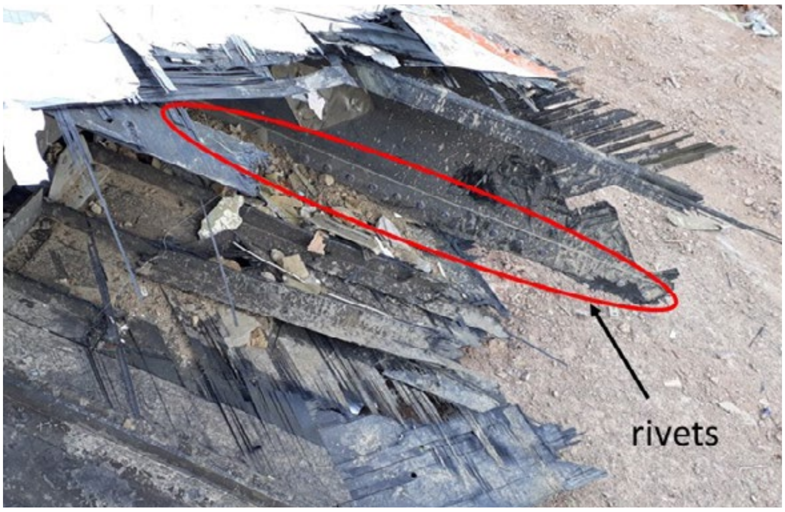


Figure 5 – Carbon fibre aircraft scrap, showing rivets which are uneconomical to remove for recycling (Image source © Stella Job)

03.2
CAPABILITY AND OPPORTUNITIES

03.2.1
UK CAPABILITY

While material impacts are addressed by the whole supply chain, a few key UK organisations in areas that need more focus are listed here:

Design for Sustainability:

University of Surrey; Imperial College London; UCL: LCA capability, including masters programmes; University of Surrey especially in relation to aerospace and airport infrastructure

Ansys Granta Materials Intelligence and Dassault Systemes 3DExperience: Eco-design tools with environmental impact data in materials databases

Sustainable materials and manufacturing:

High Value Manufacturing Catapult (HVMC); University of Bristol, Bristol Composites Institute; Cranfield University, Centre for Aeronautics; and others: Resource and energy efficient manufacturing, recycled and bio-based content coupled with LCA and design capability

Aerospace manufacturers, especially Airbus, Rolls-Royce, Spirit AeroSystems, GKN Aerospace: Many excellent initiatives in sustainability ongoing

Critical Minerals Association: Industry association to address critical minerals

Cygnet Texkimp: Expertise in building carbon fibre manufacturing lines

Many other supply chain companies are developing sustainable materials and intermediate products, supported by institutions and associations.

Maintenance, decommissioning, end of life and reuse:

Air Salvage International; AERS; Chevron Technical Solutions; eCube Solutions; GJD Services - Aircraft dismantling is strong in UK, also several companies in MRO and second-hand parts

British Institute of Non-destructive Testing: And their members, for NDE/SHM

Gen 2 Carbon: CF recycling and material supply

TWI; Oxford Brookes University, Sustainable Vehicle Engineering Centre: Joining, disassembly, disbonding adhesives

University of Nottingham, University of Bristol, National Composites Centre: CF recycling and alignment technologies

University of Strathclyde, National Manufacturing Institute Scotland: Expertise in decommissioning, MRO, glass fibre composite recycling (PRoGrESS project)

Warwick Manufacturing Group, RS Bruce, Cawleys: Battery recycling

03.2.2

OVERSEAS LANDSCAPE

International collaboration is critical in developing good practice. Some key international centres related to the topics covered here include:

Deakin University, Australia, Oak Ridge National Laboratory, USA and LeMond Carbon, USA, with Cygnet Texkimp, UK: Working together to develop low energy CF based on PAN precursors

German Institutes of Textile and Fiber Research (DITF Denkendorf) and IRT Jules Verne, France: Developing oil-based and bio-based precursor technology for low energy carbon fibre production

International Aerospace Environmental Group (IAEG), global: Good practice guidance for sustainable supply chains, carbon reporting, restricted substances, material replacement technologies, etc, supported by all major players

Responsible Minerals Initiative (RMI), global - Provide tools and resources for regulatory compliance and support responsible sourcing of minerals

RWTH Aachen University, Germany - Alternative CF precursors

03.2.3

GAPS AND RECOMMENDATIONS

There is a strong need for improved LCA capability and associated data. Encouraging appropriate LCA activity in research projects supports this and would help to embed D4S good practice, particularly important in the early design phase. Leadership is needed to develop strategy and generate good practice guidance for D4S / LCA. While trade associations such as ADS may coordinate this, support from and collaboration with ATI, AGP, primes and tier 1s is crucial. It should also link to IAEG, where strong connections are already in place in some areas, e.g. IAEG 'Replacement Technologies' working group is chaired by Rolls-Royce.

