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Low-carbon fuels for aviation

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Headlines

The aviation industry is responsible for 2.1% of global CO_2 emissions and represents 12% of CO_2 emissions from all transport sources.

Aviation is a particularly difficult sector to decarbonise because alternative fuels are relatively expensive, produce highly distributed greenhouse gas emissions in their production and combustion, and should preferably be compatible withexisting aviation infrastructure.

Emissions from aviation also include nitrogen oxides (NO_X), water vapour, particulates, carbon monoxide, unburned hydrocarbons, and sulfur oxides (SO_X). These have a 2–3 times greater climate change impact than CO_2 alone. The non-CO_2 emissions of alternative low-carbon aviation fuels can differ significantly from those of kerosene and have not been fully evaluated.

Biofuels

- Bio-jet fuels are currently the most technologically mature option for low-carbon aviation fuels because some of these feedstocks and processes are already deployed at scale for other uses.
- Bio-jet fuels must be blended with kerosene to achieve certification and can then be used with existing aviation infrastructure. This blending proportionally decreases any potential CO_2 emission saving.
- Bio-jet fuels can be made from a range of feedstocks, which are restricted in the UK to waste materials. UK biofuel feedstock availability is sufficient for only a small proportion of UK aviation fuel demand (<20%). With blending, their contribution to CO_2 emissions saving is much less (<10%).
- Life cycle assessment scenarios show very variable impacts on CO_2 emissions for biofuel processes: only some deliver emissions savings compared to fossil fuel kerosene. Calculations for forest residues appear to show consistent savings in CO_2 emissions compared to jet fuel, but these do not take account of the difference in timescale between emission and re-absorption, leading to a major underestimation of emissions. The diversion of agricultural and forestry waste to bio-jet fuel production will have detrimental effects, for example on soil quality.

Power-to-Liquid fuels

- PtL fuels must be blended with kerosene to achieve certification and can then be used with existing aviation infrastructure. This blending proportionally decreases any potential CO_2 emission saving.
- PtL fuels are currently not produced at scale. Significant technological development is required to reduce production costs and increase production scale.
- Use of PtL fuels in aviation would require a very significant increase of UK low-carbon electricity generation and storage capacity to power production of green hydrogen and CO_2 from direct air capture.
- Life cycle assessment scenarios show that PtL fuels could have 3–10 times lower emissions impact than fossil fuel kerosene if renewable electricity and CO_2 from direct air capture are used to produce the fuel.

Hydrogen

- Hydrogen cannot be used as a drop-in fuel for aircraft, and its use will require significant redesign of aviation infrastructure.
- The greenhouse gas emissions impact of hydrogen depends on its mode of production. Currently, global hydrogen production is mostly from fossil fuel sources, with much less than 1% generated from low-carbon sources.
- Increasing low-carbon hydrogen production via electrolysis (green hydrogen) will require the building of additional low-carbon electricity generation capacity.
- Low-carbon hydrogen production via methane reforming with carbon capture and storage (blue hydrogen) should use natural gas obtained from producers with low emissions intensity.

The goal of policy will be to promote whichever technologies achieve the desired sustainability targets. A molecular science and engineering approach combines an understanding of molecular behaviour with a problem-solving mindset derived from engineering. This approach is crucial to the development and the eventual deployment of the fuel technologies discussed in this paper.

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Objectives

The aviation industry is responsible for 2.1% of global CO_2 emissions and represents 12% of CO_2 emissions from all transport sources.[1] The non-CO_2 emissions from aircraft are also significant, estimated to have twice the warming effect of CO_2 emissions.[2] Therefore, reducing emissions from this hard-to-abate sector represents an important contribution towards tackling climate change. A range of strategies to replace conventional jet fuel (kerosene) with 'greener' options has been proposed. The low-carbon aviation fuels most commonly considered are biofuels, power-to-liquid fuels and hydrogen. In this report we evaluate, from a UK perspective, whether these fuels are 'greener' than kerosene, their relative greenhouse gas (GHG) emissions impact, and their viability to meet UK's demand for conventional aviation fuel.

We use three key parameters to evaluate low-carbon aviation fuels: total GHG emissions, resource demand, and scaling. These factors provide a reality check for technologies proposed to reduce GHG emissions and the resources available to achieve this goal. We ask: (1) how should the total GHG emissions impact of each fuel be calculated? (2) How would the demand for feedstocks, energy inputs and land for these technologies compete with existing demands? (3) What policy tools are available to encourage development and adoption of low-carbon fuels, and what are the pitfalls of these tools?

Introduction

The UK became the first country to legislate a net zero GHG emissions target in 2019.[3] To reach this target, a carbon budget was established to balance UK emissions and removals from the atmosphere.[4] International and domestic (including military) UK aviation account for a significant proportion of the UK's total GHG emissions (7% or 38.4Mt CO_2e; see Box 1) in 2018.[5] This contribution needs to be reduced in order for net zero emissions targets to be met. Despite this, emissions from this sector have increased, and are expected to continue to do so, as demand for aviation is expected to grow by 4.1% per year for the next 20 years.[6] Aviation brings significant social and economic benefits,[7] so governments are reluctant to cut aviation demand. Instead, significant research has been carried out into other ways to reduce emissions from aviation, including using alternative fuels.

Aviation is however a particularly difficult sector to decarbonise. This is due to the high cost and low energy density of sustainable aviation fuels relative to kerosene, and the highly distributed nature of the emissions, which are not just from combustion during flight but also from all stages of fuel production. The long lifetime of conventional aircraft means that new fuels need to match the physical, chemical and flow properties of kerosene to be useable in existing fleets. Ultimately, a complete aircraft redesign may be needed for some fuels, but these developments have long lead times. Many of the possible alternative technologies for fuel production, aircraft and airport infrastructure are also an early stage of development and commercialisation. The emissions savings from these technologies are therefore not deliverable yet.

Aviation emissions are also complex:

- In addition to CO_2, emissions from aviation also include nitrogen oxides (NO_X), water vapour, particulates, carbon monoxide, unburned hydrocarbons, and sulfur oxides (SO_X). These have 2–3 times greater climate change impact than CO_2 alone (see Box 1).
- Long-haul flights (those over 4000 km) represent 6.2% of flights but 33–50% of CO_2 emissions.[8,9] Long-haul flights require larger quantities of fuel which increase the weight carried by the aircraft, leading to increased emissions. Reducing emissions from long-haul *vs* short-hop aircraft types may therefore require different strategies.
- Approximately 10% of all aircraft CO_2 emissions are produced during ground-level and landing and take-off operations (LTO). Of these, about 30–50% are allocated to taxiing operations, which last longer (25–30 min) than take-off (<1min) and climbing to cruise altitude (4 min). The balance of non-CO_2 emissions also differs between LTO and flight. Again, a range of different technologies may be employed to reduce emissions from different aircraft operations.

Low-carbon fuels

The UK government's Jet Zero strategy outlines a plan for achieving net-zero GHG emissions in the aviation industry by 2050, with targets for airport operations, sustainable aviation fuel production and greenhouse gas removal.[10] The strategy proposes decarbonising the aviation industry by replacing conventional Jet A/A-1 fossil fuel (kerosene) with alternative fuels that have a predicted lower environmental impact. This paper discusses the three principal alternative fuels – biofuels, PtL fuels and hydrogen – in depth, and briefly comments on batteries and fuel cells.

Biofuels, PtL fuels and hydrogen are produced from a variety of feedstocks via a range of technologies and can be used to power conventional jet engines (biofuels, PtL fuels), modified jet engines (H_2) or electric motors (H_2).

Box 1. Non-CO_2 emissions from aviation[2]

- NO_X: created during high-temperature combustion in jet engines by combining atmospheric nitrogen and oxygen. Has a net warming effect.
- Sulfur: emitted primarily as SO_2. Has a net cooling effect.
- Contrails: artificial cirrus clouds produced at high altitudes (>10 km) by emitted water vapour condensing on emitted soot particles which act as condensation hotspots. Produces a net warming effect.

CO_2 equivalent or CO_2e
CO_2 equivalent is used to compare emissions from different GHGs based on their global-warming potential (GWP). CO_2e means the quantity in tons of CO_2 emissions with the same GWP as one ton of another GHG.

Figure 1 shows the different low-carbon feedstocks and their production pathways.

Fuel eligibility and sustainability criteria have been outlined in the UK Sustainable Aviation Fuels Mandate.[11] In summary, low-carbon fuels should:

- meet the requirements set out in the Defence Standard (DEF STAN) 91–091 specification.[12]
- be either waste-derived biofuels, PtL fuels (using either renewable or low-carbon energy sources) or recycled carbon fuels (produced from recycled carbon of fossil fuel origin, such as industrial flue gasses and non-biogenic municipal wastes).
- comply with the waste hierarchy[13] when derived from wastes. Priority is given to waste destined for landfill (due to the potential GHG savings from avoiding methane emissions) so there is potential for competition with other recycling and re-use routes.
- achieve at least a 50% GHG saving compared to a fossil fuel comparator of 89 gCO_2e/MJ.
- meet land criteria when derived from agricultural wastes and meet forestry criteria when derived from forestry wastes.
- use low-carbon hydrogen where hydrogen is used as an input.

