Scrutinising the future role of alternative fuels in delivering aviation decarbonisation

Executive summary

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Disclaimer

Contents

Glossary

Alternative aviation fuel – aviation fuels not produced from crude oil, including aviation biofuels (biojet) and aviation e-fuels (e-jet).

Biofuels (including biojet) – fuels produced from biomass.

Carbon footprint – see GHG intensity.

Carbon intensity – see GHG intensity.

CCS – carbon capture and permanent storage.

CORSIA – ICAO's Carbon Offsetting and Reduction Scheme for International Aviation.

Direct emissions – when we talk about direct emissions in the context of alternative fuels we are talking about the emissions that are within the control of operators somewhere in the supply chain for a given alternative fuel pathway. Note that this differs from the way that direct emissions are defined in company accounting under the GHG protocol, where direct include only emissions within the control of the company being assessed, and emissions under the control of third parties in the supply chain are characterised as indirect.

Downstream – processes that occur later in the supply chain (i.e. closer to the point at which a product is delivered to an end user).

E-fuels (including e-jet) – fuels produced from electricity be generating electrolytic hydrogen and synthesising it into hydrocarbons (or other fuel molecules).

Embedded emissions – the GHG emissions associated with the production of a material or energy stream used as an input for another process.

GHG – greenhouse gas.

GHG intensity – the GHG intensity of a fuel or of a process is a characterisation of the amount of carbon dioxide and other greenhouse gases that are released due to the production and use of the fuel or the application of the process. For fuels, in this report we express GHG intensity in terms of grams of carbon dioxide equivalent emissions (on a GWP100 basis) per megajoule of chemical energy in the fuel on a lower heating value basis. This unit is abbreviated to gCO_2e/MJ.

Indirect emissions – when we talk about indirect emissions in the context of alternative fuels we are talking about emissions that are generally outside the control of operators within the supply chain. This includes emissions from land use changes that are market driven and do not generally occur at the farms on which feedstock batches are actually produced and emissions (or GHG reductions) associated with displacement of materials out of existing markets. Note that this differs from the way that indirect emissions are defined in company accounting under the GHG protocol, where these sorts of market-mediated indirect emissions are normally treated as outside even Scope 3.

IPCC – Intergovernmental Panel on Climate Change.

LCA – lifecycle analysis, the practice of assessing the full set of emissions associated with production, use and disposal of a product or service.

LCA score – for LCA of climate impacts, the LCA score is an indicator of the GHG intensity, determined not only by the characteristics of the fuel or process but by the rules of the LCA framework.

Physical CO_2 emissions – in this series of reports, when we talk about 'physical CO_2 emissions' we mean the CO_2 emitted from a specified process ignoring lifecycle considerations and conventions such as zero accounting of biogenic CO_2.

REFuelEU – the EU's regulation setting targets and rules for alternative aviation fuel use out to 2050.

Renewable Energy Directive (RED) – the EU's framework for supporting renewable energy, including renewable fuels in transport.

Renewable Transport Fuel Obligation (RTFO) – the UK's framework for supporting renewable fuels in transport.

Sustainable aviation (SAF) – see alternative aviation fuel (AAF).

Synthetic aviation fuels – hydrocarbon fuels certified for aviation use produced from non-oil resources (e.g. biomass, electrolytic hydrogen. natural gas, coal).

True emissions – when we say 'true emissions' in this report we mean the change in total global emissions (associated with a given action) that we could identify if we were omniscient and had perfect foresight – in practice, the true emissions are not known.

Upstream – processes that occur earlier in the supply chain (i.e. closer to the point of raw material extraction).

1 Context

The fight to mitigate climate change poses a fundamental challenge to the aviation industry. Aviation is an energy intensive activity that is currently completely dependent on liquid hydrocarbon fuels. Whereas road transport has the prospect of transitioning to very significantly more efficient and lower carbon intensity electric drive technologies, the current consensus is that there is no realistic prospect of long-haul aviation in electric planes being commercially viable by 2050, and a large question mark over the range and viability for short haul electric aircraft. The use of fossil fuels in aircraft results in an amplified warming effect because cloudiness from aviation contrails traps even more heat in the atmosphere than the CO_2 released by combustion does[1]. If aviation continues to grow in line with industry targets while using fossil jet fuel, its impact on global CO_2 emissions will become increasingly incompatible with holding global warming to 2 °C, let alone 1.5 °C.

The aviation industry identifies four ways to reduce net CO_2 emissions from aviation. The first is to improve aircraft efficiency, so that less fuel is burnt per passenger kilometre. The second is to deliver operational efficiencies, such as optimising air traffic control operations to minimise the time aircraft spend in the air. The third is offsetting – paying businesses in other sectors to reduce their emissions or to capture CO_2 from the atmosphere 'on behalf of' the aviation industry. The fourth, and the one that we discuss in this series of reports, is the use of alternative fuels that have lower lifecycle greenhouse gas emissions.

