Net zero aviation fuels: resource requirements and environmental impacts

POLICY BRIEFING

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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-CO_2 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: CO_2 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 CO_2 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-CO_2 climate and environmental impacts.

- Synthetic efuels: CO_2 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-CO_2 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 CO_2 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-CO_2 climate and environmental impacts.
- Ammonia: No CO_2 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-CO_2 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-CO_2 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 CO_2 that produce net positive global warming impacts (see figure 1). The largest warming effects come from emissions of (i) nitrogen oxides (NO_x, where NO_x represents $NO + NO_2$) 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-CO_2 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[1, 2] and the UK's aviation industry is ranked amongst the largest aviation markets in the world[3]. 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.

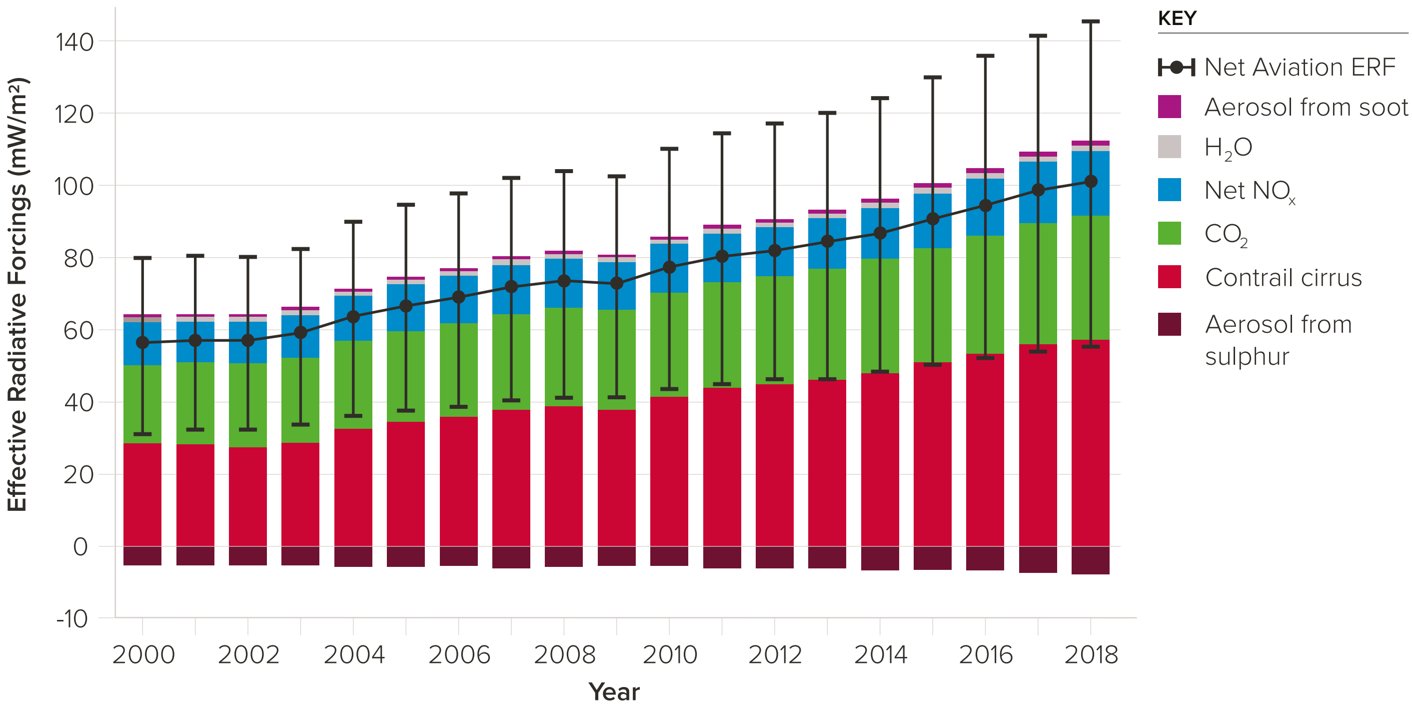
1 Aerospace Growth Partnership (2022), https://aerospacegrowthpartnership.files.wordpress.com/2022/07/destination-net-zero-agp-strategy-for-net-zero-aerospace.pdf (accessed 24 August 2022).

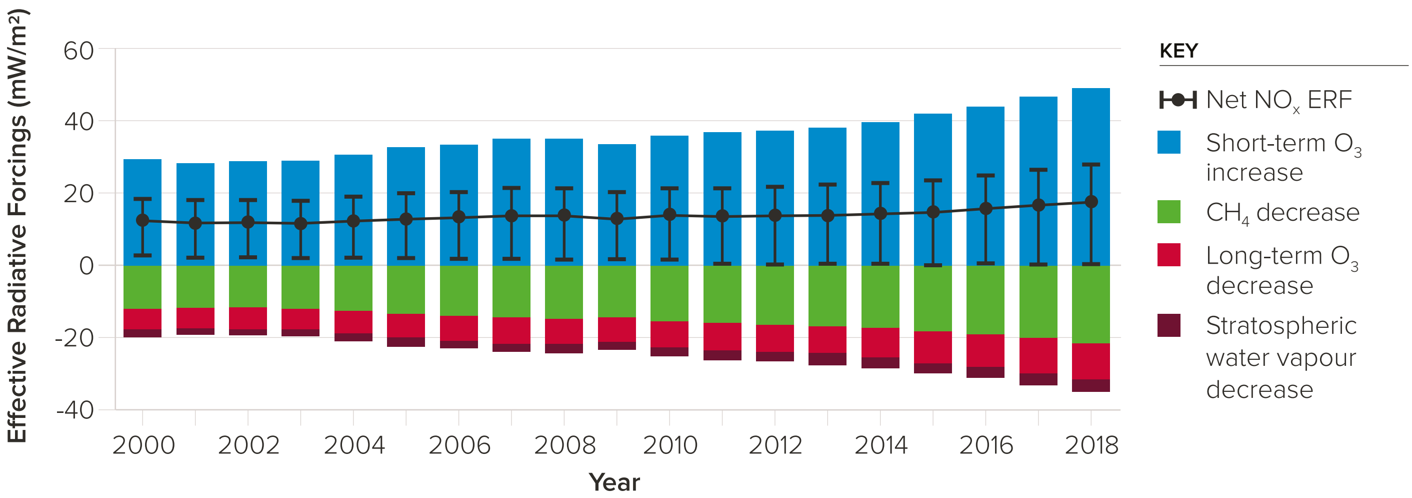
2 IATA (2019), The United Kingdom Air Transport Regulatory Competitiveness Indicators, https://www.iata.org/contentassets/d3319af9cf1a4db59d26d0503a63ecb7/uk-competitiveness-index-report-2019.pdf (accessed 24 June 2022).

3 Sustainable Aviation (2018), UK Aviation Industry Socio-Economic Report https://www.sustainableaviation.co.uk/wp-content/uploads/2018/06/SA-Socio-Economic-Report.pdf (accessed 24 June 2022).

FIGURE 1

Global aviation effective radiative forcing growth 2000 to 2018[4]





4 Lee, D S, Fahey, D. W, Skowron, A, Allen, M R, Burkhardt, U, Chen, Q, … & Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834., https://doi.org/10.1016/j.atmosenv.2020.117834.

FIGURE 2

Cost of Jet fuel from June 2015 – June 2022[5]

KEY

- Jet fuel price
- Crude oil price (Brent)

Source: S&P Global, Refinitiv, Eikon.

5 IATA (Jet Fuel Price Monitor). See https://www.iata.org/en/publications/economics/fuel-monitor/ (Accessed 28 June 2022).

1.1.1 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-A1[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].

6 GOV.UK. 2022 Statistics relating to passenger arrivals in the United Kingdom since the COVID-19 outbreak, May 2022. See https://www.gov.uk/government/statistics/statistics-relating-to-passenger-arrivals-since-the-covid-19-outbreak-may-2022/statistics-relating-to-passenger-arrivals-in-the-united-kingdom-since-the-covid-19-outbreak-may-2022 . (accessed 28 June 2022).

7 GOV.UK. 2021 Energy and environment: data tables (ENV). See https://www.gov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env . (Accessed 28 June 2022).

8 The Global Economy. (Jet fuel consumption- country rankings). See https://www.theglobaleconomy.com/rankings/jet_fuel_consumption/ . (Accessed 28 June 2022).

9 Bureau of Transportation Statistics. 2019 Traffic Data for US Airlines and Foreign Airlines US Flights - Final, Full-Year. See https://www.bts.gov/newsroom/final-full-year-2019-traffic-data-us-airlines-and-foreign-airlines . (Accessed 28 June 2022).

10 Businesswire. Technavio Announces Top Five Vendors in the Global Aviation Fuel Market from 2016 to 2020. See https://www.businesswire.com/news/home/20160725005404/en/Technavio-Announces-Top-Five-Vendors-in-the-Global-Aviation-Fuel-Market-from-2016-to-2020#:~:text=Air%20BP%20is%20one%20the,6%2C000%20flights%20in%20a%20day. (Accessed 28 June 2022).

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.

12 IATA. 2015 IATA Sustainable Aviation Fuel Roadmap. See https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/safr-1-2015.pdf (Accessed 28 June 2022).

13 Airportcodes. (GBR). See https://airportcodes.io/en/country/united-kingdom/. (Accessed 28 June 2022).

14 Ahalgren L. 2022. Heathrow Is the Largest Major Airport User Of Sustainable Aviation Fuel. British Aviation Group. 27 April 2022. See https://www.britishaviationgroup.co.uk/news/heathrow-is-the-largest-major-airport-user-of-sustainable-aviation-fuel/ (Accessed 28 June 2022).

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[15]) 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[16] 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 [17] and Shell Sky[18] forecasts. Based on these trends, the UK annual demand for aviation fuel which in 2019 was 12.3 million tonnes[19] 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).

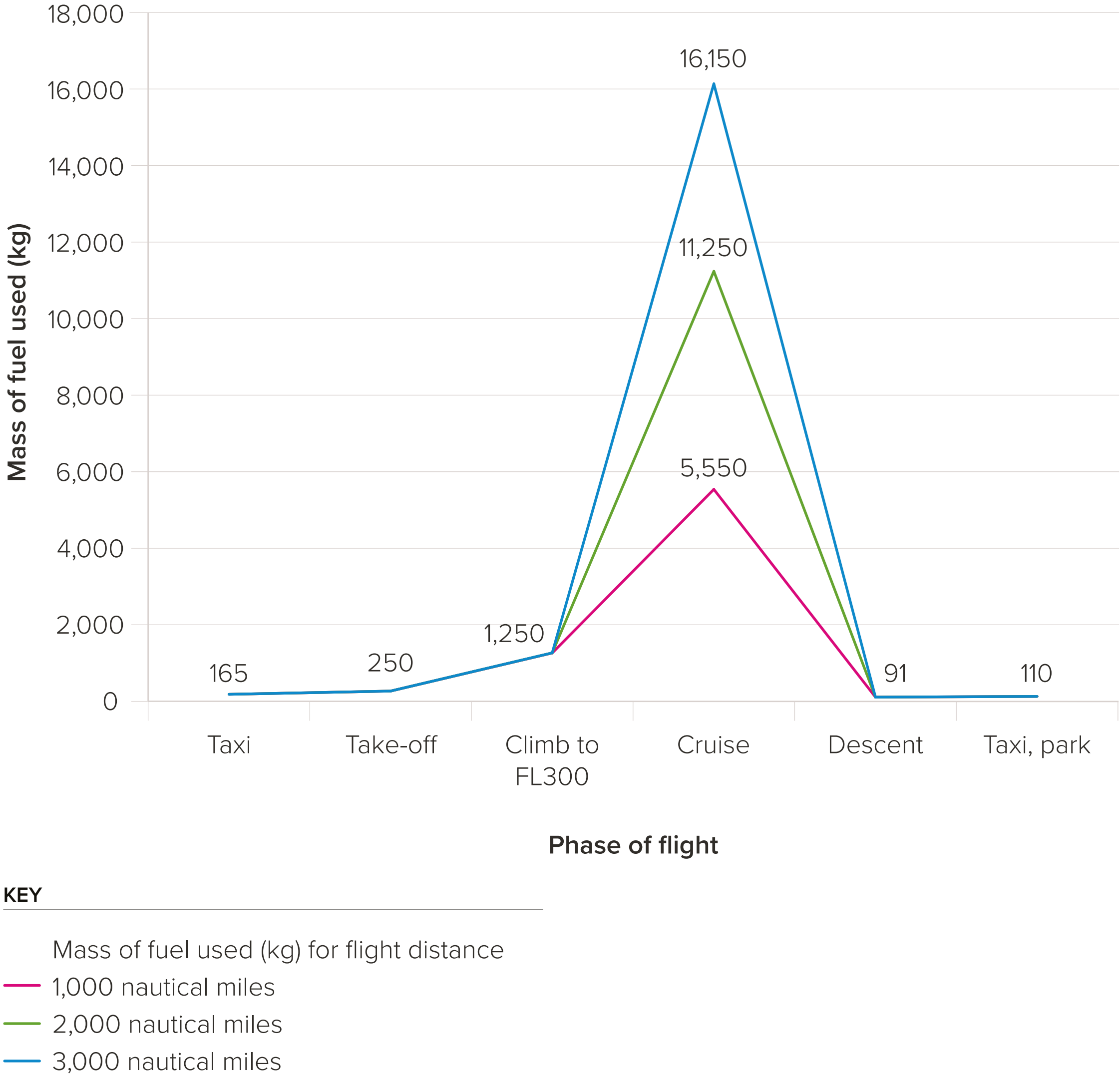
17 Data from: 2020 BP Energy Outlook 2020 edition. BP. (bp-energy-outlook-2020-chart-data-pack.xlsx (live.com)).

18 2018 Data from: Shell sky scenario data 2018. Shell (shell-sky-scenario-data-2018.xlsx (live.com)).

