AtkinsRéalis

CONTRAILS

THE IMPACT OF SUSTAINABLE AIRCRAFT SOLUTIONS ON AVIATION'S SECONDARY WARMING EFFECTS

By Raj Ranavaya, Oliver Saward

About us

We're AtkinsRéalis, a world-leading design, engineering and project management organisation. We connect people, data and technology to transform the world's infrastructure and energy systems.

Together, with our industry partners and clients, and our global team of consultants, designers, engineers and project managers, we can change the world.

We have been working in the aerospace industry for over three decades and have worked on a number of market-leading aircraft, including the A380, A350, A400M and A320. Clients we have worked with include Airbus, Cobham, FACC, Bombardier, BAE Systems, Rolls-Royce, Spirit AeroSystems and the Royal Air Force.

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Foreword

The advent of jet-powered aircraft revolutionised international connectivity within a short time span, creating a global system from which millions benefit daily. Management Consultancy, Oliver Wyman, predicts that the global aviation fleet will top its January 2020 apex of close to 28000 planes in the first half of 2023, with projected annual growth of 4.1%. This will push the global fleet to 38100 aircraft by the beginning of 2032, adding increasing pressure to the airlines and airports that manage these large volumes of traffic.

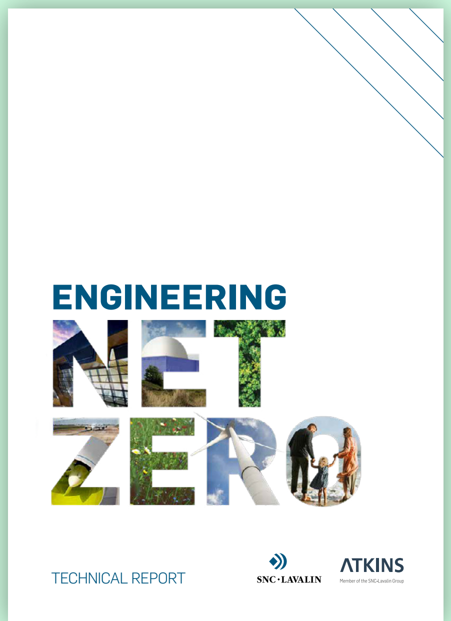
With businesses focusing primarily on meeting this ever-increasing demand, more could be done by aviation ecosystem stakeholders such as airport operators to minimise the environmental impact the industry has on the global climate. This requires an approach that considers the complete environmental impact, not just the carbon dioxide (CO_2).

In 2019, IATA estimated that aviation accounted for only 2% of global CO_2 emissions. Whilst this number may seem small in comparison to larger contributors such as the agricultural industry, other emissions produced by jet fuel combustion, such as nitrogen oxides (NO_x) and water vapour, further contribute to rising global temperatures. As the industry approaches the problem of non-CO_2 emissions, questions arise on where these impacts come from and what can be done to resolve them.

This paper explores the effect of particulates and water vapour on the production of aviation condensation trails (often abbreviated to contrails), and the impact they have on global warming. In addition, we consider how contrail production is influenced by new and alternative fuel sources, including sustainable aviation fuel (SAF) and hydrogen in its various applications. By collating the latest research in climate science, we aim to extract relevant implications for aviation stakeholders. This information can then be used to inform them of the options available for their industries to reduce contrail production, as they strive to become Net Zero leaders.

To achieve Net Zero the whole system must be Net Zero

For all of the alternative fuel options to be considered Net Zero there is a challenge on the provision of the input energy required to create them, and to recharge the batteries, to also be Net Zero – a challenge not unique to aerospace and one that must be addressed globally.



For aerospace, it is important to articulate the energy required and the form it is required in, to ensure consideration within wider energy strategies and systems. A high-level 'system of systems' approach that considers whole-life energy costs is necessary to support this.

AtkinsRéalis' Engineering Net Zero provides the basis of such a study for the UK, by considering the wider energy demands and how these can be met (Atkins, 2019).

The basis of such studies is also well-described by David MacKay in an easy to access book available for free online (MacKay, 2009).

atkinsrealis.com/EngineeringNetZero

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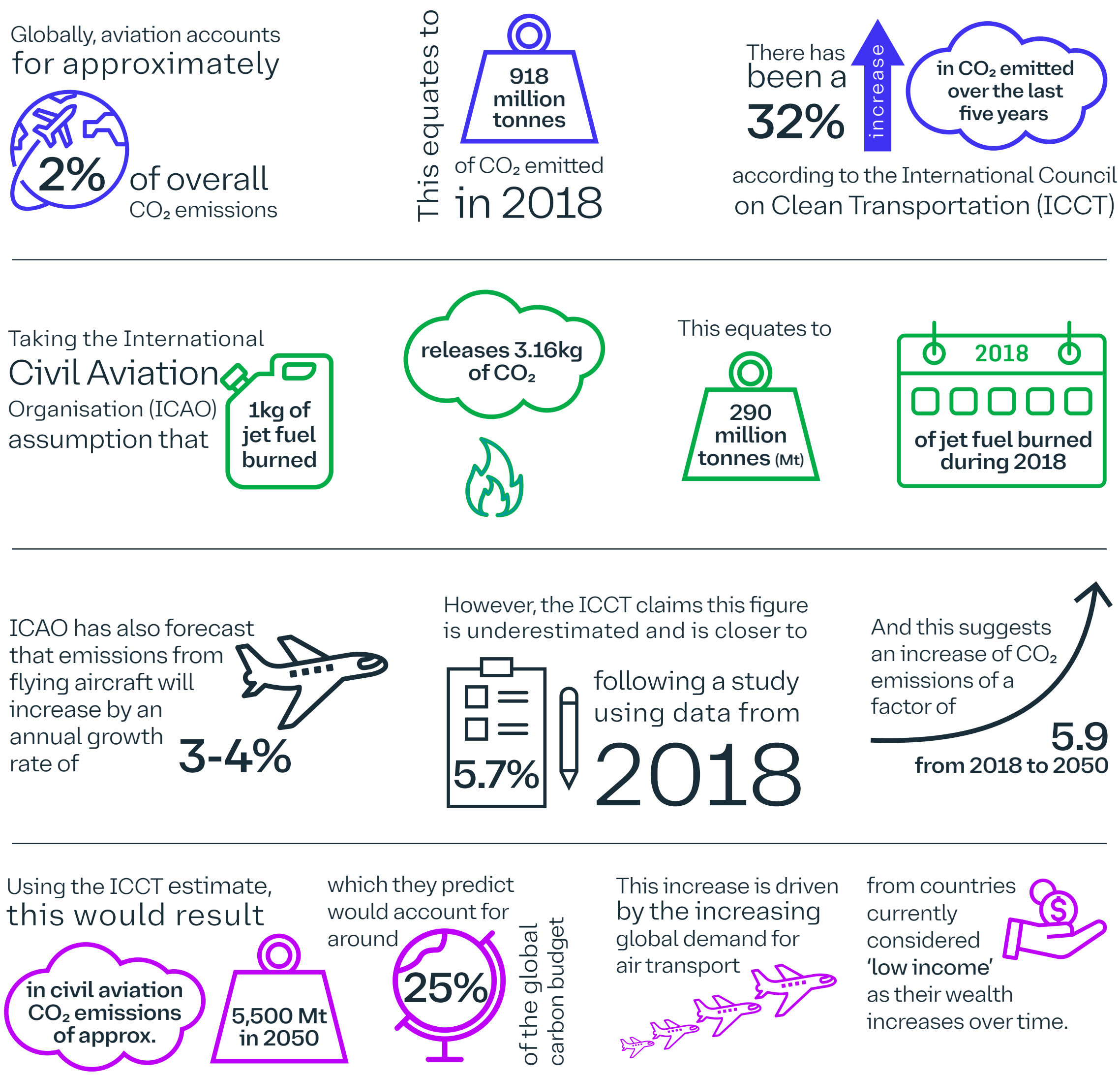
1. Sustainable aviation – the complete picture

1.1. CO_2 emissions

Aviation accounts for 2% of carbon emissions worldwide. Forecasts show that even with improved engine efficiencies this proportion could rise to a quarter of global carbon emissions within the next three decades[1]. Demand for air travel is set to increase as demand from emerging aviation countries rise, but Atkins estimates that only 6% of the world's population currently participates in the industry. Such a disproportionately small number of people being responsible for a significant carbon footprint is a challenge for both governments and aerospace corporations alike, since it informs their decisions about airport infrastructure legislation and which countries to market new products to, respectively, whilst striving to achieve their Net Zero targets.