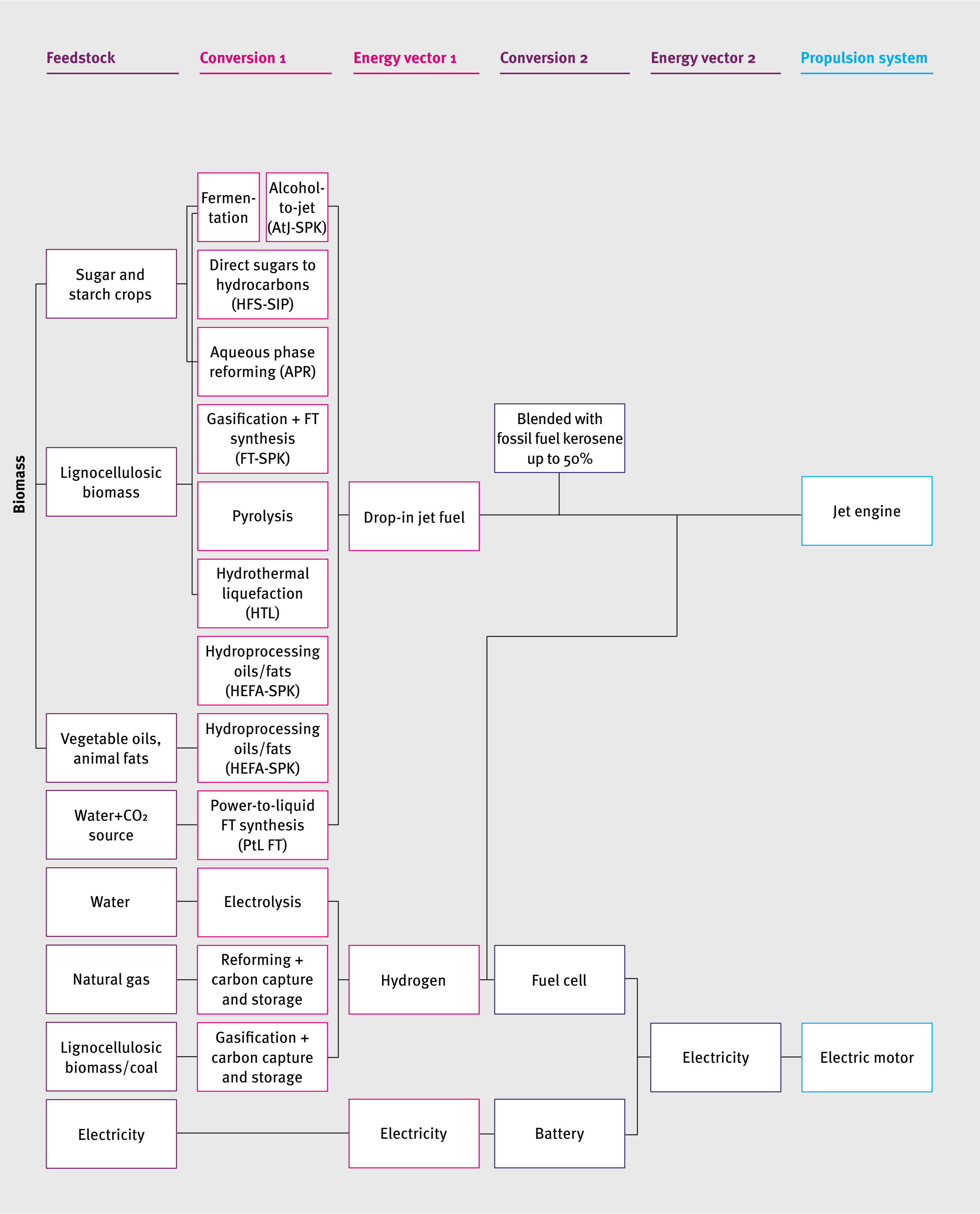

Figure 1. Feedstock routes for alternative low-carbon aviation fuels.

Note the overlap of intermediate feedstocks to multiple fuel types. Adapted from Bauen et al (2020).[14] Acronyms refer to certified biofuel synthesis pathways: SPK = Synthetic Paraffinic Kerosene, HFS-SIP = Hydroprocessed Fermented Sugars to Synthetic Isoparaffins, FT = Fischer-Tropsch, HEFA = Hydroprocessed Esters and Fatty Acids.

Bio-jet fuels

Advanced biofuels, in the form of bio-jet fuels, are currently the most mature option for low-carbon fuels because some of these feedstocks and processes are already deployed at scale to produce biodiesel for road transport.[15] This contrasts with other fuel technologies such as PtL, which rely on facilities that are still under construction or in an early stage of commercial readiness (see below).[16] The International Energy Agency anticipates that bio-jet fuels will reach 10% of global demand by 2030 and nearly 20% by 2040.[15] These are highly ambitious projections as current levels of bio-jet fuel production represents 0.004% of global jet fuel demand,[17] and would require significant scale-up of production infrastructure. The targets are also ambitious given the limited availability of appropriate feedstocks (see below, Resource demand and scale up).

A potential advantage of the biofuels approach is that it can employ a range of feedstocks, including: oily crops (e.g. rape seed, soybean, palm fruit, jatropha); lignocellulosic biomass (e.g. energy crops, grasses, wood, agricultural and forest residues); solid bio-waste (e.g. municipal food and wood waste); algae; and recycled carbon sources such as CO_2 from industrial flue gas.[18] Additionally, synthetic biology has been successfully used to engineer microorganisms to produce alcohols and/or other fuel precursor molecules, that via polymerisation and fractionation can be used to produce bio-jet fuel.[19]

Five aviation bio-jet fuel production pathways are approved for aviation use, with more awaiting approval.[20] At present, however, nearly all bio-jet fuel is derived from oily feedstocks, such as vegetable oil, used cooking oil and animal fats (Figure 2). This is because the hydroprocessing process has high conversion efficiencies and is already deployed at scale to produce road transport fuel. Airlines and fuel production companies are currently developing this pathway, sourcing feedstock from some of the major fast-food chains.[21] Alcohol-to-jet fuel and Fischer-Tropsch processes are the most likely alternative scalable options, accessing a larger array of feedstocks.[17] Large-scale facilities for those technologies are under construction or planned.[22]

The UK Sustainable Aviation Fuels Mandate[11] restricts fuel feedstocks to waste materials. On one hand, this reduces the range of potential feedstock sources (Box 2); on the other it helps safeguard the low environmental impact of bio-jet fuels. A recent industry analysis suggests that the UK does have sufficient fuel feedstocks to meet the mandated requirement of 10% of UK aviation fuel to be sustainable by 2030, but that the announced UK fuel production projects would only enable about half of this and would still require further policy support.[23] UK production of sustainable aviation fuels would enable security of supply and stability of price. Reliance on imports would expose the UK market to significant competition, given the global demand from EU mandates and targets being set in the UK, Japan, Turkey, Canada, Australia and others.

The physical, chemical and flow properties of jet fuel are defined by DEF STAN 91–091,[12] which set requirements for criteria such as volatility, fluidity, combustion, corrosion, thermal stability, contaminants and additives. All low-carbon fuels must adhere to these requirements to be considered as drop-in fuels. Up to now, bio-jet fuels have only been certified as blends with conventional kerosene, at 10–50% content, depending on the type of biofuel, the feedstock and the method used for its production.[24,25] This is because biofuels produced in refineries do not conform to DEF STAN 91–091, unless blended with kerosene, due in part to differences in chemical composition, such as lack of cyclic alkanes and aromatics.[26,27] Efforts to achieve 100% low-carbon fuel certification are currently underway, by tuning the chemical composition of bio-jet fuels by either improving the fractionation process (though this would reduce yield) or adopting synthetic biology and microbial metabolic engineering approaches.[19] In all cases, re-engineering conventional engines is also required to efficiently utilise new drop-in bio-jet fuels and reduce reliance on aromatics. It is not clear which of these approaches was adopted by the team behind the recent announcement of the first 100% “low-carbon” fuel powered flight,[28] due to commercial confidentiality.

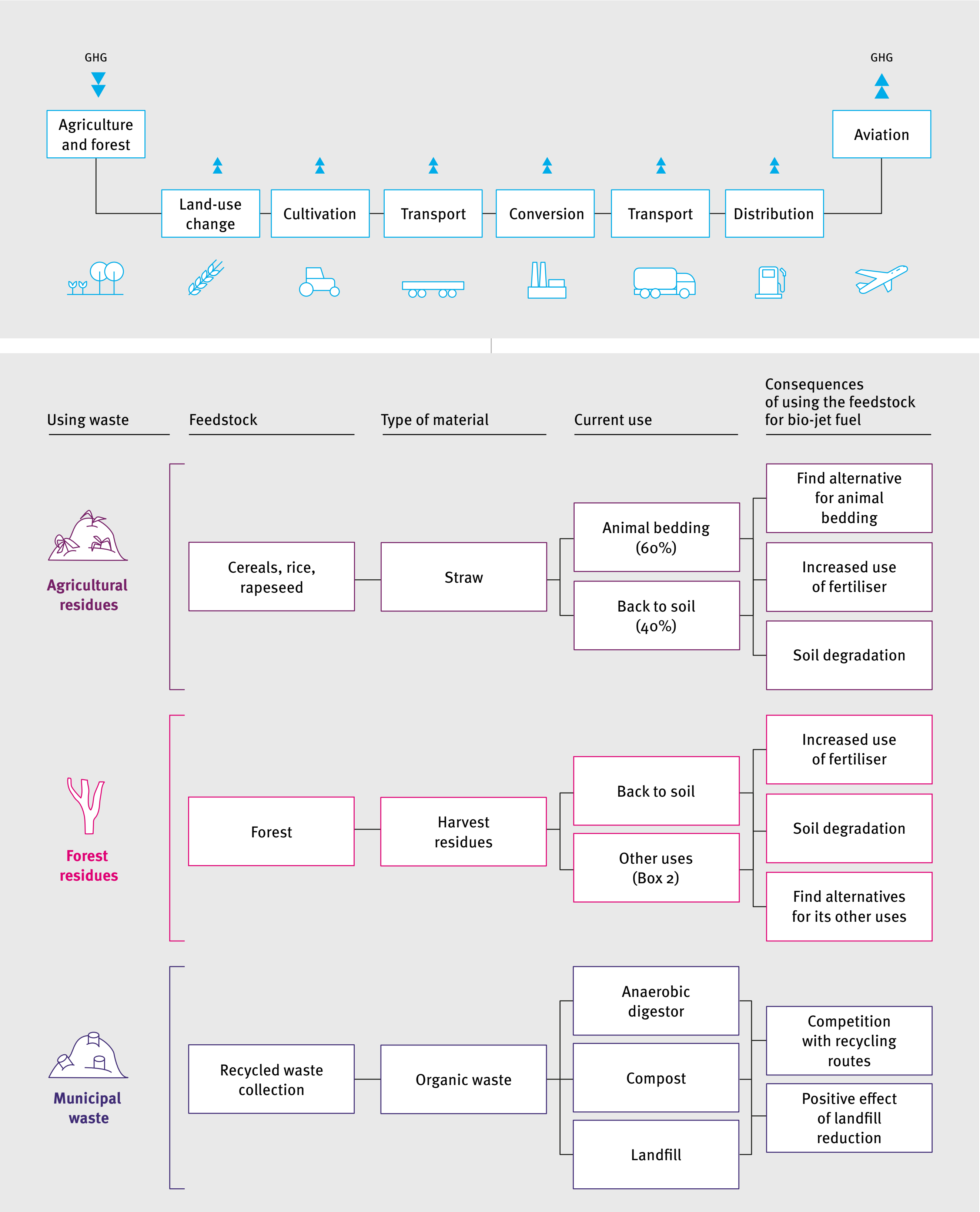

Figure 2. Flow chart of bio-jet fuel production, with absorption and emission of GHGs at each step.