19 Department for Transport. 2021 Sustainable aviation fuels mandate. See Sustainable aviation fuels mandate: A consultation on reducing the greenhouse gas emissions aviation fuels in the UK (publishing.service.gov.uk) (accessed 30 August 2022).

FIGURE 3

Mass of fuel used within phases of flight across different ranges[20]



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).

21 HM Government. 2021 Net Zero Strategy: Build Back Greener. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf (accessed 30 August 2022).

22 Department for Business, Energy & Industrial Strategy. 2021 Carbon Budgets. See https://www.gov.uk/guidance/carbon-budgets (accessed 30 August 2022).

23 Department for Transport. 2022 Jet Zero Strategy: Delivering net zero aviation by 2050. See jet-zero-strategy.pdf (publishing.service.gov.uk) (accessed 30 August 2022).

24 Department for Transport. 2022 Sustainable aviation fuels mandate: summary of consultation responses and government response. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1091915/sustainable-aviation-fuels-mandate-summary-of-consultation-responses-and-government-response.pdf

The 'carbon-neutral growth goal, 2020' (CNG2020), states that international aviation emissions of CO_2 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[25] 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'[26].

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[27].

The US government says lowering aviation emissions 20 percent by 2030 is realistic and the industry should achieve net zero emissions by 2050[28]. To hit net zero, carbon from jet fuel and other sources is to be balanced by removing an equal amount from the atmosphere.

25 International civil aviation organization. 2022 Report on the feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil aviation CO_2 Emission Reductions. See https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf (accessed 30 August 2022).

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

27 European Commission. 2021 Proposal for a Regulation of The European Parliament and of the Council on ensuring a level playing field for sustainable air transport. See https://ec.europa.eu/info/sites/default/files/refueleu_aviation_-_sustainable_aviation_fuels.pdf (accessed 2022).

28 The White House (FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation). See https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/ (accessed 30 August 2022).

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[29]), the Hydrogen Council have forecast[30] 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[31] 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[32]. 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.

29 International Energy Agency. 2019 The Future of Hydrogen. See https://www.iea.org/reports/the-future-of-hydrogen (accessed 30 August 2022).

30 Hydrogen Council. 2017 Hydrogen scaling up. See https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf (accessed 30 August 2022).

31 GOV.UK. 2022 Hydrogen BECCS Innovation Programme: Phase 1 (closed). See https://www.gov.uk/government/publications/hydrogen-beccs-innovation-programme (accessed 30 August 2022).

32 HM Government. 2021 UK Hydrogen Strategy. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf (accessed 30 August 2022).

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 propellors 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)[33] 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[34, 35].

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[36] 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).

33 IFASTAT 2022. Nitrogen Products. See https://www.ifastat.org/supply/Nitrogen%20Products/Ammonia (accessed 30 August 2022).

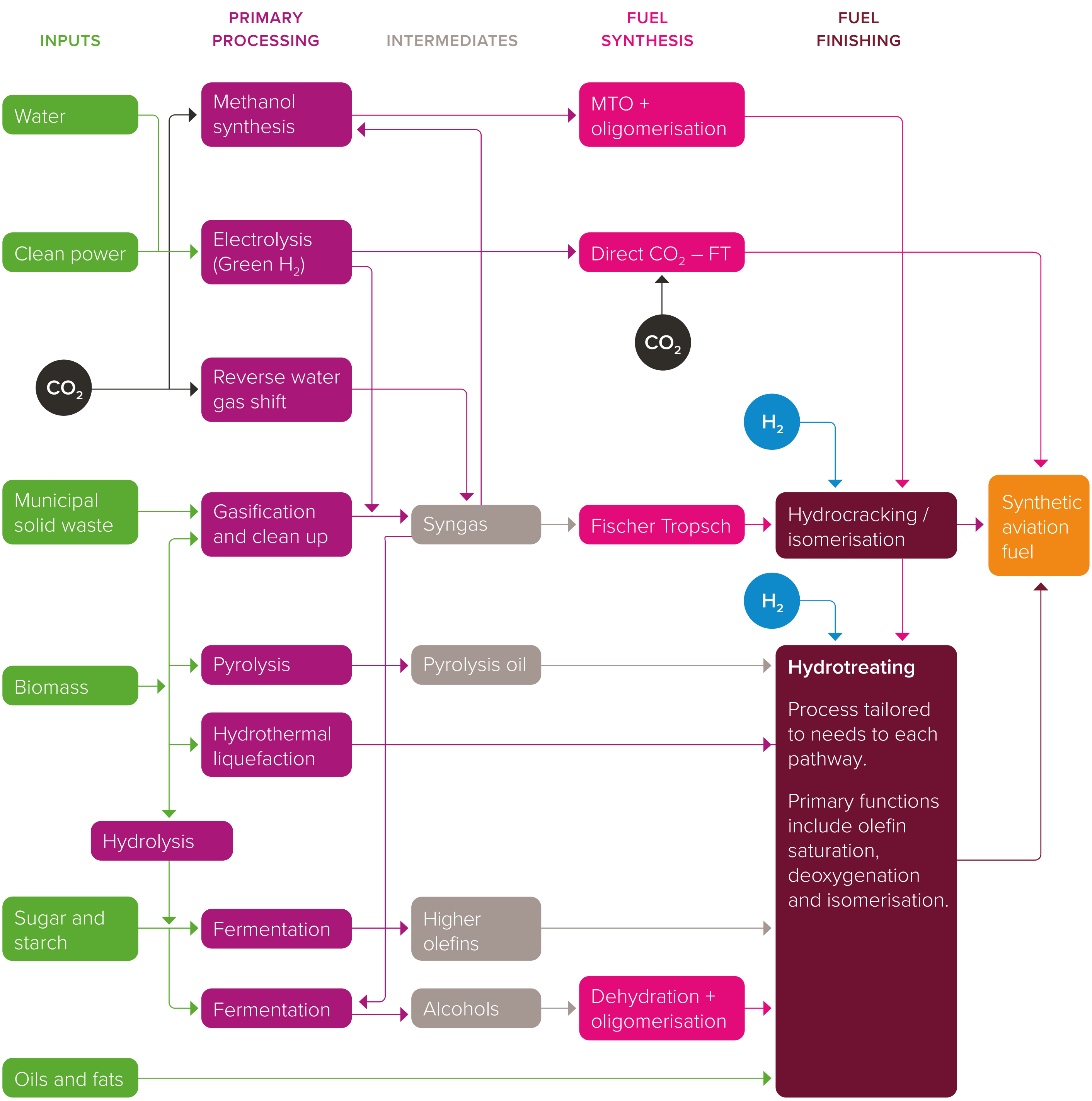
34 Kubička, D, & Tukač, V. (2013). Hydrotreating of triglyceride-based feedstocks in refineries. In Advances in chemical engineering (Vol. 42, pp. 141 – 194). Academic Press.

35 Xu, J, Long, F, Jiang, J, Li, F, Zhai, Q, Wang, F, … & Li, J. (2019). Integrated catalytic conversion of waste triglycerides to liquid hydrocarbons for aviation biofuels. Journal of Cleaner Production, 222, 784 – 792.

36 IEA (Transport biofuels) 2020. See https://www.iea.org/reports/renewables-2020/transport-biofuels (accessed 30 August 2022).

FIGURE 4

Potential routes to alternative synthetic aviation fuels



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 CO_2 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.

37 Shahabuddin M, Alam T, Krishna B, Bhaskar T, Perkins G. 2020 A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. Bioresource Technology. 312. (doi:10.1016/J.BIORTECH.2020.123596).

38 Bauen A, Bitossi N, German L, Harris A, Leow K. 2020 Sustainable Aviation Fuels: Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation. Johnson Matthey Technology Review. 64, 263 – 278. (doi: 10.1595/205651320X15816756012040).

39 NREL. 2016 Review of Biojet Fuel Conversion Technologies. See https://www.nrel.gov/docs/fy16osti/66291.pdf (accessed 30 August 2022).

40 IRENA. 2017 Biofuels for aviation: technology brief. See https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/IRENA_Biofuels_for_Aviation_2017.pdf (accessed 30 August 2022).

41 Roland Berger. 2020 Sustainable Aviation Fuels. See https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiyxo-Jz-75AhXMPsAKHUDtDS0QFnoECAIQAQ&url=https%3A%2F%2Fwww.rolandberger.com%2Fpublications%2Fpublication_pdf%2Froland_berger_sustainable_aviation_fuels.pdf&usg=AOvVaw0EcsAmxdXiQfTigqhD5xDW (accessed 30 August 2022).

42 Doliente S, Narayan A, Tapia J, Samsatli N, Zhao Y, Samsatli S. 2020 Bio-Aviation fuel: A comprehensive Review and Analysis of the Supply Chain Components. Front. Energy Res. 8, 110. (doi:10.3389/FENRG.2020.00110/BIBTEX).

43 CAAFI – Commercial Aviation Alternative Fuels Initiative (Fuel Qualification). See CAAFI – Focus Area – Fuel Qualification (accessed 30 August 2022).

44 Prussi M et al. 2021 CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. *Renewable and Sustainable Energy Reviews*. 150, 111398. (doi:10.1016/J.RSER.2021.111398).

TABLE 1

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

ASTM reference	Name	Feedstock options[44, 45, 46]	Description	Blend Limit [%]	TRL[47]
ASTM D7566	FT-SPK	Gasified sources of carbon and hydrogen: Biomass (forestry residues, grasses, municipal solid waste)	FT conversion of syngas to synthetic paraffinic kerosene (SPK)	50	5 – 6
ASTM D7566	HEFA-SPK	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	Hydro-processed esters and lipids from plant and animal sources to synthetic paraffinic kerosene	50	8
ASTM D7566	HFS-SIP	Sugars from direct (cane, sweet sorghum, sugar beets, tubers, field corn) and indirect sources (C5 and C6 sugars hydrolysed from cellulose	Hydro-processed fermented sugars to synthesised iso-paraffins	10	7 – 8 (conventional sugars) 5 cellulosic sugars)
ASTM D7566	FT-SPK/A	Same as FT-SPK, with the addition of some aromatics derived from nonpetroleum sources	FT conversion of syngas to synthetic paraffinic kerosene and aromatics	50	5 – 6
ASTM D7566	ATJ-SPK	Agricultural residues (stover, grasses, forestry slash, crop straws), forest residues, corn grain, herbaceous energy crops	Thermochemical conversion of alcohols (iso-butanol or ethanol) to paraffinic kerosene	50	5 – 6
ASTM D7566	CHJ	Triglyceride-based feedstocks (plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil)	Hydrothermal conversion of free fatty acids to paraffinic kerosene	50	6
ASTM D7566	HC-HEFA SPK	Bio-derived hydrocarbons such as algal oils	Hydroprocessed hydrocarbons, esters, and fatty acids SPK by the Botryococcus braunii species of algae	10	N/A
ASTM D1655	FOG	Fats, oils, and greases	Co-processing of fats, oils, and greases (FOG) in a traditional petroleum refinery	5	8 – 9

* See Glossary of terms.

45 Csonka S. 2022 Sustainable Aviation Fuel (SAF) Update. *Lee Enterprises*. See https://lee-enterprises.com/wp-content/uploads/2022/01/SAF-PPT.1.11.22.pdf#:~:text=A7%20Hydroprocessed%20Hydrocarbons%2C%20Esters%20and%20Fatty%20Acids%20Synthetic,produced%20by%20the%20Botryococcus%20braunii%20species%20of%20algae (accessed 30 August 2022).

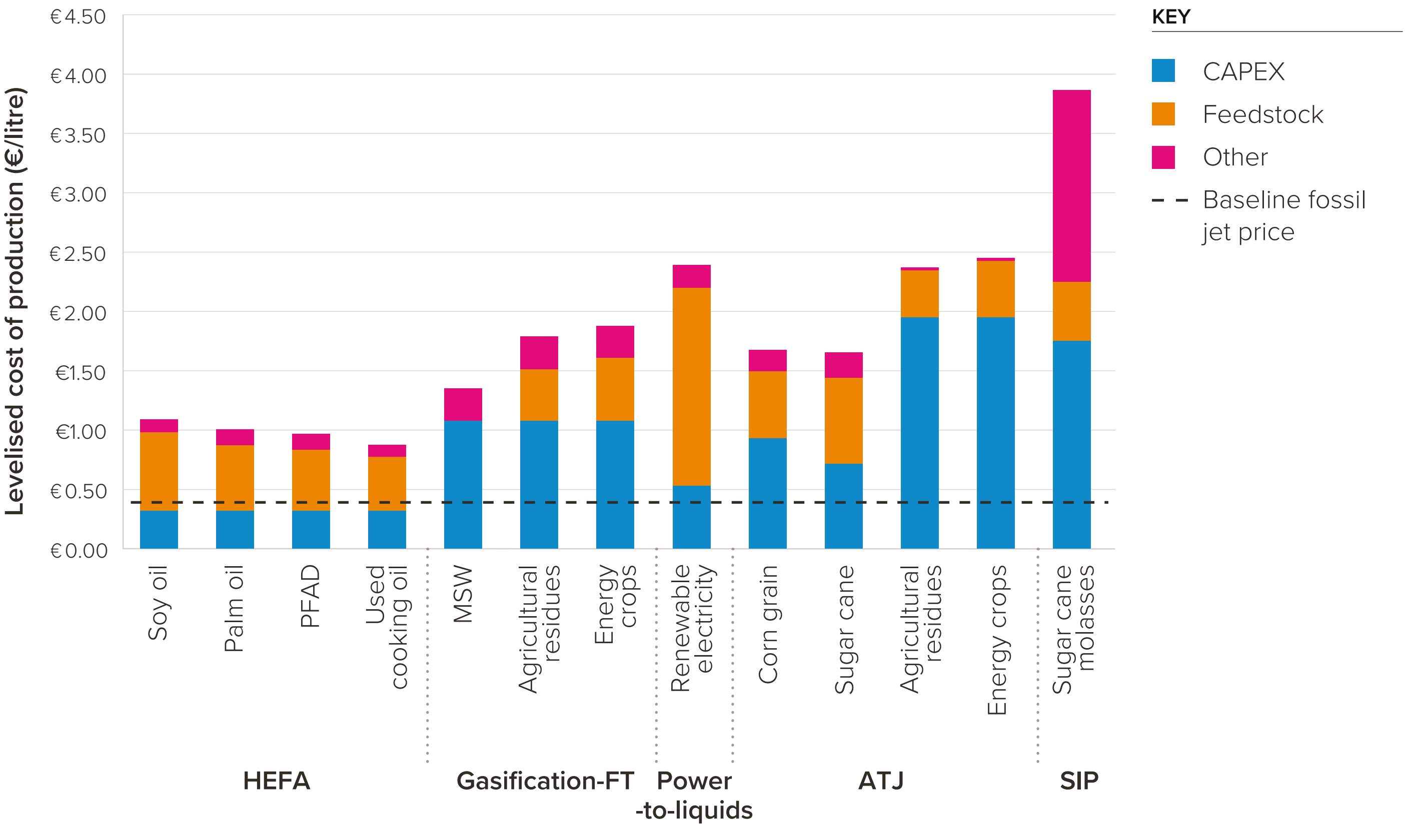
46 Green Car Congress. 2020 ASTM approves 7th annex to D7566 sustainable jet fuel specification: HC-HEFA. See https://www.greencarcongress.com/2020/05/20200514-ihi.html (accessed 30 August 2022).