[1] Sustainability in Aerospace: Exploring Alternative Fuels | James Domone, AtkinsRéalis

The 2018 special report by the Intergovernmental Panel on Climate Change (IPCC) suggested that the average global temperature will increase further, by 1.5°C by 2050. The report also highlighted the consequences from this rapid heating, including extreme weather events, sea level rise, ocean acidification and increased risk to human food security, to name a few.

1.2. Non-CO_2 emissions

The majority of international conferences on climate change have predominantly focussed on the drive to become Net Zero by the middle of the century, and the warming effects of CO_2, which accounts for more than three quarters of greenhouse gases by mass. Whilst many sectors can address the majority of the climate impact of their operations through decarbonisation alone, the specific technological and environmental factors inherent to flight add complexity to the aviation sector's path to reducing its climate impact. Aircraft are responsible for a range of emissions, large portions of which are deposited at altitude. Water vapour is frequently a forgotten product of combustion, and receives less attention than CO_2 owing to its lower warming potency. However, water vapour is the key ingredient in the formation of contrails – the purpose of this study. Regulators, original equipment manufacturers and airports all have a role to play in understanding how their industries contribute to the production of contrails, and what they can do to minimise the impacts of this phenomenon.

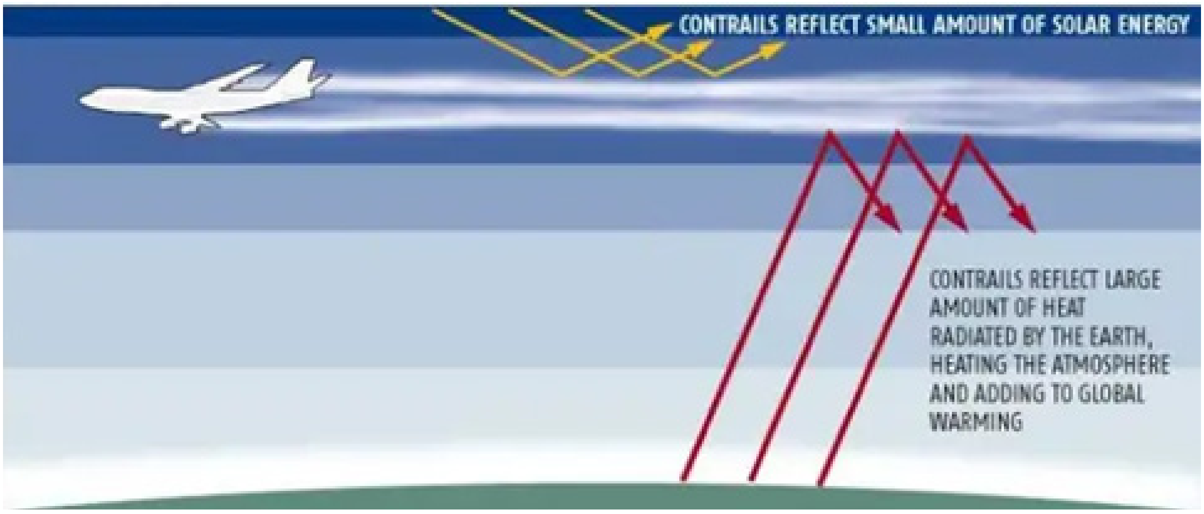


Figure 1-1 – How contrails contribute to global warming

Source: Diagram from NewScientist article[2]

[2] https://www.newscientist.com/article/dn2926-aircraft-vapour-trails-are-climate-scourge/

2. Contrails – a condensed summary

2.1. Basic principles

Contrails have been an ever-present phenomenon since the dawn of high-altitude, jet-powered flight. They are line-shaped clouds composed of ice particles which are formed from the water vapour produced from aircraft jet engines or condensing water, typically found at cruise altitudes in the upper troposphere at 8–13 km. Their presence is heavily influenced by atmospheric conditions, specifically the ambient air temperature and moisture saturation. Contrails evaporate faster and diminish in low humidity regions; in contrast, in high-humidity areas they can persist and grow. Jet engine exhaust is only a small source of the water vapour which forms ice in persistent contrails. Most of the water found in contrails is composed of water vapour naturally present along the aircraft flight path, which is entrained into the exhaust plume, providing a larger source of water to form ice crystals.

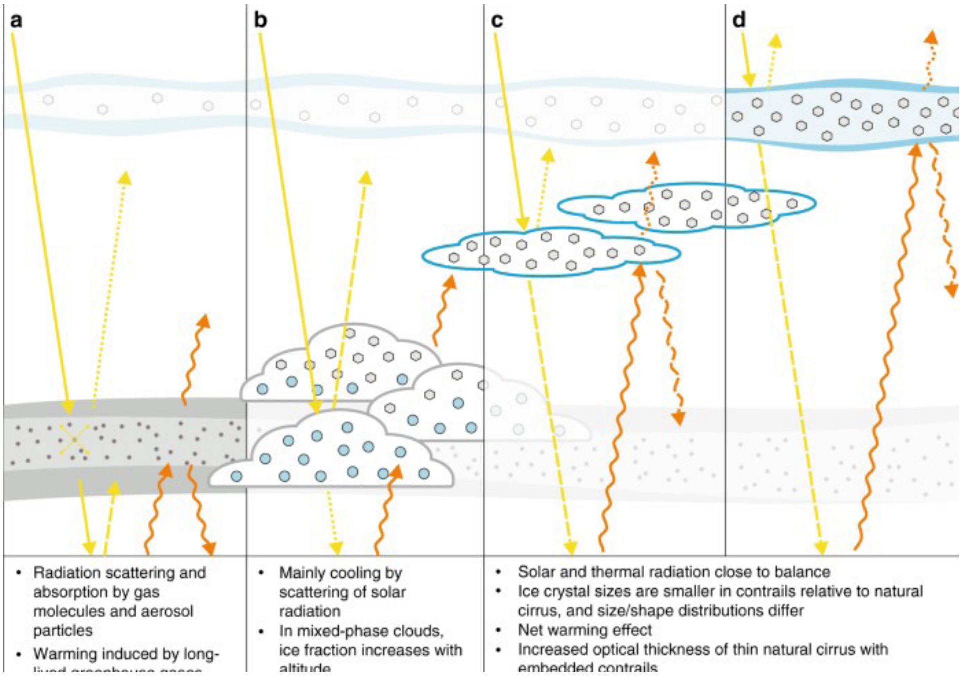


Figure 2-1 – Visualisation of reflective and greenhouse radiative forcing

Source: Diagram from Nature Communications article[3]

The water vapour in clouds reduces the proportion of thermal energy that can escape into space, providing a warming effect, referred to as positive radiative forcing (RF). The surface area of these clouds also provides a cooling effect by reflecting incoming solar energy, which outweighs the warming effect.[4] This cooling effect is highest in thick, low-altitude, droplet-bearing clouds, while optically-thinner, high-altitude clouds like cirrus are less reflective and have a greater warming effect.

Contrails behave similarly to natural cirrus clouds. As a result, contrails are responsible for more than half of the total radiative forcing derived from aviation sources, with 80% of this effect caused by persistent contrail cirrus.[3]

[3] Formation and radiative forcing of contrail cirrus | Bernd Kärcher
[4] ipcc_far_wg_I_full_report.pdf, p79

While differences in microphysical properties can alter a contrail's contribution to warming or cooling effects, the best mitigation strategy for contrail-driven climate change is not to reduce the contribution to global warming provided by contrails, but to directly reduce the formation of contrails in the first place.[5]

2.2. Jet-exhaust formation

Modern-day conventional aircraft jet engines produce water vapour, carbon dioxide (CO_2), small amounts of nitrogen oxides (NOx), hydrocarbons, carbon monoxide, sulphur gases, and soot and metal particles formed from the high-temperature combustion of jet fuel during flight. From these products, soot and sulphur gases serve as an adequate surface around which the water vapour emitted can cool and condense to form small water droplets, known as nucleotides. This process is called **heterogenous nucleation**.[6] These droplets then cool to form small ice particles which grow to form long contrails as described by the method shown in Figure 2-2. All other engine emissions are considered non-essential to contrail formation.[7]

