Net zero aviation fuels: resource requirements and environmental impacts

POLICY BRIEFING
Policy briefing
Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none. The Royal Society’s series of policy briefings is a new mechanism aiming to bridge that divide. Drawing on the expertise of Fellows of the Royal Society and the wider scientific community, these policy briefings provide rapid and authoritative syntheses of current evidence. These briefings lay out the current state of knowledge and the questions that remain to be answered around a policy question often defined alongside a partner.
Contents

Executive summary 4

Chapter one: Decarbonising aviation: challenges, targets and options 6
  1.1 The Aviation decarbonisation challenge 6
  1.2 UK and International targets 12
  1.3 Outline of fuel pathways considered 14
  1.4 Alternative fuel production costs 20

Chapter two: Scaling: estimating the resources needed for each fuel 22
  2.1 Biofuels for aviation: scaling and resource availability 22
  2.2 Hydrogen as a fuel for aviation: scaling and resource requirements 29
  2.3 Ammonia as a fuel for aviation: scaling and resource requirements 31
  2.4 Synthetic electro fuel (efuel) 32
  2.5 Alternative option using fossil fuels and separate DAC and storage 33

Chapter three: Life Cycle Analysis assessment of low carbon pathways 35
  3.1 Introduction 35
  3.2 LCA methodology considerations 35
  3.3 LCA review of bio-based jet fuels 40
  3.4 Efuel life cycle emissions 43
  3.5 Hydrogen and ammonia life cycle emissions 45
  3.6 Additional emissions from jet engines 47
  3.7 Climate impact of global aviation emissions 51

Chapter four: Aircraft and operational considerations of Alternative fuels 54
  4.1 Introduction 54
  4.2 Aircraft technologies 54
  4.3 Ground support infrastructure 57
  4.4 Skills and qualifications 59
  4.5 The potential for innovation waves in technology development 59

Chapter five: Summary of R&D challenges 60
  5.1 Global alternative aviation fuel projects 60
  5.2 R&D Challenges 60

Chapter six: Conclusion 71

Appendices
  Appendix A: Glossary of terms 73
  Appendix B: Abbreviations 75
  Appendix C: Acknowledgments 77
Executive summary

Aviation is a contributor to global warming, including through the emissions of carbon dioxide and the formation of contrails high up in the atmosphere. Globally, save for the few years of the pandemic, air travel is expected to continue to grow in the future, increasing the impact on climate change unless a close to net zero form of flying can be developed or any residual emissions offset by removals. Other than reducing the amount of air travel or relying on long-term offsets, the options are limited and revolve around replacing fossil aviation fuel with a low or zero carbon energy source. That source must consider the following parameters:

- a high enough energy density to give the range needed for up to long haul flights,
- can be produced at scale and implemented around the world,
- is cost competitive,
- can be implemented safely in the timescale required (net zero by 2050). This includes any modifications to / replacement of airframes and ground support facilities.

This briefing looks at four options: hydrogen, ammonia, synthetic fuels (efuels) and biofuels, and examines each option against:

- the equivalent resources that would be required for that option to replace fossil jet fuel,
- the life cycle analysis and non-CO₂ environmental impacts,
- the likely costs,
- the modification or replacements needed to implement the option.

Aircraft solely powered by batteries are not considered in this report as battery technologies are unlikely to have been developed to give the energy density required for most commercial flights in the timescale available to reach net zero by 2050. Hybrid systems utilising batteries to support one of the other options might be a potential solution.

Overall, the results of this analysis are uncertain and there is no clear or single net zero alternative to jet fuel. One of the problems encountered is that the parameters are difficult to measure and are interconnected, so for example, hydrogen can be produced using low-carbon generated electricity, which reduces the carbon footprint but increases the cost. Many parameters require further research, for example the formation of contrails from hydrogen-powered engines.

Each option has its benefits and limitations in a UK context:

- **Biofuels**: CO₂ would be produced from the aircraft engines. Only some biofuels can be described as net low-carbon and the scale and availability of feedstock is a restriction (perhaps with the exception of sewage). However, it has the benefit of requiring little modification to aircraft or support infrastructure and to an extent can be introduced quickly.

- **Hydrogen**: No CO₂ would be produced by the aircraft. Low-carbon hydrogen can be produced but at higher cost and might need to be imported to get the scale required. Producing the amount of renewable electricity to create the green hydrogen required would be a challenge and substantial modification and replacement of aircraft and supporting infrastructure would be needed. Safety would have to be proven and further work would be required to confirm improvement in non-CO₂ climate and environmental impacts.
• Synthetic efuels: CO₂ would be produced from the aircraft engines. Few modifications to existing systems would be needed and could be quickly used in aviation. There would likely be some improvement in non-CO₂ climate and environmental impacts, however costs would be higher. For efuels to be considered ‘net zero’, the development of green hydrogen feedstock (as above) and direct air capture (DAC) of CO₂ at scale would be needed. An alternative solution to match fossil fuel use to DAC might be attractive but also has question marks regarding future fossil fuel availability, DAC energy consumption and continuing non-CO₂ climate and environmental impacts.

• Ammonia: No CO₂ would be produced by the aircraft. Low-carbon ammonia can be produced but at a higher cost. Production will depend upon generating green hydrogen at scale and substantial modification and replacement of aircraft and supporting infrastructure might be needed. Safety would have to be proven and further work would be required to confirm improvement in non-CO₂ climate and environmental impacts.

Depending upon the fuel used, changes to aircraft operations, ground handling systems and airport layouts might be required. In addition, aviation relies upon trained, qualified and regularly refreshed staff in key roles who are licenced to carry out their jobs. Alternative low carbon jet fuel technologies cannot be introduced effectively without updating skills, training, and professional standards.

The selected solutions need to be globally accepted and each of the options considered in a holistic manner, both to provide the best solution now and for the coming years. The options available now offer some carbon savings but are not ideal. Further research and development will be needed to produce better alternative fuels, including accessing sustainable feedstocks, and the development of the efficient production, storage and use of green hydrogen, ammonia and efuels. Some of the solutions will require the substantial redesign of airframes and support infrastructure. R&D is also needed to understand and mitigate the non-CO₂ climate impacts of all the fuel options.
Decarbonising aviation: challenges, targets and options

1.1 The Aviation decarbonisation challenge

Achieving net zero carbon across all sectors of human activity is the key objective in the need to avert the threats posed by climate change. Transportation is an important sector and while some modes are being addressed using batteries and potentially ammonia, aviation is recognised as a major user of fossil fuels that poses severe challenges with respect to decarbonisation. Key amongst these concerns is that a large proportion of the aircraft fleet that will continue to be operational in 2040 – 2050 is in existence today with little or no scope for repurposing. For legacy aircraft, a drop-in fuel is needed that has the appropriate energy density and is based on sustainable resources so that these aircraft can continue in use during the overall transition to net zero carbon for the sector. In parallel to drop-in fuel, alternative fuels are being considered in line with new aircraft and propulsion designs and infrastructure requirements. This policy briefing sets out to examine the benefits and challenges of four potential low carbon aviation fuels. However, batteries are not considered as a suitable power source for the bulk of commercial aviation.

Aviation leads to emissions other than CO₂ that produce net positive global warming impacts (see figure 1). The largest warming effects come from emissions of (i) nitrogen oxides (NOₓ) where NOₓ represents NO + NO₂ that affect the chemical composition of the atmosphere including the concentration of the greenhouse gases ozone and methane, and (ii) emissions of water vapour and soot, which play major roles in the formation of contrails and contrail cirrus. These aspects of non-CO₂ effects are also dealt with in this policy briefing.

Leveraging existing infrastructure for fuel storage and delivery to the aircraft is also a key enabler to a fast transition. However, some alternative fuels will require new airframes, powertrains, and infrastructure.

Aviation is a key sector for the UK economy and the UK’s aviation industry is ranked amongst the largest aviation markets in the world. This places the UK in a leading position to drive decarbonisation in the sector globally in the pursuit of net zero carbon emissions.

A key factor for aviation is the energy content per unit mass and volume of a fuel and this along with other factors will be addressed in this policy briefing for the possible alternative fuels available, ie, sustainable liquid hydrocarbons, hydrogen, and ammonia.

---

Global aviation effective radiative forcing growth 2000 to 2018

FIGURE 2

Cost of Jet fuel from June 2015 – June 2022

$ / barrel


KEY

Jet fuel price
Crude oil price (Brent)

Source: S&P Global, Refinitiv, Eikon.

---

1.1 Fossil jet fuel use in the UK

Air travel is beginning to increase to pre-COVID-19 pandemic levels, with a reported two-year high of passenger arrival recorded in April 2022, although this remains 18% lower than statistics recorded in April 2019\(^6\).

In 2019 the UK aviation sector consumed 12.3 million tonnes of jet fuel, a 1% increase on the previous year\(^7\). When viewed on an international scale, it can be seen that the UK was the second largest consumer of jet fuel during 2019\(^8\) exceeded only by the USA which had 811 million passengers travelling by domestic flights\(^9\). The top five jet fuel suppliers to the UK have been Air BP, Shell, ExxonMobil, Chevron and Gazprom, sourcing fossil fuel feedstocks from across the globe\(^10\).


In line with the dramatic reduction in numbers of passengers in the years 2020 to 2022, the cost of jet fuel has fluctuated in price. From hitting an all-time low in 2020 to high prices seen in the first half of 2022, the cost of aviation fuel has varied dramatically (see figure 2). At present alternative fuels are currently more expensive than Jet-A\(^11\), at approximately 2 to 7 times the price\(^12\). Although it is predicted that government incentives, increasing demand, as well as enhanced infrastructure will lower this price differential over time.

UK airports are seeing a movement towards using reduced CO\(_2\) emission fuels. There are currently 27 international airports in the UK\(^13\), and London Heathrow is the largest global user of ‘sustainable’ biofuels which accounts for just 0.5% of the airport’s fuel provision\(^14\).

\(^11\) Jet-A1 is a kerosene-based fuel used in jet, turboprop, and aircraft. It is the most widespread type of jet fuel globally used in commercial aircraft.


If low carbon emission jet fuels are to have a strong positive impact on the UK’s Road to Net Zero, it is important that the alternative fuels adopted are truly beneficial to the fight against the climate crisis and do not cause unacceptable collateral ecological damage. When truly sustainable fuels are available, their use must be incentivised and used by a majority of airports locally and internationally to ensure a smooth transition to a net zero aviation future.

1.1.2 Energy use in flight for a conventional aircraft using a drop in fuel.
A conventional aircraft uses different amounts of fuel depending on the phase of flight with the cruise phase significantly consuming more fuel in total per phase, than other phases.

An illustration of fuel burn in a Boeing 737-300 taking off at about maximum take-off mass across various ranges in nautical miles is outlined in figure 3.

Example fuel consumptions
Using figure 3 (for a Boeing 737-300), the following are example fuel consumptions for typical short and long-haul flights.

Using this data, the empty mass of an aircraft will typically be around 33,000 kg, and minimum fuel at landing is likely to be around 3,000 kg – 5,000 kg, depending upon the distance to the nearest declared alternate airfields. In most circumstances the reserve fuel will not be used, and simply exists for contingencies.

Allowing 129 kg per passenger, a journey between London Heathrow Airport (LHR) to New York John F. Kennedy International Airport (JFK) (a minimum of 3000 nautical miles) would require at least 18,000 kg of alternative aviation fuel (+ 3,000 to 5,000 kg reserve fuel), assuming the same energy density as current Jet-A1.

A short haul flight from LHR to Newcastle International Airport (NCL) on the other hand is at least 219 nautical miles and would require a minimum 2,400 kg (+ 3,000 to 5000 kg reserve fuel) of alternative drop in fuel.

1.1.3 Future demand for energy in aviation
Aviation primary energy demand is predicted to be strong over the period to 2050, with projections ranging from flat demand compared to increases of 40 – 50% by 2050 in, for example, the BP and Shell Sky forecasts. Based on these trends, the UK annual demand for aviation fuel which in 2019 was 12.3 million tonnes is expected to grow up to ~17 million tonnes/yr by 2050.

---

15 Air miles calculator (Distance between London (LHR) and New York, NY (JFK). See https://www.airmilescalculator.com/distance/lhr-to-jfk/ (accessed 30 August 2022).
16 Air miles calculator (Distance between London (LHR) and Newcastle (NCL). See https://www.airmilescalculator.com/distance/lhr-to-ncl/ (accessed 30 August 2022).
FIGURE 3

Mass of fuel used within phases of flight across different ranges

<table>
<thead>
<tr>
<th>Phase of flight</th>
<th>1,000 nautical miles</th>
<th>2,000 nautical miles</th>
<th>3,000 nautical miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>1,150</td>
<td>1,250</td>
<td>1,100</td>
</tr>
<tr>
<td>Take-off</td>
<td>1,250</td>
<td>1,350</td>
<td>1,200</td>
</tr>
<tr>
<td>Climb to FL300</td>
<td>1,250</td>
<td>1,350</td>
<td>1,200</td>
</tr>
<tr>
<td>Cruise</td>
<td>16,150</td>
<td>16,250</td>
<td>16,100</td>
</tr>
<tr>
<td>Descent</td>
<td>5,550</td>
<td>5,650</td>
<td>5,500</td>
</tr>
<tr>
<td>Taxi, park</td>
<td>91</td>
<td>91</td>
<td>91</td>
</tr>
</tbody>
</table>

KEY

- Mass of fuel used (kg) for flight distance
- 1,000 nautical miles
- 2,000 nautical miles
- 3,000 nautical miles

---

20 The Boeing Company, Flight Planning and Performance Manual: Boeing 737-300 with CFM56-3_22K Engines (FAA), Revision 01, dated 14 August 2006.
1.2 UK and International targets

The UK Government recognises the need for low emission aviation fuels usage in the short, medium, and long term as a part of UK net zero strategy\(^{21}\) and the carbon budgets\(^{22}\). The UK Government recently launched the Jet Zero Strategy\(^{23}\) committing to have at least five commercial-scale UK Sustainable Aviation Fuel (SAF) plants under construction, a mandate for the supply of SAF in place by 2025, and setting a target for UK domestic flights to reach net zero by 2040. The consultation on the mandate\(^{20}\) carried out in 2021, set out several potential SAF uptake scenarios, including up to 10% and 75% uptake by 2030 and 2050 respectively which will be based\(^{24}\) on associated greenhouse gas emissions tradable credits. The strategy outlines plans for and progress on the development of zero emission aircraft using hydrogen as an alternative fuel, however it is notable that ammonia is not included in the strategy.

The international scene for the usage of fuels contributing to ‘net zero CO\(_2\)’ is dominated by the activities of the relevant UN agency, the International Civil Aviation Organization (ICAO), which has responsibility for international aviation emissions regulations and emissions reductions.

Domestic aviation and its associated fuel policies will come directly under states’ nationally determined contributions (NDCs) but since international aviation does not fall under such NDCs (effectively outside the Paris Agreement), the ICAO remains the responsible agency. ICAO established two aspirational goals related to climate and CO\(_2\) in 2010, of a 2% annual fuel efficiency improvement to 2050 and that of ‘carbon neutral growth’ from 2020 (established at the 37th ICAO Assembly).


The ‘carbon-neutral growth goal, 2020’ (CNG2020), states that international aviation emissions of CO₂ should not grow above 2020 levels. ICAO is pursuing a range of measures that includes aircraft technology improvements, operational improvements, sustainable aviation fuels and market-based measures to achieve CNG2020. It is envisaged that the CNG2020 goal is to be achieved mainly by carbon offsetting within the market-based mechanism ‘CORSIA’ (Carbon Offsetting and Reduction Scheme for International Aviation). CORSIA contains exemptions / credits for use of approved bio-based (lower C) fuels. The ICAO has produced some illustrative scenarios that suggest variable uptake of bio-fuel, waste-to-fuel, efuel, and hydrogen-powered aircraft. At the 41st ICAO assembly, member states adopted a ‘collective long-term global aspirational goal of net-zero carbon emissions by 2050’.

In the EU, following the release of the ‘Fit for 55 Package’ several legislative processes are underway in the EU to support the aviation sector’s decarbonisation. A key measure in the ‘Basket of Measures’ is increasing the use of low carbon aviation fuels, which are proposed to have significant potential to reduce aircraft emissions.