47 Ricardo and E4Tech. 2020 Targeted Aviation Advanced Biofuels Demonstration Competition – Feasibility Study. See https://cdn.ricardo.com/ee/media/downloads/final-report-aviation-abdc-feasibility-study-issue-v1-0.pdf (accessed 30 August 2022).

FIGURE 5

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[48]

48 The International Council on Clean Transportation. 2019 https://theicct.org/sites/default/files/publications/Alternative_jet_fuels_cost_EU_20190320.pdf (accessed 30 August 2022).

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[49]. In general, the current production cost merit order is shown below in figure 5[48]. 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[50, 51, 52, 53].

Figure 6 shows the minimum fuel selling price data calculated in energy terms (the cost per GJ of fuel) using lower heating values[53].

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 CO_2 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.

49 US Department of Energy. 2021 Sustainable Aviation Fuel and US Airport Infrastructure. See https://www.energy.gov/sites/default/files/2021-05/beto-sustainable-aviation-fuel-webinar.pdf#:~:text=%E2%80%A2%20ICAO%E2%80%99s%20baseline%20lifecycle%20emissions%20value%20for%20jet,SAF%20values%20range%20between%205.2%20to%2065.7%20CO (accessed 30 August 2022).

50 IRENA. 2021 Biojet fuels: reaching zero with renewables. See https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jul/IRENA_Reaching_Zero_Biojet_Fuels_2021.pdf (accessed 2 September 2022).

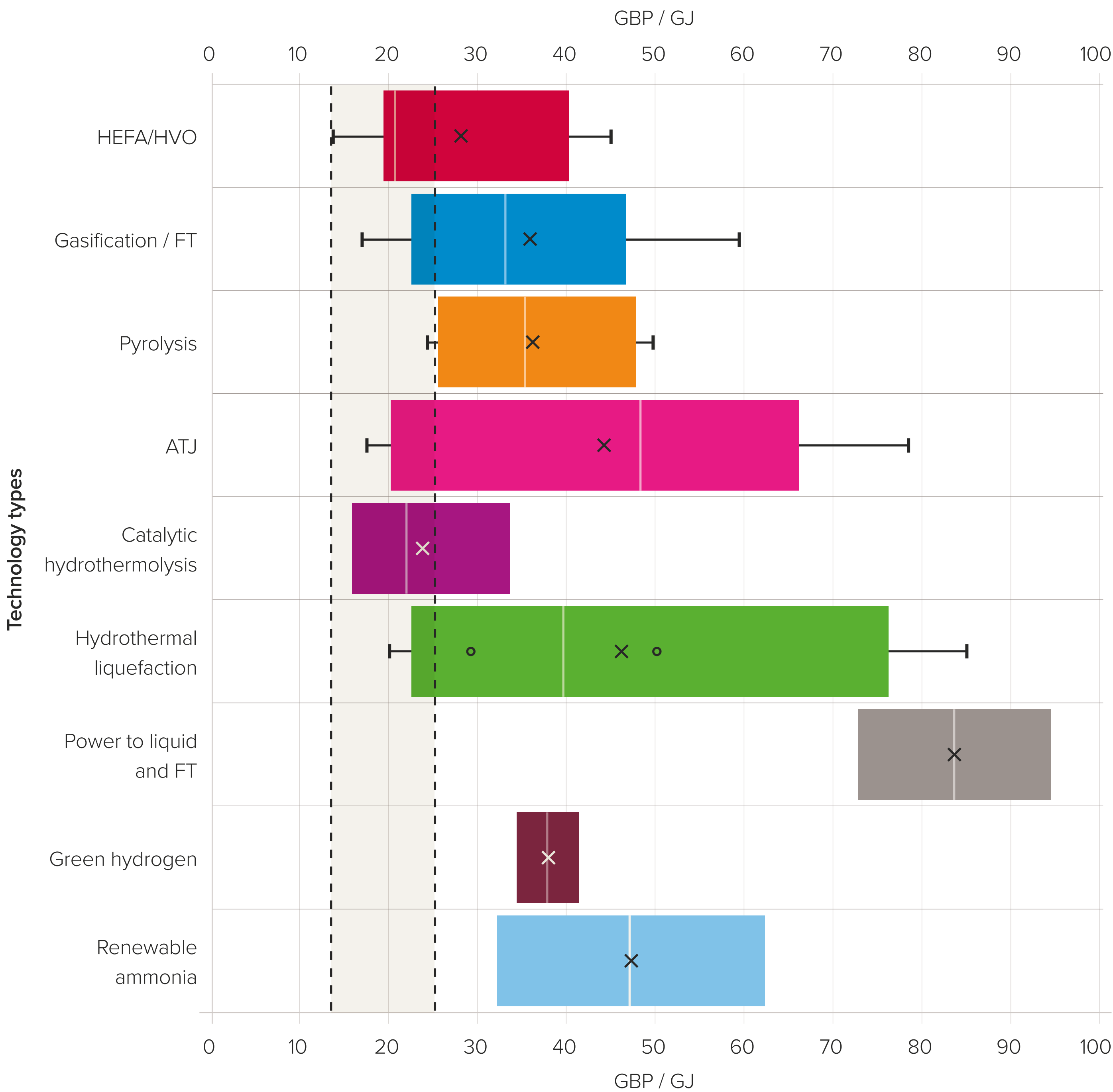
51 IRENA. 2020 Green Hydrogen: A guide to policy making https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

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

53 Boehm R, Yang Z, Bell D, Feldhausen J, Heyne J. 2022 Lower heating value of jet fuel from hydrocarbon class concentration data and thermo-chemical reference data: An uncertainty quantification. Fuel. 311, 122542. (doi:10.1016/J.FUEL.2021.122542).

FIGURE 6

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



KEY

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.

54 Department for Environment, Food and Rural Affairs (DEFRA). 2021 Agriculture in the United Kingdom 2020. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1056618/AUK2020_22feb22.pdf (accessed 30 August 2022).

55 O'Connell A, Kousoulidou M, Lonza L, Weindorf W. 2019 Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*. 101, 504-515. (https://doi.org/10.1016/j.rser.2018.11.033).

TABLE 2

Energy crops as feedstocks for proposed bio jet fuel: scaling for land use

Conversion process	Oil-to-jet fuel pathway using hydroprocessed renewable jet fuel (HRJF)	Alcohol-to-jet fuel pathway with ethanol as intermediate	Gas-to-Jet fuel pathway using Fischer-Tropsch
Feedstock	Rapeseed *(Brassica napus)*	Miscanthus	Wood – Poplar
Yield of conversion to jet fuel (US tons of jet fuel / US tons of dry biomass)	0.29[56, 39]	0.12 – 0.2[57, 39]	0.1 – 0.22[39, 58, 59]
Biomass yields (UK) (tonnes hectares^{-1} year^{-1}) [US tons]	3.3 [3.6][60]	10 [11][61]	10 [11][61]
Total amount of biomass to supply UK jet fuel demand (million tonnes)	42.4	102.5 – 61.5	123 – 55.9
Total amount of land to supply UK jet fuel demand (million hectares)	12.8	10.3 – 6.2	12.3 – 5.6
Equivalent fraction of UK agricultural land required	68%	54 – 33%	66 – 30%

56 Stratton et al. 2010: Partnership for Air Transportation Noise and Emissions Reduction Project 28. Life cycle greenhouse gas emissions from alternative jet fuels. See http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf (accessed 30 August 2022).

57 US Department of energy. 2011 U.S. Billion-ton update: biomass supply for a bioenergy and bioproducts industry. US. https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf (accessed 30 August 2022).

58 NREL. 2011 Process design and economics for conversion of lignocellulosic biomass to ethanol: thermochemical pathway by indirect gasification and mixed alcohol synthesis. See https://www.nrel.gov/docs/fy11osti/51400.pdf (accessed 30 August 2022).

59 International Council on Clean Transportation. 2021 Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand. See https://theicct.org/sites/default/files/publications/Sustainable-aviation-fuel-feedstock-eu-mar2021.pdf (accessed 30 August 2022).

60 Department for Environment, Food and Rural Affairs (DEFRA). 2020 Farming Statistics – final crop areas, yields, livestock populations and agricultural workforce at 1 June 2020 United Kingdom. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/946161/structure-jun2020final-uk-22dec20.pdf (accessed 30 August 2022).

61 Department for Environment, Food and Rural Affairs (DEFRA). 2021 Official statistics – Section 2: Plant biomass: miscanthus, short rotation coppice and straw. GOV.UK. See https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2020/section-2-plant-biomass-miscanthus-short-rotation-coppice-and-straw. (accessed 30 August 2022).

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 attention[62, 63, 64, 65] with some airlines completing trial tests[66, 67] and others signing purchase deals[68, 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 of[70] and this is by definition 'waste'. Some cooking oil waste is produced in homes and as such is difficult to collect.

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 incentives[71, 72].

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.

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62 Han Hoe Goh B et al. 2020 Progress in Utilisation of waste cooking oil for sustainable biodiesel and biojet fuel production. *Energy Conversion and Management.* 223. (doi:10.1016/J.ENCONMAN.2020.113296).

63 Chen Y, Hsieh C, Wang W. 2020 The production of renewable aviation fuel from waste cooking oil. Part ii: Catalytic hydro-cracking/isomerization of hydro-pressed alkanes into jet fuel range products. *Renewable Energy.* 156, 731-740. (doi:10.1016/J.RENENE.2020.04.154).

64 Chen R, Wang W. 2019 The production of renewable aviation fuel from waste cooking oil. Part 1: Bio-alkane conversion through hydro-processing of oil. *Renewable Energy.* 135, 819-835. (doi:10.1016/J.RENENE.2018.12.048).

65 Barbera E, Naurzaliyev R, Asiedu A, Bertucco A, Resurreccion E, Kumar S. 2020 Techno-economic analysis and life-cycle assessment of jet fuels production from waste cooking oil via in situ catalytic transfer hydrogenation. *Renewable Energy.* 160, 428-449. (doi:10.1016/J.RENENE.2020.06.077).

66 Buckley J. 2022 An A380 superjumbo just completed a flight powered by cooking oil. *CNN travel*. 30 March 2022. See https://edition.cnn.com/travel/article/airbus-a380-saf-cooking-oil-scn/index.html (accessed 30 August 2022).

67 Climate Champions (An Airbus powered by cooking oil: Is sustainable aviation fuel the future of aviation?). See https://climatechampions.unfccc.int/an-airbus-powered-by-cooking-oil-is-sustainable-aviation-fuel-the-future-of-aviation/ (accessed 30 August 2022).

68 Topham G. 2021 British Airways looks to recycled cooking oil fuel to cut jet emissions. *The Guardian.* 2 December 2021. See https://www.theguardian.com/business/2021/dec/02/british-airways-looks-to-recycled-cooking-oil-fuel-to-cut-jet-emissions (accessed 30 August 2022).

69 United signs deal to become 1st US carrier to purchase sustainable aviation fuel overseas. *ABC 13*. 11 May 2022. See https://abc13.com/united-first-airline-sustainable-fuel-neste/11838075/ (accessed 30 August 2022).

70 Parliament.UK. 2011 Environmental Audit Committee – Green Economy. Written evidence submitted by UK Sustainable Bio-Diesel Alliance (UKSBA). See https://publications.parliament.uk/pa/cm201012/cmselect/cmenvaud/1025/1025vw36.htm (accessed 30 August 2022).

71 Cater Oils (Home). See https://www.cateroils.co.uk/ (accessed 30 August 2022).

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, 76] to 11 Mt per year[77]. 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.

73 Department for Transport. 2022 Official Statistics Renewable fuel statistics 2021: Fourth provisional report. See https://www.gov.uk/government/statistics/renewable-fuel-statistics-2021-fourth-provisional-report/renewable-fuel-statistics-2021-fourth-provisional-report#feedstock (accessed 30 August 2022).

74 NNFCC. 2019 Implications of Imported Used Cooking Oil (UCO) as a Biodiesel Feedstock. See https://www.nnfcc.co.uk/files/mydocs/UCO%20Report.pdf (accessed 30 August 2022).

75 Nicholson et al. 2014. HGCA Research Review No. 81 Straw incorporation review.

76 Ricardo. 2017 Biomass feedstock availability Final report. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/597387/Biomass_feedstock_availability_final_report_for_publication.pdf (accessed 30 August 2022).