The Department of International Trade (DIT) is working to bring more environmentally friendly CF manufacturing technology into the UK and there are ongoing discussions about how to support R&D capability for both fibre and precursor manufacturing. **See section 4.3 Research infrastructure.**

Multiple projects will address improvements in sustainability of manufacturing. Funding structures such as NATEP should enable smaller companies (SMEs) in the materials supply chain to get the support that they need. Clear strategies and targets from tier 1s and OEMs help to focus SME investment priorities.

As part of technology research, ATI can promote integration of tracking for material data and diagnostics to support EOL recovery and refurbishment with systems for informing high value design and validation and optimising through life support.

04.
ENABLERS

Technology development alone will not succeed in creating a more sustainable future. Sustainable development is heavily influenced by external factors which designers and technology developers may have limited ability to change, as is illustrated in **Figure 6** below**,** but communication, collaboration and coordination of activities will accelerate alignment of the enablers and system conditions essential to success.

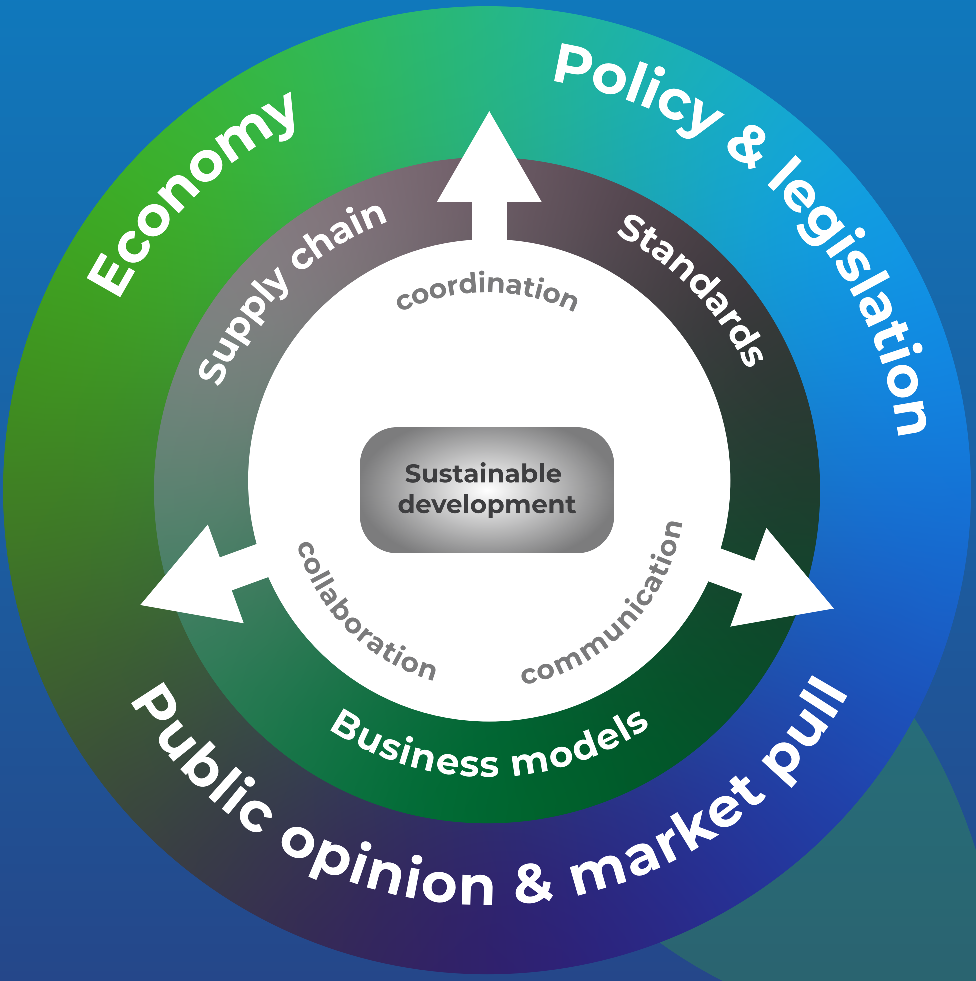


Figure 6 – Influencing the macro-influences (Image source © Stella Job)