The US government says lowering aviation emissions 20 percent by 2030 is realistic and the industry should achieve net zero emissions by 2050. To hit net zero, carbon from jet fuel and other sources is to be balanced by removing an equal amount from the atmosphere.

---


26 International civil aviation organization, 2022. States adopt net-zero 2050 global aspirational goal for international flight operations https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx


1.3 Outline of fuel pathways considered

Four energy vectors for aviation are considered in this briefing: hydrogen, ammonia, biofuels (and bio jet) and electro fuels (efuels) which are synthetic liquid hydrocarbons. Biofuels and efuels are often generically called SAF (Sustainable Aviation Fuel), which is a very broad and sometimes misused term.

1.3.1 Hydrogen

Hydrogen is a gas and can be burnt in engines to provide thrust or fed into fuel cells to produce electricity which in-turn can drive propellors or fans. It can be stored as a liquid at -253°C or as a compressed gas at 350 to 700 Bar. Produced at scale today mainly from natural gas (~70 million tonnes per yr\(^2\))\(^9\), the Hydrogen Council have forecast\(^3\) that hydrogen may be made at ten times today's production volumes using electrolysis of water with renewable power (green hydrogen) or through the reforming of natural gas, or biomass gasification\(^3\) both with carbon capture and storage (blue hydrogen).

UK hydrogen demand for all uses is expected to reach 38 TWh by 2030, rising to 165 TWh in 2035, and up to 460 TWh in 2050\(^3\)\(^2\). At present an estimated 10 – 27 TWh of hydrogen is produced in the UK, mostly for use in the petrochemical sector.

To meet the UK’s sixth carbon budget and the net zero strategy, the UK target for low-carbon hydrogen production capacity is 10 GW by 2030. There is likely to be a substantial ramp up in demand beyond 2030 reaching 18 GW of production capacity by 2037. Such future forecasts for hydrogen demand are all highly uncertain, with each growth sector starting from zero or near zero today, and market development being critically dependent on future regulatory measures to decarbonise multiple sectors of the energy system.

---

1.3.2 Ammonia
Ammonia is a gas and can be burnt in engines to provide thrust or fed into fuel cells to produce electricity which in-turn can drive propellers or fans. It can be stored as a liquid at -30°C or under pressure at 10 Bar and is produced today at scale (~185 million tonnes in 2020) from hydrogen (from natural gas) and nitrogen from the air. In the future ammonia will likely be made using green hydrogen (green ammonia) or using conventional processes with access to long term carbon storage (blue ammonia).

1.3.3 Bio-jet (a biologically based jet fuel)
Bio-jet (a sub-set of SAF) is available today but in very limited amounts. It is referred to as hydrogenated vegetable oil (HVO) or hydroprocessed esters and fatty acids (HEFA). Bio-jet is produced by the chemical processing of the triglycerides present in vegetable oils. The triglycerides require deoxygenation which is achieved by catalytic hydrotreatment.

Before the hydrotreatment the vegetable oils require pretreatment to remove potential catalyst poisons. The hydrotreating process produces a broad range of products which requires further refining to obtain the hydrocarbon fraction that is suitable for use as bio-jet.

IEA projections for 2023 – 25 show bio-jet anticipated production of 17 billion litres per year of HVO, which amounts to little more than 4% of today’s aviation energy demand, even if all that HVO were available for aviation. Bio-jet also has compatibility issues with the legacy aircraft fleet, meaning that it must be blended with fossil jet fuel (see table 1 below).

---

Potential routes to alternative synthetic aviation fuels

**INPUTS**

- Water
- Clean power
- CO₂

**PRIMARY PROCESSING**

- Methanol synthesis
- Electrolysis (Green H₂)
- Reverse water gas shift
- Gasification and clean up
- Pyrolysis
- Hydrothermal liquefaction
- Hydrolysis
- Fermentation
- Fermentation

**INTERMEDIATES**

- Syngas
- Pyrolysis oil
- Higher olefins
- Alcohols

**FUEL SYNTHESIS**

- MTO + oligomerisation
- Direct CO₂ – FT
- Fischer-Tropsch
- Hydrocracking / isomerisation

**FUEL FINISHING**

- Synthetic aviation fuel
- Hydrotreating

- Process tailored to needs to each pathway.
- Primary functions include olefin saturation, deoxygenation and isomerisation.
1.3.4 Synthetic carbon-based fuels.

Synthetic carbon-based fuels (biofuels and electrofuels) are synthesised from hydrogen and a source of carbon (for example CO₂ from the air for efuels or carbon from biological mass for biofuels). They can be made to directly replace fossil fuels in jet engines. There are many potential alternative synthetic pathways (see figure 4) to ‘lower-carbon’ aviation fuels, all of which pose differing challenges for deployment.

Several reviews of the low carbon aviation fuel technology landscape are available in the literature 37, 38, 39, 40, 41, 42. If future demand for alternative non-fossil drop-in fuels is to be met, then technological advances in synthesis pathways are necessary due to limitations of feedstock supplies for bio-jet described above.

All pathways to aviation fuel must be approved by American Society for Testing and Materials (ASTM) for use in commercial aircraft. At present there are at least 8 ASTM-approved non-fossil-fuel-based jet fuel pathways (table 1)43, 44. It should be noted that the accessibility and availability of feedstocks outlined in table 1 varies across countries, issues which are discussed in the UK context in Chapter 2.

Most alternative ‘drop in’ fuel pathways produce Synthetic Paraffinic Kerosene (SPK), which is free of aromatics. Fossil jet fuel contains around 8 wt % aromatics. The lack of aromatics has benefits, for example lower particulate production, and potential issues such as older aircraft engine types have sealing materials that do not work if aromatics are absent.

### TABLE 1

ASTM-approved non-fossil-fuel-based jet fuel pathways

<table>
<thead>
<tr>
<th>ASTM reference</th>
<th>Name</th>
<th>Feedstock options</th>
<th>Description</th>
<th>Blend Limit [%]</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D7566</td>
<td>FT-SPK</td>
<td>Gasified sources of carbon and hydrogen: Biomass (forestry residues, grasses, municipal solid waste)</td>
<td>FT conversion of syngas to synthetic paraffinic kerosene (SPK)</td>
<td>50</td>
<td>5 – 6</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>HEFA-SPK</td>
<td>Specifically, fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils, and greases (FOGs) eg tallow, used cooking oil, soybean oil, camelina</td>
<td>Hydro-processed esters and lipids from plant and animal sources to synthetic paraffinic kerosene</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>HFS-SIP</td>
<td>Sugars from direct (cane, sweet sorghum, sugar beets, tubers, field corn) and indirect sources (C5 and C6 sugars hydrolysed from cellulose)</td>
<td>Hydro-processed fermented sugars to synthesised iso-paraffins</td>
<td>10</td>
<td>7 – 8</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>FT-SPK/A</td>
<td>Same as FT-SPK, with the addition of some aromatics derived from nonpetroleum sources</td>
<td>FT conversion of syngas to synthetic paraffinic kerosene and aromatics</td>
<td>50</td>
<td>5 – 6</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>ATJ-SPK</td>
<td>Agricultural residues (stover, grasses, forestry slash, crop straws), forest residues, corn grain, herbaceous energy crops</td>
<td>Thermochemical conversion of alcohols (iso-butanol or ethanol) to paraffinic kerosene</td>
<td>50</td>
<td>5 – 6</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>CHJ</td>
<td>Triglyceride-based feedstocks (plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil)</td>
<td>Hydrothermal conversion of free fatty acids to paraffinic kerosene</td>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>ASTM D7566</td>
<td>HC-HEFA SPK</td>
<td>Bio-derived hydrocarbons such as algal oils</td>
<td>Hydroprocessed hydrocarbons, esters, and fatty acids SPK by the Botryococcus braunii species of algae</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>ASTM D1655</td>
<td>FOG</td>
<td>Fats, oils, and greases</td>
<td>Co-processing of fats, oils, and greases (FOG) in a traditional petroleum refinery</td>
<td>5</td>
<td>8 – 9</td>
</tr>
</tbody>
</table>

* See Glossary of terms.

---


Comparison of levelised costs of production for alternative jet fuel across fuel conversion pathways

The costs are broken down to capital equipment costs, the cost of feedstock (biological source and electricity) and other operational costs.

Source: The International Council on Clean Transportation

1.4 Alternative fuel production costs

The production costs for a range of alternative jet fuel pathways have been widely reported in literature. Estimates of costs vary widely depending on the assumed input price set and the capital costs of the technology deployed. It is worth noting that bio jet fuel production also competes with the established production of biodiesel. In general, the current production cost merit order is shown below in figure 5. Efuel costs are expected to fall with time as the costs of renewable power and electrolysers fall with increasing deployment globally.

As discussed below, the availability of feedstock is a significant consideration, with the HEFA route being limited by the availability of oils and fats.

The straight cost per tonne of each fuel is only one measure. For aviation, where energy density is critical, the cost per giga joule of energy is also important. Looking at minimum fuel selling price data, summarised for different pathways (including some not listed in figure 5) across different feedstocks by several authors.

Figure 6 shows the minimum fuel selling price data calculated in energy terms (the cost per GJ of fuel) using lower heating values.

The cost in energy terms (£ per GJ of fuel) follows a similar order to that shown in figure 5 above with HEFA / HVO feedstocks being one of the lowest and Power to liquid (efuels) using CO₂ from direct air capture being the highest in cost. Ammonia is on average more expensive than hydrogen, but both are on a par with many biofuels.

The current costings (figure 6) are important to judge the economic impact of a shift to alternative jet fuels. However, this is based on current usage and current manufacturing processes. These costs will change drastically with time. On one hand, new technologies and economies of scale could reduce costs, while on the other hand, resource limitations could make some processes more costly than at present and, in some cases, render the processes unfeasible. In the next section, we look at fuel demand and resource requirements needed when scaled up to meet that demand, and a comparison is made for examples of each type of alternative jet-fuel.

---


52 IRENA. 2022 Innovation outlook: Renewable Ammonia https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Range of cost of energy for different alternative fuel options and biofuel production methods

**FIGURE 6**

Jet A cost range (GBP / GJ) June 2021 to June 2022
Scaling: estimating the resources needed for each fuel

The scaling of the resources required is one of the key criteria for assessing the feasibility of any process proposed as a mitigation strategy for a future sustainable economy. To do this, an estimate of the resources required to cover the demand for jet fuel has been calculated when scaled to UK usage for one year. The resources in question differ depending on the feedstocks and methods of production specific for each type of alternative fuel. There are many feedstocks and production methods and for clarity, only representative examples are presented.

2.1 Biofuels for aviation: scaling and resource availability

2.1.1 Energy crops: oil seed rape, miscanthus and poplar

To assess the feasibility of replacing the 12.3 million tonnes of jet fuel currently consumed annually in the UK with a biofuel-based alternative, the area of land required to produce the biomass can be calculated. Table 2 shows, as examples, three sources of biomass used (or considered for use) to make a bio-jet fuel: seed oil (rapeseed), energy grass (Miscanthus), and rapid growth wood (poplar) assuming current agricultural production methods.

Example of a calculation to derive the total amount of land needed to supply the whole amount of jet fuel used in the UK using rapeseed as feedstock:

- The amount of biomass required is calculated using the values of the total amount of jet fuel used, divided by the yield of conversion from biomass to fuel.

For example, 12.3 million tonnes of jet fuel year\(^{-1}\) / 0.29 = 42.4 million tonnes of rapeseed biomass year\(^{-1}\)

- Using the yields of biomass production, we can calculate the amount of land needed to produce the total amount of fuel used in the UK.

For example, 42.4 million tonnes of rapeseed biomass year\(^{-1}\) / 3.3 tonnes of rapeseed hectares\(^{-1}\) year\(^{-1}\) = 12.8 million hectares.

- In 2018, the total area of agricultural land (arable and grass land) in the UK was 18.8 million hectares (DEFRA 2021a\(^{54}\)). Therefore, the amount of land needed to produce the required 12.3 million tonnes is 68% of the total agricultural land in the UK.

Rapeseed, as an oil crop, has the best conversion efficiency (0.29 US tons of jet fuel / US tons of dry biomass) compared to grasses (Miscanthus 0.12 – 0.2) and wood (poplar 0.1 – 0.22). However, the yield of the of the biomass (ie, just the seed in rapeseed, 3.3 Mton/year) is lower than that of grasses and wood (10 Mton/year), where most of the plant is used. Given the nature of the feedstocks (ie, lignocellulose rather than oil), the processes needed to convert wood and grasses to jet fuel are less efficient in terms of energy inputs compared to those needed to convert seed oil to a fuel\(^{55}\).

In all three example feedstocks, the amount of land needed to replace all the UK’s aviation fuel is over 50% of that available in the UK for agriculture.

---


### Table 2

Energy crops as feedstocks for proposed biojet fuel: scaling for land use

<table>
<thead>
<tr>
<th>Conversion process</th>
<th>Oil-to-jet fuel pathway using hydrotreated renewable jet fuel (HRJF)</th>
<th>Alcohol-to-jet fuel pathway with ethanol as intermediate</th>
<th>Gas-to-Jet fuel pathway using Fischer-Tropsch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock</td>
<td>Rapeseed <em>(Brassica napus)</em></td>
<td>Miscanthus</td>
<td>Wood – Poplar</td>
</tr>
<tr>
<td>Yield of conversion to jet fuel (US tons of jet fuel / US tons of dry biomass)</td>
<td>0.29&lt;sup&gt;56, 39&lt;/sup&gt;</td>
<td>0.12 – 0.2&lt;sup&gt;57, 39&lt;/sup&gt;</td>
<td>0.1 – 0.22&lt;sup&gt;39, 58, 59&lt;/sup&gt;</td>
</tr>
<tr>
<td>Biomass yields (UK) (tonnes hectares&lt;sup&gt;–1&lt;/sup&gt; year&lt;sup&gt;–1&lt;/sup&gt;)</td>
<td>3.3 [3.6]&lt;sup&gt;60&lt;/sup&gt;</td>
<td>10 [11]&lt;sup&gt;51&lt;/sup&gt;</td>
<td>10 [11]&lt;sup&gt;51&lt;/sup&gt;</td>
</tr>
<tr>
<td>Yield of conversion to jet fuel (US tons)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total amount of biomass to supply UK jet fuel demand (million tonnes)</td>
<td>42.4</td>
<td>102.5 – 61.5</td>
<td>123 – 55.9</td>
</tr>
<tr>
<td>Total amount of land to supply UK jet fuel demand (million hectares)</td>
<td>12.8</td>
<td>10.3 – 6.2</td>
<td>12.3 – 5.6</td>
</tr>
<tr>
<td>Equivalent fraction of UK agricultural land required</td>
<td>68%</td>
<td>54 – 33%</td>
<td>66 – 30%</td>
</tr>
</tbody>
</table>

---

2.1.2 Jet fuel from bio-waste
Because of the problems with the energy crops, both in terms of resource requirements (see section 2.1.1 above) and life-cycle analyses (section 3), attention has turned to waste materials, most of which have biological origins.

2.1.3 Waste cooking oil
Bio jet fuel obtained from waste cooking oil and fats has been the subject of some attention62, 63, 64, 65 with some airlines completing trial tests66, 67 and others signing purchase deals68, 69.

About 250 million litres of used cooking oil is produced in the UK each year. Much of it is not waste, as it is used to feed livestock, and to manufacture soap, make-up, clothes, rubber, and detergents. However, some is disposed of70 and this is by definition ‘waste’. Some cooking oil waste is produced in homes and as such is difficult to collect.

If 100 – 200 million litres of used cooking oil were diverted to jet fuel production, a conservative estimate of 50% conversion efficiency would produce 50 to 100 million litres of jet fuel, which is only 0.3 to 0.6% of the total amount of jet fuel used every year in the UK.

A growing number of companies in the UK have engaged in buying, selling and / or converting used cooking oil into biodiesel in answer to government incentives71, 72.