77 Department for Environment, Food & Rural Affairs. 2021 Official Statistics Area of crops grown for bioenergy in England and the UK: 2008-2020. See https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2020 (accessed 30 August 2022).

78 2019 Crops Grown For Bioenergy in the UK: 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/856695/nonfood-statsnotice2018-08jan20.pdf (accessed 30 August 2022).

79 Liska, A J, Yang, H, Milner, M, Goddard, S, Blanco-Canqui, H, Pelton, M P... & Suyker, A. E. (2014). Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. Nature Climate Change, 4(5), 398-401(doi:10.1038/nclimate2187).

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[80]. 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[81], 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.

80 Ricardo. 2017 Biomass feedstock availability Final report. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/597387/Biomass_feedstock_availability_final_report_for_publication.pdf

81 Bio Energy from BOREAL forests (2019), Swedish approach to sustainable wood use. See https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Mar/IRENA_Swedish_forest_bioenergy_2019.pdf accessed 12. March 2022

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 (ie, 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 (eg, composting, incineration for heating[82]). 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 investigated[83, 84, 85]. Some processes are in common with those proposed to treat food waste. These include hydrothermal liquefaction to produce biocrude[86, 87], followed by treatment with hydrogen to produce fuels[88, 89, 90].

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82 London Environmental Strategy (2018). See https://www.london.gov.uk/sites/default/files/waste.pdf (accessed 30 August 2022).

83 Manara, P, & Zabaniotou, A. (2012). Towards sewage sludge based biofuels via thermochemical conversion–A review. *Renewable and Sustainable Energy Reviews*, 16(5), 2566-2582.

84 Qian, L, Wang, S, & Savage, P E. (2017). Hydrothermal liquefaction of sewage sludge under isothermal and fast conditions. Bioresource technology, 232, 27-34.

85 Bashir, M A, Lima, S, Jahangiri, H, Majewski, A J, Hofmann, M, Hornung, A, & Ouadi, M. (2022). A step change towards sustainable aviation fuel from sewage sludge. *Journal of Analytical and Applied Pyrolysis*, 163, 105498.

86 Adedeji, O M, Russack, J S, Molnar, L A, & Bauer, S K. (2022). Co-Hydrothermal Liquefaction of Sewage Sludge and Beverage Waste for High-Quality Bio-energy Production. *Fuel*, 324, 124757.

87 Xu, D, Lin, G, Liu, L, Wang, Y, Jing, Z, & Wang, S. (2018). Comprehensive evaluation on product characteristics of fast hydrothermal liquefaction of sewage sludge at different temperatures. *Energy*, 159, 686-695.

88 Thorson, M R, Santosa, D M, Hallen, R T, Kutnyakov, I, Olarte, M. V, Flake, M, ... & Swita, M. (2021). Scaleable hydrotreating of HTL biocrude to produce fuel blendstocks. Energy & Fuels, 35(14), 11346-11352.

89 Ramirez, J A, Brown, R J, & Rainey, T J. (2015). A review of hydrothermal liquefaction bio-crude properties and prospects for upgrading to transportation fuels. *Energies*, 8(7), 6765-6794.

90 Subramaniam, S, Santosa, D M, Brady, C, Swita, M, Ramasamy, K K, & Thorson, M R. (2021). Extended Catalyst Lifetime Testing for HTL Biocrude Hydrotreating to Produce Fuel Blendstocks from Wet Wastes. *ACS Sustainable Chemistry & Engineering*, 9(38), 12825-12832.

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[91]. Some companies utilise sewage sludge to generate energy (using anaerobic digestion) to run their own operations or exported to the National Grid[92].

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[93, 94, 95]. 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[96, 97].

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 CO_2 from the atmosphere by photosynthesis, a solar energy-driven process[98, 99]. Thus, the CO_2 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 (see chapter three).

Given the low efficiency of photosynthesis, the additional energy inputs can cancel out the solar energy captured[55] 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[56].

91 DEFRA (2012) Wastewater treatment in the United Kingdom. Implementation of the European Union Urban Waste Water Treatment Directive – 91/271/EEC, See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69592/pb13811-waste-water-2012.pdf (accessed 26 September 2022).

92 Severn Trent Water (2022) Energy from Sewage. See, https://www.stwater.co.uk/about-us/climate-responsibility/renewable-energy/energy-from-sewage/ (accessed 26 September 2022).

93 Bashir, M A, Lima, S, Jahangiri, H, Majewski, A J, Hofmann, M, Hornung, A, & Ouadi, M. (2022). A step change towards sustainable aviation fuel from sewage sludge. Journal of Analytical and Applied Pyrolysis, 163, 105498.

94 Farooq, D, Thompson, I, & Ng, K S. (2020). Exploring the feasibility of producing sustainable aviation fuel in the UK using hydrothermal liquefaction technology: A comprehensive techno-economic and environmental assessment. *Cleaner Engineering and Technology*, 1, 100010.

95 Cronin, D J, Subramaniam, S, Brady, C, Cooper, A, Yang, Z, Heyne, J, ... & Thorson, M R. (2022). Sustainable Aviation Fuel from Hydrothermal Liquefaction of Wet Wastes. Energies, 15(4), 1306.

96 Ng, K. S, Farooq, D, & Yang, A. (2021). Global biorenewable development strategies for sustainable aviation fuel production. *Renewable and Sustainable Energy Reviews*, 150, 111502.

97 Kallupalayam Ramasamy, Karthikeyan, Thorson, Michael R, Billing, Justin M, Holladay, Johnathan E, Drennan, Corinne, Hoffman, Beau, & Haq, Zia. Hydrothermal Liquefaction: Path to Sustainable Aviation Fuel. United States. https://doi.org/10.2172/1821809

98 DeCicco, J M, Liu, D Y, Heo, J, Krishnan, R, Kurthen, A, & Wang, L. (2016). Carbon balance effects of US biofuel production and use. Climatic Change, 138(3), 667-680.

99 National Research Council. (2012). Renewable fuel standard: potential economic and environmental effects of US biofuel policy. National Academies Press.

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 CO_2 that had been captured by photosynthesis over the life of the tree upon combustion. That CO_2 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 CO_2 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

101 Department for Business, Energy & Industrial Strategy. 2021 Options for a UK low carbon hydrogen standard. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1024173/Options_for_a_UK_low_carbon_hydrogen_standard_report.pdf (accessed 31 August 2022).

Other resource requirements

- **Water requirements**
  Electrolysis requires deionised water. To produce 1 tonne of H_2 requires 9 tonnes of water. To supply the 3.8 Mt of H_2 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[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[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 H_2)[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

Jet fuel consumption (2019): energy, [mass]	145 TWh [12 Mt]
Hydrogen required to replace fossil jet fuel (2019)	145 TWh [3.8 Mt]
Electricity needed for electrolytic H_2 production	207 – 290 TWh (70 – 50% efficiency)
2020 UK electricity generation[105]	306 TWh
2020 UK ‘renewable’ electricity generation	123 TWh
2020 UK renewable electricity generation without biofuels	86 TWh

102 Greenlee, L F, Lawler, D F, Freeman, B D, Marrot, B, & Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today’s challenges. Water research, 43(9), 2317-2348.

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.

104 US Department of Energy. 2009 Hydrogen and Fuel Cells Program Record. See https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf (accessed 31 August 2022).

105 Our World in Data (Energy). See https://ourworldindata.org/energy (accessed 31 August 2022).

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 NH_3).

Using a modified Haber-Bosch process powered by renewable electricity, electrolytically produced hydrogen, and cryogenically or electrolytically purified N_2, 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 H_2 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 4

Resource requirements for ammonia

Jet fuel consumption (2019): energy, [mass]	145 TWh [12 Mt]
Ammonia required to replace fossil jet fuel (2019)	145 TWh [30.2 Mt]
Electricity required for ammonia production to replace fossil jet fuel: Haber Bosch + electrolytic H_2 production, N_2 purification etc	217 – 332 TWh[106, 107]
2020 UK electricity generation (TWh)	306 TWh
2020 UK 'renewable' electricity generation	123 TWh
2020 UK renewable electricity generation without biofuels	86 TWh

Note: The most efficient route is smart electrolysis / NH_3 synthesis integration: 7.2 MWh/tonne is 71% (78% exergy) efficient.

106 Hansen J, Topsøe H. 2017 Solid Oxide Cell Enabled Ammonia Synthesis and Ammonia based Power Production. *Haldor Topside*. See https://nh3fuelassociation.org/wp-content/uploads/2017/11/NH3-Energy-2017-John-Hansen.pdf (accessed 2 September 2022).

107 Luo Y, Chen G-F, Ding L, Chen X, Ding L-X, Wang H. 2018 Efficient Electrocatalytic N2 Fixation with MXene under Ambient Conditions. *Joule.* 3(1), 279-289. (https://doi.org/10.1016/j.joule.2018.09.011).

2.4 Synthetic electro fuel (efuel)

The production of synthetic efuels involves the reaction of CO_2 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 H_2 gas from green electrolysis and so would require de-ionised water as with H_2 production.

A near zero-carbon version of this process would include CO_2 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 CO_2 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 CO_2, to electrolyse water to produce H_2, to reduce the CO_2 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

Resource requirements for synthetic aviation fuel

Aviation fuel consumption UK [mass] in 2019	145 TWh [12 Mt]
Energy cost (electricity and heat) for power to liquid conversion – Includes DAC, hydrogen production and FT.	39 – 55 kWh/kg of fuel produced
Energy required to produce the 12 Mt of power-to-liquid e-jet fuel required in the UK.	468 – 660 TWh
2020 UK electricity generation	306 TWh
2020 UK 'renewable' electricity generation	123 TWh
2020 UK renewable electricity generation without biofuels	86 TWh

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 CO_2 at a similar rate.

Table 6 shows calculations aimed at estimating electricity use to capture the CO_2 released by aviation in the UK for one year. The table also shows the equivalent numbers for global aviation (in blue).

TABLE 6

Resource requirements of using fossil fuels and DAC

Aviation fuel consumption UK [mass] in 2019	145 TWh [12 Mt]
CO_2 emission upon combustion of 12 Mt fuel	38 Mt
Energy required by DAC to capture the 38 Mt of CO_2 from the air (1.6 to 3.9 MWh/t CO_2[108, 109] excluding compression etc.)	61 – 148 TWh
2020 UK electricity generation for comparison	306 TWh
2020 UK 'renewable' electricity generation	123 TWh
2020 UK renewable electricity generation without biofuels	86 TWh
Equivalent numbers for global aviation	
Total fuel consumption World [mass]	3680 TWh [288 Mt]
Total energy required to produce the 288Mt of fuel required in the world via the power to liquid conversion.	10,944 – 15,840 TWh
CO_2 emission upon combustion of 288 Mt fuel	900 Mt
Energy required to absorb an equivalent amount of CO_2 via DAC	1,440 – 3,510 TWh

108 Babacan O, De Causmaecker S, Gambhir A, Fajardy M, Rutherford AW, Fantuzzi A, Nelson J. 2020 Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage. *Nature Energy.* 5, 720-728. (DOI: 10.1038/s41560-020-0646-1).

109 Realmonte, G, Drouet, L, Gambhir, A, Glynn, J, Hawkes, A, Köberle, A C, & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature communications, 10(1), 1-12. (https://doi.org/10.1038/s41467-019-10842-5).

To remove the CO_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_2 can be as much as the energy in the jet fuel[108, 109].

This option would have no impact on the non-CO_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 CO_2 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 CO_2 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).

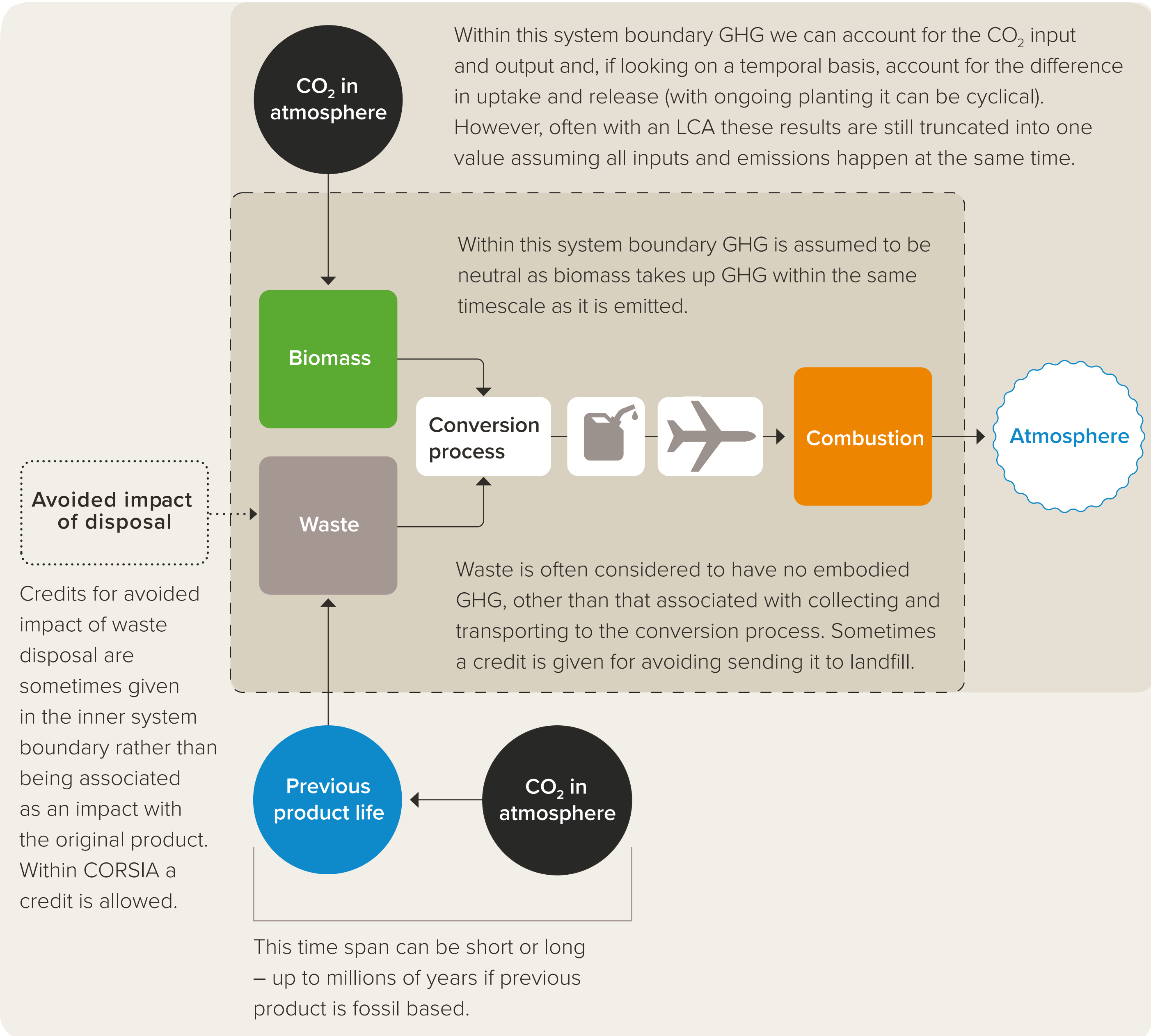
When producing fuels from biomass or wastes the issue of carbon modelling also becomes more complex and can also be considered a system boundary issue.