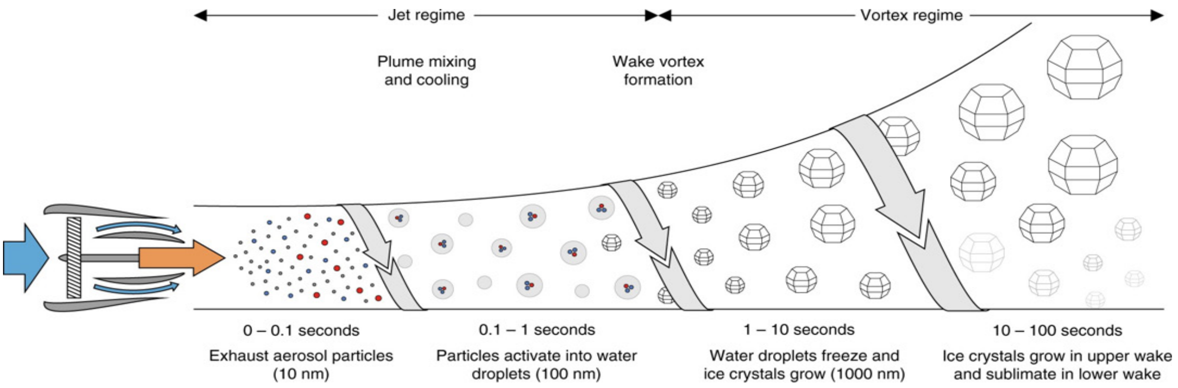


Figure 2-2 – Stages of jet-exhaust contrail formation

Source: Diagram from Nature Communications article[8]

The surrounding atmospheric conditions are crucial to this process, as they will largely determine whether or not a contrail will form after an aircraft's passage. Since the underlying processes are very well understood, contrail formation for a given aircraft flight can be accurately predicted with known temperature and humidity values. Once the initial ice crystals form, the contrail may evolve in one of two ways depending on the surrounding atmospheric humidity. If humidity is lower than that required for ice condensation to occur, the contrail is short-lived. Newly formed ice crystals will quickly evaporate as hot exhaust gases are completely mixed into the surrounding atmosphere. As a result, the limited line-shaped contrails will only extend a short distance behind the aircraft as shown in Figure 2-3.

Persistent contrails form when humidity is higher than that needed for ice

[5] A Summary of the Physical Properties of Cirrus Clouds in: Journal of Applied Meteorology and Climatology Volume 29 Issue 9 (1990) (ametsoc.org)
[6] The Physics of Ice: It All Begins with Nucleation | ThermoFisher Scientific
[7] contrails.pdf (faa.gov)
[8] Formation and Radiative Forcing of Contrail Cirrus | Bernd Kärcher

Evolving persistent contrail[9]	Short-lived contrail[9]
	
The persistent contrail shown here was formed at a lower altitude where higher humidity was present	Short-lived contrails evaporate soon after being formed due to low atmospheric humidity
High humidity	Low humidity
Long contrail, ~several km long, 100s of metres high	Short contrail, ~100s m long, ~10s m high
Can persist for hours	Only last minutes

Figure 2-3 – Persistent versus short-lived contrail formation

Source: United States Environmental Protection Agency[9]

condensation to occur, as newly formed ice particles continue to grow in size through subsequent water molecules present in the surrounding atmosphere. The spreading out of contrails occurs due to the turbulent wake generated by the source aircraft, along with shifting wind speeds and direction along the flightpath, as well as through the effects of solar heating.

When persistent contrails merge and overlap with each other, or existing high-humidity cirrus, they become contrail cirrus clouds, which are dispersed by wind-shear over a large area. These clouds evolve in accordance with the atmosphere, with crystal growth increasing the solidity (optical depth) of the cloud when passing through colder or ice-supersaturated air, and thinning when passing through warmer, subsaturated air as ice crystals sublimate. These clouds are the largest and most persistent form of contrail that can increase global warming.

2.3. Aerodynamic contrail formation

2.3.1. High-altitude, high-speed flight

Aerodynamic contrails form via changes in pressure and temperature as air flows across the wings of aircraft in transonic cruise flight. As the airflow around the top of the wing accelerates, the pressure drops as described by Bernoulli's principle. At the trailing edge, downwards-rotating air (known as downwash) is produced which directly influences the production of wingtip vortices, as shown in Figure 2-4.

[9] Aircraft Contrails Factsheet | EPA

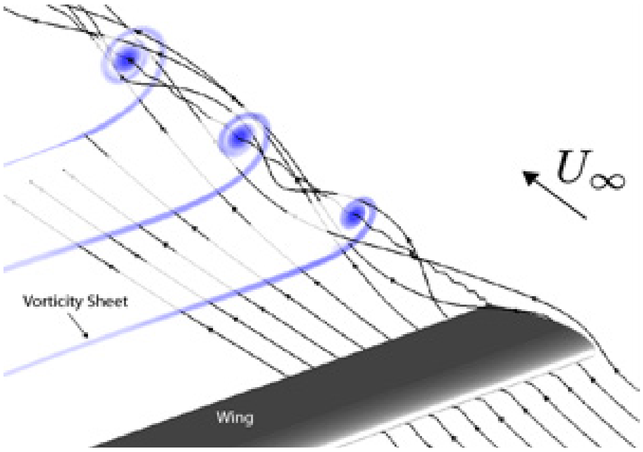


Figure 2-4 – Wingtip vortex generation due to downwash behind a wing

Source: Citzenthom[10]

The cores of these vortices spin at very high speed and are regions of very low pressure which, as they leave the vicinity of the wing, undergo a process known as adiabatic expansion. Rapidly cooled by this expansion, highly moisture-saturated air pockets trigger swift condensation of ambient liquid aerosol particles across the wingspan, which forms a thin contrail.

During high-altitude, high-speed flight this phenomenon is distinct from the formation of jet-exhaust contrails and is known as **homogenous nucleation**, due to the lack of nucleation sites (particles/impurities) present. This process is environment-dependent and occurs independently of the fuel used by the aircraft, and is illustrated in Figure 2-5 , alongside the process for heterogeneous nucleation. Note the difference in crystal sizes.

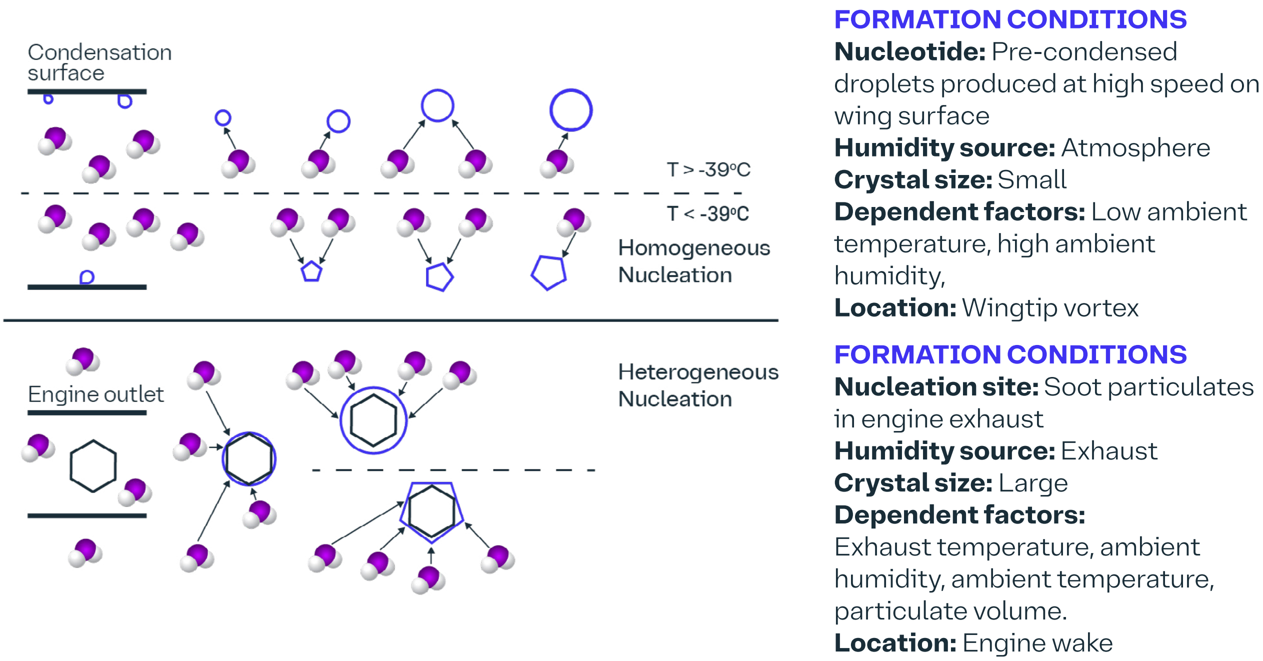


Figure 2-5 – Homogeneous and heterogeneous nucleation processes

[10] Generation of trailing vortices | Citizenthom

The formation of aerodynamic contrails is dependent on temperature, as pure water will freeze at approximately -39°C in the absence of nucleation sites[11] and optically thin contrails will become visible around -41°C. However, Figure 2-6 shows both jet and aerodynamic contrails being produced by a wide-body aircraft in cruise at a surprisingly high temperature of -32°C, much higher than the homogenous nucleation threshold. The cause of this aerodynamic contrail still forming is high ambient humidity at warmer temperatures. Visually and volumetrically, the aerodynamic contrails are far smaller than their jet-exhaust counterparts. For this reason, the environmental impact of such contrails is much lower and so greater focus should be placed on minimising the formation of jet-exhaust contrails.