72 We Buy Waste Oil (Home). See https://www.webuywasteoil.co.uk/ (accessed 30 August 2022).
The UK is highly reliant on importing feedstocks for its renewable fuel needs with over 423 million litres of used cooking oil sourced from China alone in 2021\(^73\). There is some concern that some of the imported cooking oil is not waste but virgin oil or oil with a secondary use in country, and that unless importation is properly controlled and regulated, could lead to encouraging suppliers to clear more land and/or cut food production in order to expand oil production\(^74\).

2.1.4 Agricultural residues

In the UK, agricultural residues are mostly straw from cereal production (wheat, barley, and oats) with a small contribution from oilseed rape. The estimated total amount of straw available, based on the crop production yields, is 10 Mt per year\(^75\) to 11 Mt per year\(^76\). Approximately 50 – 60% of this is currently sold or used locally on the farm for animal bedding and feed\(^78\). Around 40% is chopped and returned to the soil as a soil conditioner, source of minerals and fertiliser. Increasingly straw is being burnt for electricity production, with currently 0.3 Mt being used in this way and a projected increase to 0.8 Mt.

Estimates on the availability of this feedstock for jet fuel production range from 2 to 5 Mt/year\(^76\). These estimates imply competition with current use, preventing it from being returned to the soil. In this case, soil carbon and nutrient content will be depleted leading to increased use of fertilisers and therefore increased greenhouse gas (GHG) emissions. The loss of carbon, phosphorus, potassium, and several minerals from the soil is already a problem for its current and projected use in electricity production.

The estimated land-use change penalty caused by the removal of the straw from the soil alone corresponds to an average emission of 50 – 70 gCO\(_2\)/MJ from biofuel\(^79\) compared to “90 gCO\(_2\)/MJ for emissions fossil jet fuel.

As a feedstock, straw with its low energy content is spread thinly over a large area (everywhere there is arable agriculture). Collection and transportation to the refinery will incur a penalty in terms of GHG emissions and the energy balance.


\(^{75}\) Nicholson et al. 2014. HGCA Research Review No. 81 Straw incorporation review.


If the maximum amount of 5 Mt/year is taken (half of all straw in the UK taken from its current usage), and if a yield of conversion to jet fuel is assumed to be 0.16 (as per Miscanthus in table 2), this will produce 0.6 Mt/year of fuel, that is 6% of the required amount of fuel.

In conclusion, the UK’s agricultural waste can only provide a small fraction of the demand for jet-fuel, its status as waste is debateable, and its removal from current usage will have negative impacts on the LCA’s for energy accounting and GHG emissions.

2.1.5 Forest residues
Forest residues consist of small roundwood (SRW) (ie, stem-wood and branch-wood less than 18 cm diameter (over bark) and more than 7 cm diameter), and forest residues (comprising brash, stumps and small round wood not suitable for other purposes). The sum of these two potential feedstocks is estimated to be 2.7 Mt/year. Of this, approximately 50% is left on the ground with various functions, including protection of the soil and to return some of the nutrients back to the soil itself. Estimates of feedstock availability in the UK for jet fuel production range from 0.8 to 2 Mt/year, but they are in competition with current uses. Using the high estimated 2 Mt/year and assuming the yield of conversion of 0.1 for wood material, this amount of forest residue feedstock will produce 0.2 Mt/year of fuel, that is 1.7% of the total amount of fuel required.

Sawmill residues are also considered among the products of the forest available for bioenergy production. They are clean wood residues from timber processing, such as chips, slabs, sawdust, and bark. They are not waste materials because they currently have several different uses, such as animal bedding, board manufacture, horticultural chips, and use in pulp mills. 1.4 Mt/year of sawmill residues is estimated to be produced, potentially corresponding to ~1.2% jet fuel required in the UK per year, though their availability will be in competition with their existing uses.

The UK is one of the least forested countries in Europe. In contrast, other countries that are less deforested potentially have proportionally greater forest waste resources. Although some of this could be available, it would have to compete with the already well-established uses and markets for these residues. Already the UK is by far the biggest importer of wood pellets, importing more than the next three importing countries combined.

The situation is improved if all of Europe is considered. According to the Swedish IRENA report, forest residues could provide 378 TWh of energy. Although this could be available, to manufacture jet fuel it would have to compete financially with the already well-established markets for these.

2.1.6 Municipal Waste

Municipal solid waste is defined as the Local Authorities Collected Municipal Waste. The renewable fraction of this is the waste of biological origin (i.e., the carbon originated from photosynthetic carbon fixation). When this is destined for landfill, its use for energy generation is usually assumed to have a relatively low GHG emission. Local authorities are striving to eliminate biodegradable waste from landfill.

The total renewable content of the municipal solid waste in the UK is estimated to be about 40 Mt/year. Of this amount, it is estimated that 12 Mt/year could be used for bioenergy production. As the material is already collected by the local authorities, it should be readily available for deployment with little additional GHG emission penalty. On the other hand, because this is a very heterogenous material, the yields of fuel production will vary and may be lower than for the other materials listed above.

As with other waste, some municipal waste has uses or potential uses (e.g., composting, incineration for heating82). The waste for jet fuel will compete with the current uses, this will affect cost but also the life cycle analyses, as other inputs of energy and GHG emissions will be incurred to replace them in their other uses.

Using the estimated 12 Mt/year and assuming the yield of conversion of 10% (this is an estimate based on wood and mixed materials), this amount of waste as feedstock could produce 1.2 Mt/year of fuel, that is 10% of the total amount of fuel required.

2.1.7 Sewage

Sewage and animal manure is considered as another carbon-rich biological feedstock for energy production. A range of conversion approaches have been investigated83, 84, 85. Some processes are in common with those proposed to treat food waste. These include hydrothermal liquefaction to produce biocrude86, 87, followed by treatment with hydrogen to produce fuels88, 89, 90.

---

Around 1.4 million tonnes of sewage sludge dry solids are produced in the UK per year, the majority of which is used in agriculture. Some companies utilise sewage sludge to generate energy (using anaerobic digestion) to run their own operations or exported to the National Grid.

Despite the competing uses, some authors have identified this as a plentiful and promising feedstock but have cautioned that production plants require significant investment and assurance that supply demands will be consistently met. Some have noted that production processes are currently limited to laboratory settings and would require further process optimisation and development before they come to market.

2.1.8 Use of wood to make fuel.

Biofuels are often considered as carbon neutral because all the carbon in the biofuel had been captured as CO₂ from the atmosphere by photosynthesis, a solar energy-driven process. Thus, the CO₂ released upon combustion has come from the atmosphere and will be recaptured with new plant growth. However, consideration also must be given to the additional processes required in the agricultural or forestry practises such as planting, fertilising, pesticide use, irrigation, harvesting, drying, transport and finally conversion into a fuel.

Given the low efficiency of photosynthesis, the additional energy inputs can cancel out the solar energy captured and the additional GHG emissions from these processes can be as big as (or bigger than) those from the fossil fuel that is being replaced.
Even if biofuels were truly carbon neutral, there is a specific problem from the use of forests: fuel produced from trees is burnt faster than replacement trees can grow. Forest residues and felled trees, after processing, release all the CO₂ that had been captured by photosynthesis over the life of the tree upon combustion. That CO₂ goes into the atmosphere at that moment and the equivalent will not be removed from the atmosphere until a replacement tree has fully grown back. That usually takes years, sometimes many decades depending upon the type of tree. The amount of CO₂ is not linear with growth but slower at first and at a maximum when it reaches maturity in decades\(^{100}\).

2.2 Hydrogen as a fuel for aviation: scaling and resource requirements

To estimate the resource requirement for H\(_2\)-powered aviation, the following approach was used.

i. The UK’s (2019) annual jet fuel use (~12 million tonnes (Mt)) was converted to energy units (145 TWh);

ii. It was assumed that the same amount of energy would be needed from H\(_2\) as from fossil jet fuel, ie, 145 TWh (~3.8 Mt);

iii. Comparisons to the resources required were then made directly in terms of electricity (table 3). Whilst there are a range of methods of generating electricity, each with different energy requirements and GHG emissions, ‘green’ renewable electricity is taken in all its forms as the most sustainable option.

Electricity: Electrolysis is considered a sustainable route for H\(_2\) production (‘green hydrogen’) because it can be generated using renewable resources (wind and solar).

Electrolysis is reported to be between ~50 and ~70% energy efficient for hydrogen production with the potential of improved efficiencies to 76% by 2050\(^{101}\). The electricity required to provide the hydrogen to replace the UK’s 2019 aviation fuel consumption would be between 207 TWh (at 70% efficiency) and 290 TWh (at 50% efficiency). This is 68 – 95% of the UK’s current electricity generation, but to be sustainable only renewable electricity should be considered (around 2.4 to 3.4 times current renewable generation without biofuels).

The use of green hydrogen for aviation to replace current fossil jet fuels requires ~2.4 to 3.4 times the total current renewable electricity in the UK. This route requires increases in wind and solar power generation.

\(^{100}\) European Academies Scientific Advisory Council (EASAC), 2019 Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf

Other resource requirements

- **Water requirements**
  Electrolysis requires deionised water. To produce 1 tonne of H₂ requires 9 tonnes of water. To supply the 3.8 Mt of H₂ for aviation, 34.2 Mt of ionised water is required. It has been proposed that water could be provided at offshore wind power sites and could include desalination. Some authors\(^\text{102}\) note that the energy requirement of desalination by reverse osmosis is negligible (<0.2% of the energy requirement of electrolysis) and would add about $0.01 to the cost of hydrogen produced per kg. Some note that green hydrogen production will consume less water than sectors such as irrigated agriculture, fossil fuel energy production and power generation\(^\text{103}\).

- **Liquefaction of H₂**
  Hydrogen use in aviation is as a compressed / liquified gas, and compression and refrigeration for liquefaction requires significant energy input (typically 10 – 13 kWh/kg liquid H₂)\(^\text{104}\) and this must be maintained in flight and storage using appropriately robust containers.

- **The hardware for electrolysis**
  The energy and GHG costs require the manufacture of robust electrolysers; these are costly in terms of GHG emissions and energy use.

### TABLE 3

Hydrogen as jet fuel: scaling for energy use

<table>
<thead>
<tr>
<th>Description</th>
<th>Energy/ Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet fuel consumption (2019): energy, [mass]</td>
<td>145 TWh [12 Mt]</td>
</tr>
<tr>
<td>Hydrogen required to replace fossil jet fuel (2019)</td>
<td>145 TWh [3.8 Mt]</td>
</tr>
<tr>
<td>Electricity needed for electrolytic H₂ production</td>
<td>207 – 290 TWh (70 – 50% efficiency)</td>
</tr>
<tr>
<td>2020 UK electricity generation(^\text{105})</td>
<td>306 TWh</td>
</tr>
<tr>
<td>2020 UK ‘renewable’ electricity generation</td>
<td>123 TWh</td>
</tr>
<tr>
<td>2020 UK renewable electricity generation without biofuels</td>
<td>86 TWh</td>
</tr>
</tbody>
</table>


\(^\text{103}\) Beswick, R R, Oliveira, A M, & Yan, Y. (2021). Does the green hydrogen economy have a water problem?. ACS Energy Letters, 6(9), 3167-3169.


2.3 Ammonia as a fuel for aviation: scaling and resource requirements

Ammonia is considered as a potential replacement for fossil fuels, particularly in the maritime industry. It is a liquid between -77.7°C and -33.3°C (at 1 bar) and has a significantly higher volumetric energy density than both liquid and high-pressure hydrogen. While ammonia has six times less energy by mass than hydrogen, the system storage mass for hydrogen is at least a factor of two more than that for ammonia.

To estimate how much ammonia is required for annual aviation in the UK, the amount of energy in the fossil jet fuel used in 2019 was calculated (145 TWh), then the mass of ammonia needed to supply this quantity of energy was calculated (30.2 Mt of NH₃).

Using a modified Haber-Bosch process powered by renewable electricity, electrolytically produced hydrogen, and cryogenically or electrolytically purified N₂, the amount of electricity required is 217 – 332 TWh.

For green ammonia production, the production of green hydrogen is the first and most energy intensive step. The reaction of hydrogen with nitrogen to produce ammonia also produces heat, which can be used to diminish the overall energy input into the process. Overall, green ammonia production requires between 5 – 10% more energy than the equivalent H₂ production. As with the forms of ‘green’ synthetic fuels, ammonia as a jet fuel requires a major increase (2.5 – 3.9) times in the annual UK sustainable (solar and wind) electricity production (2020).

<table>
<thead>
<tr>
<th>Resource requirements for ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet fuel consumption (2019): energy, [mass]</td>
</tr>
<tr>
<td>Ammonia required to replace fossil jet fuel (2019)</td>
</tr>
<tr>
<td>Electricity required for ammonia production to replace fossil jet fuel: Haber Bosch + electrolytic H₂ production, N₂ purification etc</td>
</tr>
<tr>
<td>2020 UK electricity generation (TWh)</td>
</tr>
<tr>
<td>2020 UK ‘renewable’ electricity generation</td>
</tr>
<tr>
<td>2020 UK renewable electricity generation without biofuels</td>
</tr>
</tbody>
</table>

Note: The most efficient route is smart electrolysis / NH₃ synthesis integration: 7.2 MWh/tonne is 71% (78% exergy) efficient.


2.4 Synthetic electro fuel (efuel)
The production of synthetic efuels involves the reaction of CO₂ and water to form ‘syn-gas’ (a mix of carbon monoxide and hydrogen), and then using that to generate a liquid hydrocarbon fuel. This process is the reverse of combustion and thus costly in energy, requiring more energy to be put in than is extracted during combustion. Much of the energy input would be used to make H₂ gas from green electrolysis and so would require de-ionised water as with H₂ production.

A near zero-carbon version of this process would include CO₂ capture from the air (direct air capture or DAC) a process that is itself energy demanding (see next section), although concentrated industrial point sources of CO₂ could be used initially.

To assess the resource requirements for this process (see table 5, estimates must be made for the renewable (wind / solar) electricity needed to capture the CO₂, to electrolyse water to produce H₂, to reduce the CO₂ to CO and to drive the reaction in the Fischer Tropsch (FT) process.

The power-to-liquid efuels route requires significantly more energy than for hydrogen or ammonia production for the reasons given above. The process when done sustainably using renewable electricity, requires 5 – 8 times the UK’s 2020 renewable electricity capacity (without biofuels).

This route requires significant energy input that outweighs the energy produced from the fuel itself. It takes between 140 and 198 GJ to make 1 tonne of synthetic efuel which is 3.2 – 4.6 times the energy content of the end fuel (when compared to jet fuel at the same energy density).

### TABLE 5

<table>
<thead>
<tr>
<th>Resource requirements for synthetic aviation fuel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation fuel consumption UK [mass] in 2019</td>
<td>145 TWh [12 Mt]</td>
</tr>
<tr>
<td>Energy cost (electricity and heat) for power to liquid conversion – Includes DAC, hydrogen production and FT.</td>
<td>39 – 55 kWh/kg of fuel produced</td>
</tr>
<tr>
<td>Energy required to produce the 12 Mt of power-to-liquid e-jet fuel required in the UK.</td>
<td>468 – 660 TWh</td>
</tr>
<tr>
<td>2020 UK electricity generation</td>
<td>306 TWh</td>
</tr>
<tr>
<td>2020 UK ‘renewable’ electricity generation</td>
<td>123 TWh</td>
</tr>
<tr>
<td>2020 UK renewable electricity generation without biofuels</td>
<td>86 TWh</td>
</tr>
</tbody>
</table>
2.5 Alternative option using fossil fuels and separate DAC and storage

Given the problems with resource use at scale for the options discussed above, it is worth considering the feasibility of continuing the use of fossil fuel for aviation but having the greenhouse gas emissions linked to direct air capture (DAC) of an equivalent amount of CO₂ at a similar rate.

Table 6 shows calculations aimed at estimating electricity use to capture the CO₂ released by aviation in the UK for one year. The table also shows the equivalent numbers for global aviation (in blue).