110 IEA. 2021 Aviation. See https://www.iea.org/reports/aviation (accessed 31 August 2022).

111 UK Parliament. 2021 Aviation, Decarbonisation and climate change. See https://commonslibrary.parliament.uk/research-briefings/cbp-8826/ (accessed 31 August 2022).

FIGURE 7

LCA system boundary considerations



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[112] and several authors have examined the consequences of applying these neutrality assumptions, cautioning that they lead to accounting errors[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[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.

112 Röder M, Thiffault E, Martínez-Alonso C, Gagnon A, Paradis L, Thornley P. 2019 Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. Biomass and Bioenergy. 121, 99-114. (doi:10.1016/J.BIOMBIOE.2018.12.019).

113 Head M, Bernier P, Levasseur A, Beauregard R, Margni M. 2019 Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment. Journal of cleaner production. 213, 289-299. (doi:10.1016/J.JCLEPRO.2018.12.122).

114 Wiloso E, Heijungs R, Huppes G, Fang K. 2016 Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: challenges to the neutrality assumption. Journal of Cleaner Production. 125, 78-85. (https://doi.org/10.1016/j.jclepro.2016.03.096).

115 European Academies Scientific Advisory Council (EASAC). 2018 Forest Bioenergy and Negative Emissions Update. See https://easac.eu/projects/details/carbon-neutrality/ (accessed 30 August 2022).

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'[116] 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[117].

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 products 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 (ie 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[118].

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.

116 Nguyen T, Hermansmen J. 2012 System expansion for handling co-products in LCA of sugar cane bio-energy systems: GHG consequences of using molasses for ethanol production. Applied Energy. 89(1), 254-261. (doi:10.1016/J.APENERGY.2011.07.023).

117 Nicholson A, Olivetti E, Gregory J, Field F, Kirchain R. 2009 End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. IEEE International Symposium on Sustainable Systems and Technology. 1-6. (doi:10.1109/ISSST.2009.5156769).

118 Cooper S, Green R, Hattam L, Röderd M, Welfle A, McManus M. 2020 Exploring temporal aspects of climate-change effects due to bioenergy Biomass and Bioenergy. 142, 105778. (doi:10.1016/J.BIOMBIOE.2020.105778).

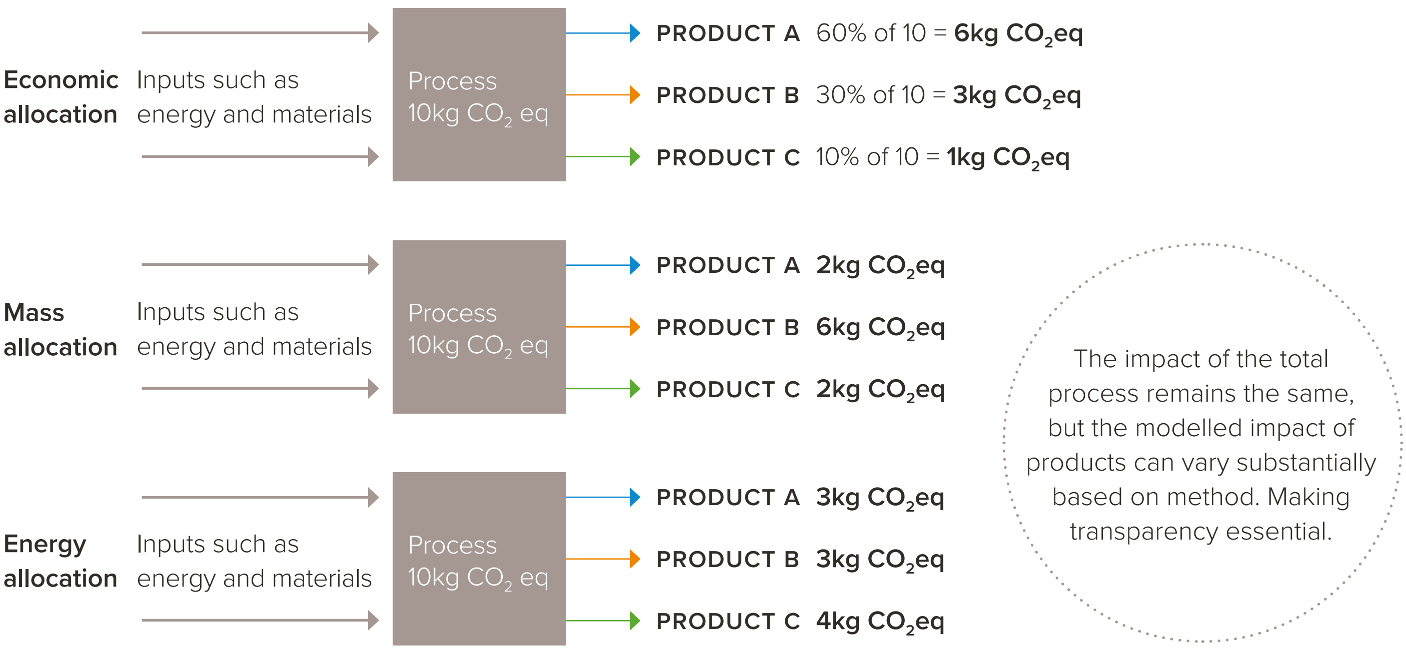
FIGURE 8

LCA allocation methods showing how the CO_2 generated by a process can be attributed differently to the products of that process

	Cost (%) (Economic value)	Mass (%)	Energy value (%)
Product A	60	20	30
Product B	30	60	30
Product C	10	20	40

The total GHG impact of the process that makes Products A,B and C is 10kg CO_2 eq.

Allocation is used in LCA* used to determine how much of the total process impact is allocated to the individual products (eg 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.

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 -10g CO_2 eq/MJ (Oil crops) to almost +150g CO_2 eq /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 — 146g CO_2 eq/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[119, 120].

Oil crops provide one of two of the negative GHG emissions shown, (-12 — 55 g CO_2 eq/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[121].

Interestingly, and especially considering the UK governments consultation[20], 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 CO_2 eq/MJ)[122]. 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.

119 Guo F, Wang X,Yang X. 2017 Potential pyrolysis pathway assessment for microalgae-based aviation fuel based on energy conversion efficiency and life cycle. *Energy Conversion and Management*. 132, 272–280.

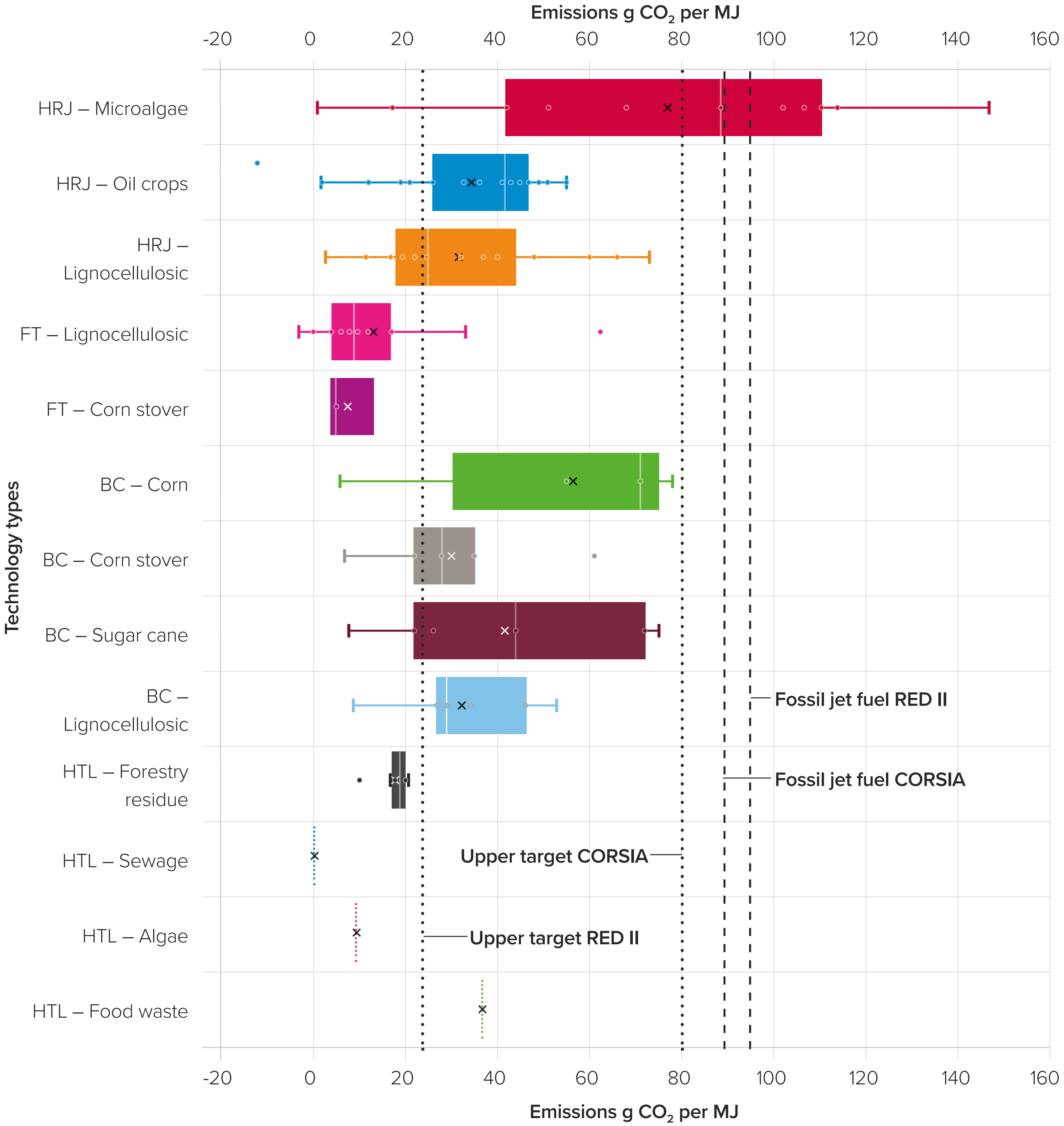
120 Guo F, Zhao J, Lusi A, Yang X. 2016 Life cycle assessment of microalgae-based aviation fuel: Influence of lipid content with specific productivity and nitrogen nutrient effects. Bioresource Technology. 221, 350–357. (doi:10.1016/j.biortech.2016.09.044).

121 Ukaew, S, Shi, R, Lee, J H, Archer, D W, Pearlson, M, Lewis, K. C, ... & Shonnard, D R. (2016). Full chain life cycle assessment of greenhouse gases and energy demand for canola-derived jet fuel in North Dakota, United States. ACS Sustainable Chemistry & Engineering, 4(5), 2771-2779. (doi:10.1021/ACSSUSCHEMENG.6B00276/SUPPL_FILE/SC6B00276_SI_001.PDF).

122 Suresh P. 2018 Life Cycle Greenhouse Gas Emissions and Costs of Production of Diesel and Jet Fuel from Municipal Solid Waste. *Environmental Science & Technology*. 52(21), 12055–12065. (doi:10.1021/ACS.EST.7B04277/SUPPL_FILE/ES7B04277_SI_001.PDF).

FIGURE 9

Spread of GHG results of selected biofuel LCA studies



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 CO_2 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 above[125]. 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 levels[44].

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 CO_2/MJ) as well as not being made from biomass from land with high carbon stock[126]. From 2024, comprehensive environmental, social and economic sustainability criteria apply under CORSIA.

123 De Jong, S, Antonissen, K, Hoefnagels, R, Lonza, L, Wang, M, Faaij, A, & Junginger, M (2017). Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnology for biofuels, 10(1), 1-18.

124 Sieverding H, Zhao X, Wei L, Stone J. 2016 Life-Cycle Assessment of Oilseeds for Biojet Production Using Localized Cold-Press Extraction. *Journal of Environmental Quality*. 45(3), 967–976. (doi:10.2134/jeq2015.06.0313).

125 International Civil Aviation Organisation (ICAO). 2021 CORSIA Methodology for Calculating Actual Life Cycle Emissions Values. See https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20March%202021.pdf (accessed 5 September 2022).

126 Prussi, M, Lee, U, Wang, M, Malina, R, Valin, H, Taheripour, F, ... & Hileman, J. I. (2021). CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renewable and Sustainable Energy Reviews, 150, 111398.

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_2e/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_2e/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].

127 International Civil Aviation Organisation (ICAO). 2021 CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. See https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO document 06 - Default Life Cycle Emissions - March 2021.pdf (accessed 5 September 2022).