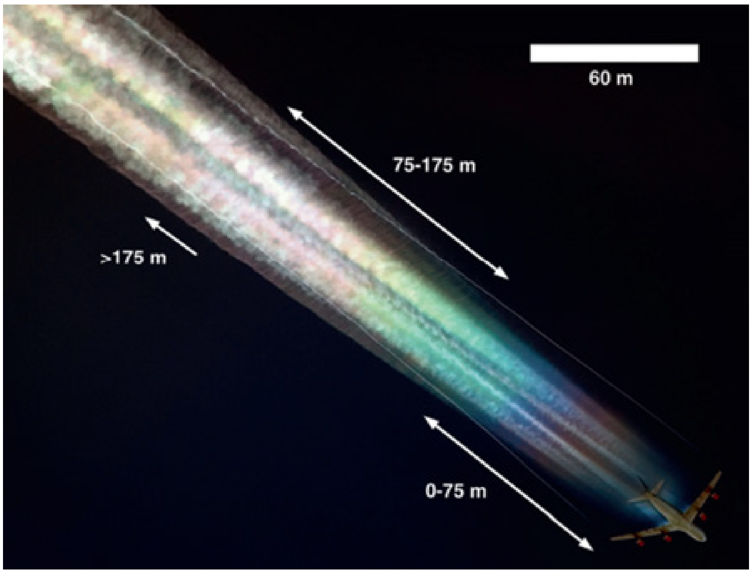


Figure 2-6 – Contrails being produced by an Airbus A340 at FL315

Source: Diagram from Nature Communications article[12]

2.3.2. Low-altitude, low-speed flight

When flying low and slow, aircraft fly at a higher pitch attitude in order to maintain lift and prevent stalling. This angle produces more downwash, resulting in a larger turbulent wake and wing-tip vortices. Average temperatures at lower altitudes are too high for homogenous nucleation to occur, however wingtip vortices may still be visible in very humid conditions, where heterogenous nucleation by low-level particulates such as dust can augment the adiabatic expansion processes mentioned earlier to produce the visible vortex trail shown in Figure 2-7.

Figure 2-7 – Wingtip vortices trailing behind a B777

Source: IMechE – photo credit: Ryoh Ishihara[13]

However, it should be noted that these vortices do not persist for very long and do not have any warming effect on the atmosphere, unlike high-altitude persisting contrails. This is because low-altitude tip vortices dissipate much more quickly owing to the local temperature drop being only temporary.[14]

[11] The Physics of Ice: It All Begins with Nucleation (thermofisher.com)
[12] Aerodynamic Contrails: Microphysics and Optical Properties
[13] Wing shape research could reduce dangerous vortex turbulence | Joseph Flaig, IMechE
[14] Wing tip vortices in Fluid Vortices | Sheldon I. Green, University of British Columbia

3. Could alternative fuels offer a solution?

3.1. Pathways

Alternative fuels are offered as solutions to minimise the climate impact of aviation and, while all promise to reduce or negate the carbon footprint of air travel, their ability to reduce the climate impact caused by contrails is often less scrutinised. This is complicated by the wide range of alternative fuels and their applicability to the aviation industry, which governs both the size and nature of the effect they can have on the industry's impact.

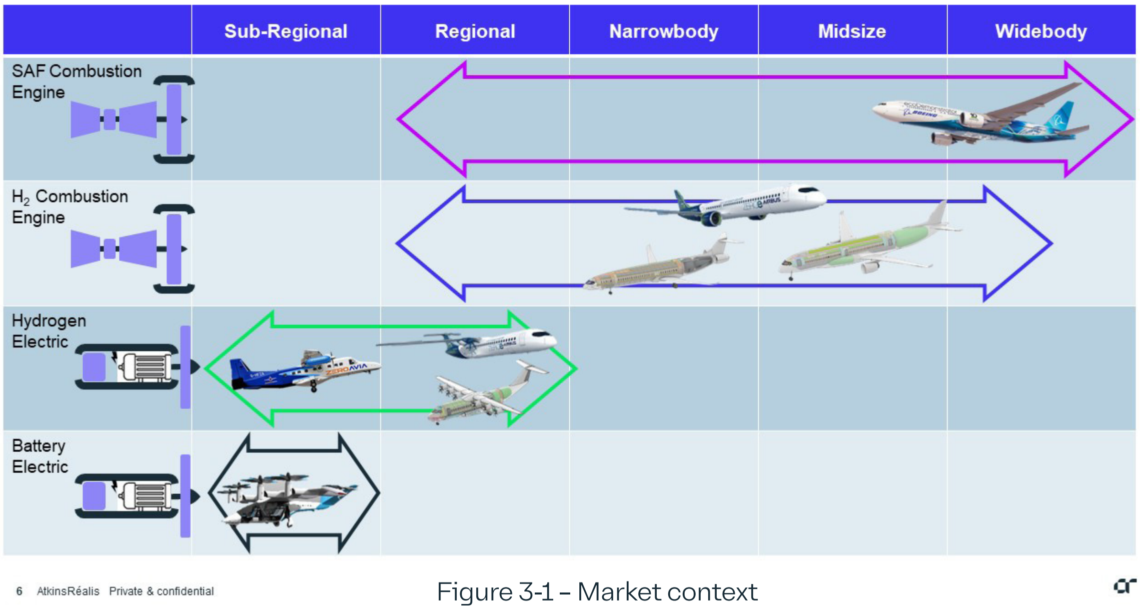


Figure 3-1 – Market context

Source: Images from FlyZero, ZeroAvia, Boeing, Airbus, eVTOL.news[15,16,17,18,19]

The capabilities and market applicability of electric aircraft is dependent on the performance of the motor and batteries, which all require immense development to be viable at ranges outside short, sub-regional or intra-city journeys, and will therefore have a limited effect on the global climate impact of aviation.

As with many sustainable aviation technologies, hydrogen propulsion systems cannot yet be applied to the industry at scale due to their technological limitations, necessitating a piecemeal introduction to the market segment that suits them best. Hydrogen fuel cell solutions are restrained from wider application by the currently-insufficient performance of the fuel cell, motor and energy storage systems, but can be applied to smaller short-range aircraft with additional development. Hydrogen combustion engines are lighter and more scalable than fuel cells, making them better suited to use on longer-range aircraft. However, they require significant development before they can enter service and their adoption will lag behind fuel cells.

[15] First Practical Zero Emission Aviation Powertrain | USA & UK | ZeroAvia
[16] ecoDemonstrator (boeing.com)
[17] ZEROe - Zero emission - Airbus
[18] eVTOL.news | Vertical Aerospace VX4 (production model)
[19] FlyZero | Zero-Carbon Emission Aircraft Concepts

There are also development challenges on the ground that must be overcome before hydrogen aviation becomes market ready, but once these technologies occupy a large enough niche, their high energy density and zero-carbon emissions can substantially and positively affect the climate impact of aviation.[20,21]

Sustainable aviation fuels (SAFs) are intended as a substitute for any and all existing aircraft that are compatible with conventional aviation fuel (CAF), making them theoretically applicable to all areas of the aviation market and able to heavily influence the climate impact of aviation when adopted.

3.2. Sustainable aviation fuels

3.2.1. Technology overview

Sustainable aviation fuels are "derived from non-fossil carbon resources"[22], negating the carbon emitted during combustion through the use of carbon-positive feedstocks as their derivation source. They contain the same types of hydrocarbons found in conventional aviation fuels, but the proportions of these hydrocarbons vary. Aromatic compounds are one such type, composed of hydrocarbons that contain a benzene ring and play a critical role within the jet engine.

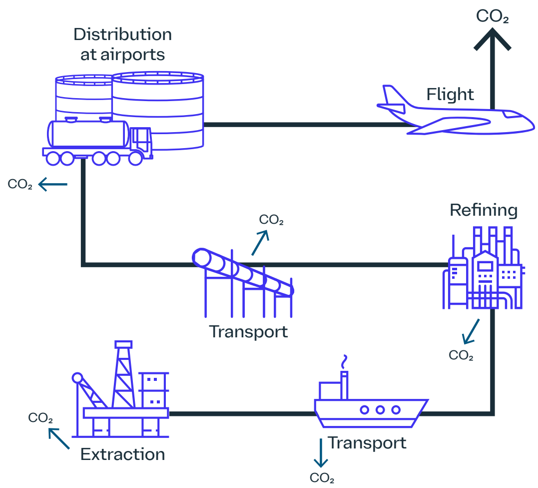
Low aromatic content in jet fuel results in seal shrinkage of the fluorosilicone and nitrile fuel seals found in most jet engines, leading to fuel leakage and damage within the engine.[23] Crucially, most SAFs do not naturally contain aromatic compounds, rendering them incompatible in their raw form.