### Table 6

<table>
<thead>
<tr>
<th>Resource requirements of using fossil fuels and DAC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation fuel consumption UK [mass] in 2019</td>
<td>145 TWh [12 Mt]</td>
</tr>
<tr>
<td>CO₂ emission upon combustion of 12 Mt fuel</td>
<td>38 Mt</td>
</tr>
<tr>
<td>Energy required by DAC to capture the 38 Mt of CO₂ from the air (1.6 to 3.9 MWh/t CO₂ excluding compression etc.)</td>
<td>61 – 148 TWh</td>
</tr>
<tr>
<td>2020 UK electricity generation for comparison</td>
<td>306 TWh</td>
</tr>
<tr>
<td>2020 UK ‘renewable’ electricity generation</td>
<td>123 TWh</td>
</tr>
<tr>
<td>2020 UK renewable electricity generation without biofuels</td>
<td>86 TWh</td>
</tr>
</tbody>
</table>

#### Equivalent numbers for global aviation

<table>
<thead>
<tr>
<th>Resource requirements of using fossil fuels and DAC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fuel consumption World [mass]</td>
<td>3680 TWh [288 Mt]</td>
</tr>
<tr>
<td>Total energy required to produce the 288 Mt of fuel required in the world via the power to liquid conversion.</td>
<td>10,944 – 15,840 TWh</td>
</tr>
<tr>
<td>CO₂ emission upon combustion of 288 Mt fuel</td>
<td>900 Mt</td>
</tr>
<tr>
<td>Energy required to absorb an equivalent amount of CO₂ via DAC</td>
<td>1,440 – 3,510 TWh</td>
</tr>
</tbody>
</table>


To remove the CO\textsubscript{2} fraction of the GHG emission from fossil jet fuel use, the energy needed for the process of DAC would be at least 0.7 – 1.7 times the current renewable electricity generation. This option then would also require a major increase in renewable electricity production (solar and wind). It is worth noting that the estimate for energy needed just to capture the CO\textsubscript{2} can be as much as the energy in the jet fuel\textsuperscript{108, 109}.

This option would have no impact on the non-CO\textsubscript{2} warming effects from contrails which would continue to grow, so additional effort and research would be needed to address these, or more DAC deployed to counter the indirect warming effects.

It may well be the case that keeping and improving existing fossil fuel technology and offsetting emissions through direct air capture may be a viable option for a large part of the industry, especially legacy aircraft. This briefing however doesn’t explore life cycle analysis of this kerosene – DAC scenario. It should also be noted that growth in the use and adoption of alternatives may severely impact the economics of refineries that currently produce jet fuel which will lead to uncertainty around the future scale and cost of kerosene.
Life cycle analysis assessment of low carbon pathways

3.1 Introduction
Global aviation CO₂ emissions were approximately 1,000 million tonnes per year in 2018/19, representing 2.4% of global emissions, dropping in 2020 to 600 million tonnes and increasing in 2021 to 720 million tonnes [110]. UK aviation (international and domestic) emissions accounted for 8% of UK greenhouse gases emissions in 2019 [111].

The effects of aviation’s impacts on climate are not just through CO₂ emissions, but also the emission of other pollutants and the formation of contrails.

As previously described, numerous alternative jet fuels have been developed from wastes, bio-fuels and through the use of renewable technologies. The aim of these is to produce the lower carbon fuels needed to help meet our decarbonisation targets. The environmental impact of these fuels differs due to their production and feedstocks, and Life Cycle Assessment (LCA) is often used to improve production processes, select the lowest impact fuels, and develop policy and technology.

In order to complete an LCA, an examination of the production, use and waste produced for each option is required. Although simple in concept, the practice of LCA can become complex, especially when using wastes and biomaterials as feedstocks.

3.2 LCA methodology considerations
Although LCAs generally follow a process outlined in ISO standards, there are various methodology considerations and variations that impact results. Broadly speaking these are system boundaries and allocation methods. As described below, the accounting of emissions and environmental impacts in such studies depends upon the rules and assumptions employed, including where the system boundary is put, and the upstream production methods assumed. For example, the different carbon footprints for the generation of electricity using solar farms based on arable land, desert or cleared forest. This can make comparisons between fuel types difficult.

3.2.1 System boundaries
System boundaries are critical to knowing what is included and excluded in a study. For example, in aviation fuel, a system could be fuel production to pump, or fuel production to exhaust (known as wake). Within aviation, as previously discussed, the impact of fuel burning in the atmosphere is particularly important – therefore within this discussion the system boundaries are set around the latter (to include fuel use).

When producing fuels from biomass or wastes the issue of carbon modelling also becomes more complex and can also be considered a system boundary issue.

Chapter Three

**FIGURE 7**

LCA system boundary considerations

Within this system boundary GHG we can account for the CO₂ input and output and, if looking on a temporal basis, account for the difference in uptake and release (with ongoing planting it can be cyclical). However, often with an LCA these results are still truncated into one value assuming all inputs and emissions happen at the same time.

Within this system boundary GHG is assumed to be neutral as biomass takes up GHG within the same timescale as it is emitted.

Waste is often considered to have no embodied GHG, other than that associated with collecting and transporting to the conversion process. Sometimes a credit is given for avoiding sending it to landfill.

This time span can be short or long – up to millions of years if previous product is fossil based.

Credits for avoided impact of waste disposal are sometimes given in the inner system boundary rather than being associated as an impact with the original product. Within CORSIA a credit is allowed.

Source: Marcelle McManus, 2022.
Where the system boundaries are set is critical in how the carbon is accounted for, (see figure 7). Using fuel produced from waste as an example, one LCA might set the system boundaries tightly round the middle section (dashed line). In this scenario the waste would be considered a ‘free’ resource with no associated embodied GHG other than that associated with its collection and processing. If a production to pump approach is taken, then no GHG emissions are counted. If the system is expanded a little, then in some cases a credit is given for dealing with the waste. This is because the waste is not being, for example, sent to a landfill. In this scenario the production of the fuel may be shown as having little, or negative impact due to the associated credit. In order to model the carbon fully from atmosphere to atmosphere (a full carbon life cycle) then the impact of the previous product life would need to be included. This is more rarely undertaken.

When biomass is the feedstock, the impact of biogenic carbon is often considered as neutral. That is, it is assumed that the carbon released during combustion will be taken up within a reasonable time, by crop growth and therefore their carbon (and other GHG) flows can be omitted. In many instances, this means that biogenic carbon is not modelled as an emission to the atmosphere. These temporal nuances of bioenergy are particularly complex – with some crops taking up carbon faster than others\textsuperscript{112} and several authors have examined the consequences of applying these neutrality assumptions, cautioning that they lead to accounting errors\textsuperscript{113, 114} because the carbon is not always taken up and emitted within a short timescale, for example with trees. A recent report from EASAC\textsuperscript{115} proposed that wood from forests should be left as forests for as long as possible, and when harvested, used as wood in structures that will remain un-combusted for as long as possible. This applies to forest residues and sawmill waste: current uses in composites for building material should encouraged, and combustion should be discouraged and allowed only as a final use.


3.2.2 Allocation

Besides system boundaries, another important issue is the allocation method, for example ‘methods to allocate the environmental burden of a specific production system between products and co-products’ which can significantly impact results of an LCA. This issue arises because few processes only have one output, and it would not be realistic if the main product is responsible for all the environmental burdens of the process. However, inconsistencies in assumptions and calculations of allocation methods can lead to different environmental impact values being attributed to the same feedstock.

Figure 8 shows the common allocation methods – energy, mass and economic / market. It illustrates how allocation works for a process that has three product outputs, A, B and C. This shows that even when the whole system is the same, the modelled output of one part of a system with co-products can vary significantly based on the allocation method. Although market / economics often drives decisions and processes – this is the most changeable method as prices will fluctuate during a product's life.

Finally, and not restricted to LCA, Global Warming Potential (GWP) aggregates the impacts of different GHGs. Normally this is shown over a 100 year timescale, which is a widely used policy metric. However, some GHGs such as methane, have a far higher impact on climate change over a shorter time scale than others, for example carbon dioxide. When comparing fuels or processes that have higher emissions of methane (i.e., where the impact is stacked in the shorter term) it is beneficial to disaggregate GHG if one is concerned by short term over long term impact.

Despite these complexities, the LCA approach is well documented and accepted and within those boundaries there are many LCA data to explore and compare. However, different methodological issues as well as different feedstock and processes give a range of GHG values for different fuels.

---


FIGURE 8

LCA allocation methods showing how the CO₂ generated by a process can be attributed differently to the products of that process

<table>
<thead>
<tr>
<th>Product</th>
<th>Cost (%)</th>
<th>Mass (%)</th>
<th>Energy value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>60</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Product B</td>
<td>30</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Product C</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

The total GHG impact of the process that makes Products A, B, and C is 10kg CO₂ eq.

Allocation is used in LCA* used to determine how much of the total process impact is allocated to the individual products (e.g., between A, B, and C). Common allocation options include mass, economics, and energy (particularly in energy-based systems).

* ISO standards recommend ‘system expansion’ instead of allocation. In system expansion, if the impact of Product A is required, alternative ways of making B and C would be calculated and subtracted from the total system impact.

Source: Marcelle McManus and Ariane Sbrice, University of Bath.
Chapter Three

3.3 LCA review of bio-based jet fuels

Numerous LCAs have been undertaken in bio-aviation fuels and figure 9 shows key GHG results from literature showing differing results associated with each of the different pathways and allocation method. The upper red dotted lines show the range for conventional aviation fuel (RED II and CORSIA). The respective reduction targets are shown in green. This figure shows that many, but not all, of the fuels meet the less stringent CORSIA target. Fewer meet the RED II target.

The results have wide ranges within the individual fuels for several reasons – partially for methodological differences discussed and partially due to differences in production methods or crop growth efficiencies etc. Overall, the results show GHG emissions per MJ ranging from approximately -10 g CO₂eq/MJ (Oils crops) to almost +150 g CO₂eq/MJ (microalgae). Those with significant savings over the impact of traditional jet fuel are associated with microalgae which is examined in two of the selected studies with GHG emissions from 17.2 — 146 g CO₂eq/MJ, dependent on the chosen pathway and lipid content of microalgae. High impacts are due to a number of factors including energy input used in running production facilities, nutrient input used in growth, and overall yields.

Proponents of this technology / pathway are exploring ways to reduce the impact by developing more suitable strains and growth options for the algae.

Pyrolysis pathways show an improvement in GHG emissions over traditional jet fuel only when high lipid yield feedstock was used\(^1\)\(^{119,120}\).

Oil crops provide one of two of the negative GHG emissions shown, (-12 — 55 g CO₂eq/MJ) – with the variation in results due partially to the effect of crop price on land use change (differing price resulting in displacing soybean or canola / oilseed rape) and differing allocation methods\(^1\)\(^2\)\(^1\)\(^{21}\).

Interestingly, and especially considering the UK governments consultation\(^1\)\(^2\)\(^3\), where some of the projects under the green skies scheme utilise municipal solid waste, significantly larger well to wake (exhaust) GHG emissions were calculated to be associated with the use of municipal solid waste (MSW) as the feedstock for FT synthesis (32.9—62.3 g CO₂eq/MJ)\(^1\)\(^2\)\(^4\). This is attributed to the higher global warming potential of the non-cellulosic waste content. Additionally, despite GHG emission savings resulting from avoiding landfill and incinerating, this benefit was mitigated by the volume of landfill gas that would no longer be recovered (which would usually displace fossil fuel use). This, however, would change over time.

---


**FIGURE 9**

Spread of GHG results of selected biofuel LCA studies

<table>
<thead>
<tr>
<th>Technology types</th>
<th>Emissions g CO₂ per MJ</th>
</tr>
</thead>
</table>
| HRJ – Microalgae | ![Graph for HRJ – Microalgae](image1)
| HRJ – Oil crops | ![Graph for HRJ – Oil crops](image2)
| HRJ – Lignocellulosic | ![Graph for HRJ – Lignocellulosic](image3)
| FT – Lignocellulosic | ![Graph for FT – Lignocellulosic](image4)
| FT – Corn stover | ![Graph for FT – Corn stover](image5)
| BC – Corn | ![Graph for BC – Corn](image6)
| BC – Corn stover | ![Graph for BC – Corn stover](image7)
| BC – Sugar cane | ![Graph for BC – Sugar cane](image8)
| BC – Lignocellulosic | ![Graph for BC – Lignocellulosic](image9)
| HTL – Forestry residue | ![Graph for HTL – Forestry residue](image10)
| HTL – Sewage | ![Graph for HTL – Sewage](image11)
| HTL – Algae | ![Graph for HTL – Algae](image12)
| HTL – Food waste | ![Graph for HTL – Food waste](image13)

Source: Data from Gyen Wah Angel, 2019. University of Bath.
Hydrothermal liquefaction (HTL) of forest residues gives comparatively lower GHG emissions of 17—20.5 g CO₂ eq/MJ (irrespective of allocation method)¹²³,¹²⁴. HTL methods appear to have the lowest GHG balance across the board. For example, using HTL on a range of food waste, sewage sludge and algae, is reported to provide reductions from traditional aviation fuel reported of 58%, 99% and 89% respectively. The regional resource assessment reveals that just under 23% of UK jet fuel demand could be met with the technology if all available resource were used.

Critical aspects in the level of uncertainty for many of the bio-based feedstocks are Land Use Change (LUC), Indirect Land Use Change (ILUC) and allocation. The inclusion of LUC in these studies is low; but when included the GHG impacts increase significantly. There are high levels of uncertainty for LUC, but this should not mean its exclusion. This highlights the importance of having a unified reporting and assessment method for low carbon jet fuels.

3.3.1 International aviation industry carbon reduction targets

In 2016 the International Civil Aviation Organisation (ICAO) agreed that there would be a global market-based scheme to limit GHG emissions from international aviation. The methodology also aims to counter some of the issues associated with allocation etc. seen above¹²⁵. This has been called the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and it requires airlines to offset GHG emissions that exceed 2019 levels⁴⁴.

CORSIA has been framed to allow offsetting either through credits or through the use of CORSIA Eligible Fuels (CEFs)¹²⁶. The aim of this is that international aviation achieves carbon neutral growth from 2020 (although to be noted this was set up before the pandemic).

In order to be deemed a CORSIA Eligible Fuel (CEF) the fuel must meet ‘sustainability criteria’ defined as having life cycle GHG emissions that are at least 10% below those of petroleum jet fuel (which they benchmark as 89g CO₂/MJ) as well as not being made from biomass from land with high carbon stock¹²⁶. From 2024, comprehensive environmental, social and economic sustainability criteria apply under CORSIA.

Under RED II in order to qualify biofuels as renewable energy sources, fuels have to achieve a 65% greater reduction in emissions against their fossil fuel baseline of 94 g CO$_2$/MJ. The UK mandate, which has a target of 10% SAF by 2050, defines SAF as having to achieve at least a 50% GHG saving compared to a fossil fuel comparator of 89 g CO$_2$/MJ$^{24}$. Different methodological approaches are responsible for the differing targets; for example, the CORSIA method includes the impacts associated with Indirect Land Use Changes (ILUC) emissions in the LCA calculation, whereas the UK / EU approach generally excludes feedstocks that present high risk of ILUC. CORSIA also credits fuels in proportion to the emissions they reduce.

A set of default life cycle emissions for eligible fuels has been created by ICAO$^{127}$. Whilst in this context a 10% reduction might not be described as ‘sustainable’, the reviewed average life cycle intensity baseline of 89g CO$_2$/MJ well-to-wake is a useful benchmark (and lower than that in RED II). Although previous reviews have shown a range to be from approximately 80 – 90g CO$_2$/MJ (see figure 9), and the benchmarks might be considered a little high, they are in alignment with other international schemes.

From the results above, biofuels save GHGs however LCA tools can be very flexible in how they are applied which would significantly produce different results depending on how the boundaries are set. The inclusion of Indirect Land Use Changes for example in many studies is low and when included, the GHG impacts increase significantly, and few hit the renewable energy directive target. There is a need for full transparency on data, methods, assumptions used and a unified reporting and assessment method for low carbon jet fuels.

### 3.4 Efuel life cycle emissions

Greenhouse gas emissions of power to liquid efuels can be close to carbon neutral and considerably below fossil fuel options$^{128}$.

The combustion of efuels has often been treated as carbon neutral because the carbon atoms were either extracted from the atmosphere or from a waste gas stream that would have been emitted into the atmosphere$^{129}$. While investigating life cycle emissions of efuels, it is important to consider the source of carbon dioxide used for fuel manufacture and the GHG emissions intensity of electricity used$^{47}$.