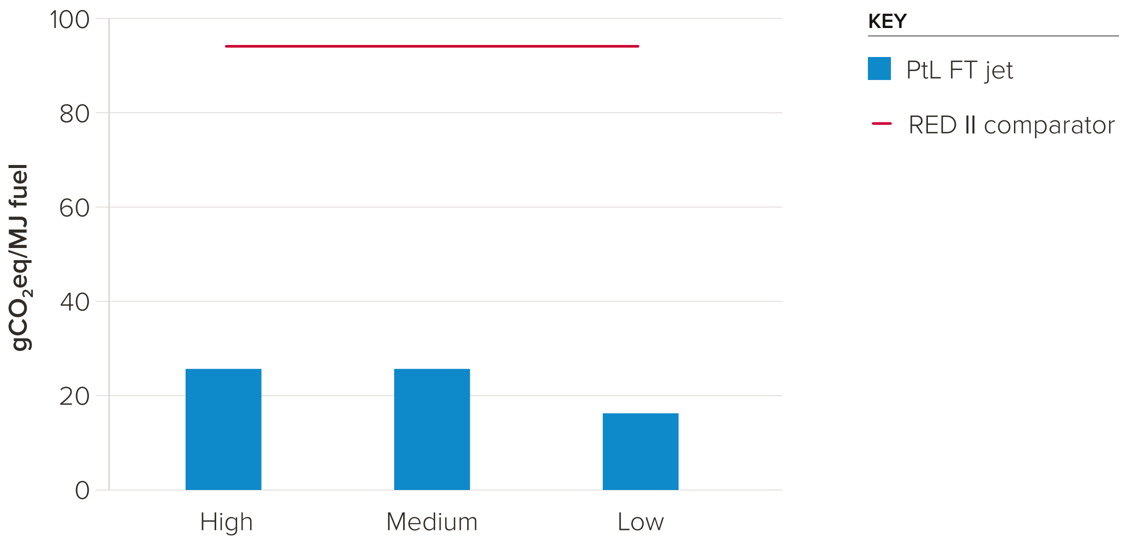
128 Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T. 2018 Power-to-Liquids as Renewable Fuel Option for Aviation: A Review. Chemie Ingenieur Technik. 90(1-2), 127-140. (doi:10.1002/CITE.201700129).

129 Cerulogy. 2017 What role is there for electrofuel technologies in European transport's low carbon future? See https://www.transportenvironment.org/wp-content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf (accessed 5 September 2022).

FIGURE 10

GHG emissions savings for power to liquid FT-SPK

Pathways compared to the fossil RED II comparator in figure 9



Source: Department for Transport, UK (2020).

IATA's 2015 report on alternative fuels[130] 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 gCO_2 eq per kWh_{el} for wind power generation would translate into specific GHG emissions of 6 gCO_2 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 agency[131] highlighted that the GHG emissions without land use change for efuels (wind / PV in Germany) are about 1g CO_2–eq per MJ of the final PtL jet fuel.

Significant differences in emissions were found depending on the capture and purification of CO_2 used as reported by Ricardo[132], noting that emissions could be higher if fossil sources of energy are used.

130 IATA. IATA 2015 Report on Alternative Fuels. See https://www.iata.org/contentassets/462587e388e749eeb040df4dfdf02cb1/2015-report-alternative-fuels.pdf (accessed 5 September 2022).

131 Germany Environment Agency. 2016 Power-to-liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. See https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf (accessed 5 September 2022).

132 Ricardo and E4Tech 2020. Targeted Aviation Advanced Biofuels Demonstration Competition – Feasibility Study. See https://cdn.ricardo.com/ee/media/downloads/final-report-aviation-abdc-feasibility-study-issue-v1-0.pdf (accessed 30 August 2022).

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)[128].

3.5 Hydrogen and ammonia life cycle emissions

Despite growing investments in Hydrogen and Ammonia technologies[133, 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 assumptions[137]. 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 production[138].

The data below[138] (see figure 11) indicates that renewable routes offer CO_2 savings over conventional kerosene fuelled aircraft, however as discussed earlier, the LCA results can be skewed by the boundaries and the allocations used.

133 Rolls-Royce (The H Factor). See https://www.rolls-royce.com/media/our-stories/discover/2020/intelligentengine-the-h-factor.aspx (Accessed 12/07/22).

134 Siemens (‘Green’ ammonia is the key to meeting the twin challenges of the 21st century). See https://www.siemens-energy.com/uk/en/offerings-uk/green-ammonia.html (Accessed 12/07/22).

135 UKRI (Ground-breaking study to find a truly green aviation power system). See https://www.ukri.org/news-and-events/responding-to-climate-change/moving-towards-net-zero/ground-breaking-study-to-find-a-truly-green-aviation-power-system/ (Accessed 12/07/22).

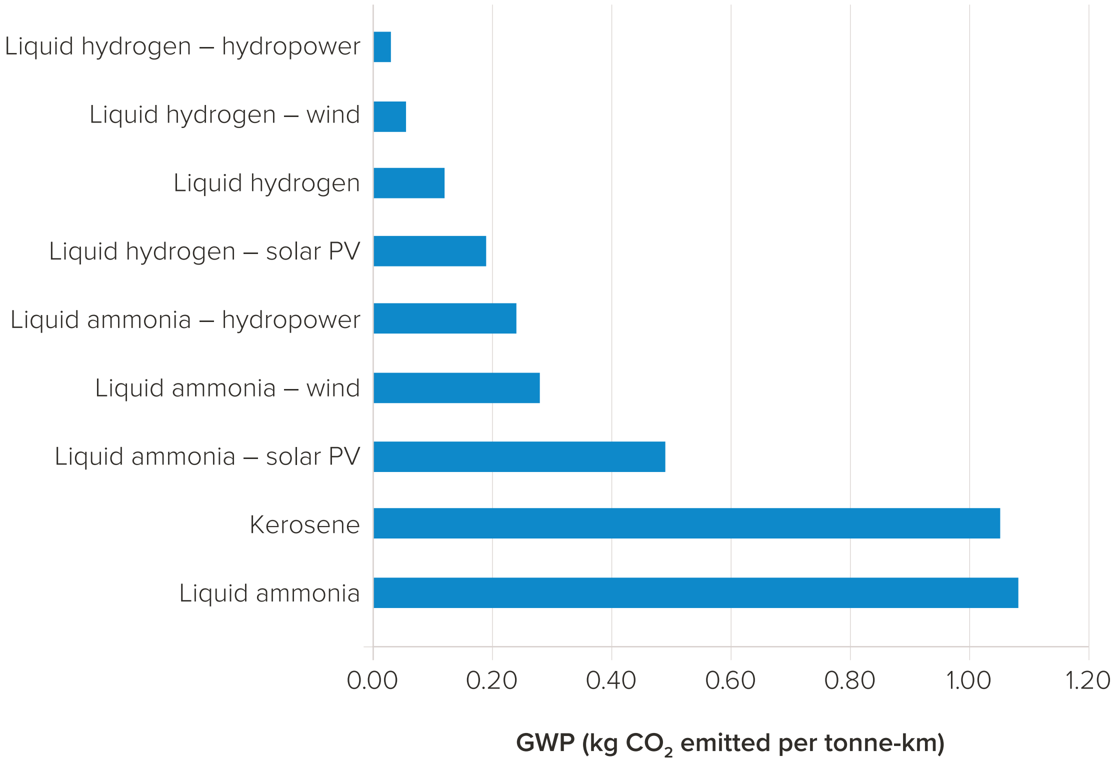
136 Ammonia Energy Association (Zero emissions aircraft: ammonia for aviation). See https://www.ammoniaenergy.org/articles/zero-emission-aircraft-ammonia-for-aviation/ (accessed 5 September 2022).

137 Howarth R. 2021 How green is blue Hydrogen? See https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.956 (accessed 5 September 2022).

138 Bicer Y, Dincer I. 2017 Life cycle evaluation of hydrogen and other potential fuels for aircrafts. *International Journal of Hydrogen Energy*. 42(16), 10722-10738. (doi:10.1016/J.IJHYDENE.2016.12.119).

FIGURE 11

Global warming potential of various fuelled aircrafts per travelled tonne-km



Source: Bicer Y, Dincer I, 2017.

The recently published UK Low carbon Hydrogen Standard[139] sets a GHG emissions intensity of 20gCO_2e/MJ (lower heating value) of produced hydrogen or less for the hydrogen to be considered low carbon.

For hydrogen produced in the UK[101], GHG emissions results for hydrogen production pathways range from 10 – 45g CO_2e/MJ for abated natural gas pathways and 0 – 5 g CO_2e/MJ for renewable and nuclear electrolysis.

For hydrogen imported to the UK[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_2e/MJLHV threshold.

139 Department for Business, Energy & Industrial Strategy. 2022. UK Low Carbon Hydrogen Standard: Guidance on the greenhouse gas emissions and sustainability criteria. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092809/low-carbon-hydrogen-standard-guidance-v2.1.pdf (accessed 5 September 2022).

140 Department for Business, Energy & Industrial Strategy. 2022 Expansions of hydrogen production pathways analysis – import chains. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092367/expansion-hydrogen-production-pathways-analysis-import-chains.pdf (accessed 5 September 2022).

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 gCO_2/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 CO_2[141], 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:

- CO_2, water vapour, carbon monoxide (CO);
- nitrogen oxides (NO_X, where NO_X represents $NO+NO_2$);
- soot and sulphur-based aerosol particles, sulphur dioxide (SO_2);
- volatile organic compounds.

CO_2 and water vapour are emitted with a fixed emission index ('EI') of 3.16 kg and 1.231 kg per kg fuel combusted and SO_2 1.2g per kg fuel. Soot, NO_X and CO EIs are variable across engine types and combustion conditions. The overall global fleet $EINO_X$ 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 CO_2, water vapour, NO_X and soot and sulphate particles. Aviation CO_2 emissions are relatively well-quantified, and the associated radiative (climate) effect well characterised, whereas the non-CO_2 effects from water vapour, NO_X 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 CO_2 emissions[142].

141 Department for Business, Energy & Industrial Strategy. 2022. Atmospheric implications of increased Hydrogen use. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmospheric-implications-of-increased-hydrogen-use.pdf (accessed 5 September 2022).

142 Lee, D.S. et al. (2021), The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, 244, 117834, https://doi.org/10.1016/j.atmosenv.2020.117834.

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[143], 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[143]. The primary emission from the engine exit is sulphur dioxide (SO_2). The emitted SO_2, 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[144].

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[145]. 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.

143 Miller, Brook & Eyers, 2009. Reduction of sulphur limits in aviation fuel standards (SULPHUR. European Aviation Safety Agency (EASA).

144 Kärcher, 2018. Formation and radiative forcing of contrail cirrus. Nature Communications, 9, 1824.

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[146, 147, 148]. The aromatic content and particularly the naphthalene content[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: n-alkanes[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).

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.

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[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[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.

146 Dagaut & Cathonnet, 2006. The ignition, oxidation, and combustion of kerosene: A review of experimental and kinetic modeling. Progress in Energy and Combustion Science, 32, 48-92.

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

148 Richter H & Howard J. 2000 Formation of polycyclic aromatic hydrocarbons and their growth to soot – a review of chemical reaction pathways. *Progress in Energy and Combustion Science.* 26(4-6), 565-608. (https://doi.org/10.1016/S0360-1285(00)00009-5)

149 Chin J & Lefebvre A. 1990 Influence of Fuel Chemical Properties on Soot Emissions from Gas Turbine Combustors. *Combustion Science and Technology.* 73(1-3), 479-486. (https://doi.org/10.1080/00102209008951664)

150 alkanes' are sometimes referred to as 'paraffins', so read 'iso-paraffins', 'cyclo-paraffins' etc. as equivalencies

151 Burkhardt U, Bock L, Bier A. 2018. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. NPJ Climate and Atmospheric Science. 1(1), 37. (doi:10.1038/s41612-018-0046-4).

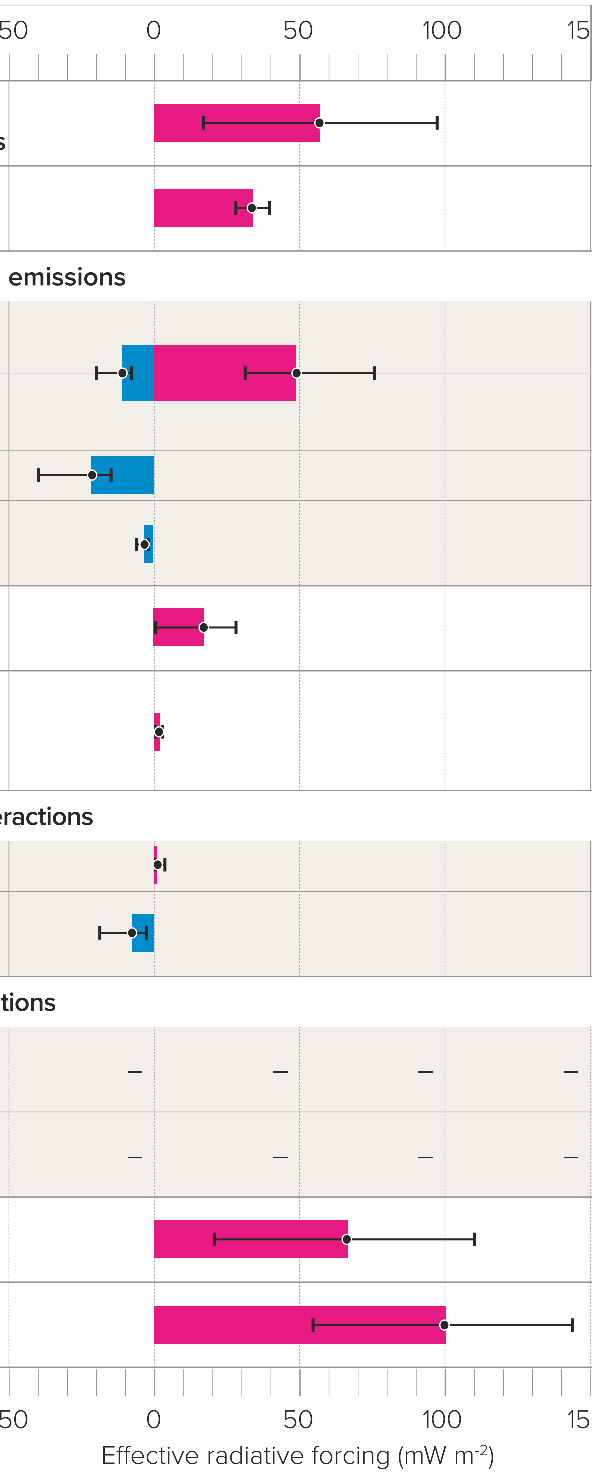
152 Bier, A, & Burkhardt, U. (2019). Variability in contrail ice nucleation and its dependence on soot number emissions. Journal of Geophysical Research: Atmospheres, 124(6), 3384-3400.