Power-to-Liquid

PtL fuels is a broad term covering all fuels produced using electricity; e-kerosene refers to the subcategory of these fuels suitable for aviation. This type of low-carbon fuel is generated by combining hydrogen (H_2) and carbon dioxide (CO_2) and applying electricity. The terms synthetic fuel and e-fuel are also used to refer to e-kerosene. Several industrial processes can be used to produce PtL fuels, the two most common being Fischer-Tropsch (FT) synthesis and methanol synthesis.

Similar to bio-jet fuels, PtL fuel is considered a drop-in fuel and needs to be blended with fossil fuel kerosene to conform with industry fuel standards. PtL fuels produced via FT lack aromatic molecules that are needed to prevent leaks in conventional aircraft fuel systems.[29,30] Currently only the FT process has been certified for use in blends up to 50%, so this is the only synthesis pathway considered in the remainder of this paper. More research in the area is needed to develop PtL fuels with the exact properties of Jet Air 1.

There is currently only one plant in the world that produces e-kerosene at pilot scale, i.e. up to 350 tonnes of PtL fuel per year.[31] This represents only 0.0001% of UK fuel demand in 2019. To produce PtL with a 'low' environmental impact, production must fit the following criteria:[32]

- any H_2 used must be low carbon, i.e. produced via water electrolysis or via methane reforming with CO_2 capture and storage (CSS);[33]
- CO_2 must be captured from air using direct air capture (DAC) technologies, or from biogenic sources e.g. fermentation or anaerobic digestion;
- the energy input for these processes must be provided by low-carbon energy sources.

There is currently no large-scale production or use of e-kerosene. Scaling up production and commercialising this fuel type requires significant R&D and also policy support in order to (1) reduce the cost of production, which is currently 3–9 times greater than fossil fuel kerosene,[34] (2) increase the availability of raw materials such as green hydrogen and CO_2 from DAC, and (3) increase low-carbon electricity generation capacity to power these processes. Furthermore, technologies in all stages of e-fuels production must reach the same maturity level in order for production to be feasible.[35]

Hydrogen

Hydrogen produces no CO_2 emissions when burned so plays a central role in the net zero emissions strategies of the UK and many other countries.[36–38] The true emissions savings for hydrogen-powered aircraft will depend on the GHG emissions during the production and distribution of hydrogen and the amount of non-CO_2 emissions generated during flight.

Currently, most global hydrogen production is from fossil fuel sources, with less than 1% generated from a low-carbon source (Table 1). Furthermore, hydrogen is a crucial feedstock for the production of both bio-jet fuels and PtL, which drives up demand. Increasing the availability of low-carbon hydrogen is an important strategic goal for decarbonising aviation.

Table 1. Current global hydrogen production sources.

Description	Process	% of global production[39]
Grey	Reforming of natural gas	60
Brown	Coal gasification	19
Blue	Reforming of natural gas with CCS	<1
Green	Water electrolysis	<1
–	By-product of oil refining	19

Hydrogen combustion engines

Unlike bio-jet fuels and PtL, hydrogen cannot be used directly as a drop-in fuel in existing aircraft. Liquid hydrogen is around three times lighter than conventional jet fuel but occupies a volume four times larger. Large and heavy insulated storage tanks are required to store liquid hydrogen at cryogenic temperatures (≈20K, -253°C). Liquifying H_2 is energy-demanding and costly, manipulating liquid H_2 cryogenic temperatures (for fuelling) is problematic, and keeping hydrogen at cryogenic temperatures means it cannot be stored in the wings of the aircraft like conventional jet fuel. The hydrogen aircraft airframe must be redesigned to integrate large fuel tanks into the fuselage, e.g. the Airbus ZEROe.[40] Moving the storage tanks on-board requires special provisions to be made for the aircraft to maintain its crashworthiness, e.g. in the event of an emergency landing. Advanced construction materials will also be needed, to avoid hydrogen embrittlement and leakage and increase the lifetime and durability of onboard hydrogen storage systems.[41]

Hydrogen fuel is more energy-dense than conventional jet fuel (10–21 kWh/kg[42] *vs* 9 kWh/kg[43]). However, the benefit of the reduced weight of the fuel is offset by the additional structural weight of the insulated fuel tanks, therefore the net benefit is dependent on the aircraft design.[44]

Hydrogen combustion aircraft have the potential to replace conventional aircraft with relocated storage tanks on short- and medium-range routes. The size of the storage tanks required for long-range flights may be too large for operation if integrated into existing aircraft.[45] However, designs for long-range aircraft based on conventional and next-generation aircraft designs have been proposed.[40,46]

Hydrogen fuel cells

Hydrogen fuel cell aircraft operate by converting hydrogen to electricity, which is used to power the propeller. At present, several start-ups are developing fuel cells currently used in heavy goods vehicles for adaptation to aircraft.[47] Fuel cell aircraft are suitable for light (<80 passengers) regional routes, with a range of less than 1000 km (representative of only 3–4% of aviation CO_2 emissions).[45] The number of fuel cells needed to power longer-range flights would release so much heat that large and heavy cooling systems would be required.[45] The technology is unlikely to overcome the challenge of the combined weights of the hydrogen storage tanks, fuel cells and cooling systems, which would make the aircraft too heavy to operate over long distances.

Ammonia

Ammonia is seen as an alternative to hydrogen for aviation fuels.[48] Green ammonia production requires the availability of green hydrogen.[49]

Ammonia has significantly higher energy density than both liquid and high-pressure hydrogen, and requires more energy to produce (by 5–10%). However it requires less energy to store as it needs to be cooled only to -77°C instead of -253°C. It is considered a safer alternative to hydrogen. Unlike hydrogen, ammonia will not require alternative fuel tanks and re-fuelling stations. Using ammonia as aviation fuel will reduce CO_2 and hydrocarbon emissions, and reduce contrail formation due to the absence of soot. However high NO_x emissions will occur from N_2 oxidation and ammonia oxidation.[50]

Ammonia combustion performance is still unsatisfactory and therefore further studies are needed for large scale application in aviation. For these reasons, we do not discuss ammonia further in this paper.

Batteries

Battery energy storage can power electric aircraft with zero in-flight GHG emissions. The climate impact of this option therefore depends on the GHG emissions intensity of the electricity generation on the ground, and the amount of energy needed to fuel the aircraft. Despite significant improvements over the past decades, the energy density of batteries (0.2–0.5 kWh/kg) is still much lower than conventional jet fuel: 1 kg of jet fuel yields 15 times more energy than a 1 kg battery.[43] The weight of large batteries in aircraft must also be lifted by those batteries, and of course this weight does not reduce during the flight, unlike for conventional fuel. Thus, although electric motors are more efficient than combustion engines at converting power to output,[51] battery powered aircraft are only suitable for short-range flights with few passengers. Because of this, we do not discuss batteries further in this paper.

Assessing the environmental impact of low-carbon fuels with LCA

The International Civil Aviation Organization, with the support of more than 100 nations including the UK, has established a global offsetting scheme, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).[52] This scheme was developed to standardise the calculation of the GHG emissions savings via Life Cycle Assessment (LCA), which is the preferred tool to evaluate the environmental impact of a total product or process. Results obtained from LCA studies demonstrate large variations, depending on the system boundaries chosen and the input data used. Figure 3 shows the system boundaries that are typically applied to low-carbon fuels:

- Well-to-tank includes feedstock extraction, transport, fuel refining and delivery to the tank of the aircraft.
- Well-to-wake includes all the well-to-tank steps plus the emissions from the combustion of the fuel.