This risk can be mitigated by blending these SAFs with CAFs or aromatic-containing SAFs, thereby raising the overall aromatic content level to between 8% and 25%. This allows for the creation of 100% blends that are safer for older engines, while new, advanced engines such as the Rolls-Royce Ultrafan use synthetic fuel seals that do not degrade and are capable of using 100%, aromatic-free blends.[24]

All sustainable aviation fuels must comply with the American Society for Testing and Materials (ASTM) international fuel standards, which approves production methods and governs the limits on fuel properties and chemical composition. There are seven SAF certified production methods included in the annexes of ASTM D7566, with two additional standards for producing FT and HEFA fuels using existing refinery equipment. Their derivations, compositions and permitted blend ratios are shown in Table 3-1. (Note: two contain longer carbon chains that limit them to a 10% blend proportion rather than the more conventional 50%).

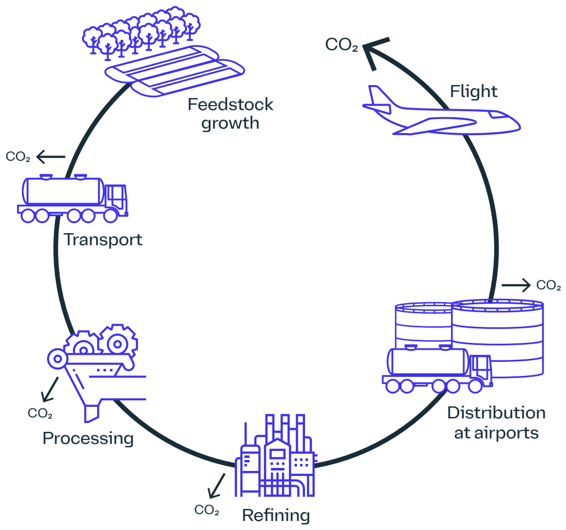
[20] FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf (ati.org.uk)
[21] FZO-ALL-REP-0004-FlyZero-Our-Vision-for-Zero-Carbon-Emission-Air-Travel.pdf (ati.org.uk)
[22] saf-integration.pdf Integration of Sustainable Aviation Fuels into the air transport system - ATI
[23] Effect of fuels, aromatics and preparation methods on seal swell | The Aeronautical Journal | Cambridge Core
[24] GREEN FOR GO ROLLS-ROYCE TARGETS ENVIRONMENTAL AMBITIONS | Aerospace Tech Review

Carbon lifecycle diagram: fossil fuels



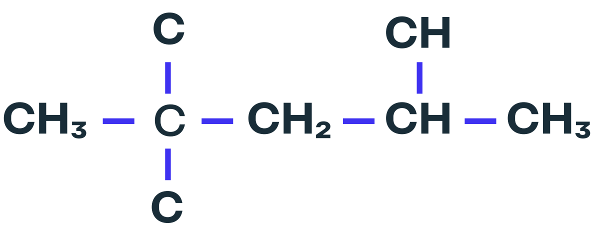
At each stage in the distribution chain, carbon dioxide is emitted through energy use by extraction, transport, etc.

Carbon lifecycle diagram: sustainable aviation fuel

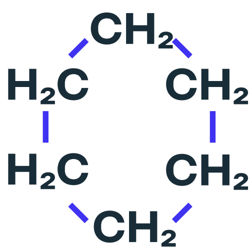


Carbon dioxide will be reabsorbed as the next generation of feedstock is grown. Note: the diagram above does not demonstrate the lifecycle process of SAF derived from municipal waste.

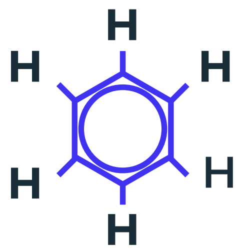
Paraffins



Isoparaffins



Cycloparaffins



Aromatics

Figure 3-2 – Production and components of SAFs

Fuel	Derivation	Composition	Permitted Blend
FT-SPK	Fisher-Tropsch reaction of H_2 and CO syngas produced by gasification of biomass or coal.	Primarily isoparaffins	50% (to increase paraffin and aromatic content)
HEFA-SPK	HEFA conversion of free fatty acids, fatty acid esters and glycerides from oil-bearing plants or biomass.	Primarily isoparaffins	50% (to increase paraffin and aromatic content)
HFS-SIP	Two-step process of microorganism fermentation of sugars, followed by hydro processing of derived olefin.	Long-chain farnesane isoparaffin	10% (to avoid hydrocarbon overloading)
FT-SPK/A	FT-SPK method with additional mixing of FT olefins with benzene-rich steam from coal gasification.	Isoparaffins with 15-20% aromatics	50% (to allow accumulation of service experience)
ATJ-SPK	Dehydration and partial polymerisation of sugar-derived alcohol, followed by separation and hydroprocessing.	Primarily isoparaffins	50% (to increase paraffin and aromatic content)
CHJ	Catalytic hydrothermal conversion and hydrotreatment of HEFA feedstocks.	Identical to Jet A-1 (including aromatic content)	50% (to allow accumulation of service experience)
HC-HEFA	HEFA conversion process using hydrocarbons alongside fatty acids and esters derived from Botryococcus braunii algae.	Mix of paraffins, isoparaffins and cycloparaffins.	10% (ratio limited in exchange for reduced testing under fast track

Table 3-1 – Seven SAFs approved under ASTM D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons)

To ensure that SAFs are scalable, sustainable, and compatible, two development paths lie open: the development of SAFs with high enough aromatic content to be compatible with existing engines (known as 'drop-in' fuels); or the development of aircraft engines to be compatible with aromatic-free SAFs. Both of these approaches come with their own development costs and integration issues, either at the aircraft or the supply-chain level. Blending is therefore widely considered a more economical, more technologically-ready approach to SAF introduction, but the presence of aromatics in these fuels has a substantial impact on contrail production.

3.2.2. Contrail formation

Conventional and sustainable aviation fuels are largely made up of the same chemical composition, as shown in Figure 3-2. However, the proportions in which these compounds are found in SAFs differ from CAFs, which are normally composed of 60% paraffins, 25% cycloparaffins and 15% aromatics.[25]

The chemical structure of aromatics makes them the dominant source of soot particulates in engine exhaust. These particulates play a key role in contrail formation by providing a nucleotide around which water molecules can condense and form ice crystals. Five of the seven approved fuels are aromatic free, and trials have shown that a 50/50 fuel blend using aromatic-free SAF reduction produces 50% less soot particulates than pure CAF. To corroborate this, preliminary tests have suggested that the use of a SAF blend is capable of reducing contrail formation, although further experimentation is needed to determine the magnitude of this improvement.[4] However, to avoid engine compatibility issues, aromatics are blended into aromatic-free SAFs in the form of CAFs, or purposefully incorporated during the production process to create an aromatic-bearing 'drop-in' SAF. This results in a no-win situation, where any SAF with an aromatic content suitable for general use will inevitably generate contrails.

Both blended and drop-in SAFs generate particulates when burned and are capable of driving contrail formation. However, controlled production allows suppliers to confine aromatic composition, typically at around 8%. This allows for a reduction of nucleation sites that results in fewer ice crystals, whose increased size encourages settling and leads to thinner contrails, but does not fully negate them. A 100%, aromatic free SAF may be capable of fully eliminating soot production, thereby eliminating contrail production, but its compatibility issues make it difficult to implement sector-wide. As a result, while SAFs are capable of significant CO_2 reduction, they cannot negate the production of climate-affecting contrails unless significant and expensive steps are taken to accommodate them.

[25] Frontiers | Qualification of Alternative Jet Fuels (frontiersin.org)

3.2.2. Other non-carbon emissions

The two main non-carbon emissions from aviation fuels, besides CO_2 and particulates, are sulphur and nitrogen oxides (NOx). In aircraft engines, sulphur plays a triple role, by forming both sulphur dioxide, the greenhouse gas responsible for acid rain; serving as a nucleotide in contrail production; and enhancing the activation of soot particles during contrail production. Sulphur is typically found in CAFs in quantities between 0.05%, and 0.1% with up to 0.3% permitted by the ASTM. A pure blend of SAF would produce very little sulphur dioxide, as SAFs typically contain less than 0.003% sulphur by weight.[26]

However, while it is known that a reduction in soot and sulphur reduces contrail formation,[3] the reduction is not quantified, and activated soot is still found in emissions from engines burning extremely low-sulphur CAFs.[27]

NOx are a key ingredient in the formation of both smog and acid rain, and are formed in engine combustion chambers, where temperatures of over 1200°C cause atmospheric nitrogen and oxygen to react together.[28] Nitrogen dioxide plays a key role in the formation of ozone, which is considered a greenhouse gas at low altitudes. While CAFs can contain very small amounts of nitrogen, the main driver of NOx emissions from aircraft is combustion chamber temperature, not the fuel used. The higher power settings used during take-off and climb leads to the most abundant quantities of NOx being produced during these phases of flight. As such, the use of SAFs does not have a meaningful effect on NOx emissions.