FIGURE 12

Climate forcing terms from global aviation from 1940 to 2018

KEY

Best estimates   5 – 95% confidence



	ERF (mW m-2)	RF (mW m-2)	ERF / RF	Confidence levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Medium
Short-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9(-34, -13)	1.18	Medium
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	–	Low
Water vapour emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Medium
Aerosol-radiation interactions				
From soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
From sulphur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
From sulphur emissions				
From soot emissions	No best estimates	No best estimates	–	Very low
Net aviation (non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	–	–
Net aviation (all terms)	100.9 (55, 145)	149.1 (70, 229)	–	–

Source: Lee *et al* (2021)[153].

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%, ie net aviation ERF 0.08 W m^{-2} out of the net anthropogenic ERF of 2.29 W m^{-2} [153]. 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[154].

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[145]. Hydrogen and ammonia combustion also has the potential to produce even fewer particles[155]. 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.

153 Lee, D S, Fahey, D. W, Skowron, A, Allen, M R, Burkhardt, U, Chen, Q, ... & Wilcox, L J. 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment.* 244, 117834. (https://doi.org/10.1016/j.atmosenv.2020.117834).

154 Climate Change Committee. 2020. The Sixth Carbon Budget: The UK's path to Net Zero. See https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf (accessed 5 September 2022).

155 Ström L, Gierens K. 2002 First simulations of cryoplane contrails. *Journal of Geophysical Research.* 107, 4346. (https://doi.org/10.1029/2001JD000838).

A series of numerical simulations were performed[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, ie, optically thinner than contrails from kerosene combustion aircraft[156].

Another study[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 (ie, ~10%) 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_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_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[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_X. The science on these effects is quite outdated but generally lots of flying in the stratosphere is likely to have adverse environmental impacts.

156 Gierens K. 2021 Theory of Contrail Formation for Fuel Cells. *Aerospace*. 8, 164. (https://doi.org/10.3390/aerospace8060164).

157 Ponater, M, Pechtl, S, Sausen, R, Schumann, U, & Hüttig, G. (2006). Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. Atmospheric Environment, 40(36), 6928-6944. (https://doi.org/10.1016/j.atmosenv.2006.06.036).

158 Matthes, S, Lee, D S, De Leon, R R, Lim, L, Owen, B, Skowron, A, … & Terrenoire, E. (2022). The Effects of Supersonic Aviation on Ozone and Climate. Aerospace, 9(1), 41. (doi.org/10.3390/aerospace9010041).

3.7.3 Other non-CO_2 considerations

Oxides of nitrogen (NO_x) emissions might expect to be reduced with newer engine designs reducing its ERF. However, NO_x 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 NO_x is a balance of warming and cooling effects which may be changed in the future, as the aviation effect of NO_x 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-CO_2 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-CO_2 effects

In summary, alternative fuels will have continued non-CO_2 effects on climate. However, there is potential hope that the non-CO_2 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-CO_2 effects both through careful aircraft and engine designs and improved operations.

159 Grewe, V, Bock, L, Burkhardt, U, Dahlmann, K, Gierens, K M, Hüttenhofer, L, ... & Levy, Y. (2017). Assessing the climate impact of the AHEAD multi-fuel blended wing body. Meteorologische Zeitschrift, 26(6), 711-725.

160 Warwick et al, 2022 Atmospheric implications of increased Hydrogen use. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmospheric-implications-of-increased-hydrogen-use.pdf (accessed 30 July 2022).

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 research[161]. 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.

161 Dwivedi S, Vishwakarma M. 2018 Hydrogen embrittlement in different materials: A review. Int J Hydrogen Energy. 43(46), 21603-21616. (https://doi.org/10.1016/j.ijhydene.2018.09.201)

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].

Other fluid energy storage media – such as hydrogen or ammonia will require their own specialist fuel gauging systems that may not presently exist.

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].

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162 Aerospace Testing International (Largest study yet of 100% biofuel-use for airliners starts at Airbus). See https://www.aerospacetestinginternational.com/news/engine-testing/largest-study-yet-of-100-biofuel-use-for-large-airliners-starts-at-airbus.html (accessed 5 September 2022).

163 Safran (Fuel gauging systems). See https://www.safran-group.com/products-services/fuel-gauging-systems (accessed 5 September 2022).

164 Wu, J, Yuan, X Z, Martin, J J, Wang, H, Zhang, J, Shen, J, … & Merida, W. (2008). A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies. Journal of Power Sources, 184(1), 104-119.. See https://doi.org/10.1016/j.jpowsour.2008.06.006 (accessed 5 September 2022).

165 Airbus (ZEROe). See https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (accessed 5 September 2022).

166 Airbus (Exploring Hydrogen). See https://aircraft.airbus.com/en/newsroom/news/2021-09-exploring-hydrogen (accessed 5 September 2022).

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 irritation[167] 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.

167 Public Health England. 2019 Ammonia: Incident Management. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/825191/Ammonia_IM_PHE_140819__1_.pdf#:~:text=Standard%20%28UK%29%20dangerous%20goods%20emergency%20action,codes%20Ammonia%2C%20anhydrous%20UN%201005%20Ammonia%2C%20anhydrous (accessed 5 September 2022).

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 cylinders[168]. 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 spaces[169]. 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 chain[170].

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.

168 Office of Energy Efficiency & Renewable Energy (Liquid Hydrogen Delivery). See https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery (accessed 5 September 2022).

169 Health and Safety Executive. 2010 Hazards of liquid hydrogen: Position paper. See https://www.hse.gov.uk/research/rrpdf/rr769.pdf (accessed 5 September 2022).

170 Airports council international. 2021 Integration of Hydrogen Aircraft into the Air Transport System: An Airport Operations and Infrastructure Review. See https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf (accessed 5 September 2022).

FIGURE 14

Tampa Airport (FL, USA) Illustrating optimisation for present aircraft shapes and use of extensive present / legacy technology support equipment

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[171].

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[172], 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[173]. 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.

171 ICAO (ICAO SAF facilities map). See https://datastudio.google.com/u/0/reporting/2532150c-ff4c-4659-9cf3-9e1ea457b8a3/page/p_2sq3qol5nc?s=mGz_sTv1l-c (accessed 5 September 2022).

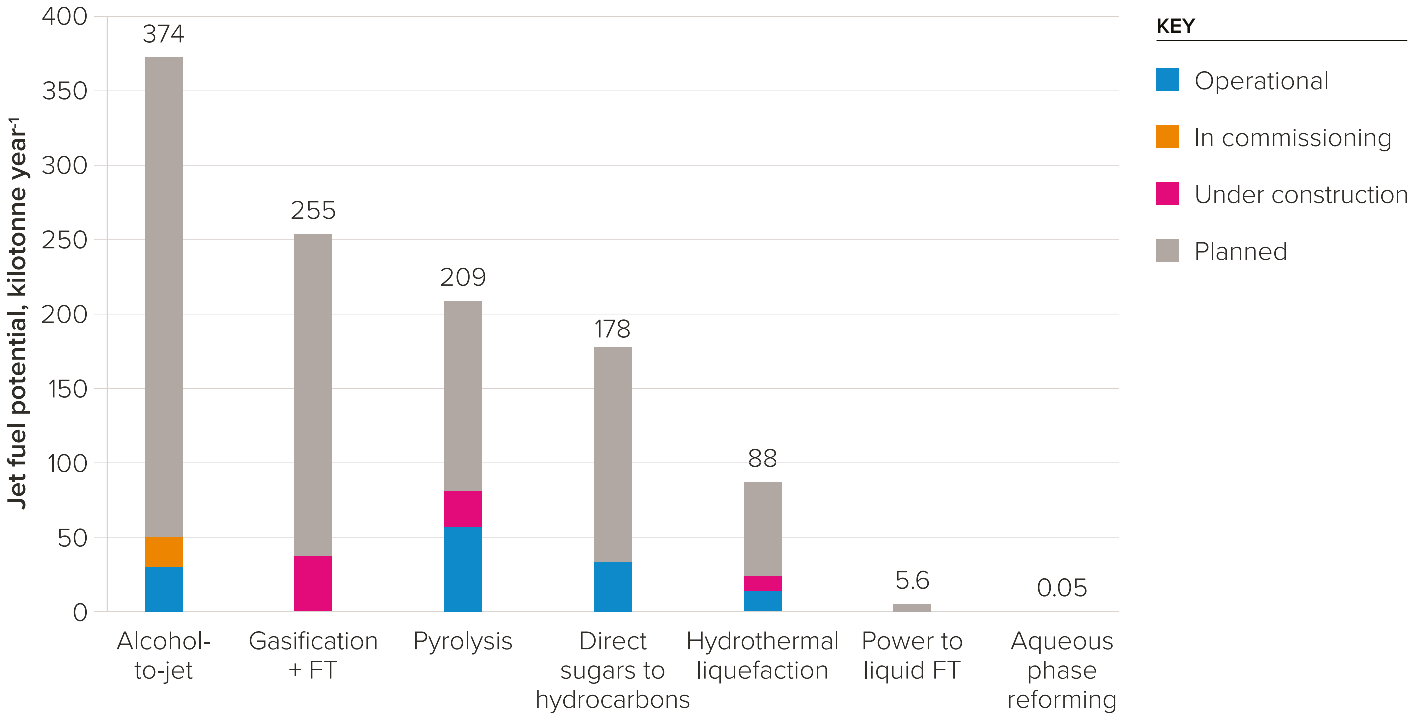
172 Department for Transport (UK), (2021). Green Fuels, Green Skies (GFGS) competition. See https://www.gov.uk/government/publications/green-fuels-green-skies-gfgs-competition (Accessed 20 June 2022).

173 Ricardo Energy and Environment (2021) Green Fuels, Green Skies Competition. See https://ee.ricardo.com/gfgs (Accessed 20 June 2022).

FIGURE 15

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.

BOX 1

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 60litres / day (40litres / 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.

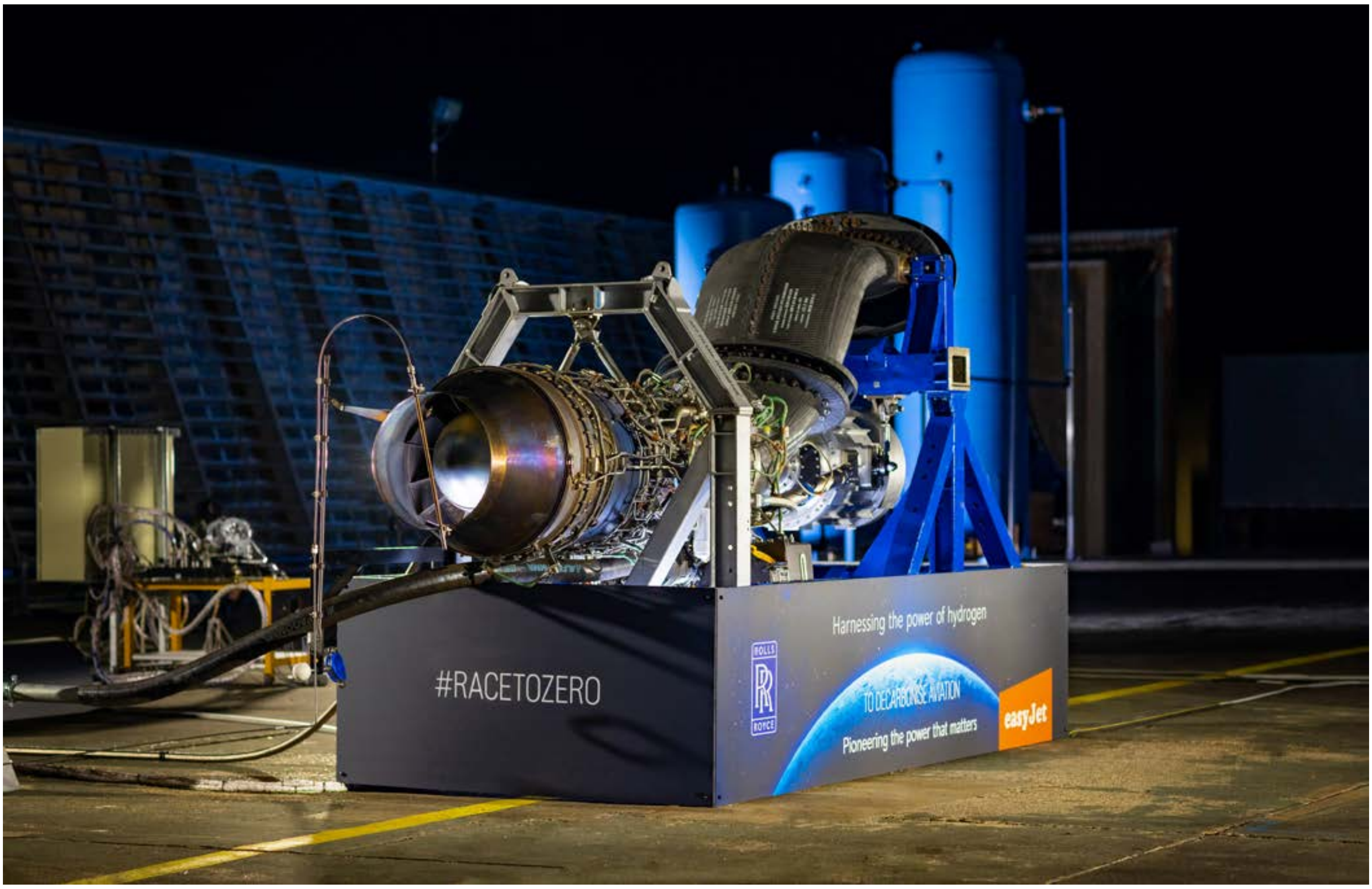
Lanzatech UK Ltd and Carbon Engineering
Proposes the integration of innovative technologies to produce over 100 million litres per year of SAF. Carbon dioxide (CO_2) captured from the atmosphere using DAC technology, and hydrogen from water electrolysis, will be converted into SAF using LanzaTech's gas 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[174].