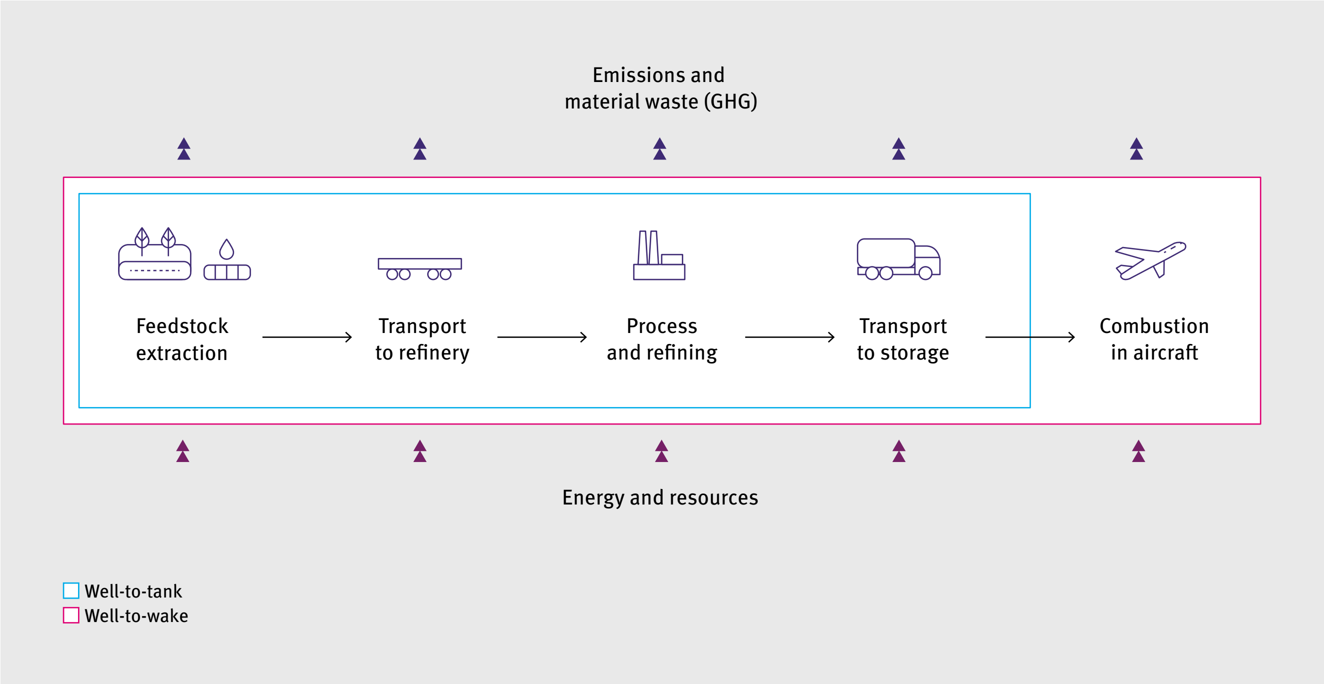

Figure 3. Typical LCA system boundaries for a generic aviation fuel pathway.

Most published LCAs set their boundaries as well-to-wake. However, they effectively use a well-to-tank approach, which includes only the emissions of fuel production, because the CO_2 emitted upon combustion of the fuel is considered to be offset by the CO_2 captured during the production of the feedstock, by photosynthesis or DAC. This assumes that these events occur on the same timescale. This might be the case for DAC, but it is certainly not the case for photosynthesis: absorption of CO_2 from air by plants and algae is much slower than emission of CO_2 from combustion of fuel in a jet engine. This difference in timescale can lead to a large underestimation of overall GHG emissions, especially for forest or forest residue feedstocks.[53–55] Dynamic LCAs and other methodologies should be employed to assess the extent of this offset.

Estimating non-CO_2 effects is difficult but important (see Table 2):

- The non-CO_2 emissions from aircraft are estimated to have twice the warming effect of CO_2 emissions alone (Box 1).[2]
- Bio-jet fuels and synthetic kerosene are hydrocarbons, so their non-CO_2 effects at high altitudes (i.e. contrail formation, SO_x, NO_x and water vapour) are similar to conventional fuel.
- Both bio-jet fuel and e-kerosene contain reduced quantities of the aromatic compounds that produce soot, thus in theory reducing contrail formation. However, these aromatic compounds contribute to the correct working of rubber seals in aircraft engines and therefore are currently added to drop-in low-carbon fuels. New engine technologies being developed could eliminate the requirement for aromatics.[30] Furthermore, the work directed at improving the chemical composition of low-carbon fuels to match that of Jet A-1 could utilise cyclic alkanes instead of aromatics.[26,27]
- Although hydrogen combustion produces more water vapour than conventional jet fuel combustion,[56] the contrails produced are predicted to have a lower warming effect as they contain no soot. Small altitude changes to a small number of flights could significantly reduce the climate effects of contrails with minimal impact on fuel consumption and additional CO_2 emissions.[57]

The non-CO_2 effects related to low-carbon fuels must be reduced in parallel with the CO_2 effects. While research is underway, currently only significant efficiency improvements, climate-friendly routing, traffic reduction and offsetting emissions elsewhere can help address non-CO_2 effects.[58]

Figure 4 compares estimated emissions for low-carbon fuel pathways, derived from LCA studies using a well-to-tank approach, compared to conventional fossil fuel kerosene.

Table 2. Estimated in-flight climate impact of aviation.(i)
These figures do not include the climate impact of fuel production.

Technology	CO_2	NO_x	Water vapour	Contrails	Total
Kerosene	100%	100%	10%	100%	310% (range 205–415%) (ii)
PtL	By definition 0% net (iii)	100%	10%	75–100% (iv)	185–210%
Bio-jet fuel	By definition 0% net (v)	100%	10%	75–100%	185–210%
Hydrogen combustion	0%	35%	25%	60%	120% (range 85–300%)

Notes: (i) estimates of climate impact consider global warming potential over 100-year time horizon. CO_2e is determined by the methodology outlined in Clean Aviation (2020).[45] (ii) Estimated ranges reflect uncertainty regarding the warming effect of NO_x, water vapour, and contrails. (iii) Defined as zero or close to zero if DAC is used as a carbon source. (iv) Range depends on whether aromatics are added back in as at present levels (100%) or lower levels (with future improved engine technology, 75%). (v) Net CO_2 emissions of combustion for bio-jet fuels are defined as zero but this does not take account of the difference in timescale between photosynthetic and combustion processes. Data from references.[2,45,56,57,59]

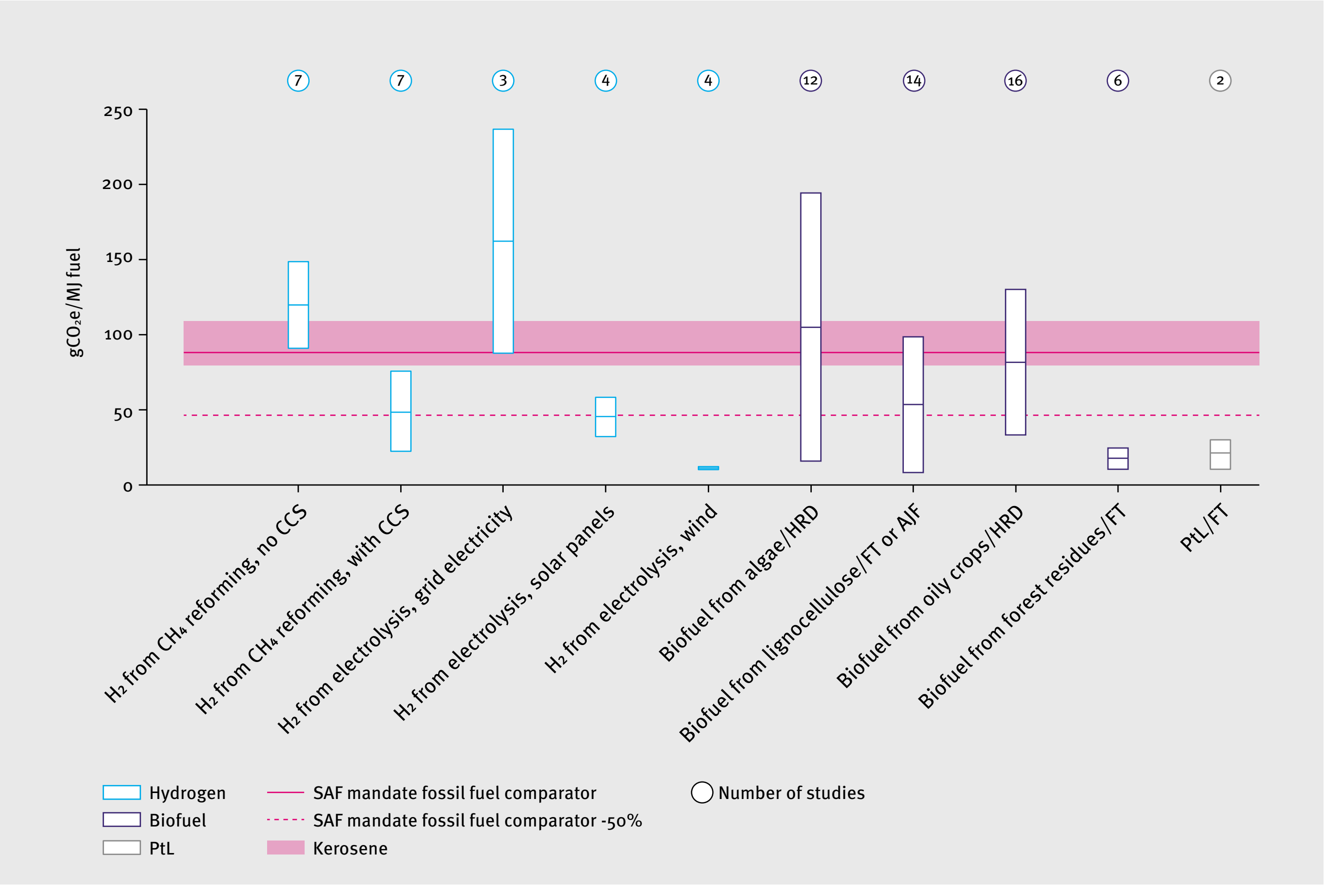

Figure 4. LCA comparison between fuel pathways in gCO_2e/MJ of fuel.

Data for kerosene includes production and combustion (well-to-wake).[60] For other fuels, well-to-tank and well-to-wake are equivalent because combustion values are either zero (for hydrogen) or defined as zero in the carbon accounting model (bio-jet fuels, PtL fuels).[61] Data excludes non-CO_2 emissions. Sustainable Aviation Fuel Mandate fossil fuel comparator values are from Department of Transport (2022).[11] Ranges reflect variation in literature values, and assumptions made in calculations in each study; numbers above each bar indicate number of studies for that fuel type. Notes: (i) for H_2 from CH_4 reforming, the range includes methane emission factors of 0.5% to 6.5%. (ii) for bio-jet fuels, HRD = hydroprocessed renewable diesel; AJF = alcohol to jet fuel; FT = Fischer-Tropsch process; range includes both with and without CCS and land-use change calculations. (iii) for PtL, Fischer-Tropsch synthesis with CO_2 from DAC; range depends on calciner type used for DAC.