---


IATA’s 2015 report on alternative fuels130 shed light on emissions associated with efuels considering the generation of electricity as the only source of GHG emissions in the production pathway. The report noted that favourable GHG emissions of 11 gCO₂ eq per kWhₑₑₑ for wind power generation would translate into specific GHG emissions of 6 gCO₂ eq per MJ of jet efuel which corresponds to a reduction of more than 90% compared to conventional jet fuel.

A 2016 report by the German Environmental agency131 highlighted that the GHG emissions without land use change for efuels (wind / PV in Germany) are about 1g CO₂–eq per MJ of the final PtL jet fuel.

Significant differences in emissions were found depending on the capture and purification of CO₂ used as reported by Ricardo132, noting that emissions could be higher if fossil sources of energy are used.

---


The high values in figure 11 below were based on direct air capture powered by renewable electricity and natural gas for heat, the medium figures based on capture from cement production and the low figure based on capture from a natural gas Combined Cycle Gas Turbine (CCGT) with 95% capture rate.

Based on the figures discussed by Ricardo, it is worth noting that:

- Emissions could be reduced significantly by use of renewable energy to levels similar to those outlined by the Germany Environmental agency report discussed above.
- Energy consumption could be reduced by integration with the Fischer–Tropsch unit, which could provide about half of the heat required by the capture system.
- Capture from CCGT flue gas would probably not count under RED II.

However as discussed above, emission sources other than electricity generation along the process chain increases the overall carbon footprint of efuels.

In a world whose contribution of renewables to the overall energy supply is increasing, the GHG emissions of renewable jet efuel manufacture can be expected to decrease further in the future (>95% reduction compared to conventional jet fuel).138

3.5 Hydrogen and ammonia life cycle emissions

Despite growing investments in Hydrogen and Ammonia technologies133, 134, 135, 136 data on emissions associated with hydrogen- and ammonia-powered flights is limited within public domains. This may be due to the maturity level of these technologies.

Data on emissions, and life cycle analyses conducted have often been scrutinised for selective bias and flawed assumptions137. However, as investors are communicating that there is real hope for these modalities of aviation fuelling, it is imperative that comprehensive life cycle analyses are conducted to ensure that these options deliver significant GHG savings over conventional jet fuel.

An attempt at these is a well to wake (exhaust) life cycle analysis of hydrogen and ammonia in the aviation context considered conventional and renewable routes of fuel production138.

The data below138 (see figure 11) indicates that renewable routes offer CO₂ savings over conventional kerosene fuelled aircraft, however as discussed earlier, the LCA results can be skewed by the boundaries and the allocations used.

The recently published UK Low carbon Hydrogen Standard\textsuperscript{139} sets a GHG emissions intensity of 20gCO\textsubscript{2}e/MJ (lower heating value) of produced hydrogen or less for the hydrogen to be considered low carbon.

For hydrogen produced in the UK\textsuperscript{140}, GHG emissions results for hydrogen production pathways range from 10 – 45g CO\textsubscript{2}e/MJ for abated natural gas pathways and 0 – 5 g CO\textsubscript{2}e/MJ for renewable and nuclear electrolysis.

For hydrogen imported to the UK\textsuperscript{140}, emissions vary by carrier (ammonia, liquid organic hydrogen carriers) and distance of shipping. Imports will rely on decarbonisation of ships and use of renewable power along the import chains will have a big role to play in reducing emissions to or below the 20 gCO\textsubscript{2}e/MJLHV threshold.


The GHG emissions in SAF value chains arise largely from the choice of energy source, for example in the liquefaction of hydrogen. The threshold for hydrogen to be regarded as low carbon of 20 gCO₂/MJ of energy can by attained by green hydrogen or green ammonia if sufficient renewable energy is available, or for example if green hydrogen is consumed to provide energy.

For hydrogen pathways, there is often the issue of boil off from liquid hydrogen storage. Since hydrogen is an indirect greenhouse gas, this can contribute to the overall emissions of the pathway. All efforts should be made by design to minimise heat gain from the environment and thus minimise boil off. Some boil off is however inevitable. In stationary storage systems, this can be mitigated by capturing the hydrogen, or combusting it. In on-board fuel tanks, such measures are not likely to be feasible, and some boil off and leakage of hydrogen seems to be inevitable.

Estimates of the expected boil off from aircraft liquid hydrogen tanks were not available in the current literature at the time of evidence gathering for this policy briefing. Using a 100 yr horizon GWP estimate for hydrogen of 11 times the impact of CO₂¹⁴¹, as long as the leakage is less than ~20% of the hydrogen used as fuel, then the low carbon threshold can be met.

3.6 Additional emissions from jet engines

Conventional gas turbine aircraft engines burning fossil fuel-derived kerosene emit:

- CO₂, water vapour, carbon monoxide (CO);
- nitrogen oxides (NOₓ, where NOₓ represents NO+NO₂);
- soot and sulphur-based aerosol particles, sulphur dioxide (SO₂);
- volatile organic compounds.

CO₂ and water vapour are emitted with a fixed emission index (EI) of 3.16 kg and 1.231 kg per kg fuel combusted and SO₂ 1.2g per kg fuel. Soot, NOₓ and CO EIs are variable across engine types and combustion conditions. The overall global fleet EI_NOₓ is calculated to be around 15 g per kg fuel, and the soot EI is far less well characterised at around 0.03 g per kg fuel. Emissions of CO and VOCs are very small and primarily associated with engine idle conditions.

In terms of aircraft emissions that impact climate, these are CO₂, water vapour, NOₓ and soot and sulphate particles. Aviation CO₂ emissions are relatively well-quantified, and the associated radiative (climate) effect well characterised, whereas the non-CO₂ effects from water vapour, NOₓ and aerosols are more uncertain by a factor of 8. Nevertheless, there is high confidence that they are delivering additional warming to the climate system, over and above the effects of aviation CO₂ emissions¹⁴².


The emissions that are fuel composition dependent are primarily those of sulphur and soot, although the latter is also dependent on combustion conditions.

Sulphur compounds are present in conventional aviation fossil fuel at ppm levels, with the regulatory limit being specified by UK Defence Standard 91-091 and in the US by ASTM D1655 at 3000 parts per million by mass (ppm). In practice, levels are found at around 600–800 ppm. The primary emission from the engine exit is sulphur dioxide (SO2). The emitted SO2 is oxidised relatively slowly, so will form at 10 to 100 km scale distances from the aircraft’s emission (at cruise altitudes).

Aircraft engine non-volatile particulate (nvPM) emissions are regulated under different combustion conditions in terms of number and mass by the International Civil Aviation Organization’s Committee on Aviation Environmental Protection’s (ICAO-CAEP) Standards and Recommended Practices.

Soot emissions are important for the formation of contrails and contrail cirrus and potentially for soot aerosol-cloud interactions. Contrails are formed from the emission of water vapour into cold atmospheres forming ice crystal clouds that can persist under conditions of ice-supersaturation. Contrails have both cooling (mostly during the day) and warming effects (at night), although the net balance is warming.

Water vapour condensation occurs on soot particles emitted in the exhaust and other background particles. If background atmospheric conditions are favourable, contrails can persist and spread through wind shear and further uptake of water vapour into extensive cirrus cloud-like coverages.

Many ground-based measurements and more recently, measurements at altitude have shown that bio- and synthetic based kerosene that have reduced aromatic content over conventional fossil fuels, emit fewer soot particles. Nonetheless, the relationship between fuel composition and soot emissions is imperfectly understood, firstly because fuel composition is only regulated in terms of broad physical and chemical properties and secondly, the formation chemistry of soot particles is not well understood.


145 Voigt C et al. 2021 Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment. 2(1), 114. (doi:10.1038/s43247-021-00174-y)
An extensive review of surrogate fuels (fuels containing a simplified number of hydrocarbon components and designed to emulate commercial fuel) has shown that sites are created for incomplete combustion that in turn result in the formation of different hydrocarbons that nucleate and agglomerate to form soot particles\textsuperscript{146, 147, 148}. The aromatic content and particularly the naphthalene content\textsuperscript{149} of jet fuel is widely associated with the production of soot particles.

The composition of aviation jet fuel typically contains a range of different molecules in different proportions from the following chemical families: \textit{n}-alkanes\textsuperscript{150} (straight chain alkanes), iso-alkanes (branched chain alkanes), cyclo-alkanes (or naphthenes, saturated ring), and aromatics (unsaturated rings). Alkenes (or olefins, unsaturated chains) are not normally present. Within the aviation fuel specifications, the aromatic family is the only group to have specifically identified control limits (8% to 25% v/v).

Some model studies have found that as ice crystal sizes increase, contrail optical density is reduced, and lifetime is reduced for an assumed reduction in soot number emission number of 80% from a 50:50 blend of biofuel\textsuperscript{151}. Further modelling has considered details of the spatial patterns of differences, especially between the tropics and extra-tropics, where there are potentially large changes between proximity to threshold formation conditions\textsuperscript{152}.

If the modelling is correct, this would imply that alternative lower-carbon footprint fuels that are lower in inherent aromatic content would reduce soot emissions and consequentially could potentially reduce contrail cirrus effective radiative forcing (ERF, see section 3.7). Moreover, local air quality at airports would be improved by lower soot number emissions, representing a climate / air quality ‘win-win’ situation.

The radiative effect of persistent contrails and aviation induced cirrus clouds can only be determined with climate models and only limited efforts have been made so far, to translate reductions in soot number emissions to global contrail cirrus changes in large-scale models, with different modelling groups producing inconsistent results.


\textsuperscript{147} Frenklach M. 2002 Reaction mechanism of soot formation in flames. Physical Chemistry Chemical Physics. 4, 2028-2037. (https://doi.org/10.1039/B110045A)


\textsuperscript{150} alkanes’ are sometimes referred to as ‘paraffins’, so read ‘iso-paraffins’, ‘cyclo-paraffins’ etc. as equivalencies


Climate forcing terms from global aviation from 1940 to 2018

### KEY
- **Best estimates**
- 5 – 95% confidence

<table>
<thead>
<tr>
<th>Term</th>
<th>ERF (mW m⁻²)</th>
<th>RF (mW m⁻²)</th>
<th>ERF RF²</th>
<th>Confidence levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contrail cirrus in high-humidity regions</strong></td>
<td>57.4 (17, 98)</td>
<td>111.4 (33, 189)</td>
<td>0.42</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Carbon dioxide (CO₂) emissions</strong></td>
<td>34.3 (28, 40)</td>
<td>34.3 (31, 38)</td>
<td>1.0</td>
<td>High</td>
</tr>
<tr>
<td><strong>Nitrogen oxide (NOₓ) emissions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-term ozone increase</td>
<td>49.3 (32, 76)</td>
<td>36.0 (23, 56)</td>
<td>1.37</td>
<td>Medium</td>
</tr>
<tr>
<td>Short-term ozone decrease</td>
<td>-10.6 (-20, -7.4)</td>
<td>-9.0 (-17, -6.3)</td>
<td>1.18</td>
<td>Low</td>
</tr>
<tr>
<td>Methane decrease</td>
<td>-21.2 (-40, -15)</td>
<td>-17.9 (-34, -13)</td>
<td>1.18</td>
<td>Medium</td>
</tr>
<tr>
<td>Stratospheric water vapor decrease</td>
<td>-3.2 (-6.0, -2.2)</td>
<td>-2.7 (-5.0, -1.9)</td>
<td>1.18</td>
<td>Low</td>
</tr>
<tr>
<td>Net for NOₓ emissions</td>
<td>17.5 (0.6, 29)</td>
<td>8.2 (-4.8, 16)</td>
<td>–</td>
<td>Low</td>
</tr>
<tr>
<td>Water vapour emissions in the stratosphere</td>
<td>2.0 (0.8, 3.2)</td>
<td>2.0 (0.8, 3.2)</td>
<td>[1]</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Aerosol-radiation interactions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From soot emissions</td>
<td>0.94 (0.1, 4.0)</td>
<td>0.94 (0.1, 4.0)</td>
<td>[1]</td>
<td>Low</td>
</tr>
<tr>
<td>From sulphur emissions</td>
<td>-7.4 (-19, -2.6)</td>
<td>-7.4 (-19, -2.6)</td>
<td>[1]</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Aerosol-cloud interactions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From sulphur emissions</td>
<td>–</td>
<td>–</td>
<td>No best estimates</td>
<td>No best estimates</td>
</tr>
<tr>
<td>From soot emissions</td>
<td>–</td>
<td>–</td>
<td>No best estimates</td>
<td>No best estimates</td>
</tr>
<tr>
<td>Net aviation (non-CO₂ terms)</td>
<td>66.6 (21, 111)</td>
<td>114.8 (35, 194)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Net aviation (all terms)</td>
<td>100.9 (55, 145)</td>
<td>149.1 (70, 229)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Source: Lee et al (2021)³³
3.7 Climate impact of global aviation emissions

Current aviation effective radiative forcing (ERF) estimates indicate that in 2011 the contribution of air traffic to global warming was roughly 3.5%, i.e., net aviation ERF 0.08 W m\(^{-2}\) out of the net anthropogenic ERF of 2.29 W m\(^{-2}\). This contribution had been growing until the COVID lockdown due to the global aviation emissions accelerating from an annually averaged growth rate of 2.2% over 1970 – 2012 to 5% during 2013 – 2018.

The most recent estimate for the net global aviation ERF (corresponding to 2018) is 100.9 mW m\(^{-2}\) (uncertainty range 55 – 145 mW m\(^{-2}\)), of which 34% (34.3 mW m\(^{-2}\)) are caused by CO\(_2\) emissions and 66% (66.6 mW m\(^{-2}\)) by non-CO\(_2\) effects (see figure 12) for the present day.

Note that in considering the relative proportions of non-CO\(_2\) ERF to total ERF, this is growth-rate dependent. CO\(_2\) ERF is determined by its cumulative emissions whilst non-CO\(_2\) ERFs are from present day-emissions. Therefore, for the UK, with a longer history of flying and less growth than other parts of the world, its aviation ERF would be expected to be dominated by CO\(_2\) and not the non-CO\(_2\) contributions.

The largest of the non-CO\(_2\) effects are caused by aviation-induced cirrus cloud (AIC) (57.4 mW m\(^{-2}\)) and emissions of NO\(_x\) (17.5 mW m\(^{-2}\)) via associated changes in atmospheric concentrations of ozone and methane, with smaller contributions from water vapour emissions and aerosols. However, these non-CO\(_2\) ERFs are associated with low confidence and large uncertainties.

Both CO\(_2\) emissions and non-CO\(_2\) emissions can dramatically change with proposed new aircraft design. The main potential effects of these changes are discussed below.

3.7.1 Aviation-induced cirrus clouds

The nature of contrails from alternative fuels and hydrogen- / ammonia-powered aircraft is likely to be very different to those from kerosene combustion. As discussed in the previous section, jet fuels derived from plants with less aromatic material produce fewer particles and fewer ice crystals in contrails. Hydrogen and ammonia combustion also has the potential to produce even fewer particles. Contrails will also be affected by the temperature and humidity of the exhaust. The engine efficiency also plays a role. Higher exhaust temperatures make contrails less likely, but more water vapour emitted makes them more likely. Changes to flight profiles especially cruise height can also have large effects.

---

A series of numerical simulations were performed\textsuperscript{155} to show that contrails from liquid hydrogen aircraft are similar in structure and appearance to kerosene fuelled aircraft contrails, but different in terms of their microphysical properties. The experiments concluded that liquid hydrogen contrails have smaller optical depths as they consist of fewer but larger ice particles. This in of itself could be expected to reduce the ERF and warming impact of a given contrail.

From preliminary theory, fuel cell-powered aircraft contrail microphysical and optical properties will be similar to those from liquid hydrogen combustion, i.e., optically thinner than contrails from kerosene combustion aircraft\textsuperscript{156}.

Another study\textsuperscript{157} found larger contrail coverage but smaller optical depths associated with liquid hydrogen-powered aircraft contrails compared to kerosene-powered aircraft contrails. In terms of climate impact, these two effects act against each other and together led to only a slightly smaller (i.e., \textasciitilde10\%) linear contrail radiative forcing. However, this estimate is likely to be affected by the specific design and technology used and does not account for soot changes.