3.3. Hydrogen

3.3.1. Technology overview

Hydrogen offers an alternative approach to Net Zero aviation fuel, with options for zero-carbon production of the fuel through renewable electrolysis, and no carbon released at point of use. However, this fuel is hampered by the immaturity of its underpinning technology, with six key areas identified as needing further development to make the technology feasible, shown in Figure 3-3. Hydrogen propulsion systems are split between fuel cells, which react hydrogen with oxygen to generate electricity and drive motors; and combustion engines, which burn hydrogen to produce thrust like a jet engine. As fuel cells and combustion engines occupy different market niches, industry commitments vary, as denoted in Figure 3-4. Division on fuel storage systems also exists, but Liquid Hydrogen (LH_2) has been shown as the more optimum long-term fuel, due to its increased energy density and reduced tankage weight compared to gaseous hydrogen (GH_2).[20,21]

[26] 3 Pollutant Emissions | State of the Industry Report on Air Quality Emissions from Sustainable Alternative Jet Fuels |The National Academies Press, C6 P11.
[27] (PDF) Interactions between sulfur and soot emissions from aircraft and their role in contrail formation 1. Nucleation (researchgate.net)
[28] B&W Learning Center Articles » Babcock & Wilcox

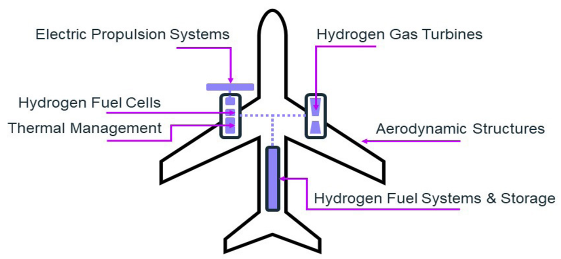


Figure 3-3 – H_2 Key Development Areas

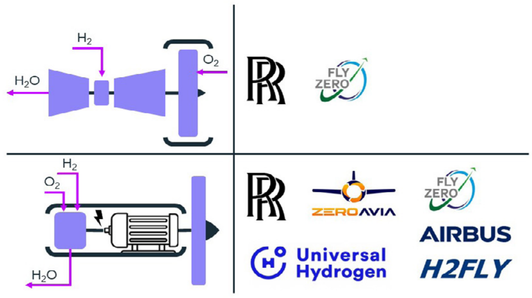


Figure 3-4 – Industry commitments on fuel cell vs combustion engine technologies

3.3.2. Contrail formation

Both hydrogen fuel cells and combustion engines react hydrogen and oxygen to produce energy, be it electric or thermal. This reaction produces large quantities of water vapour with very few particulates, resulting in an exhaust plume that is super-saturated with water vapour that comprises fewer nucleation sites.

Homogeneous nucleation, as demonstrated in Figure 2-5, drives the formation of contrails from hydrogen aircraft. In aerodynamic contrails, wing surfaces provide the source of pre-condensed droplets that serve as nucleation sites, but other surfaces can play this role too. Figure 3-5 shows that homogeneously-nucleated contrails can be seen on engines with very high temperatures, such as rocket engines, should the exhaust humidity be high enough.

Figure 3-5 – Short-lived contrail produced by a LH_2-fuelled Delta IV Heavy Launch Vehicle at T+2m[29]

While particulate-bearing contrail formation relies more heavily on ambient humidity, studies have shown that the exhaust plume humidity of hydrogen engines is high enough to drive condensation and contrail production at higher temperatures and lower altitudes than CAF-burning aircraft. This is indicated in Figure 3-6, which shows a fuel cell exhaust plume at 475°C can form a contrail in conditions as warm as 2°C and as low as 6000ft.[30]

Exhaust temperature also affects contrail formation. When exhausted into the atmosphere, the water vapour produced from hydrogen engines ranges from 80°C to over 1000°C in temperature. High-efficiency fuel cells are expected to emit on the low end of this scale, with the highest end encompassing the emissions from combustion engines and low-voltage, low-efficiency fuel cells. While increasing exhaust temperature limits the formation of contrails to areas with lower ambient temperatures, they can still form at altitudes as low as 18000ft, although the increased air content in combustion engine exhaust may raise this threshold further.

[29] File: Delta IV Heavy Contrail.JPG - Wikimedia Commons
[30] Theory of Contrail Formation for Fuel Cells (dlr.de)

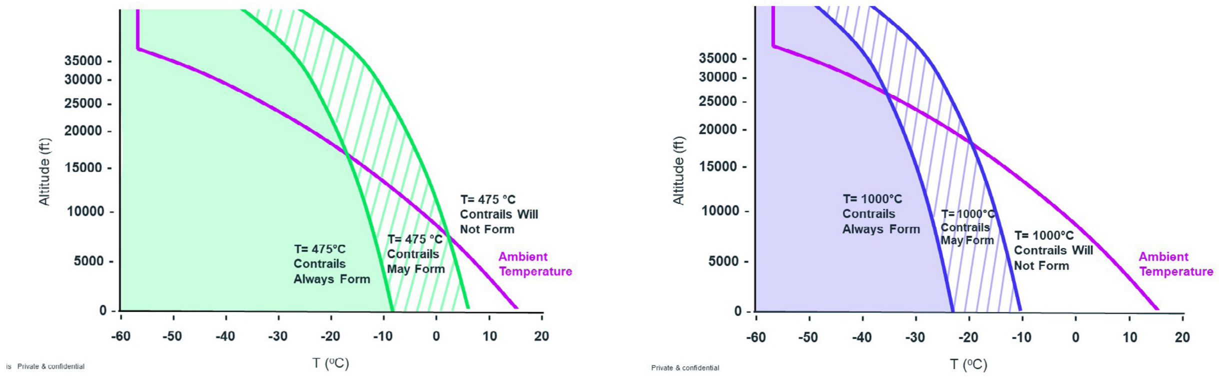


Figure 3-6 – Contrail formation conditions for fuel cell (left) and combustion (right) engines[30]

Persistent hydrogen contrails are situational, only forming if the temperature is below -39°C and the ambient air is also supersaturated. Hydrogen contrails can use existing atmospheric particulates as sites for heterogeneous nucleation, but these crystals are larger, restricted in number by the concentration of particulates in the surrounding air, and more prone to settling. This results in similar volumes of contrails compared to CAF-burning aircraft, but with less optical depth and less persistence. As a result, these contrails will produce less positive radiating forcing and a smaller warming effect. At low altitudes, hydrogen contrails may form more readily, but will quickly evaporate in warmer or drier air, unable to contribute to radiative forcing due to their short lifetime.

The production of contrails from hydrogen fuel cells requires a gaseous exhaust plume. The incorporation of condenser systems into fuel cell exhausts allows for full negation of contrails by emitting water in a liquid form, effectively as rain. This sort of system does, however, bring with it some concerns. The emission of liquid water onto runway surfaces poses a hazard due to reduced runway friction. To combat this, FlyZero's fuel cell design incorporates a water storage system onboard the aircraft, with plans for reuse or ejection systems. This system is exhibited in Figure 3-7, using a case study of the FlyZero regional concept.