Box 2. Using waste for bio-jet fuel production

Agricultural waste

In the UK, agricultural residues are mostly straw from cereal production (wheat, barley, and oat) with a small contribution from oilseed rape residues. Total production is approximately 10 Mt, of which 50–60% is used for animal bedding and feed. Less than 1% is used for electricity production (0.3 Mt), with a projected increase to 0.8 Mt. The rest (~40%) is chopped and returned to the soil as conditioner. If this so-called "waste" material is used for biofuel production, it will be diverted from soil, so soil carbon and nutrient content will be depleted,[66] leading to increased use of synthetic fertilisers (burden shifting). This will increase the GHG emissions of the fuel production process due to increased synthetic fertiliser production. Furthermore, because straw production occurs over large geographical areas, collection and transportation to the refinery will result in additional GHG emissions. LCA produces an average land use change penalty of 50–70 gCO_2/MJ of biofuel.[67,68]

Waste cooking oils

Currently about 250 million litres of used cooking oil are produced annually in the UK. This production is distributed over a large geographic area and much of it is disposed of down the drain or sent to landfill.[69] If this material could be efficiently collected, this would produce between 50–100 million litres of jet fuel, or 0.3–0.6% of the total annual UK demand. The UK is currently highly dependent on imported feedstock to produce renewable fuels from waste cooking oil. Over 423 million litres of used cooking oil was sourced from China in 2021 for biodiesel production.[70] This demand may drive overseas production of cheap virgin oils, such as palm oil, which are sold as waste used cooking oil, and have potential significant adverse environmental effects.[71]

Forest and sawmill residues

Forest residues consist of stem-wood, branch-wood (7–18cm in diameter), brush and stumps which are not suitable for other purposes. Sawmill residues are clean wood residues from timber processing, such as chips, slabs, sawdust, and bark. Approximately 50% of forest residue is left on the ground to protect soil, and the rest is used for animal bedding, board manufacturing, or horticultural chips. Using this material for biofuel production would compete with these uses. As production is geographically dispersed, collection and transportation will incur additional greenhouse gas emissions.

The bioenergy industry initially sought to use forest residues as feedstock, but as these are insufficient for energy demand, it also uses sustainably managed forestry sources.[72] Using a primary forest product has a different environmental impact from using a waste product, so this use must re-evaluated. Trees grow relatively slowly so the difference in timescale for emission and re-absorption is large, which will decrease emission savings.

Municipal waste

Municipal solid waste is collected by local authorities and includes both biogenic and non-biogenic components, which would normally go to landfill. The biogenic fraction includes waste wood from construction, and food waste, both domestic and industrial. It is assumed to have low GHG emissions. As the material is already collected by the local authorities, there is no additional GHG emission penalty for collection. However, it is a very heterogenous material, so fuel yield will be lower than for other, more homogenous feedstocks.

The UK Sustainable Aviation Fuels mandate[11] regulates the use of waste according to the waste hierarchy, which produces incentives for diverting biogenic municipal waste from landfill. Additional pressure on local authorities to increase reuse and recycling might result a smaller amount of waste available for bio-jet fuel production.

Bio-jet fuels

LCA estimates for GHG emissions from bio-jet fuel production processes can vary by a factor of up to 30, even for the same feedstock and process (Figure 4). For all bio-jet feedstocks examined, there are some scenarios where the process would deliver emissions savings compared to fossil fuel kerosene, but in many scenarios it would not. Forest residues seem to be the exception showing consistent savings scenarios. However, these calculations do not take account of the difference in timescale between emission and re-absorption, leading to an underestimate of emissions, and also do not consider the current need to blend bio-jet fuels with fossil fuel kerosene.

The variations observed in LCA estimates are due to system boundary choice, the calculated greenhouse gas savings associated with the co-products of biofuels production (e.g. animal feed, heat, electricity, biochemicals) and the effects of land-use change (LUC).[62] Other examples of elements that are considered with different weight and impact are: water, fertiliser use, biomass transportation and biomass preparation (drying, chopping, etc.). Hydrogen is required in most of the conversion processes due to the need to reduce

Table 3. Estimated production quantities for bio-jet fuel basedon the current available feedstocks in the UK, with calculated contributions to annual national fuel demand.[73,74]

Feedstock type	Total production, Mt/year	Available for biofuels, Mt/year	Yield of conversion to jet fuel	Max annual bio-jet production, Mt/year	Max % annual fuel demand fullfilled
Agricultural residues	10	2–5	0.12	0.6	5%
Forest residues	2.7	0.8–2	0.1	0.2	1.7%
Municipal residues	40	12	0.1	1.2	10%

the highly oxidised carbon typical of biological material, and the source of hydrogen strongly affects the overall greenhouse gas emissions of the process (see below).[19,63,64] Quantifying direct and indirect LUC[19] can be difficult because it is highly dependent on context-specific conditions such as soil type, previous land use and land management practices.[65] Deployment on marginal land has often been proposed to minimise the impact on food security. Nevertheless, soil quality of marginal land is much lower than for agricultural land, which limits yields of biomass production and thus the potential to reduce greenhouse gas emissions, especially at scale.

Considering limits of scale is important when applying standardised LCAs like CORSIA. For example, plant residues obtained from oily crops after oil extraction are used as an animal feed supplement. This co-product offsets the emissions of soy-based animal feed. However, if the market demand for this supplement is smaller than production quantities, the emissions savings associated with the co-product will not be fully scalable. A similar factor affects bio-jet fuels produced from biological municipal waste. Avoiding sending this to landfill is calculated to generate an emissions saving (for methane), but if this waste fraction is currently not sent to landfill but instead to composting, then the emission saving will not apply.

The UK Sustainable Aviation Fuels mandate[11] limits feedstocks to waste materials exclusively. This should relieve direct pressure on food security, but will still have repercussions on LUC, fertiliser use, water, etc (Box 2). Table 3 shows the availability of these feedstocks and the predicted amount of fuel produced. This demonstrates that expanding production of bio-jet fuel using these methods and feedstocks in the UK will be limited by lack of resources. Diverting forest and agricultural residues away from current uses will have large-scale detrimental effect on soil, while the amount of jet fuel produced using UK resources will be barely significant.

PtL fuels

There are very few LCA studies that evaluate the environmental impact of e-kerosene, though some have focused on e-methanol and e-methane (other types of PtL fuel, not directly suitable for aviation).[75] Around two-thirds of the GHG emissions from PtL fuel production come from the generation of electricity for H_2 production, with a further dependence on the type of DAC calciner (electric *vs* oxy-fired).[76] In Germany, GHG emissions for e-kerosene synthesis were lower for wind-produced electricity than solar,[29] but these results are geography-dependent and will also depend on national investment strategy in renewable and low-carbon energy sources.

When compared to the fossil fuel kerosene baseline, PtL fuels could have 3–10 times lower environmental impact, if renewable electricity and CO_2 from DAC are used. The CO_2 captured from air through DAC processes yields negative CO_2 emissions and therefore in a well-to-wake approach (i.e. including fuel combustion), PtL CO_2 fuel emissions could be very low or close to zero. However, this depends on the availability of low carbon energy and CO_2 from DAC (see below, Resource demand and scale up).

Hydrogen

To achieve real CO_2 emissions reductions, hydrogen must be produced from low carbon sources. In its hydrogen strategy, the UK Government committed to produce large quantities of both electrolytic green and CCS-enabled blue hydrogen.[36]

Blue hydrogen from reforming natural gas

Hydrogen is generated from natural gas via steam reforming of methane. This process produces CO_2, which can be captured using CCS. The climate impact of this process depends on the capture rate for CO_2. High capture rates (>90%) and minimal supply chain leakage are required for production to be considered low carbon. The main component of natural gas is methane. Methane has a high global warming potential (GWP), particularly in the short term, and is responsible for at least 20% of global warming since the industrial revolution.[77] Leakage of methane into the environment from venting, flaring, and other fugitive emissions are important sources of GHG emissions in the hydrogen supply chain.[78] Optimal natural gas supply chain management will be required for CCS-enabled blue hydrogen production to be a viable option.[33] In the UK, half the natural gas demand is supplied from North Sea gas fields, with the remaining supply split between pipeline gas from Norway with low GHG emission intensity, and liquefied natural gas (LNG) which has a significantly higher than average GHG emissions intensity due to liquefaction, transportation, and regasification.[79]

LCAs were carried out for UK GHG emissions using natural gas, using a range of emissions intensities to reflect different supply options (Figure 4).[80,81] It is crucial to source additional natural gas supplies with low GHG emissions intensity. This is especially important considering UK natural gas production has halved over the past 20 years, and in the context of the ongoing global energy crisis.[81]

Green hydrogen from electrolysis

The GHG emissions intensity of hydrogen produced via electrolysis depends on the source of electricity and electrolysis efficiency.

Figure 4 shows the GHG emissions intensity for hydrogen production powered by three different sources of electricity. For electrolysis, hydrogen produced from wind power has lower emissions intensity than that produced using solar power, which in turn has lower emissions intensity than hydrogen produced using grid electricity. The emissions intensity of hydrogen produced from electrolysis using grid electricity is even higher than for hydrogen produced by methane reforming with no CCS. The majority of the emissions for wind and solar are produced during manufacturing of the electricity-generation equipment.[82] Large differences in the efficiency of solar electricity in different regions are responsible for the spread in reported emissions intensities. In the UK, onshore and offshore wind make up 24% of electricity generation, and 59% of low carbon electricity generation.[83] Low carbon hydrogen production via electrolysis will therefore require the building of additional low carbon electricity generation capacity.

Resource demand and scale-up

The viability of new pathways for fuel production depends not only on their reduction of net GHG emissions but also on their scalability to levels of current or future fuel demand. Here we discuss limits to total yield, limits to speed of scale-up, and how this growth will affect the availability of all necessary resources, especially where these are in competition with existing uses. In 2019, 2,960 Mt of jet fuel were consumed globally,[84] of which 12.4 Mt was consumed in the UK, including international flights departing from the UK.[83] Figure 5 represents the hypothetical demand for UK natural gas, electricity and land use if all 2019 UK jet fuel consumption were replaced by bio-jet fuels, PtL fuel or hydrogen, respectively. We do not imply that UK aviation fuel self-sufficiency is or should be a policy goal, or that low-carbon fuel demand should be met by one fuel type only: the comparison is used to provide a sense of the scale of demand for energy feedstocks. None of the solutions so far developed are sufficient to meet this demand. Significant scale-up of low-carbon fuel production infrastructure, as well as of innovative solutions, will be required to replace current UK annual kerosene demand.