04.1

UK AND INTERNATIONAL POLICY AND LEGISLATION

Policy direction will play a critical role to facilitate the early entry into service of zero-carbon aircraft and their contribution to net zero by 2050. While the cost of liquid hydrogen is expected to be competitive with fossil jet fuel without carbon tax in the longer term, the development of new aircraft and changes to infrastructure would not occur without strong fiscal policies to incentivise. The inclusion of aviation in the 'UK Hydrogen Strategy' and in the 'Sixth Carbon Budget' legislative target for 78% reduction in emissions by 2035 are significant steps towards this **[21] [22].** The 'UK Hydrogen Strategy' also supports the development of hydrogen supply infrastructure for other sectors, in advance of it being required for aviation, though further work will be required, such as liquefaction and airport infrastructure, to account for future aviation needs.

The position of the ATI and the influence of the FlyZero outputs at the level of the Jet Zero Council provides an opportunity to accelerate introduction of appropriate policy to provide technology funding and, more importantly, fiscal incentives for the move to zero carbon aviation. Early action could secure this is delivered successfully and look forward to its inclusion in the publication of the Jet Zero Strategy in 2022. International collaboration is needed for markets to become viable, so it is vital that there is an informed UK representation at international bodies such as the International Civil Aviation Organization (ICAO).

The recent passing of the Environment Act 2021 requires long term (15 years+) environmental targets to be set for resource efficiency and waste reduction, air quality, water and biodiversity. This paves the way for more producer responsibility regulation, for which the aerospace industry needs to be prepared. It also allows for stricter targets for air quality, which a move to hydrogen fuels would support.

There needs to be careful consideration of non-CO_2 impacts as science develops, and whether there is sufficient certainty to warrant regulatory or policy action. If navigational contrail avoidance is found to be feasible, policy, regulations and standards will be needed to put it into practice.

04.2
STANDARDS AND REGULATIONS

Standards and certification pathways can be a blocker or an enabler for sustainable development, and take time to develop, so should be addressed at an early stage. Key areas that are likely to need addressing in this context include:

- **Cruise NO_x.** Current NO_x limits in ICAO Annex 16 apply to landing and take-off covering local air quality requirements below 3,000 ft. As part of standards and recommended practices (SARPs) cruise NO_x may need to be considered if it is technically feasible, environmentally beneficial and economically reasonable.
- **Navigational contrail avoidance:** If this is found to be feasible, standards will be needed for:
    - a. Air traffic management procedures to accommodate rerouting;
    - b. Temperature/humidity/atmospheric measurement with a possible algorithm to identify contrail formation conditions.
- **Fuel sustainability standards:** While SAFs have existing sustainability criteria and standards by different organisations, this is not the case for hydrogen. A robust sustainability criteria that will ensure sufficient life-cycle emissions reductions of hydrogen as a fuel will need to be developed.
- **Hydrogen release and handling:** Standards exist for handling hydrogen generally, but not specific to aviation fuel use. This should take into account the high flammability of hydrogen and the greenhouse gas effect of its release, and consider venting hydrogen into the atmosphere under abnormal or emergency conditions, both in ground (airport and fuel supply) and air systems.
- **Fuel cell by-product water:** Release into the atmosphere under normal operation and system and the identification of any potential hazards to the aircraft and over flown third parties
- **Test methods and failure criteria for materials:** Standards for traditional materials are often not suitable for novel and sustainable materials and so become a blocker for certification. Also fire performance standards may change with novel fuels.
- **Material and diagnostics data tracking:** Formats which allow for data for EOL / reuse to be integrated into data passports / digital twins for informing design and validation and optimising through life support.

Key players in this area are ICAO, the International Organization for Standardization (ISO), SAE International, ASTM International, Civil Aviation Authority (CAA), European Union Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA). Certification can be accelerated by reviewing standards at an early stage in research projects.