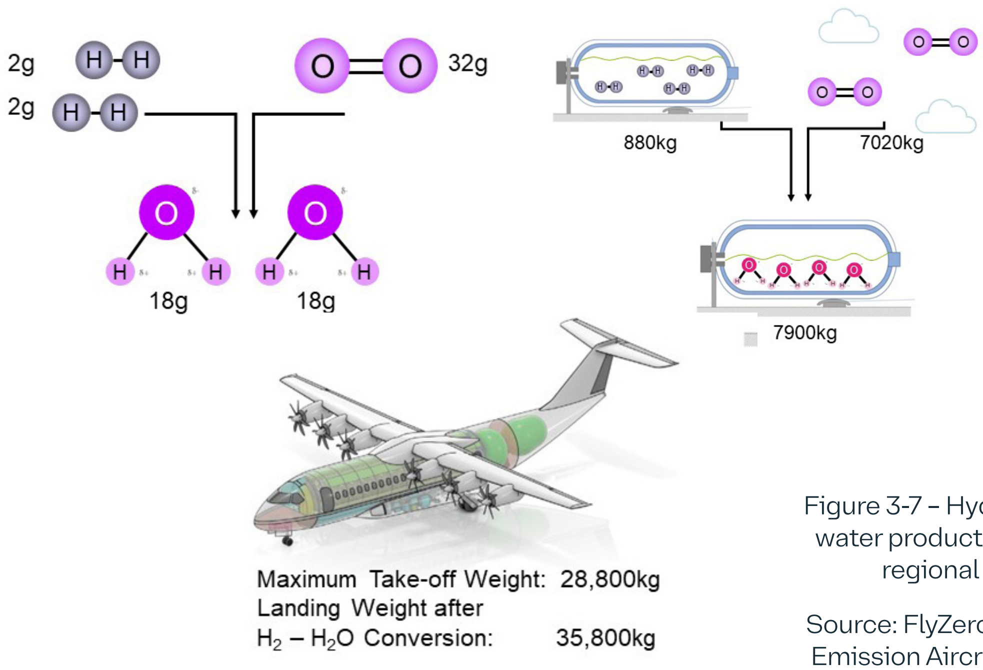


Figure 3-7 – Hydrogen fuel cell water production for FlyZero regional concept

Source: FlyZero | Zero-Carbon Emission Aircraft Concepts[19]

To avoid designing an aircraft that is 24% heavier on landing than on take-off, careful consideration must be made for the storage and discharge of this water. A similar system to grey-waste water discharges from aircraft drain masts may be viable, but would require regulator certification and permissions from local authorities.

3.3.3. Other non-carbon emissions

NOx formation only occurs at temperatures above 1200°C and, as fuel cells operate well below this temperature, they are expected to produce no NOx. Studies have shown that, while the high flame temperature and fast combustion speed of hydrogen inside hydrogen combustion engines can lead to increased NOx production[31], careful design of the combustion chamber can reduce these emissions to a level ten times lower than CAF engines[32] Full replacement of CAF with H_2 could reduce the presence of tropospheric ozone by up to 6%, reducing the presence of greenhouse gases in the atmosphere. These studies also show that a reduction of NOx leads to increased levels of methane in the atmosphere due to a decrease in OH^- (hydroxide) ions, a product of ozone photolysis that shortens the lifetime of hydrocarbons in the atmosphere. However, initial calculations suggest an overall negative RF of approximately -0.016 W/m^2 when accounting for the competing effects of ozone and methane.[33]

[31] Kawasaki Develops Low-NOx Hydrogen-fueled Gas Turbine Combustion Technology | Kawasaki Heavy Industries, Ltd.
[32] Injector design space exploration for an ultra-low NOx hydrogen micromix combustion system (cranfield.ac.uk)
[33] Atmosphere | Free Full-Text | The Emissions of Water Vapour and NOx from Modelled Hydrogen-Fuelled Aircraft and the Impact of NOx Reduction on Climate Compared with Kerosene-Fuelled Aircraft (mdpi.com)

4. How can the wider aviation sector contribute to contrail impact mitigation?

Airport operators are responsible for addressing issues in the quality of air in their immediate vicinity and reducing the emission of all pollutants that affect air quality, not just carbon dioxide. Any airport seeking to reduce their carbon impact by incorporating SAF and hydrogen aircraft into their operations must consider the three following implications.

4.1. Adapting to SAF

The two certified SAF production pathways that are closest to producing a fully-compatible 'drop-in' fuel substitute are FT-SPK/A and CHJ, as they are only limited from using 100% blends on the basis of accruing service experience. Both these fuels contain soot-producing aromatics, albeit at a lower level than conventional fuels. Switching to these fuels will aid in the reduction of airport air pollution by particulates, but will not mitigate them fully. Additionally, as the production of NOx from aircraft engines is proportional only to engine temperature, sustainable aviation fuels are predicted to have little effect on the reduction of NOx and tropospheric ozone. This is particularly relevant as the International Civil Aviation Organization's CAEP12 meeting in February 2022 mandated the development of a new metric system for NOx, and more stringent restrictions on the emissions of NOx and non-volatile particulate matter, with the goal of increasing air quality in and around airports. Delivery of these new regulations is expected by 2025.[34] Airports looking to reduce their Scope 3 emissions in line with these regulations will not be able to solely meet compliance by switching to SAFs.

[34] CAEP.12.WP_.062.16.en-VIEWS-OF-THE-UNITED-STATES-ON-EMISSIONS-FUTURE-WORK-DURING-THE-CAEP13-CYCLE.pdf (usmission.gov)

Flight testing of SAFs is already under way using 'drop-in' fuels that are compatible with current aircraft engines. On 30th January 2023, Emirates operated its first milestone demonstration flight on a Boeing 777-300ER, powering one of its engines with 100% SAF. This demonstration flight represents an increase in the willingness of airline operators to take up these technologies, and paves the way to support broader efforts to reduce lifecycle CO_2 emissions as the industry looks to scale up its use of SAF. Such flights will also help to refine the playbook for future SAF demonstrations and support future certification where 100% 'drop-in' SAF is approved for long-range commercial operations. More importantly, this move will promote further funding to adapt existing engines to operate SAFs, thus also reducing their contrail footprint.

Figure 4-1 – Emirates 777-300ER with SAF Engine
Source: Emirates[35]

4.2. Accommodating hydrogen

While the increased generation of low-altitude, short-lived contrails by hydrogen aircraft, likened to the emission from a steam train, will not contribute to radiative forcing, large-scale operation of hydrogen aircraft will have an impact on airport operations. Understanding the full effects of this will require further study, but during cold, humid weather conditions, the emission of short-lived ground-level fogs or clouds by hydrogen aircraft may require adaptations to be made by airports to preserve safety, such as increasing take-off intervals and separation distances to provide dispersal times. Should hydrogen aircraft choose to condense and store this exhaust water onboard, airports may need to adapt their grey water handling systems to accommodate the increased load that hydrogen aircraft would put on the system.

At altitudes where temperature is below the -39°C threshold required for homogenous nucleation to occur, the persistence of hydrogen contrails is bottlenecked by the low number of ambient particulates that serve as nucleation sites. However, the cross-contamination of hydrogen contrails with high-particulate CAF contrails may fuel accelerated crystal growth and make CAF contrails more persistent. While hydrogen flight testing may validate this expectation, care needs to be taken to separate the flight paths of hydrogen and CAF aircraft to prevent the effects of CAF contrails being worsened.

[35] Emirates operates milestone demonstration flight powered with 100% Sustainable Aviation Fuel

4.3. Airport operations

ASTM standards that approve the use of 100% SAF blends that 'mirror conventional Jet-A and Jet-A1' are predicted to conclude development by 2025[36], while the UK government is mandating that fuel suppliers blend at least 10% SAFs into the UK fuel mix by 2030, either by CAF blending or offering 100% SAF at airports.[37] This increasing regulatory and governmental pressure for SAF adoption will impact airports, who must consider the infrastructure required for storage, handling and provision of this new fuel. With aromatic-free SAFs offering an attractive reduction in particulates and contrail formation, airports that supply these fuels must ensure there are sufficient safeguards in place to prevent cross-contamination and inappropriate fuelling, or else risk damaging aircraft with incompatible fuel systems.