Fuel type	Proportion of current UK renewable electricity production	Proportion of other UK resources
Blue hydrogen	x0.4	Natural gas x0.55
Green hydrogen	x2.5	
PtL	x4.9	CO2 from DAC and green hydrogen currently not produced at scale
Biofuel from waste vegetable oil/oily crops	x1.8	Agricultural land x0.5
Biofuel from forest residues	x5.1	Forest residues x46
Biofuel from agricultural waste	Not currently quantified	Agricultural waste x19
Biofuel from municipal waste	Not currently quantified	Municipal waste x8

Figure 5. Resource requirements for each low-carbon aviation fuel pathway compared to current UK production of each feedstock.

Calculations are based on 2019 UK aviation fuel consumption. UK annual resource figures for natural gas and electricity are from 2019.[85] Thermal energy values converted to electricity equivalent. DAC data are from 2021 and global rather than UK.[86] Biofuels data are from 2020.[87] Total fuel demand is 5Mt H_2 or 12.4 Mt PtL/bio-jet fuel per year. Notes: (1) Calculations for H_2 assume process efficiency of 70%. Total electricity demand includes electricity for liquefaction. For H_2 from CH_4 reforming, a 9% efficiency penalty for CO_2 capture was applied. (2) Assume 1 ton kerosene = 1 ton e-kerosene. Total electricity demand includes DAC, electrolysis and fuel synthesis using Fischer-Tropsch. (3) Calculations are based on yields of production of 3–10 Mt biomass per hectare-year, and average efficiency of conversion of 15%, derived from LCA.[88] Boundary conditions as for Figure 4. These numbers are indicative of the proportional differences between the pathways. For bio-jet fuels, calculations are highly dependent on LCA boundary selection, especially co-product incorporation.[89,90,19] These calculations do not consider the viability of scaling of co-products.

Bio-jet fuels

Scaling the production of bio-jet fuel in the UK requires estimating the availability of feedstocks, and the impact that their use and processing will have on resources such as land, water, electricity, natural gas and hydrogen. Estimates of available land for biofuel production vary by several orders of magnitude, due to variation in feedstock yield and efficiency of conversion to fuel.[91] However because fuel demand is high, impact on resources will be big: e.g. growing dedicated biofuel crops would require 50% of the UK arable land to meet current UK aviation fuel demand (Figure 5). This is clearly untenable. Full consideration of scaling of co-products in LCAs is likely to further reduce estimated emission savings.

The UK Sustainable Aviation Fuels mandate[11] has now tightly limited feedstocks to waste, which should reduce the impact on land availability, LUC, biodiversity and competition with food production. The availability of waste materials for fuel production will be limited by competition from other uses and will have to comply with the existing waste hierarchy. We estimate conservatively that in the UK, waste feedstock sources would produce less than 20% of UK aviation fuel demand (Table 3). This is only a small proportion of fuel demand, and is likely to have been overestimated, as estimates of amounts of municipal waste available for fuel production tend to be optimistic,[92] given that municipal waste collection practices vary across the UK, yielding a non-standardised feedstock. The diversion of agricultural and forest residues from their existing uses as soil conditioners to fuel production will result in soil depletion, which is undesirable. These estimates also minimise the emissions impact of factors such as the need for the collection and transportation of geographically dispersed material (Box 2).

The conversion of biomass into jet fuel requires electricity, natural gas and/or hydrogen, depending on the process (Figure 1). In order to reduce GHG emissions associated with bio-jet fuel generation, these processes must utilise energy from renewable or nuclear sources. Estimating energy requirements is difficult because this strongly depends on yield of conversion and fractionation efficiency, but we calculate it to be 2–5 times greater than current UK renewable energy production, depending on feedstock used (Figure 5).

PtL fuels

Scaling up e-kerosene requires green or low-carbon hydrogen, water and CO_2 from DAC or other biogenic sources. To produce these two resources, and to power the synthesis process, additional low-carbon electricity generation and storage infrastructure is required. Synthesis facilities, DAC plants and energy production and storage facilities will all impact land use. The environmental impacts of this transformation are yet to be quantified.

Hydrogen production together with the FT synthesis process represent 70% of the electricity requirement in PtL production, with the remaining 30% being used for DAC. To fulfil the total 2019 UK fuel demand with e-kerosene, the UK would need 4.9 times greater renewable electricity capacity than is currently available, or 3.3 times greater low-carbon electricity capacity (i.e. including nuclear energy). Around 7 Mt of green hydrogen would be required per year for PtL. We estimate that 20–68 billion tonnes of water would be needed to meet the 2019 UK fuel demand with synthetic fuel. Finally, 45–56 Mt of CO_2 from DAC or other biogenic sources is also needed (Box 3).

Large-scale deployment of PtL for aviation is currently not economically feasible. Cost reductions are necessary, and could be achieved through low-carbon electricity costs, which will reduce the cost of green hydrogen and DAC.[93] There is a critical need to optimise fuel synthesis efficiency, which is currently a two-step process. New bifunctional catalysts that can perform both reactions at the same time are being developed.[94] Low-temperature processes and catalysts for FT synthesis are preferred because they require less energy, but they do not yet yield products of the same quality as those from their high temperature equivalents.[95] Catalyst research and development, as well as heat recovery and integration systems during fuel production, are required to bring production costs down.

Hydrogen

Scaling up hydrogen depends on two factors: production of hydrogen gas at scale, and development of aircraft and airports suitable for hydrogen-powered aircraft. A hydrogen supply of around 5 Mt/y would be needed to meet the whole of UK air travel demand in 2019.

Globally, steam reforming of methane produces approximately 53 Mt/y of grey hydrogen at present.[39] However, only 0.7 Mt/y is produced from reforming with CCS, from 16 projects, with 35 more under development.[39] Methane reforming is an established technology, but much larger-scale projects are needed to advance CCS knowledge and practice. The UK's first CCS-enabled methane reformer is currently under development as part of the Zero Carbon Humber project, and is expected to start production in 2026.[100] At 600 MW, it can produce up to 0.125 Mt/y of low-carbon hydrogen, or about 0.25% of the current UK annual demand.[101]

Currently, 0.05 Mt/y of green hydrogen is produced via electrolysis globally.[39] Production of hydrogen via electrolysis is likely to be limited by energy price and the availability of a low carbon electricity supply. The largest currently operating electrolyser is 150 MW.[102] Most projects have been small-scale and there is limited experience with units above 100 MW. Electrolysis is an early-stage industry and scale-up will bring increased automation, some cost reduction, and increased knowledge through practice, research and development.[103]

Box 3. Direct air capture of CO_2

Direct air capture is key to PtL production but is still at an early stage of commercialisation. Key players are focusing on scale-up, reduction of energy use, demonstrated industrial operation, reliability, and cost reduction.[96]

Current reasonable estimates of price range for capturing CO_2 via DAC is \$600–1,000 per ton.[97] The deployment of DAC systems in the near term depends on the number of technology providers and their scale-up capacity. In the longer-term, deployment will likely depend on the economic viability of DAC technology, and its relative economic attractiveness, which will depend on policy support.

Why use DAC and not 'smoke-stack' CO_2 for e-kerosene?

Utilising atmospheric CO_2 can help close the carbon cycle, while using 'smoke-stack' CO_2 from concentrated industrial sources such as power plants or refineries contributes to GHG accumulation in the atmosphere.[32] Direct air capture technologies or CO_2 from biogenic sources are preferred.

How much CO_2 is needed *vs* how much do we have?

Between 45 and 56 Mt CO_2 per year would be required to produce the equivalent of all the jet fuel consumed in the UK in 2019. With increasing fuel demand, 83–104 Mt CO_2 per year would be required by 2030. Worldwide production of CO_2 by DAC is currently at 0.01 Mt per year, and needs to increase to 85 Mt per year in 2030 to meet carbon emission reduction requirements.[86]

The UK government is currently incentivising DAC expansion and recently announced up to £100 million funding for new research and development for DAC technologies in the UK.[98] The UK plans to remove at least 5 Mt atmospheric CO_2 per year from 2030.[99] However, this would only represent about 5% of the DAC required to fulfil UK synthetic fuel demand. Furthermore, DAC capacity will be needed to provide permanent CO_2 removal from the atmosphere to offset residual emissions from other hard-to-abate sectors (e.g. agriculture).[5] It is likely that aviation or private companies would need to develop their own DAC capacity for PtL fuel production.

Around 54 GW of capacity under development could be brought online by 2030, generating up to 10 Mt of green hydrogen per year.[39]

Scaling up electrolysis to meet the demands of the UK and global aviation sector would require a significant increase in electrolysis capacity and significant investment in additional low carbon electricity supplies. The currently relatively large GHG emissions intensity of solar panels is likely to fall, following the decarbonisation of electricity in the manufacturing sector.[104] The 55% increase in natural gas supply required for reforming with CCS is more straightforward to achieve, but the additional supply must not be sourced from countries with high upstream GHG emissions intensities.