04.3
RESEARCH INFRASTRUCTURE

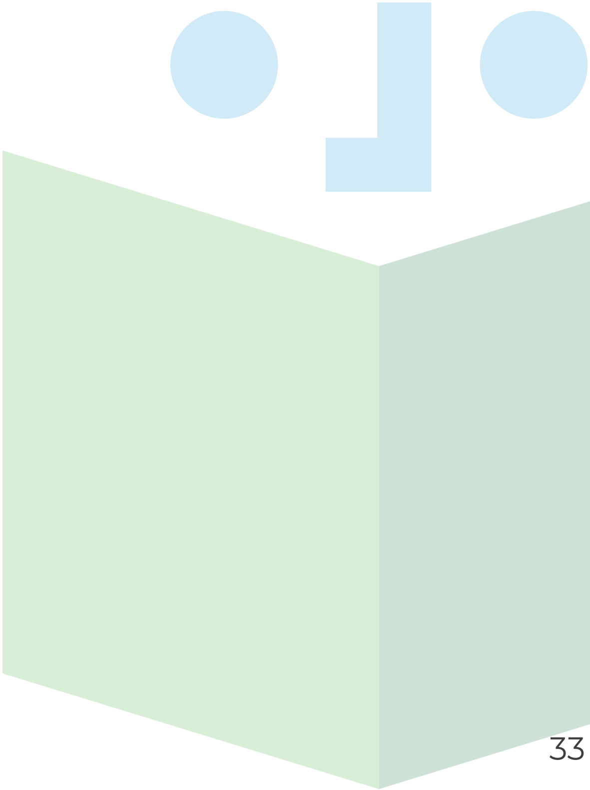
Suitable research infrastructure facilitates and accelerates technology development, verification and validation. Some areas where funding to extend UK research infrastructure is particularly needed in the context of the sustainability of hydrogen powered aircraft include the following.

- **Test rigs:** Building rigs to study hydrogen gas turbine combustion and fuel cell emissions, with suitable measurement capability, and investigation of novel ways of understanding contrail formation in ground based facilities
- **Chase plane:** Provision of a chase plane and associated infrastructure, capable of flying at altitudes around the tropopause. Investigate the need for enhancements to the current instrumentation
- **Computing facilities for atmospheric modelling:** Suitable computing facilities to allow data sharing, model assembly and assessment and benchmarking between multiple stakeholders and high performance computing to accelerate the delivery of results

It is recommended that industry, universities and funding bodies work together to establish what is needed to accelerate understanding of contrail impacts from SAF, hydrogen fuel cell and hydrogen combustion aircraft. Research infrastructure needs to be in place to align with hydrogen gas turbine development and optimise the critical path to providing increased confidence in the relative impacts of different fuels in the shortest possible timescale (Goals C1, C2). To achieve this, an audit of current capabilities to identify gaps should be produced with a costed plan by September 2022 (Goal C3). For chase plane studies in particular, the value of extending UK capability should be established compared to working in international collaboration, e.g. with DLR.

Carbon fibre pilot lines

Pilot scale research capability for both fibre and precursor manufacturing would provide a step change in potential to move towards more sustainable and bio-based CF, ahead of international competition and complementing the world-leading UK capability in CF intermediate materials, manufacturing and recycling.



05.
SUMMARY AND PRIORITIES

There are several fundamental questions around the climate impact of aviation for which answers are not adequate at present, such as:

- What is the balance of cooling and warming effects of NO_x in the future?
- What effect does changing the design cruise altitude have on the climate impacts of contrails, NO_x and water vapour emissions?
- What are the effects of soot and sulphur with current fuels? Are they creating a lot of cooling that would be lost by moving to hydrogen?
- Are contrails as bad as current models suggest? (The effect recorded during the pandemic was smaller than expected.)
- Could weather prediction be good enough for navigational contrail avoidance and is it possible to integrate into air traffic management systems?
- Should non-CO_2 impacts be regulated and if so, how would they be measured?

Hence, 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 and associated research infrastructure. 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, EPSRC and NERC.

Short, medium and long term goals are shown in **Table 1** in order of priority. This highlights the need for swift action to accelerate climate research for aviation.

Short term goals (1-3 years)	*Medium term goals (3-6 years)*	*Long term goals (7+ years)*
C5 - Computational study of altitude effects	*C2 - Improve confidence for contrail cirrus ERF*	*C4 - Implementation of navigational contrail avoidance*
C3 - Costed plan for research infrastructure for contrail impacts V&V	*C6 - Understanding of soot and sulphur ACIs*	
C1 - Improved UK climate modelling capability		
C7 - Improved simulations of hydrogen GHG impact		

Table 1 – Climate impact goals

Based on FlyZero analysis, material impacts through the life of the FlyZero aircraft concepts are of the order of 1% of the impacts of in-flight emissions on climate, so the emphasis in design should focus on weight reduction and efficiency improvements to reduce fuel use. These aspects are covered in the ATI FlyZero hydrogen aircraft roadmaps. Nevertheless, with increasing producer responsibility and reducing resources there needs to be a persistent and transparent drive for more environmentally and socially sustainable aircraft manufacture.