174 Rolls-Royce (2022). Rolls-Royce and EasyJet set new world first. See https://www.rolls-royce.com/media/press-releases/2022/28-11-2022-rr-and-easyjet-set-new-aviation-world-first-with-successful-hydrogen-engine-run.aspx (accessed 29 November 2022).

FIGURE 16

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



Source: Rolls-Royce.

TABLE 8

Aviation fuel pathway

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.

Fuel Type	Feedstock / pathway	Resource Implications	Cost and Technology readiness level (TRL)
Biofuels	**Rapeseed** (*Brassica napus*)	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.	HEFA -SPK, TRL 7-8 **Energy cost** £42.1/GJ of fuel
	Miscanthus Alcohol-jet pathway with ethanol as an intermediate	102.5 – 61.5 million tonnes of biomass would be required to meet UK Jet fuel demand. 54 - 33% equivalent fraction of UK agricultural land is required to produce this amount of biomass.	ATJ-SPK, TRL 5-6 **Energy cost** £17.5/GJ of fuel
	Wood (poplar) Gas to jet pathway using Fischer Tropsch	123 - 55.9 million tonnes of biomass would be required to supply UK Jet fuel demand. 66 – 30% equivalent fraction of UK agricultural land is required to produce this amount of biomass.	FT-SPK, TRL 5-6 FT-SPK/A, TRL 5-6 **Energy cost** £40.3 – 59.4/GJ of fuel £40.3 – 59.4/GJ of fuel
	Sugarcane and sugary biomass Currently fermented and hydro processed to produce synthetic iso-paraffinic kerosene (HFS-SIP)	Not currently used to produce aviation fuel as there are other higher value uses for this feedstock.	HFS – SIP, TRL 5-6 ATJ-SPK, TRL 5-6 **Energy cost** £22.8 – 48.3/GJ of fuel
	Waste cooking oil	About 250 million litres of used cooking oil is produced in the UK each year. 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.	HEFA-SPK, TRL 8 Co-processing, TRL 8-9 **Energy cost** £13.7 – 20.7/GJ of fuel
	Municipal waste	Total renewable content is estimated to be 40 Mt/year. Ricardo (2017) estimate that 12 Mt/year could be used for bioenergy production. 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.	FT-SPK/A, TRL 5 -6 **Energy cost** £22.6 – 33.1/ GJ of fuel
	Sewage	Feedstock is plentiful and has few competing uses.	Not available

	Life Cycle Impacts	R&D Challenges and Future work
	Oil crops show a wide range of emissions based on allocation methods (-12—55 g CO_2eq/MJ).	**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.
	The processes needed to convert grass to biofuel requires a significant energy input and that leads to GHG emissions.	**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.
	FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO_2eq/MJ) depending on allocation method.	**Resource implications** Availability of sustainable feedstock
	Alcohol-to-jet fuel production using corn, corn stover and sugarcane give GHG emissions of 55—78 g CO_2eq/MJ. Sugarcane through Direct Sugar to Hydrocarbon (DSHC) pathways show a high GHG emission regardless of allocation method (72—75 g CO_2eq/MJ)	**Resource implications** Availability of sustainable feedstock **HFS-SIP** This process is characterised by low overall efficiency which leads to high operational costs. Producers' interests have shifted away from fuels and focused on chemicals and pharmaceutical buyers.
	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.	**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.
	Significantly large GHG emissions (32.9—62.3 g CO_2eq/MJ WTW) are associated with the use municipal solid waste.	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.
	HTL of sewage sludge provides 58% GHG savings when compared to conventional Jet fuel.	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)

Fuel Type	Feedstock / pathway	Resource Implications	Cost and Technology readiness level (TRL)
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, 1.7% 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.

	Life Cycle Impacts	R&D Challenges and Future work
	FT synthesis of willow, poplar and forest residues provides GHG emission savings (4—13 g CO_2eq/MJ) depending on allocation method. Pyrolysis of forest residues vary from in-situ (22 g CO_2eq/MJ) and ex-situ (40 g CO_2eq/MJ). Hydrothermal liquefaction (HTL) of forest residues shows GHG emissions of 17—20.5 g CO_2eq/MJ). Using fermentation, slightly improved GHG emissions (19.41g CO_2eq/MJ) in forest residues are observed, representing a 78% improvement over traditional jet fuel.	**Resource implications** The UK is one of the least forested countries in Europe and may have to rely on importing this resource.
	For UK produced hydrogen, GHG emissions pathways range from 10 – 45gCO_2e/MJ for abated natural gas pathways and 0 – 5 gCO_2e/MJ for renewable and nuclear electrolysis. **Non-CO_2 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. 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. 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. 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). 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 NOx. A lot of flying in the stratosphere is likely to have adverse environmental impacts. 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.	**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. This alternative aviation route requires increases in wind and solar power generation and would result in significant cost increase to the consumer. **Storage and distribution requirements** Infrastructure changes will be required to safely store, liquefy, transport, and use Hydrogen at the airport and in the aircraft. Cryogenic storage in tanks onsite or close to the airport is an energetically expensive process. Staff will need to be trained on safety standards. **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. There is an urgent need for independent modelling experiments, laboratory studies and testing. **Design considerations** Nitrogen Oxides emissions might expect to be reduced with newer engines reducing its ERF. Direct sulphur and soot climate effects would reduce as their emissions would reduce with new engine designs. **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

TABLE 8 (continued)

Fuel Type	Feedstock / pathway	Resource Implications	Cost and Technology readiness level (TRL)
Ammonia (NH_3)	**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	**CO_2 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 CO_2 from direct air capture 72.7 £/GJ – Using CO_2 from a concentrated source

	Life Cycle Impacts	R&D Challenges and Future work
	Renewable routes of ammonia fuel production offer CO_2 savings over conventionally fuelled routes, depending upon the source of renewable power.	**Renewable energy requirements** NH_3 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. Staff will need to be trained on safety standards. **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.
	GHG emissions can be close to carbon neutral, but this depends on the source of CO_2 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.

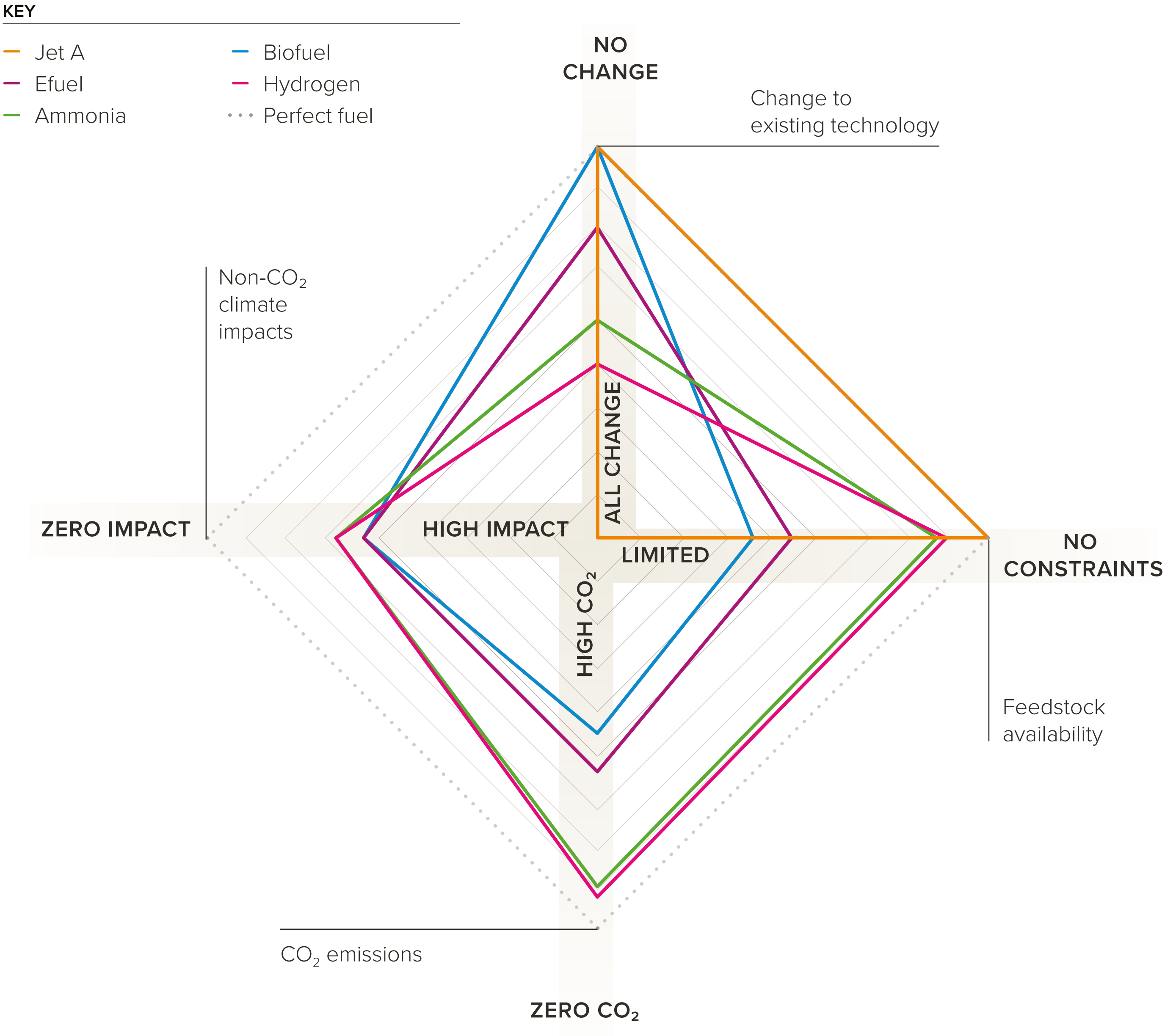
It is important to consider that waste is different in different regions, and its availability varies across regions and countries. Increased recycling will lead to less waste and availability of waste will thus be more restricted in the future. Standardisation of very many different waste to fuel pathways 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 CO_2. 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.

FIGURE 17

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).



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_2eq/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 "CO_2 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

Acronym	Detail
ABSL	Advanced biofuel solutions
AIC	Aviation-induced cloudiness
ASTM	American society for testing and materials
ATI	Aerospace technology institute
ATJ-SPK	Alcohol to jet- synthetic paraffinic kerosene
AVGAS	Aviation gasoline
AVTUR	Aviation turbine fuel or Jet-A1
BEIS	Department for Business, Energy and Industrial Strategy
CCU	Carbon capture and use
CHJ	Catalytic hydrothermolysis jet
CORSIA	Carbon offsetting and reduction scheme for international aviation
DAC	Direct air capture
DEFRA	Department for Environment, Food and Rural Affairs
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German aerospace center)
DLS	Deck launch speed
DSHC	Direct sugars to hydrocarbons
EASAC	European Academies' Science Advisory Council
ERF	Effective radiative forcing
EU	European Union
FCC	Fluid catalytic cracker
FEED	Front end engineering design
FOG	Fats, oils and grease
FT-SPK	Fischer Tropsch Synthetic Paraffinic Kerosene
FT-SPK / A	Fischer Tropsch Synthetic Paraffinic Kerosene with aromatics
GGR	Greenhouse gas removal
GHG	Greenhouse gas
GWP	Global warming potential
HC-HEFA-SPK	Hydrocarbon-hydroprocessed esters and fatty acids synthetic paraffinic kerosene
HEFA-SPK	Hydroprocessed esters and fatty acids synthetic paraffinic kerosene
HFS-SIP	Hydroprocessed fermented sugars- synthesised iso-paraffins
HRJ	Hydrotreated renewable jet
HRJF	Hydro-processed renewable jet fuel
HTL	Hydrothermal liquefaction
HVO	Hydrogenated vegetable oil
ICAO	International Civil Aviation Organization
ICAO-CAEP	International Civil Aviation Organization's Committee on Aviation Environmental Protection

IEA	International Energy Agency
IPCC	Intergovernmental Panel for Climate Change
LCA	Life cycle analysis
LGF	Lighthouse green fuels
LHV	Lower heating value
LUC	Land use change
MSW	Municipal solid waste
MTO	Methanol to olefins
NCAR	National Center for Atmospheric Research
NDC	Nationally determined contribution
PtJ	Power to jet
PtL	Power to liquid
RCFs	Recycled carbon fuels
RF	Radiative forcing
RFFS	Rescue and firefighting services
RFNBOs	Renewable fuels for non-biological origin
RTFO	Renewable transport fuel obligation
RWGS	Reverse water gas shift
RWGSR	Reverse water gas shift reaction
SAF	Sustainable aviation fuel
SMR	Small modular reactors
SPK	Synthetic paraffinic kerosene
SRW	Small roundwood
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate Change
VTOL	Vertical take-off and landing
WTW	Well-to-wake

Appendix C: Acknowledgments

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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.

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