Contrail avoidance flight routing might become effective if a local contrail cirrus forcing can be predicted, calculated, and weighed against any CO\textsubscript{2} emission penalty. A major constraint is the reliable prediction of conditions of ice-supersaturation on individual flights. Moreover, the overall global contrail cirrus forcing is not well constrained at present, with large uncertainties remaining.

In summary, the ERF and climate impact from aviation-induced cirrus may be less under alternative fuel, hydrogen fuel and fuel cell-powered aircraft, compared to a like-for-like replacement with kerosene aircraft. However, these findings are largely the results from a single model and the magnitude or even sign of the change is not certain. Further, the engine parameters and soot emitted will have considerable impact on the resulting ERF. With more knowledge, there may be the potential to design-in a smaller non-CO\textsubscript{2} impact.

### 3.7.2 Water vapour and stratospheric flights

Water vapour is a small ERF as most is emitted into the troposphere and quickly rained out (see figure 12). Hydrogen-powered aircraft and fuel cells emit roughly 2.6 times as much water vapour as kerosene-based aircraft. This alone would increase the water vapour ERF by the same factor. However, changes to flying altitude could have an even bigger effect. If water vapour is emitted into the stratosphere, it can have a very large warming effect\textsuperscript{158}, depending on how high in the stratosphere the water vapour is emitted. However, the contrail impact would be reduced from stratospheric flights. Flying in the mid to upper stratosphere might have a strong effect on the ozone layer, primarily from the emissions of NO\textsubscript{x}. The science on these effects is quite outdated but generally lots of flying in the stratosphere is likely to have adverse environmental impacts.


3.7.3 Other non-CO₂ considerations

Oxides of nitrogen (NOₓ) emissions might expect to be reduced with newer engine designs reducing its ERF. However, NOₓ emissions are very dependent on the combustion temperature, so for liquid hydrogen engines that have higher flame temperatures in the combustor, emissions might increase. A separate consideration is that the net ERF from NOₓ is a balance of warming and cooling effects which may be changed in the future, as the aviation effect of NOₓ is strongly coupled to the composition of the background atmosphere. The net effect of contrails is similarly a balance of warming and cooling effects.

The direct sulphur and soot climate effects emissions would reduce with new engine designs and fuel composition changes.¹⁵⁹

One of the largest remaining uncertainties on aviation’s non-CO₂ effects on climate are those from modification of background clouds, from soot and sulphur emissions. The magnitude of these effects and even their sign, is highly uncertain.¹⁵³ Any effects would reduce in magnitude under the alternative fuel scenarios covered in this paper.

Note hydrogen itself, if leaked at ground level as part of an active cryogenic cooling process or otherwise, has a global warming effect by removing OH and increasing the lifetime of methane (a 100 year global warming potential is around 11 ± 5, compared to around 29 for methane).¹⁶⁰ These figures have not been assessed for hydrogen released in flight.

3.7.4 Summary of non-CO₂ effects

In summary, alternative fuels will have continued non-CO₂ effects on climate. However, there is potential hope that the non-CO₂ effects might be considerably smaller than for kerosene fuel. Yet, the findings are very preliminary and largely based on a single model from the DLR in Germany. There is an urgent need for independent modelling experiments, laboratory studies and testing to give confidence in this hope. These results are very dependent on engine and aircraft design and aircraft operation. With more knowledge it might become possible to achieve reduced magnitude non-CO₂ effects both through careful aircraft and engine designs and improved operations.


Aircraft and operational considerations of alternative fuels

4.1 Introduction
It is unclear which technologies will become dominant as the search for low emissions and net zero fueled flight continues. Some solutions might combine technologies: for example in a hybrid battery fuel system. Therefore, consideration will need to be made of multiple technologies and energy handling capabilities, both in airports, and in aircraft. Almost certainly integrating technologies into aircraft will be the most demanding, but airport and energy distribution infrastructure cannot be disregarded.

4.2 Aircraft technologies
Aircraft technologies will have to be able to be certified to standards ratified by the International Civil Aviation Organization (ICAO) standards. At the present time, none of these standards have a mature form suitable for certification of public transport aircraft with radically new energy storage and powertrain systems. The amount of work required to create these standards will be very large and needs to be done in parallel with the creation and testing of actual aircraft and subsystems.

These technologies will include:

4.2.1 Onboard storage
If non-drop-in alternative fluid fuels are to be carried (eg, hydrogen, or ammonia) then these will usually be significantly bulkier for the same energy availability than kerosene or petroleum. As a result, fuel tanks will have to be considerably larger, forcing significant aircraft shape changes. For hydrogen at around ambient temperatures, the tanks will also need to be pressurised (typically to 300 – 700 bar). Cooling systems, bringing the hydrogen to below the critical point of -253°C will allow the hydrogen to be stored at 2 bar or less: a complex trade-off of structural mass and volume, for that of the cooling system. The tendency of hydrogen, including at low temperatures, to cause embrittlement in metals will also be a critical factor in the design of such systems, and will likely also require new engineering science research161. Ammonia can be stored as a liquid at a lower pressure (around 10 bar) or higher temperature (-330°C).

Save for the short-term expediency of SAF, it is likely that all new fuels will force substantially new aeroplanes to be developed and built. Recent estimates have shown the cost of certifying new large airliners to be in the range $20 – 30 billion, and it is likely that the costs of these new aeroplanes, using significant new technology will exceed that by 50 – 100%, as will development costs; these figures and the associated decadal timescales are not necessarily prohibitively expensive for that industry, but are highly likely to be disruptive.

---
If high-capacity batteries are used in any solution eg, fuel cell systems, then they will require installation design within aircraft, consideration of cabling designs, safe mounting, fireproofing and crash resistant housings.

4.2.2 Energy gauging
At present most aircraft use capacitance-based fuel gauging utilising the dielectric constant of the fuel to estimate fuel remaining in a tank. There is limited evidence that biofuel type Aviation Fuel\(^{162}\) may have different dielectric properties to fossil fuel generated jet fuel, potentially invalidating fuel gauge indications. This consideration will become increasingly important as alternative aviation fuels become more widely used, it being clearly intolerable for aircraft captains not to have accurate knowledge of fuel state. Biofuel compatible fuel gauging systems have become available but are not presently widespread\(^{163}\).

4.2.3 Fuel cell ageing
Hydrogen and ammonia technologies are most likely to use fuel cells to convert fuel into electrical energy. These are known to degrade in performance with age\(^ {164} \). Similarly to batteries therefore, new science, and associated robust regulation design may be needed for some aircraft designs to ensure predictable performance throughout aircraft lives.

4.2.4 Aircraft design to accommodate new form powertrains
Whilst bio-based jet fuel and efuels require minimal modification of aircraft design, that is true of no other sustainable fuel solution. Gaseous hydrogen will require significantly larger fuel storage, cryogenic hydrogen would require onboard refrigeration systems. Future generations of aircraft may have significantly different forms to today\(^ {165} \). These form changes will include internal systems, as present fuel system designs — neither aircraft systems for kerosene fuels, nor ground based systems for hydrogen, ammonia or other fuels will automatically adapt to aircraft use. There will also be a substantial need for new understanding of the safety of these systems, with creation of airborne safety standards and best practices — potentially borrowing from mature knowledge developed for spacecraft\(^ {166} \).

---

4.2.5 Changes to aircraft operating practices

Present large aeroplane operating practices assume the availability of fuel at every airport, and the inadvisability of tankering (that is, carrying excess fuel to mission requirements, potentially consuming additional fuel to do so). Limited availability of specialist fuels, combined in some cases by the high energy density of hydrogen, may require and / or permit modification of those practices, and the legal basis behind them.

Operating practices also universally assume a single form of pumpable liquid fuel on board the aeroplane. With hybridisation, this will cease to be the case, and may permit more imaginative approaches – such as heavy but sustainable batteries being used for mission energy (eg, on inter-island routes) whilst less sustainable but lighter energy sources (such as kerosene) could be used to carry the seldom used but mandatory safety reserves. There are many such routes where mission energy requirements will be less than 15 minutes, but safety reserves exceed diversion plus 45 minutes for example include between the Channel Islands (see figure 13).

FIGURE 13

Jersey (EGJJ) – Guernsey (EGJB) air route

24 nautical miles with likely safety diversion to Lessay (LFOM), to which 30 – 45 minutes additional reserves must be added.

Source: Flightpaths generated using the Great Circle Mapper (www.gcmap.com).
4.2.6 Alternative fuel consumption

The use of straight-replacement low carbon jet fuel variants changes little concerning fuel consumption behaviours.

Considerable technology development will be needed to bring fuel cell systems from present levels (~TRL5 – 6) to that required for aircraft use.

4.3 Ground support infrastructure

Whilst the primary focus should rightly be upon air vehicles, the ground infrastructure requirements cannot be ignored. The specific requirements will depend very much upon what technologies are adopted by aircraft operating through particular sites, but may include:

4.3.1 New fuel energy storage

At present there are essentially only two fuels in use at most airports: Jet-A1 (also called AVTUR) which is a kerosene-based fuel used in jet, turboprop, and turboshaft aircraft. The second is AVGAS, which is a form of high octane petroleum used in the piston engines of smaller aircraft. The storage and management of these fuels is well understood.

The introduction of alternative jet fuels, bio-fuels and eFuels adds complexity to infrastructure but essentially remains in known territory.

As new fuels are introduced, such as hydrogen and ammonia, there will need to be developed means to get those to airports, store, monitor the quality, and transfer to aircraft these fluids.

4.3.2 Ammonia and hydrogen safety aspects

The transport and use of hydrogen and ammonia pose different challenges that would need to be overcome for them to be used widely in aviation.

**Ammonia**

Ammonia is a common, naturally occurring gas widely used as a fertiliser, a refrigerant and as a cleaning agent. It is normally stored as a liquid under pressure (around 10 bar) or at a temperature below -33°C. It is classed as a toxic gas and a corrosive substance that causes irritation167 and it represents a chronic hazard to terrestrial ecosystems as well as providing an increasing burden to air pollution. It is flammable over a narrow concentration range. Road, rail and shipping tankers are used to transport ammonia, but pipelines can be used to transport liquid ammonia reducing the risks of spillages. Ammonia can be stored in bulk onsite in refrigerated tanks.

---

Hydrogen

Hydrogen is a lighter than air, highly reactive, flammable gas. It is widely used in the petrochemical industries, notably in the production of ammonia and methanol and is stored under high pressure (350 to 700 atmospheres) or as a liquid at temperatures below -253°C. Liquid hydrogen poses additional risks related to its very low temperature and careful material selection is required. Hydrogen is transported as either a cryogenic liquid in tankers, a compressed gas in cylinders or liquid or gas in pipelines. It is stored in bulk in cryogenic tanks or in cylinders168. It is a very difficult gas to contain due to its low viscosity and its high flammability range poses an explosion risk if leaks occur in confined spaces169. Should any liquid hydrogen leakages occur, any pipes, tanks or valves utilised in transport and storage that are not well insulated will be frozen causing significant health and safety risks for staff and crew involved in the supply and distribution chain170.

4.3.3 Fire and rescue

At present little is known of what the requirements will be for fire and rescue training and equipment as aircraft operating using either batteries or alternative fuels are introduced to service. In recent decades the significant increase in use of composite materials requires significant Rescue and Firefighting services (RFFS) upskilling and equipment changes, and sustainable fuels are unlikely to be less significant in that regard.

This will need to be aligned with safety and crashworthiness criteria in aircraft safety standards. The potential for accidents off-airport must also be considered.

4.3.4 Airport / apron architecture

Airports (see figure 14) are designed around a legacy form of airliners that have been with us since the 1950s. Those airliners were all in large part designed around the use of kerosene or petroleum fuels, leading to the classical ‘metal tube + wing’ form with which we are all familiar. It is likely that some future aeroplane designs, particularly those using hydrogen, will be significantly different. In order to accommodate that, practices for the design of large parts of airports will need to be changed, and in many cases implemented retrospectively.

---

4.4 Skills and qualifications

It cannot be overstated that aviation relies upon trained and qualified individuals in key roles who often undergo refresher training. In most cases, those people are licenced to carry out their particular jobs, and that is aligned to syllabi which have matured over many years. Alternative low carbon jet fuel technologies cannot be introduced effectively without creating new syllabi, built upon valid and tested science, for these professions. This training need is likely to include:

- Pilots
- Cabin crew
- Aircraft maintenance staff
- Refuellers
- Firefighters
- Quality assurance professionals
- Dispatchers
- Regulators

It will be essential that the science and engineering communities provide high quality timely advice to support the construction of syllabi and testing regimes, and licencing of these and other individuals in the air transport system.

4.5 The potential for innovation waves in technology development

It is unlikely that over the period from now to 2050, a single technology step will achieve society’s requirements for sustainable air transport. It is more likely that many technical changes will be made over several years. These changes to aircraft technology, and to ground infrastructure support requirements are feasible, and may permit a net zero air transport infrastructure by 2050. They are nonetheless a highly demanding trajectory requiring investment in research, infrastructure, and industry capability on a global scale, with multiple iterations. The disruption this will cause provides many opportunities that should also be explored.
Summary of R&D challenges

5.1 Global alternative aviation fuel projects
There are several pilot and demonstration scale projects running globally, but to date there are no full scale advanced SAF units in operation\(^1\).

Figure 15 below summarises the potential for low carbon jet fuel production (as of 2019) from plants that were operating or in the planning stages at the time. As of summer 2022, none of these advanced routes has been operated at commercial scale.

5.1.1 Projects demonstrated on small scale
In July 2021\(^2\), the UK Department for Transport (DfT) stimulated the development of eight Sustainable Aviation Fuels projects though the Green Fuels, Green Skies competition as part of a drive to develop a SAF industry in the UK. These projects are currently in the ‘Front End Engineering Design (FEED)’, ‘Pre-FEED’ and ‘Feasibility Study’ stages of a project’s development life cycle\(^3\). The FEED studies will be followed by £168m in competitive capital support for UK sustainable aviation fuel (SAF) demonstration projects.

5.2 R&D Challenges
Table 8 seeks to summarise findings from previous sections, and further outline major challenges, research and development required (for selected feedstocks / pathways) to enable the timely roll out and deployment of the different alternative fuel types.

---

\(^{1}\) ICAO (ICAO SAF facilities map). See https://datastudio.google.com/u/0/reporting/2532150c-f4c-4659-9cf3-9e1ea457b8a3/page/p_2sz3q015nc?si=mGz_sTvIl-c (accessed 5 September 2022).


SAF potential production capacity (excluding oil-based routes) as of June 2019

Operational capacity refers to potential jet fuel production volumes. Pyrolysis oil and farnesene produced in the pyrolysis and DSHC plants are not currently being upgraded to jet fuel.

Source: Johnson Matthey Plc.

KEY
- Operational
- In commissioning
- Under construction
- Planned
A selection of small-scale projects and those under development in the UK

**Translational Energy Research Centre**
Funded by BEIS + EU pilot-scale facilities to produce 60 litres / day (40 litres / day SAF) using DAC + Green Hydrogen, RWGSR + FT (hybrid catalyst).

**Advanced Biofuel Solutions Ltd (ABSL)**
British refinery and British engineering company are producing a detailed engineering design for a new facility in Cheshire. The plant will use gasification and FT technology to convert 133,000 tonnes of waste a year into a biocrude that can be upgraded to aviation fuel.

**Alfanar’s lighthouse green fuels (LGF)**
The project in Tees Valley, uses gasification and FT technology to convert household and commercial waste into around 180 million litres of SAF and naphtha.

**The Fulcrum North-Point project**
Developed at the Stanlow Manufacturing Complex in Ellesmere Port, will use proven technology and processes based on the company’s first commercial-scale facility currently being commissioned in the US. Once fully operational, NorthPoint will convert residual waste into around 100 million litres of SAF using gasification and FT technology. Funding will support the FEED stage of project work.

**The firefly project**
A joint endeavour between Green Fuels, Petrofac and Cranfield University that aims to demonstrate and certify a technology route to SAF from sewage sludge, a fully biogenic, UK-derived waste feedstock. Funding will support the project’s pre- FEED development stage.

**Proposed Lanzatech facility**
Located in Port Talbot, South Wales will produce over 100 million litres a year of SAF, using ethanol from biogenic wastes and industry flue gases.