Short, medium and long term goals are shown in **Table 2** in order of priority. M2 focuses on understanding the impacts of fuel production, as an enabler for full LCA. The longer timescales of M5 and M6 acknowledge that development of internationally agreed standards takes a long time. Recycling processes that are led by other sectors are not included in the goals.

While too broad for a specific target, continuous improvement in resource and energy efficient manufacturing will become a clearer focus as D4S and LCA capability become more mature.

Short term goals (1-3 years)	*Medium term goals (3-6 years)*	*Long term goals (7+ years)*
M2 - Improved understanding of comparative LCA impacts of fuels	*M1 - Integrate D4S good practice and LCA capability (continues to long term)*	*M3 - More sustainable carbon fibre manufacturing*
M4 - Review opportunities for recycled and bio-based content		*M5 - Procedures for traceability for critical / high social impact materials*
		M6 - Standards for material data and diagnostics in digital twins

Table 2 – Material impact goals

Engaging with policymakers at the highest level, both in the UK and internationally, is essential to seeing the vision for hydrogen-powered aviation move forward. Organisations such as the ATI play a strategic role in providing information to inform policy to incentivise the right path. As scientific knowledge develops, there needs to be coordination between aerospace technology developers, climate scientists and policymakers on issues such as navigational contrail avoidance and whether non-CO_2 impacts could or should be regulated.

New standards will be required in many areas, and they typically take a long time to be developed. Early intervention and a strategic approach from an early stage will accelerate this and reduce the risk of limiting certification of more sustainable routes.

Suitable research infrastructure facilitates and accelerates technology development, verification and validation. Identifying the equipment needed to measure emissions to develop understanding of contrail formation for hydrogen and SAF aircraft, and seeking suitable funding routes, should be an urgent priority. This may involve international collaboration. Suitable computing facilities for the data-intensive climate impact modelling is needed to facilitate understanding of climate change impact. Provision of UK pilot scale research capability for carbon fibre and precursors would provide a step change in potential to move towards more sustainable carbon fibre, which is currently the most significant material in terms of aircraft embodied energy.

06.
LIST OF ACRONYMS

ACI - Aerosol-cloud interaction

ADS - Trade association for aerospace, defence, security and space in the UK

AGP - Aerospace Growth Partnership

AIA - Aviation Impact Accelerator

ATM - Air traffic management

ATI - Aerospace Technology Institute

CF - Carbon fibre

CNRS - Centre national de la recherche scientifique, France

CO_2 - Carbon dioxide

CRM - Critical raw material

D4S - Design for sustainability

DIT - Department of International Trade

DLR - Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Germany

EASA - European Union Aviation Safety Agency

EOL - End-of-life (adjective) or end of life (noun)

EPSRC - Engineering and Physical Sciences Research Council

ERF - Effective radiative forcing

FC - Fuel cell

FAA - Federal Aviation Administration (USA)

GHG - Greenhouse gas

GT - Gas turbine

GWP - Global warming potential

H_2 - Hydrogen

HVMC - High Value Manufacturing Catapult

IAEG - International Aerospace Environment Group

ICAO - International Civil Aviation Organization

ISO - International Organization for Standardization

ISSR - Ice super-saturated region (where persistent contrails form)

LCA - Life cycle assessment

LH$_2$ - Liquid hydrogen

Li-ion - Lithium ion (battery type)

LTO - Landing and take-off

MIT - Massachusetts Institute of Technology, USA

MRO - Maintenance, repair and overhaul (also used to refer to organisations carrying out these activities)

NASA - National Aeronautics and Space Administration, USA

NCAR - National Center for Atmospheric Research, USA

NDE - Non-destructive evaluation

NERC - Natural Environment Research Council

NO$_x$ - Nitrogen oxides

OEM - Original equipment manufacturer, or manufacturing prime

PtL - Power-to-liquid, sometimes referred to as e-fuel or electrofuel

R&D - Research and development

RBBC - Recycled and bio-based content

RF - Radiative forcing, the net energy flux per unit of earth's area into earth's system

RMI - Responsible Minerals Initiative

SAF - Sustainable aviation fuel

SARP - Standards and recommended practice

SHM - Structural health monitoring

SME - Small to medium enterprise

TRL - Technology readiness level

UCL - University College London

07.
TABLE OF FIGURES

08.
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LIFECYCLE IMPACT

Future Work on Climate Science and Material Impacts

FLY ZERO

AEROSPACE
TECHNOLOGY
INSTITUTE