A hydrogen-powered aviation industry would require a significant shift from conventional aircraft and airport infrastructure, equipment, and operational practices. New designs for long-range aircraft are required which may be at least a couple of decades away from entry into service. Hydrogen combustion engines capable of operating at high altitude (low pressure and low temperature) need to be developed. Aircraft have a service lifetime of 30 years, which means transition to new technologies takes time. Aviation has strict safety regulatory standards, and the standards for hydrogen aircraft do not yet exist, though an analysis by Airbus found there was no fundamental problem that would prevent the successful operation of commercial aircraft running on liquid hydrogen from a safety point of view.[105]

Airports will require costly infrastructure upgrades to enable the transport, supply, and storage of hydrogen to fuel aircraft. Additionally, refuelling hydrogen aircraft takes longer than conventional jet fuel aircraft due to the larger volumes of hydrogen required, increasing the turnaround time of the aircraft and impacting profitability. More efficient refuelling schemes therefore need to be developed. Hydrogen has a GWP of 5.8 (100-year horizon) and therefore hydrogen leakage must be monitored and limited to around 1% to avoid indirectly contributing to climate change.[106] The large electricity requirement for hydrogen liquefaction is likely to exceed the current electricity consumption of entire airports.[107] This demand must be met by firm (not intermittent) low-carbon electricity capacity, and coordination with energy providers will be needed to prevent electricity shortages impacting airport operations and safety.

Table 4. Summary of scale-up readiness comparison for the three principal types of low-carbon fuel.

	Bio-jet fuels	PtL	Hydrogen
Fuel production TRL	🟦	⬛	⬛
Feedstock availability	🟥	⬛	⬛
Land demand	🟥	🟦	🟦
Water demand	⬛	⬛	🟦
Aircraft TRL	🟦	⬛	🟥
Airport infrastructure	⬛	⬛	🟥

Note: 🟦, ⬛, 🟥 represent few, limited and severe barriers to deployment, respectively. TRL = technology readiness level.

Policy and regulatory instruments

Barriers for sustainable aviation fuel deployment

All the low-carbon fuels discussed in this paper face significant barriers to investment and commercialisation. The cost of all these fuels is considerably higher than conventional jet fuel. Supportive policy or regulatory measures can help facilitate technology scale-up and deployment.

Domestic aviation is regulated under national laws, whereas international aviation is overseen by the International Civil Aviation Organization. The development of a robust low-carbon fuel market will require alignment between the international systems and national policy. However, reaching a consensus on international policy takes time due to differing political ambitions to reduce GHG emissions.

Current sustainable aviation fuel policy landscape

National and regional policy is central to the development of a low-carbon fuel value chain, for example incentivising the production of feedstocks (e.g. renewable or low carbon electricity), development of national infrastructure and the use of sustainable aviation fuels.[108]

- The European Union has set a net-zero target by 2050 through its European Green Deal and is considering a low-carbon fuel blending mandate in its ReFuelEU aviation proposal.[109] The European Commission aims to increase the uptake of low-carbon fuels for air transport as part of the ‘Fit for 55’ package.
- In the UK, the Renewable Transport Fuel Obligation (RTFO) provides some incentive for low-carbon fuels, bridging the gap in cost. The RTFO currently extends to 2032 and now includes a “development fuels” target to encourage investment in the production of fuels from wastes and residues.[24] Recently, the UK Government released a net zero strategy which includes plans to increase the national use of low-carbon fuels.[99] The Jet Zero Council, a partnership between industry and the UK Government, has been established to develop low-carbon fuel production facilities and the regulatory frameworks required for net zero aviation. The UK Government plans to introduce a Sustainable Aviation Fuels mandate in 2025 requiring at least 10% of jet fuel (equivalent 1.5 billion litres) to be made from sustainable sources by 2030. Eligible fuels will be produced from waste-derived biofuels, recycled carbon feedstocks (e.g. unrecyclable plastic, industrial waste gases) and PtL. This mandate will apply to jet fuel suppliers and will operate as a GHG emissions reduction with tradeable certificate, outside of the RTFO.[11]
- The US Government plans to decrease aviation GHG emissions by 20% by 2030 through the production and use of billions of gallons of sustainable fuel. Congress has established legislation for the Sustainable Aviation Fuel tax credit, which offers financial incentives for low-carbon fuel producers.[110] The American Society for Testing and Materials has, since 2009, certified six biomass-based fuels for blending with conventional aviation fuel at proportions of 5–50%.[25,24]

The policy approach for different regions varies in terms of policy instruments, emission reduction ambition and targets. This will have implications in terms of the degree of technology deployment and sustainable aviation fuel adoption within these different jurisdictions. The next section outlines the policy pathways that address some of the key barriers for sustainable aviation fuel deployment.

Policy instruments to address key barriers

There are three policy pathways to promote low-carbon fuel deployment, which include an array of policy instruments (Figure 6):

- grow supply of low-carbon fuel by increasing production capacity and feedstock availability;
- increase low-carbon fuel uptake by stimulating voluntary, mandatory and market-based demand, e.g. by using blending mandates or providing subsidies;
- improve effectiveness of the supply (A) and demand (B) measures by developing a sustainable aviation fuel marketplace, overcoming the barriers to scale-up and harmonising low-carbon fuel certification.

Table 5. Thresholds for minimum greenhouse gas savings and maximum greenhouse gas intensity of low-carbon fuel under different schemes.

	Green Fuels, Green Skies (GFGS)	**Renewable Transport Fuel Obligation (RTFO)**	**Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)**
Details	Competition in the UK to support sustainable aviation uel development.	In the UK, the RTFO regulates renewable fuels used for transport.	The scheme was developed by the ICAO to reduce CO_2 emissions for international flights.
Baseline fossil fuel CO_2 intensity for comparison (gCO_2e/MJ)	94	94 (includes indirect LUC emissions)	89
Minimum GHG saving	70%	65%	10%
Maximum GHG intensity of fuel (gCO_2e/MJ)	28.2	32.9	80.1
Minimum GHG saving using the same fossil fuel baseline (89 gCO_2e/MJ)	68%	63%	10%

Adapted from the UK Department for Transport (2022).[11]

A well-designed policy framework would coordinate and balance the effects of the policy instruments for supply and demand stimulation. Importantly, a policy framework should avoid cumulative effects from combined or mismatched policy instruments, e.g. excessive subsidies when an individual low-carbon fuel project qualifies for multiple support mechanisms.[108]

To ensure that low-carbon fuel deployment makes a meaningful contribution to reducing emissions at a national and global scale, appropriate thresholds for minimum GHG savings and maximum GHG intensity will be required, based on a standardised LCA methodology for low-carbon fuel production to ensure the credibility and consistency of reported CO_2 intensity and GHG reduction. Table 5 summarises the proposed low-carbon fuel thresholds for minimum GHG savings and maximum GHG intensity of the fuel through 3 different schemes. Those proposed in the UK (i.e. GFGS and RTFO) are much more ambitious than CORSIA.[11] As low-carbon fuel technologies scale-up and improve, these thresholds could be tightened over time to achieve greater emission reductions.

In addition to the policy instruments that focus on sustainable aviation fuel production, policy interventions dedicated to supporting the development of infrastructure essential for sustainable aviation fuel production will also be very important. This includes the production of low-carbon energy, green hydrogen and CO_2 from DAC.

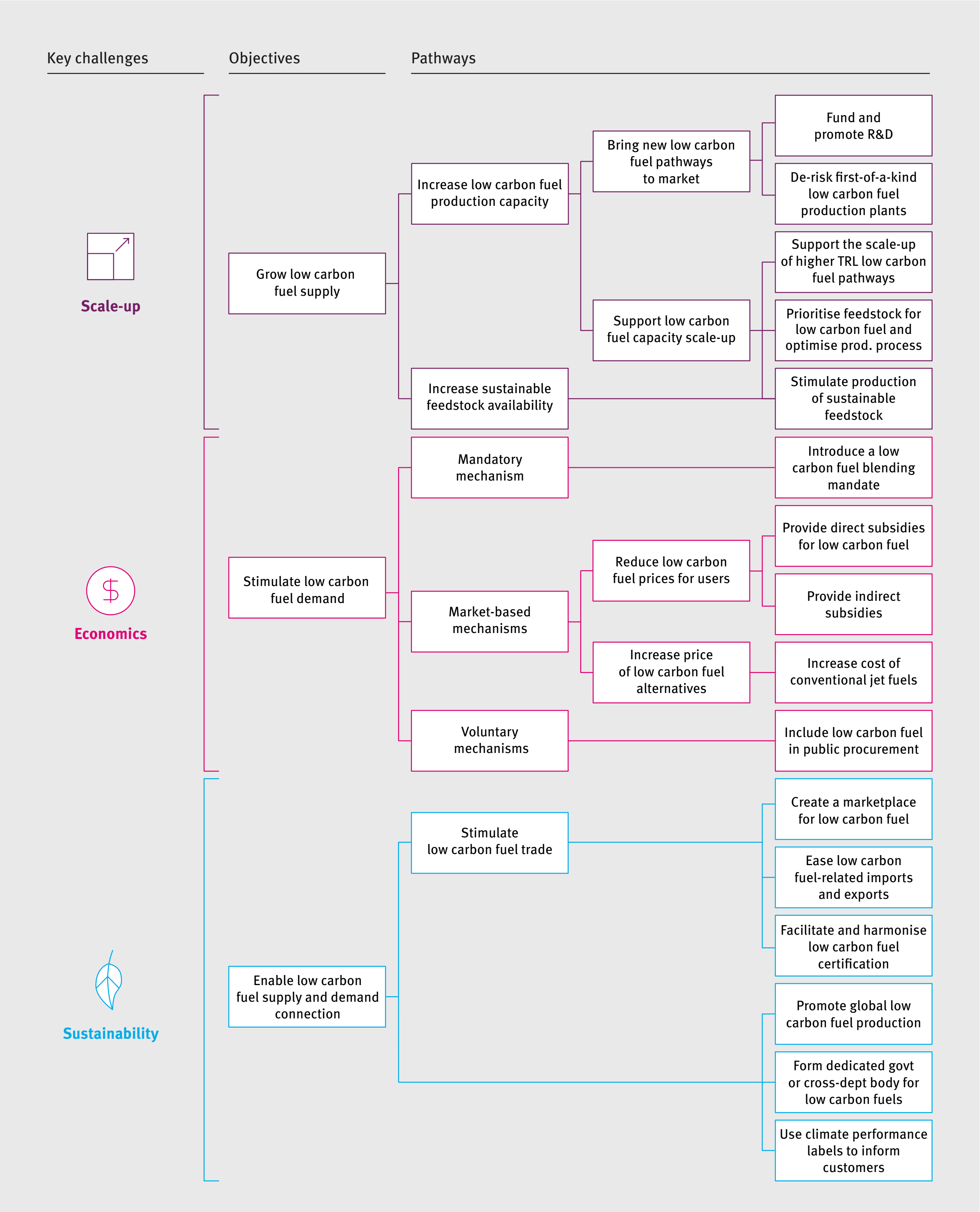

Figure 6. The three pathways to facilitate large scale low-carbon fuel deployment using policy and regulatory measures to either grow low-carbon fuel supply, stimulate demand or enable the connection between low-carbon fuel supply and demand. Adapted from the World Economic Forum (2021).[108]

Conclusion

Sustainable aviation fuels could potentially make a big contribution to meeting the UK's net zero emissions targets. However, for all three fuel types considered, biofuels, power-to-liquid (PtL) fuels and hydrogen, a significant scale-up from current capacity would be needed to meet aviation fuel demand. Scale-up of all three fuel types share common challenges of minimising energy use, water use and land use, and there are additional challenges which are specific each fuel type.