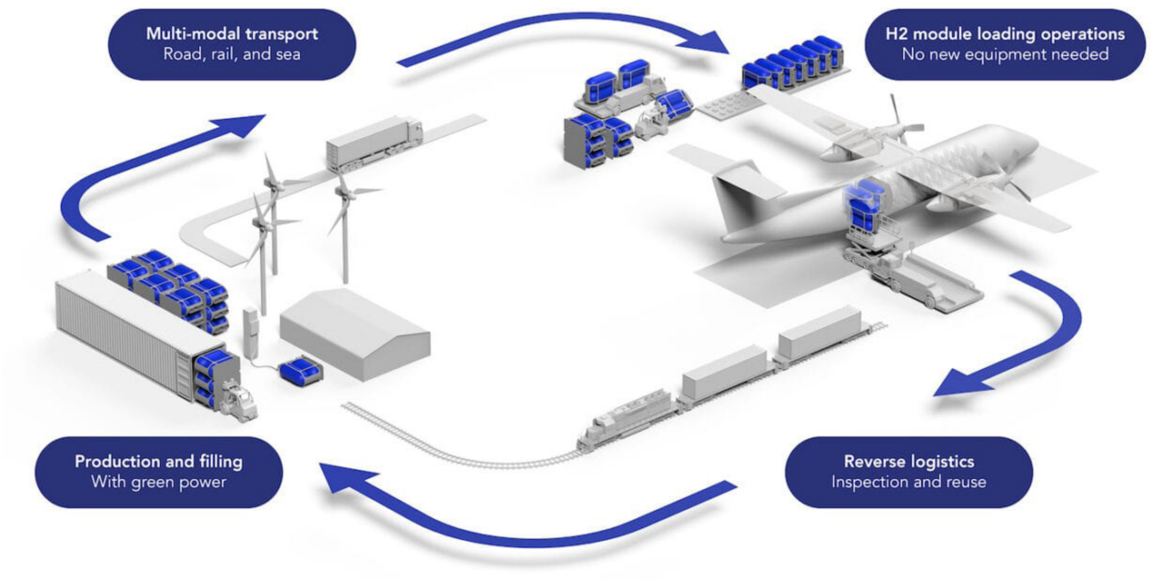


Figure 4-2 – Universal Hydrogen's new Concept of Operations for LH_2 airport infrastructure

Source: Avionics International[38]

Both liquid and gaseous hydrogen aircraft will require bespoke infrastructure solutions to support them, including specialised fuel management systems, ground handling equipment and refuelling gear. Universal Hydrogen's ConOps is one solution to this change, shown in Figure 4-2. Hydrogen is highly flammable and poses a temperature hazard in cryogenic form, necessitating increased safety standards, handling procedures and safeguards, all of which must be co-signed by regulatory authorities. These fuel systems must also be capable of interfacing with larger hydrogen production and distribution systems, which may include complex steps such as local liquefaction or refinement from intermediaries such as ammonia. Gaseous hydrogen is more readily available, easier to handle and can be supplied by road to support 2030 operations but is limited at scale by tank weight and low energy density.

[36] Standard for 100 percent Drop-in SAF Likely Two Years Away | Air Transport News: Aviation International News (ainonline.com)
[37] Sustainable aviation fuels mandate - Summary of consultation responses and government response (publishing.service.gov.uk)
[38] Universal Hydrogen Eyes Disruptive New Concept to Power Turboprop Aircraft | Avionics International

Figure 4-3 – LH_2 storage tank facility at NASA Kennedy Space Centre

Source: FuelCellWorks [39]

Large LH_2 stores are a mature technology found in space launch facilities. If installed at airports, these stores could initially be supplied by road deliveries, with a transition towards dedicated pipelines or on-site electrolysis plants by the 2050s.[40] Airports will have a large stake in determining the demand, and therefore the development attention for such systems.

[39] Kennedy plays critical role in large-scale liquid hydrogen tank development | FuelCellWorks

[40] How Can Airports Get Hydrogen Ready Now to Land Net Zero Targets? - Jacobs - Hydrogen Central (hydrogen-central.com)

5. Conclusions

Using the information from the previous sections, the impact on contrail production, as well as emission variations and contrail properties for each fuel type has been represented below.

	CAFs	SAFs	H_2 Fuel Cells	H_2 Combustion engines
Engine temp	Baseline	Identical	−	+
NOx emissions	Baseline	Identical	Zero	−
H_2O emissions	Baseline	Identical	++	+
Particulates	Baseline	−	Zero	−
Sulphur content	Baseline	−	Zero	Zero
Crystal size	Baseline	+	−	+
Crystal volume	Baseline	−	−	−
Formation altitude	Baseline	Identical	−	−
Thickness	Baseline	−	Zero	−
Persistence	Baseline	−	Zero	−
Contrail environmental impact	Baseline	−*	Zero	−

*The reduced reflectivity of thin contrails provides a small increase to their individual warming effect, very slightly offsetting the reduction in overall warming effect caused by fewer contrails.

While SAFs cannot promise a complete elimination of contrails due to their aromatic content, they offer incremental improvement over existing fuels, and are the closest to commercial operation at scale. SAFs hold a great potential for reducing the aviation industry's carbon footprint and addressing climate change through their marginal improvement in contrail generation.

Hydrogen offers the fullest promise of zero emission flight, and with careful management can also reduce contrails versus CAF by eliminating the particulates that allow contrails to grow and become persistent. Its attractiveness as an alternative fuel is offset by its relative immaturity compared to current fuels, especially at scale, and there are many technical and commercial challenges to overcome as this solution is developed in the coming months and years.

For example, OEMs developing fuel cell aircraft have a range of options when determining how their exhaust is managed, including vapour emission, condensation, liquid emission and onboard storage. This decision bears an uncharacteristically large technological, regulatory and climate impact, given the stated factors of contrail production from vapour emissions and water weight for onboard storage.

H_2 fuel cells generate water as they are expended, which must be carefully managed to prevent unintended contrail generation. H_2 combustion at altitude requires further study to fully understand the impact, but factors such as burn and exhaust temperature may influence contrail generation.

While significant development is still required to bring it to fruition, the technology to leap into a future of hydrogen-powered flight is not only well understood but is further backed by investment and industrial motivation. The next stage is extensive demonstration of these technologies to support the regulation, certification and development activities that are needed to make them operationally-ready. Assessing the environmental and climate impact of hydrogen technologies is a key part of this process, and must now be supplemented by practical demonstrations to back up the assessment.

This analysis has shown that there are multiple technology pathways which lead to zero-emission flight. Carbon reduction is only one aspect of the challenge – the impacts of the transition to new aviation propulsion on contrail generation must still be studied and considered further in greater detail to produce a viable solution.

Figure 5-1 – Renders of the retrofit Dash-8 at an airport being loaded with capsules

Source: Financial Times[41]

[41] Universal Hydrogen to start testing fuel cells in passenger jet | Financial Times

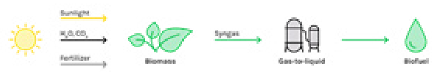
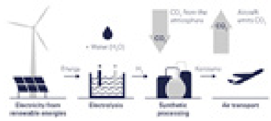
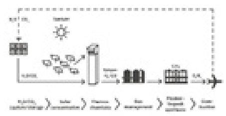
Ultimately, the success of zero-emission aviation is dependent on an end-to-end adoption of alternative fuels across the sector, both from the OEMs and also the critical ecosystem players. The urgency of the climate crisis, the pace of the global transition to cleaner fuels, and the continued need for vital connectivity provided by aviation means that it is essential for these organisations to maintain a proactive approach to enable a swift transition to zero-emission flight.

The advancement of the underpinning climate science around the impact of contrails should be supported, and the aviation industry as a whole has an interest in better understanding this. Quantifying the net effect of contrails will aid OEMs and operators in taking steps to mitigate their impact, and assist regulators in developing effective strategies to encourage and accelerate sustainable aviation. A holistic approach to resolving these challenges, across technology, operations, market-based measures and regulation, will be required to ensure the aviation sector is successful in becoming a zero-emission sector.

Appendices

Appendix A. SAF derivation sources

There are three main types of SAF production methods:

Fuel	Biomass to Liquid (BtL)		Power to Liquid (PtL)	Solar to Liquid (StL)
Method	HEFA (Hydro-processed Esters and Fatty Acids)	Gasification of carbon source, followed by Fisher-Tropsch process	Fisher-Tropsch	Fisher-Tropsch
Carbon Source	Oil-bearing crops, sugar-bearing crops, waste cooking oil, animal tallow, algae	Agricultural residues, forestry residues, organic matter from municipal solid waste.	CO from carbon capture or industrial flue gases H_2 from renewable electrolysis of water	CO and H_2 from water/ CO_2, thermochemically processed using solar thermal energy
				
Pros	▪ Makes up vast majority of currently available SAFs		▪ Most scalable ▪ Abundant feedstocks	▪ Low energy requirement ▪ Abundant feedstocks
Cons	▪ Dependent on carbon neutrality of supply chain. ▪ Limited by volume of available feedstocks. ▪ High land and water usage, food vs fuel crops.		▪ Requires progressively larger and larger amounts of green electricity ▪ Current production very small.	▪ Least technologically developed.

The overarching challenge with SAFs is scale. As of 2022, the current annual SAF production is estimated at 300 million litres[42], or 240000 tonnes. In order to play a significant role in the decarbonisation of aviation, the production of SAFs must increase into the order of hundreds of millions of tonnes by 2040. As such, scalability is a crucial aspect of production. This is represented in the UK government's mandate on SAF production, which recommends placing a cap on HEFA-BtL fuels, to mitigate the negative effects inherent in their production which magnify greatly when produced at scale. This mandate also introduces a sub-target for the production of PtL fuels to encourage the growth and development of 'strategically important SAF pathways'.[29]

[42] IATA - 2022 SAF Production Increases 200% - More Incentives Needed to Reach Net Zero

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