**Lanzatech UK Ltd and Carbon Engineering**
Proposes the integration of innovative technologies to produce over 100 million litres per year of SAF. Carbon dioxide (CO₂) captured from the atmosphere using DAC technology, and hydrogen from water electrolysis, will be converted into SAF using LanzaTech’s gas fermentation and LanzaJetTM’s alcohol-to-jet.

**Rolls Royce**
In November 2022, Rolls-Royce successfully tested a hydrogen-powered jet engine (see figure 16). Green hydrogen used to run the test was produced from electricity generated by wind and tidal power.

FIGURE 16

Rolls-Royce AE 2100-A hydrogen test at Boscombe Down

Source: Rolls-Royce.
Life Cycle Impacts R&D Challenges and Future work

HTL of sewage sludge provides 58% GHG savings when compared to conventional Jet fuel.

### TABLE 8

Summary table highlighting resource implications, associated costs, technology readiness levels, life cycle assessments as well as additional work needed in order for large scale industrial application of each pathway.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Feedstock / pathway</th>
<th>Resource Implications</th>
<th>Cost and Technology readiness level (TRL)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biofuels</strong></td>
<td><strong>Rapeseed</strong> <em>(Brassica napus)</em></td>
<td>42.4 million tonnes of biomass would be required to meet UK Jet fuel demand. 68% equivalent fraction of UK agricultural land is required to produce this amount of biomass.</td>
<td>HEFA-SPK, TRL 7-8</td>
</tr>
<tr>
<td></td>
<td><strong>Miscanthus</strong></td>
<td>Alcohol-jet pathway with ethanol as an intermediate</td>
<td>ATJ-SPK, TRL 5-6</td>
</tr>
<tr>
<td></td>
<td><strong>Wood (poplar)</strong></td>
<td>Gas to jet pathway using Fischer Tropsch</td>
<td>FT-SPK, TRL 5-6</td>
</tr>
<tr>
<td></td>
<td><strong>Sugarcane and sugary biomass</strong></td>
<td>Currently fermented and hydro processed to produce synthetic iso-paraffinic kerosene <em>(HFS-SIP)</em></td>
<td>FT-SPK/A, TRL 5-6</td>
</tr>
<tr>
<td></td>
<td><strong>Waste cooking oil</strong></td>
<td>About 250 million litres of used cooking oil is produced in the UK each year.</td>
<td>HEFA-SPK, TRL 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Using a conservative estimate of about 50% conversion efficiency, this would produce 50 to 100 million litres of jet fuel which is 0.3 to 0.6% of the total jet fuel used every year in the UK.</td>
<td>Co-processing, TRL 8-9</td>
</tr>
<tr>
<td></td>
<td><strong>Municipal waste</strong></td>
<td>Total renewable content is estimated to be 40 Mt/year. Ricardo (2017) estimate that 12 Mt/year could be used for bioenergy production.</td>
<td>FT-SPK/A, TRL 5 -6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assuming a yield of conversion of 0.1, this could produce 1.2 Mt/year of fuel which is 10% of the total jet fuel UK demand.</td>
<td>Energy cost</td>
</tr>
<tr>
<td></td>
<td><strong>Sewage</strong></td>
<td>Feedstock is plentiful and has few competing uses.</td>
<td>Not available</td>
</tr>
</tbody>
</table>

**energy cost**
- £42.1/GJ of fuel
- £22.6 – 33.1/ GJ of fuel
- £13.7 – 20.7/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £13.7 – 20.7/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
- £17.5/GJ of fuel
- £40.3 – 59.4/GJ of fuel
- £22.8 – 48.3/GJ of fuel
### Life Cycle Impacts

| **Oil crops** show a wide range of emissions based on allocation methods (-12—55 g CO₂eq/MJ). |
| **The processes** needed to convert grass to biofuel requires a significant energy input and that leads to GHG emissions. |
| **FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.** |
| **Alcohol-to-jet fuel production using corn, corn stover and sugarcane give GHG emissions of 55—78 g CO₂eq/MJ. Sugarcane through Direct Sugar to Hydrocarbon (DSHC) pathways show a high GHG emission regardless of allocation method (72—75 g CO₂eq/MJ).** |
| **There is concern that some of the imported cooking oil is not waste but virgin oil. Importation needs to be properly controlled and regulated as the growing market of this resource could encourage suppliers to clear more land and / or cut food production in order to expand oil production.** |
| **Significantly large GHG emissions (32.9—62.3 g CO₂eq/MJ WTW) are associated with the use municipal solid waste.** |
| **HTL of sewage sludge provides 58% GHG savings when compared to conventional Jet fuel.** |

### R&D Challenges and Future work

| **Resource implications** Availability of sustainable feedstock |
| **HEFA–SPK** Hydrogen consumption through this route is high leading to a higher cost fuel (three to five times) than fossil fuel. |
| **ATJ-SPK** Low energy yields which negatively affecting the overall yield of the conversion from biomass to jet fuel combined with high capital costs makes alternative fuel production via this route relatively expensive. |
| **Resource implications** Availability of sustainable feedstock |
| **FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.** |
| **Resource implications** Availability of sustainable feedstock |
| **HEFA–SPK and CHJ** Hydrogen consumption through this route is high. |
| **Resource implications** Availability of sustainable feedstock. Resource if available is cheaper per tonne than other feedstocks within the HEFA pathway. |
| **HEFA–SPK and CHJ** Hydrogen consumption through this route is high. |
| **Difficulties over site proximity, feedstock abundance and competition may inhibit this large-scale production.** |
| **High impact on fuel production yields due to heterogenous nature. Local authorities could be unwilling to invest in further conversion technology when their landfill diversion targets are met.** |
| **Production plants require significant investment and assurance that supply demands will be consistently met. Production processes are currently limited to laboratory settings and would require further process optimisation and development before they come to market.** |
TABLE 8 (continued)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Feedstock / pathway</th>
<th>Resource Implications</th>
<th>Cost and Technology readiness level (TRL)</th>
</tr>
</thead>
</table>
| Biofuels (continued)             | Forest residues                       | Estimates of feedstock (such as Small roundwood (SRW) and forest residues) availability for jet fuel production range from 0.8 – 2 Mt/year. Assuming feedstock availability of 2 Mt/year and 0.1 yield conversion, 0.2 Mt/year of fuel could be produced, 17% of the total amount of fuel required. Sawmill residues (Clean wood residues derived from timber processing, such as chips, slabs, sawdust and bark) are also considered as a potential resource. 1.4 Mt/year of sawmill residues is estimated to be produced which would yield approximately ~1.2% of the total jet fuel required. | FT-SPK, TRL 5-6  
FT-SPK/A, TRL 5-6  
ATJ-SPK, TRL 5-6  
Energy cost  
Varying costs of energy depending on pathway chosen.  
FT Forest residues – £40.3 – 59.4/GJ  
Pyrolysis Forest residues – £29.2 – 41.5/GJ  
HTL – Forest residues – £20.2 – 29.1/GJ  
ATJ Fermentation Forest residues – £53.8 – 78.5/GJ |
| Hydrogen                         | Electrolysis of water with renewable power (green Hydrogen). | Electricity required to replace the UK’s 2019 aviation fuel consumption would be between 207 – 290 TWh (at 70% and 50% efficiency respectively).                                                                                   | Energy cost  
Green Hydrogen £34.4 – £41.3/GJ  
Flight costs  
Short haul: Operational costs will increase by £4 – £8 per passenger adding 10% to passenger costs  
Medium-range aircraft: Requires significantly extended fuselages for liquid hydrogen storage and would consume 25% more energy than conventional aircraft adding 30 – 40% to passenger costs  
Long-range aircraft: Larger tanks would increase airframe length and energy demand adding 40 – 50% passenger costs. |
Hydrogen electrolysis of water (continued)

Biofuels

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Feedstock / pathway</th>
<th>Resource Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofuels</td>
<td>ATJ Fermentation Forest residues  – £20.2 – 29.1/GJ</td>
<td>Non-Co2 impacts – 5 gCO₂e/MJ for renewable and nuclear electrolysis.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>HTL – Forest residues  – 59.4/GJ</td>
<td>For UK produced hydrogen, GHG emissions pathways range from 10 – 45gCO₂e/MJ for abated natural gas pathways and 0 – 5 gCO₂e/MJ for renewable and nuclear electrolysis.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>Non-CO₂ impacts – The Effective Radiative Forcing ERF and climate impact from aviation-induced cirrus may be less compared to a like-for like replacement with kerosene aircraft.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>Liquid hydrogen contrails have smaller optical depths as they consist of fewer but larger ice particles. This could be expected to reduce the ERF and warming impact of a given contrail.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>Water vapour is a small ERF as most is emitted into the troposphere and quickly rained out. Hydrogen-powered aircraft and fuels cells emit roughly 2.6 times as much water vapour as kerosene-based aircraft. This alone would increase the water vapour ERF by the same factor.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>If water vapour is emitted into the stratosphere, it can have a very large warming effect (depending on how high in the stratosphere the water vapour is emitted).</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>Contrail impact would be reduced from stratospheric flights.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>Flying in the mid to upper stratosphere might have a strong effect on the ozone layer, primarily from the emissions of NOx.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>A lot of flying in the stratosphere is likely to have adverse environmental impacts.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>NOx emissions are very dependent on the combustion temperature, so for Liquid Hydrogen engines that had higher flame temperatures in the combustor, emissions might increase.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>Renewable energy requirements – The use of green hydrogen for aviation to replace current fossil jet fuels requires ~2.4 to 3.4 times the total current renewable electricity in the UK.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>This alternative aviation route requires increases in wind and solar power generation and would result in significant cost increase to the consumer.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>Storage and distribution requirements – Infrastructure changes will be required to safely store, liquefy, transport, and use Hydrogen at the airport and in the aircraft.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>Cryogenic storage in tanks onsite or close to the airport is an energetically expensive process.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>Staff will need to be trained on safety standards.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>Climate impacts – Findings on ERF and climate impact from aviation induced cirrus are largely based on a single model and are very dependent on engine and aircraft design and aircraft operation.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>There is an urgent need for independent modelling experiments, laboratory studies and testing.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO₂eq/MJ) depending on allocation method.</td>
<td>Design considerations – Nitrogen Oxides emissions might expect to be reduced with newer engines reducing its ERF.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Pyrolysis of forest residues vary from in-situ (22 g CO₂eq/MJ) and ex-situ (40 g CO₂eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO₂eq/MJ.</td>
<td>Direct sulphur and soot climate effects would reduce as their emissions would reduce with new engine designs.</td>
</tr>
<tr>
<td>Biofuels</td>
<td>Using fermentation, slightly improved GHG emissions (19.4g CO₂eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.</td>
<td>Future work – Comprehensive life cycle analyses of hydrogen in the aviation context are needed to ensure that the entire pipeline is designed to deliver significant savings over conventional jet fuel.</td>
</tr>
</tbody>
</table>
## Chapter Five

### Fuel type Feedstock / pathway Resource Implications Cost and technology readiness level (TRL)

**Ammonia (NH₃)**  
**Green Hydrogen**  
217 – 332 TWh of electricity is required for ammonia production to replace the 2019 UK’s fossil jet fuel consumption.  
**Energy cost**  
32 – 62.2 £/GJ  
Production of green ammonia via electrolysis is operating at TRLs 5 – 9.  

**Renewable routes of ammonia fuel production offer CO₂ savings over conventionally fuelled routes, depending upon the source of renewable power.**  
**Renewable energy requirements**  
NH₃ as jet fuel requires a major increase (2.5 – 3.9) times in 2020 sustainable electricity production.  
**storage and distribution requirements**  
Infrastructure changes will be required to mitigate the hazards presented by ammonia to enable the safe storage, transport, and use at the airport and in the aircraft.  
**Future work**  
Comprehensive life cycle analyses of ammonia in the aviation context are needed to ensure that the entire pipeline is designed to deliver significant savings over conventional jet fuel.  
Ammonia is important in aerosol formation and the climate impacts from its use should be investigated in a practical aviation setting.

**Efuels**  
**CO₂ from direct air capture and concentrated sources**  
More energy intensive than Hydrogen and Ammonia.  
468 – 660 TWh of energy is required to produce the 12 Mt of fuel required to replace current UK Jet fuel.  
**Energy cost**  
94.5 £/GJ – Using CO₂ from direct air capture  
72.7 £/GJ – Using CO₂ from a concentrated source  

### Table 8 (continued)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Feedstock / pathway</th>
<th>Resource Implications</th>
<th>Cost and Technology readiness level (TRL)</th>
</tr>
</thead>
</table>
| Ammonia (NH₃) | Green Hydrogen | 217 – 332 TWh of electricity is required for ammonia production to replace the 2019 UK’s fossil jet fuel consumption. | Energy cost  
32 – 62.2 £/GJ  
Production of green ammonia via electrolysis is operating at TRLs 5 – 9. |
| Efuels | CO₂ from direct air capture and concentrated sources | More energy intensive than Hydrogen and Ammonia.  
468 – 660 TWh of energy is required to produce the 12 Mt of fuel required to replace current UK Jet fuel. | Energy cost  
94.5 £/GJ – Using CO₂ from direct air capture  
72.7 £/GJ – Using CO₂ from a concentrated source |
### Renewable routes of ammonia fuel production offer CO₂ savings over conventionally fuelled routes, depending upon the source of renewable power.

<table>
<thead>
<tr>
<th>Life Cycle Impacts</th>
<th>R&amp;D Challenges and Future work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable energy requirements</strong></td>
<td>NH₃ as jet fuel requires a major increase (2.5 – 3.9) times in 2020 sustainable electricity production.</td>
</tr>
<tr>
<td><strong>Storage and distribution requirements</strong></td>
<td>Infrastructure changes will be required to mitigate the hazards presented by ammonia to enable the safe storage, transport, and use at the airport and in the aircraft. Staff will need to be trained on safety standards.</td>
</tr>
<tr>
<td><strong>Future work</strong></td>
<td>Comprehensive life cycle analyses of ammonia in the aviation context are needed to ensure that the entire pipeline is designed to deliver significant savings over conventional jet fuel. Ammonia is important in aerosol formation and the climate impacts from its use should be investigated in a practical aviation setting.</td>
</tr>
</tbody>
</table>

### GHG emissions can be close to carbon neutral, but this depends on the source of CO₂ used and the GHG emissions intensity of the electricity used.

| Renewable energy requirements | When done sustainably requires 5 – 8 times the UK’s 2020 renewable electricity capacity. PtL fuels will be significantly more expensive than fossil fuels due to higher electricity costs and high capital costs. |
| Storage and distribution requirements | Alternative fuel is potentially compatible with existing storage, transport and fuelling infrastructure. |
Conclusion

All alternative fuel options have unique opportunities and limitations as illustrated in figure 17. It is evident that there is no single simple answer to decarbonising aviation and the solution is likely to be a portfolio. In the longer term, more disruptive solutions may be advocated but this will depend on the availability of new engines and airframes. Despite best endeavours at developing and rolling out alternative fuels, a scenario may arise where the reliance is predominantly on hydrocarbon fuels if the alternatives can’t be manufactured and safely deployed at the scale needed.

6.1 Feedstock availability
Feedstock availability and accessibility is an international challenge and not unique to the UK. Industry should exercise caution when choosing one solution over another as alternative fuel solutions will need to be accepted globally. The pathways to decarbonisation are different in different parts of the world and there is a need to encourage the best solution for each region / place rather than a one solution fits all, noting that long distance travel will require compatible solutions at each end.

Bio-based routes exhibit significant resourcing implications particularly energy crops which would require at least half of all UK agricultural land for their cultivation to supply the whole amount of jet fuel used in the UK. This would incur significant trade-offs with food production, increasing the risk of carbon leakage as domestic agricultural produce is substituted with imports, as well as having potentially negative environmental consequences through soil erosion and pollution. There is also much debate around what feedstocks constitute waste as well as the effects of competition from other industries. For example, forestry, agricultural and sawmill residues use in aviation fuel production may lead to unwanted ecological problems such as soil nutrient depletion leading to increased use of fertilisers and thus increasing greenhouse gas emissions.