The total quantity of biomass available to convert to bio-jet fuels is limited and is now further restricted by mandate in the UK to use "waste" feedstocks only. Bio-jet fuel production can therefore fulfil only a small fraction of low-carbon fuel demand. Consequently, reduction of carbon emissions from aviation will have to be achieved by other means.

The physical and chemical properties of bio-jet fuels and PtL are closer to those of kerosene, so these are certified for use as blends with kerosene in current engine types. Improvements of production processes could generate fuels which match kerosene's properties more closely, enabling the use of 100% (i.e. unblended) low-carbon fuel. If achieved by improving fractionation, this will reduce the yield from the feedstock and will therefore be difficult to scale up. Ideally, innovating the chemistry of the conversion process would optimise fuel composition without reducing yield. The wide biochemical range of biofuel feedstock types could be an advantage here.

The physical and chemical properties of hydrogen are significantly different from kerosene. Hydrogen-powered aviation will require the development of new aircraft, new fuel storage systems and infrastructures. This introduces a significant time lag for development, safety testing and regulatory approval. It also needs to be integrated with commercial fleet replacement cycles. So, hydrogen-powered aviation is unlikely to contribute to carbon emissions reduction by aviation in the short to medium term.

Short- to medium-term development of low-carbon fuels must be considered in the context of current global challenges (e.g. high energy prices, geopolitical tensions, supply chain constraints, and changing water availability). High fossil fuel prices could be beneficial to the development of low-carbon fuels, as they make investing in low-carbon energy generation more economically attractive. The production of hydrogen and PtL fuels is very energy intensive, so they will require a significant investment in increased low-carbon energy production and storage.

Policy recommendations from a molecular science and engineering perspective

A molecular science and engineering approach combines an understanding of molecular behaviour with a problem-solving mindset derived from engineering. This approach is crucial to the development and eventual deployment of the fuel technologies discussed in this paper. The use of hydrogen, PtL fuels and bio-jet fuels in aircraft requires new development or adaption of manufacturing technologies, catalysts, storage facilities, transport facilities, engines, aircraft, and airports. The goal of policy will be to promote whichever technologies achieve in the desired sustainability targets. This requires a considerable research effort.

We make the following policy recommendations:

For all low-carbon fuel types:

- Implement policy support only where a low-carbon fuel technology has been demonstrated to achieve the following criteria: (i) to provide at least 50% CO_2 emissions saving when deployed at scale *vs* the kerosene baseline, in line with the UK Sustainable Aviation Fuel Mandate;[11] (ii) where there is enough feedstock for its production at a meaningful scale; (iii) its use will not have a negative environmental impact.
- Support the development of infrastructure (e.g. aircraft, airports, fuel transport, fuel storage, operational practices) for low carbon fuels, when these fulfil the criteria in the previous point.
- Implement more rigorous life cycle analyses for low-carbon fuels, and update standardised methodologies such as CORSIA[52] to:
  - Include evaluation of the secondary impacts of resource use choices (burden-shifting) relative to current fossil fuels.
  - Take into account the CO_2 emissions from fuel production as well as its combustion (well-to-wake approach).
  - Include non-CO_2 effects of both production and combustion in assessments of the impact of low-carbon fuels.
- Develop aircraft fuel systems which do not require the presence of aromatics in the fuel.
- Collaborate with commercial entities in the sector, especially those who own infrastructure, to generate momentum for change.

- Build systems to promote information-sharing between commercial entities and the independent research sector to help define research priorities and enable research projects, while protecting IP appropriately.

For bio-jet fuel technologies:

- Standardised life cycle analysis methodologies, such as CORSIA, should address the scalability of the benefits of the co-products and land-use change, and also the time delay between CO_2 emission and photosynthetic reabsorption.
- Improve existing bio-jet fuel production processes to optimise fuel composition and reduce the need for blending.
- Improve existing bio-jet fuel production processes to improve yield of conversion and reduce resource pressure.
- For municipal waste and other heterogeneous sources of feedstock material, develop robust processes that can efficiently convert this to fuel.

For PtL fuel technologies:

- Increase UK production of low-carbon electricity and energy storage. Reduce and stabilise the price of low-carbon electricity.
- Scale up production of green hydrogen.
- Assess the scalability of direct air capture using existing technologies.
- Develop novel solid adsorbents and membranes to reduce direct air capture cost.
- Develop mechanisms to reduce the price of PtL fuel relative to fossil fuel kerosene.
- Develop novel affordable catalysts to improve the efficiency of fuel production, preferably in a single step reaction and at low temperature.
- Develop novel fuel production pathways (in addition to Fischer-Tropsch) that meet certification requirements.
- Develop PtL fuels which can be used as a 100% replacement for kerosene.
- Promote and support the commercial development and implementation of improved technologies for all stages of PtL fuels production chain.

For hydrogen technologies:

- Increase UK production of low-carbon electricity and energy storage. Reduce and stabilise the price of low-carbon electricity.
- Scale up production of green hydrogen.
- Scale up carbon capture and storage (for blue hydrogen production) by developing improved absorbents, adsorbents and membranes in scaled-up industrial CO_2 capture units with lower energy demands.
- Develop advanced materials for cost-effective electrolysers to enhance both performance and durability.
- Develop new pressurising and cooling infrastructure for efficient storage and refuelling of hydrogen,
- Redesign aircraft to locate fuel tanks in the fuselage.

Major technical improvements are required before any of the fuels discussed here can be considered as a viable replacement for jet fuel in terms of sustainability and cost. The Institute for Molecular Science and Engineering will work to identify solutions that will overcome existing limitations by using the expertise available at Imperial College London.

Sustainable aviation fuel work at Imperial College London

Imperial hosts a number of researchers and institutes whose work is relevant to the sustainable aviation fuels challenge:

- Professor Niall Mac Dowell's research is focused on understanding the transition to a low carbon economy, at the molecular, unit operation, integrated process, and system scales.
- Professor Nilay Shah combines chemistry with modelling and engineering to improve process design and speed up process development in the design and analysis of energy systems, including bioenergy, CCS, and hydrogen. He is a co-founder of Zero Petroleum.
- Professor Klaus Hellgardt devises and applies novel reactor and catalyst concepts, measures intrinsic kinetics and develops new technologies and models for sustainable fuels and chemicals production.
- Dr Rodrigo Ledesma Amaro uses synthetic biology tools to create new properties and enhanced behaviours in microbial cells, to produce high-value chemicals and fuels (biodiesel, lipid-derived compounds, food additives, etc), increase yields, and facilitate the upstream and downstream paths of bioprocesses.
- Professor Magda Titirici works on electrocatalytic processes to convert waste into fuels and chemicals using electricity and sustainable catalysts free of critical metals.
- Professor Yannis Hardalupas studies control of emissions and combustion properties for improved thermodynamic cycle efficiency in the power generation and propulsion industries.

- Professor George Britovsek designs and applies catalysts for the functionalisation of carbon feedstocks such as alkanes, biomass and CO_2 as alternative carbon-based resources for chemical synthesis and industrial applications. Current projects involve the catalytic conversion of methanol to high-octane fuels, the photocatalytic upgrading of CO_2, and liquid organic carbon-based materials for hydrogen storage.
- Professor Benoit Chachuat uses advanced computational modelling, optimisation methods and process data to build safe and sustainable chemical and biological processes. His group employs rigorous computation to predict the performance at scale of both existing and novel technologies.
- Dr Ifan Stephens' work enables the large-scale electrochemical conversion of renewable energy to fuels and valuable chemicals, and vice versa. He develops electrocatalyst materials for renewable energy storage, fuel cells, green chemical synthesis and batteries.
- Professor Lorenzo Iannucci is the RAEng/AIRBUS Chair in Aerospace Composite Structures. His research focuses on material and modelling techniques for the design of aerospace composite structures. These include novel composite materials for sustainable aircraft, and advanced structural design of aircraft.
- Professor Bill Rutherford works on understanding solar-driven biological water oxidation. His work covers light collection, photochemical charge separation, proton-coupled electron transfer, multielectron catalysis, protective mechanisms, resilience, and energy accounting. He takes a specific interest in energy and GHG accounting and in resource scaling for fossil fuel replacements.

Additional relevant research is carried out at The Brahmal Institute for Sustainable Aviation, founded in 2022. The Brahmal Institute seeks to create new cross-disciplinary research and evidence-based decision making across technology development, entrepreneurship, finance and policy, in order to bring about a circular economy to the aviation sector.

www.imperial.ac.uk/brahmal-institute

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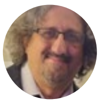
About the authors



Andrea Fantuzzi is a Research Fellow in the Department of Life Sciences. He studies bioenergetic processes, with a special interest in how natural systems can be used as a blueprint for artificial catalysts for energy and fuel production. He takes a specific interest in life cycle assessments for energy and GHG accounting and in evaluating resource scaling for fossil fuel replacements.

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