It is important to consider that waste is different in different regions, and its availability varies across regions and countries. Increased recycling will lead to less waste and availability of waste will thus be more restricted in the future. Standardisation of very many different waste to fuel pathways may pose a significant challenge in the future and Fuel Standards will need to be debated and negotiated.

The energy source for hydrogen, ammonia and efuels must be renewable electricity if the final product is to be considered net zero CO₂. Accessing the required amount of electricity will be a challenge, particularly as other energy uses will also require large amounts of renewable electricity. The production of ammonia and efuels require more energy than hydrogen however this is partly offset by reductions in the energy needed to store these fuels.
The relative opportunities and challenges associated with the different aviation fuel options

Note that all points are subjective and axis scales indicate the changes to existing infrastructure needed to implement the fuel, availability, and emissions improvements relative to an ideal solution (from the fossil triangle to a ‘perfect’ fuel).

KEY
- Jet A
- Efuel
- Ammonia
- Biofuel
- Hydrogen
- Perfect fuel

Non-CO₂ climate impacts

CO₂ emissions

Change to existing technology

Feedstock availability

NO CONSTRANTS

ZERO IMPACT

HIGH IMPACT

LIMITED

ALL CHANGE

NO CHANGE
6.2 Life cycle analysis
The life cycle analyses discussed illustrate that different fuels have different greenhouse gas savings when compared to conventional jet fuel. However, GHG savings alone is not the only criteria to guide investments with feedstock cost, availability, and accessibility key factors. As an example, Hydrothermal liquefaction (HTL) of forest residues shows low GHG emissions of 17–20.5 gCO$_2$eq/MJ and a low cost of energy of £20.2/GJ but can only yield less than 2% of the UK’s annual Jet fuel needs (if all UK forest residues were entirely used for just this purpose).

Life cycle analyses of hydrogen, ammonia and efuels systems are scarce and those that are publicly available have often been criticised for selective bias and lack of rigour. More work is needed to investigate the LCAs associated with these systems to ensure that production of these fuels delivers better GHG savings when compared to conventional Jet fuel.

The further development of LCA tools for alternative aviation fuels is critical to clarifying the emissions across the entire cycle to guide investment and highlight key mitigation opportunities. As discussed in Chapter 3, there is a need to fund research that explores the climate impacts of aviation in a practical setting, with data on overall impacts of hydrogen and ammonia in aviation lacking, and the uncertainties around non-$CO_2$ impacts from all alternative fuels very large. The UK could play a major role on becoming a world leader in this field.

6.3 Cost implications
It is unlikely that all aircraft flying today could be removed from service in the short term and the cost of developing and certifying new aircraft types is very high. A holistic approach with regards to alternative fuel and engine and airframe development will be needed. A considerable amount of renewable electricity will be required to produce hydrogen (207 – 290 TWh), ammonia (217 – 332 TWh), or efuels (468 – 660 TWh) in the quantities required to replace current Jet fuel used in the UK and cryogenic storage of hydrogen at airports is an energetically expensive process. This leads to the cost of energy of these alternative fuels being much higher (£34.4 – £41.3/GJ – hydrogen, £32 – £62.2/GJ – ammonia and £72.7 – 94.5£/GJ – efuels) than that of conventional jet fuel (£11 – £27/GJ).

The price of many alternative low-carbon fuels varies depending on the feedstock available. For example, the cost of fuel from used cooking oil ranges between £595 to £900 per tonne which is less than half the cost of fuel from Jatropha oil at £1950 per tonne. It is also worth noting that majority of airlines bunker at the cheapest price and this will fuel global competition for the alternative fuels.

6.4 Safety concerns
Green ammonia and green hydrogen hold promise as potential fuels but have significant safety concerns that would need to be addressed. Whilst both are widely used in industry, existing standards on handling of these fuels would need to be updated to suit the civil aviation context.

6.5 Operational considerations
Considerations will have to be made on handling multiple technologies both in the airport and aircraft. Staff and crew will be need specialised training on handling alternative fuels, and the public will need to be informed about the relevant safety concerns within the airport and aircraft.
Appendix A: Glossary of terms

Biofuels
A liquid or gaseous fuel used in transport that are produced wholly from biomass. Biofuels for jet aircraft are known in the industry as ‘biojet’ fuels.

Biogenic carbon
Carbon that is sequestered from the atmosphere during biomass growth and may be released back to the atmosphere later due to combustion of the biomass or decomposition.

Biomass
Any organic material that has stored sunlight in the form of chemical energy, such as plants, agricultural crops or residues, municipal wastes, and algae.

Blue hydrogen
Blue hydrogen is made from a fossil fuel, typically, natural gas, with carbon capture and storage technology applied to the manufacturing processes.

Blue or green ammonia
Ammonia produced from blue or green hydrogen.

Carbon capture and use (CCU)
CCU is defined by the IPCC as a process in which "CO₂ is captured and then used as a chemical feedstock reagent to produce a new product".

Effective radiative forcing (ERF)
The change in the earth-atmosphere energy since pre-industrialisation. ERF is used to quantify present-day impacts from current and (largely) historical emissions (in the case of long-lived greenhouse gases) as it has an approximately linear relationship with the equilibrium global mean surface temperature change since the onset of industrialisation.

Electro fuels (efuels)
Synthetic fuels manufactured using captured carbon dioxide or carbon monoxide together with low-carbon hydrogen. They are termed electro- or efuels because the hydrogen is obtained from sustainable electricity sources eg wind, solar and nuclear power.

Feedstock
Raw material used to produce transport fuels.

Gasification
Reacting organic material with a controlled amount of oxygen at temperatures greater than 700°C without combustion. This produces ‘synthesis gas’, which is primarily a mixture of hydrogen and carbon monoxide with some carbon dioxide.

Green hydrogen
Produced by electrolysis of water in a process driven by sustainable energy.

Hydro processed Esters and Fatty Acids (HEFA) / Hydrotreated Vegetable Oil (HVO)
Hydro-processed esters and lipids from plant and animal sources.

Life cycle assessment (LCA)
An established approach to evaluating and comparing environmental impact over the life cycle of a product or process.

Power to liquid fuels (PtL)
Synthetically produced liquid hydrocarbon. It is produced using sustainable energy, and sources of hydrogen and carbon through synthesis.

Pyrolysis
The thermal decomposition of biomass occurring in the absence of oxygen. The process produces hydrogen, methane, carbon dioxide and carbon monoxide gases, condensable vapours (tars and oils) and solid charcoal, depending upon the temperature.
**Sustainable aviation fuels**
A broad term referring to low carbon alternatives to fossil-derived aviation fuel, which can be blended into conventional jet fuel without requiring significant aircraft or engine modifications. Can be from biological (biofuels) or inorganic origin (efuels).

**Synthetic fuels**
Carbon based liquid fuels manufactured, via chemical conversion processes, from a carbon source such as coal, carbon dioxide, natural gas, biogas or biomass.

**Synthetic biofuels**
Fuels synthesised from biomass or waste or biofuels using chemical or thermal processes.
## Appendix B: Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSL</td>
<td>Advanced biofuel solutions</td>
</tr>
<tr>
<td>AIC</td>
<td>Aviation-induced cloudiness</td>
</tr>
<tr>
<td>ASTM</td>
<td>American society for testing and materials</td>
</tr>
<tr>
<td>ATI</td>
<td>Aerospace technology institute</td>
</tr>
<tr>
<td>ATJ-SPK</td>
<td>Alcohol to jet- synthetic paraffinic kerosene</td>
</tr>
<tr>
<td>AVGAS</td>
<td>Aviation gasoline</td>
</tr>
<tr>
<td>AVTUR</td>
<td>Aviation turbine fuel or Jet-A1</td>
</tr>
<tr>
<td>BEIS</td>
<td>Department for Business, Energy and Industrial Strategy</td>
</tr>
<tr>
<td>CCU</td>
<td>Carbon capture and use</td>
</tr>
<tr>
<td>CHJ</td>
<td>Catalytic hydrothermolysis jet</td>
</tr>
<tr>
<td>CORSIA</td>
<td>Carbon offsetting and reduction scheme for international aviation</td>
</tr>
<tr>
<td>DAC</td>
<td>Direct air capture</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department for Environment, Food and Rural Affairs</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt (German aerospace center)</td>
</tr>
<tr>
<td>DLS</td>
<td>Deck launch speed</td>
</tr>
<tr>
<td>DSHC</td>
<td>Direct sugars to hydrocarbons</td>
</tr>
<tr>
<td>EASAC</td>
<td>European Academies’ Science Advisory Council</td>
</tr>
<tr>
<td>ERF</td>
<td>Effective radiative forcing</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FCC</td>
<td>Fluid catalytic cracker</td>
</tr>
<tr>
<td>FEED</td>
<td>Front end engineering design</td>
</tr>
<tr>
<td>FOG</td>
<td>Fats, oils and grease</td>
</tr>
<tr>
<td>FT-SPK</td>
<td>Fischer Tropsch Synthetic Paraffinic Kerosene</td>
</tr>
<tr>
<td>FT-SPK / A</td>
<td>Fischer Tropsch Synthetic Paraffinic Kerosene with aromatics</td>
</tr>
<tr>
<td>GGR</td>
<td>Greenhouse gas removal</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global warming potential</td>
</tr>
<tr>
<td>HC-HEFA-SPK</td>
<td>Hydrocarbon-hydroprocessed esters and fatty acids synthetic paraffinic kerosene</td>
</tr>
<tr>
<td>HEFA-SPK</td>
<td>Hydroprocessed esters and fatty acids synthetic paraffinic kerosene</td>
</tr>
<tr>
<td>HFS-SIP</td>
<td>Hydroprocessed fermented sugars- synthesised iso-paraffins</td>
</tr>
<tr>
<td>HRJ</td>
<td>Hydrotreated renewable jet</td>
</tr>
<tr>
<td>HRJF</td>
<td>Hydro-processed renewable jet fuel</td>
</tr>
<tr>
<td>HTL</td>
<td>Hydrothermal liquefaction</td>
</tr>
<tr>
<td>HVO</td>
<td>Hydrogenated vegetable oil</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>ICAO-CAEP</td>
<td>International Civil Aviation Organization’s Committee on Aviation Environmental Protection</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel for Climate Change</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle analysis</td>
</tr>
<tr>
<td>LGF</td>
<td>Lighthouse green fuels</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
</tr>
<tr>
<td>LUC</td>
<td>Land use change</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
</tr>
<tr>
<td>MTO</td>
<td>Methanol to olefins</td>
</tr>
<tr>
<td>NCAR</td>
<td>National Center for Atmospheric Research</td>
</tr>
<tr>
<td>NDC</td>
<td>Nationally determined contribution</td>
</tr>
<tr>
<td>PJ</td>
<td>Power to jet</td>
</tr>
<tr>
<td>PL</td>
<td>Power to liquid</td>
</tr>
<tr>
<td>RCFs</td>
<td>Recycled carbon fuels</td>
</tr>
<tr>
<td>RF</td>
<td>Radiative forcing</td>
</tr>
<tr>
<td>RFFS</td>
<td>Rescue and firefighting services</td>
</tr>
<tr>
<td>RFNBOs</td>
<td>Renewable fuels for non-biological origin</td>
</tr>
<tr>
<td>RTFO</td>
<td>Renewable transport fuel obligation</td>
</tr>
<tr>
<td>RWGS</td>
<td>Reverse water gas shift</td>
</tr>
<tr>
<td>RWGSR</td>
<td>Reverse water gas shift reaction</td>
</tr>
<tr>
<td>SAF</td>
<td>Sustainable aviation fuel</td>
</tr>
<tr>
<td>SMR</td>
<td>Small modular reactors</td>
</tr>
<tr>
<td>SPK</td>
<td>Synthetic paraffinic kerosene</td>
</tr>
<tr>
<td>SRW</td>
<td>Small roundwood</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology readiness level</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>VTOL</td>
<td>Vertical take-off and landing</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-wake</td>
</tr>
</tbody>
</table>
Appendix C: Acknowledgments

Working Group members
The members of the Working Group involved in producing this report are listed below. The Working Group members acted in an individual and not organisational capacity. No conflict of interest was declared for this report. Members contributed on the basis of their own expertise and good judgement.

The Royal Society would like to acknowledge the contributions from participants who attended the workshops in December 2020 and March 2022 that helped to shape the policy briefing.

<table>
<thead>
<tr>
<th>Working Group Chair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professor Graham Hutchings FRS, Regius Professor of Chemistry, Cardiff University</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Working Group members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Alberto Almena, Research fellow, Aston University</td>
</tr>
<tr>
<td>Professor Bill David FRS, Professor of Inorganic Chemistry, University of Oxford</td>
</tr>
<tr>
<td>Professor Piers Forster, Director Priestley International Centre for Climate, University of Leeds</td>
</tr>
<tr>
<td>Dr Guy Gratton, Associate Professor of Aviation and the Environment, Cranfield University</td>
</tr>
<tr>
<td>Professor David Lee, Professor of Atmospheric Science, Manchester Metropolitan University</td>
</tr>
<tr>
<td>Professor M Mercedes Maroto-Valer, School of Engineering and Physical Sciences, Heriot-Watt University</td>
</tr>
<tr>
<td>Professor Marcelle McManus, Director, Institute for Sustainability, University of Bath</td>
</tr>
<tr>
<td>Adam Morton, Head of Technology – Sustainability and Strategy, Aerospace Technology Institute</td>
</tr>
<tr>
<td>Dr Mike Muskett, Independent Consultant</td>
</tr>
<tr>
<td>Dr Naresh Kumar, Sustainability Advisor, Aerospace Technologies Institute</td>
</tr>
<tr>
<td>Professor John Pickett FRS, Professor of Biological Chemistry, Cardiff University</td>
</tr>
<tr>
<td>Professor Mohamed Pourkashanian, Managing Director, Sustainable Aviation Fuels Innovation Centre, University of Sheffield</td>
</tr>
<tr>
<td>Professor Matthew Rosseinsky FRS, Royal Society Research Professor, University of Liverpool</td>
</tr>
<tr>
<td>Professor Alfred William Rutherford FRS, Chair of Biochemistry of Solar Energy, Imperial College London</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Andrea Fantuzzi, Research fellow, Department of Life Sciences, Imperial College London</td>
</tr>
<tr>
<td>Michael High, Postgraduate Researcher, Department of Chemical Engineering, Imperial College London</td>
</tr>
<tr>
<td>Professor Pericles Pilidis, Professor of Gas Turbine Performance, Cranfield University</td>
</tr>
<tr>
<td>Paola A Saenz Cavazos, Postgraduate Researcher, Department of Chemical Engineering, Imperial College London</td>
</tr>
</tbody>
</table>
## Reviewers

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Penny Atkins</td>
<td>School of Architecture, Technology and Engineering, University of Brighton</td>
</tr>
<tr>
<td>Professor Frank Kirkland</td>
<td>School of Mechanical and Aerospace Engineering, Queen's University Belfast</td>
</tr>
<tr>
<td>Professor Keith P Shine FRS</td>
<td>Regius Professor of Meteorology and Climate Science, University of Reading</td>
</tr>
<tr>
<td>Professor Magda Titirici</td>
<td>Chair in Sustainable Energy Materials, Imperial College London</td>
</tr>
</tbody>
</table>

## Royal Society staff

Many staff at the Royal Society contributed to the production of this report. The project team are listed below.

## Royal Society Secretariat

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paul Davies</td>
<td>Senior Policy Adviser</td>
</tr>
<tr>
<td>James Musisi</td>
<td>Policy Adviser and Project Lead</td>
</tr>
<tr>
<td>Ethan Petrou</td>
<td>Policy Intern (until December 2022)</td>
</tr>
<tr>
<td>Elizabeth Surkovic</td>
<td>Head of Policy, Resilient Futures</td>
</tr>
<tr>
<td>Daisy Weston</td>
<td>Project Coordinator</td>
</tr>
</tbody>
</table>
The Royal Society is a self-governing Fellowship of many of the world’s most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society’s fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

The Society’s strategic priorities emphasise its commitment to the highest quality science, to curiosity-driven research, and to the development and use of science for the benefit of society. These priorities are:

• The Fellowship, Foreign Membership and beyond
• Influencing
• Research system and culture
• Science and society
• Corporate and governance

For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
W royalsociety.org

Registered Charity No 207043