There is currently broad agreement between airlines, airframe manufacturers, fuel suppliers, key governments and the International Civil Aviation Organisation (ICAO) that policy should be used to increase the use of alternative fuels in aviation, but the precise nature of these policy frameworks is still under development. Europe has just adopted targets (REFuelEU, European Commission, 2021) for 2030, 2040 and 2050 for the percentage of renewable aviation fuels in the EU aviation fuel supply, aiming to reach 70% by 2050. The USA has launched the 'Sustainable Aviation Fuel Grand Challenge'[2] with a declared aim of reaching 100% alternative aviation fuel by 2050. The UK has consulted on launching an alternative aviation fuel mandate in 2025. ICAO has developed a system to credit GHG savings delivered by use of alternative aviation fuels under its CORSIA offsetting programme. While in some respects the direction of travel for these policies is the same, there are also important distinctions and differences, both regarding which sorts of alternative fuels should be encouraged and regarding what the appropriate systems of incentives, mandates and sustainability governance are to deliver the desired outcomes. Some academics and environmental organisations have meanwhile begun to question: the scalability of some proposals for increasing the production of alternative fuels; how sustainable the proposed alternative fuels really are; and what the 'lifecycle analysis' associated with these fuels can and can't tell us.

Alternative fuels can be considered in three categories. Firstly, there are biofuels[3]. The energy in these fuels is sourced from biogenic material, and ultimately derived from photosynthetic activity by plants. Biofuels have been controversial in recent years because biofuel producers can compete with food markets for agricultural products, and even the production of non-

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[1] Based on current best estimates on a 100-year timescale.

[2] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

[3] Including fuels sourced from crop products and fuels sourced from biogenic wastes, residues or by-products.

food biofuel feedstocks can compete with food crops for agricultural land. REFuelEU and the UK mandate are both expected to withhold support from food-based fuels. There is also a question mark over the net GHG impact of biofuel production. If the land needed to produce biofuels is converted from other uses (forest, pasture, shrubland) this generally leads to reductions in carbon storage by biomass and soils on that land, which undermines the GHG credentials of biofuel policy. The potential for the use of biofuels is limited by the potential supply of biomass, and by the competition for different land uses. If land is committed to bioenergy crops it reduces the potential for food production or for reforestation.

Secondly, there are ‘recycled carbon fuels’. The energy in recycled carbon fuels comes from fossil resources that are not fully consumed by existing industrial systems. This includes chemical energy in oil-based waste plastics and in carbon monoxide in some industrial flue gases. Burning recycled carbon fuels involves releasing fossil carbon into the atmosphere as CO_2, and therefore recycled carbon fuels are only associated with net GHG savings if the carbon would otherwise have been released anyway, either without any energy recovery or with a less efficient form of energy recovery. The potential for production of recycled carbon fuels is limited by the availability of fossil wastes that fit this criterion.

Thirdly, there are e-fuels, fuel synthesised from electrolytically produced hydrogen. The energy in e-fuels comes from the source of the electricity used. If the electricity is renewably produced, this can lead to low lifecycle GHG emissions. However, if the electricity is produced in whole or in part from fossil fuels then the inefficiencies in the production process can lead to GHG emissions higher than for conventional fossil jet. Much more energy can be delivered by a hectare of solar panels or wind turbines than by a hectare of photosynthesising bioenergy crops, and therefore e-fuels have been identified by some commentators as the most scalable alternative fuel option for aviation. The biggest challenge for e-fuel production at the moment is the cost – unless electricity can be sourced very cheaply, costs per litre produced are much higher than for either biofuels or fossil fuels. The prospects for e-fuels are therefore dependent on the potential for low cost renewable electricity deployment (and on competition with other potential electricity consumers).

In this series of reports, we have reviewed key issues relating to delivering real climate benefits from the use of alternative aviation fuels. Part 1 reviews issues in lifecycle analysis, part 2 reviews issues relating to the use of waste and by-product materials as feedstock, and part 3 looks at the role of alternative fuels in the pathway to 2050. This summary briefly reviews each of these in turn, and concludes with some implications for alternative aviation fuel policy.

We have preferred to use the term ‘alternative aviation fuel’ (AAF) over the term ‘sustainable aviation fuel’ (SAF) which is more widely used by the aviation industry and policymakers. We have made this choice of terminology because sustainability is an aspect of a fuel production system that must be assessed, and because there is no single universally accepted metric to identify when a fuel can be considered fully sustainable. To say that a batch of fuel is produced in a way that meets the criteria of some specific sustainability standard, which may not cover all aspects of sustainability, is not the same as to say that the production of that type of fuel is actually sustainable across the fullest range of sustainability concerns.

2 Assessing the benefits

From a climate change perspective, there is no point in using alternative aviation fuels unless doing so reduces net global GHG emissions. This means that we need tools to assess the emissions associated with the adoption of each fuel production pathway, and a basis for comparing different pathways against each other. The discipline of lifecycle analysis (LCA) has been developed to answer these types of questions. LCA can be used to assess a wide range of impacts from a process or product, but here we will consider specifically LCA to assess GHG emissions. Depending on the scope, this can include steps from production (and production of associated inputs) through distribution, use, and disposal of wastes and by-products.

While LCA is a technical discipline, there is no one single correct way to perform an LCA. The details of the methodology for a given LCA exercise should be determined based on carefully specifying the question that is to be answered: it is possible for two apparently similar LCA questions to give quite different numerical answers. A particularly important distinction can be drawn between questions that can best be assessed using an 'attributional' framework and questions that can best be assessed using a 'consequential' framework. Consider the following two questions as the basis for LCA:

- What is the sum of the emissions associated with each of the processes that is required to produce a megajoule of a given alternative aviation fuel?
- What is the net reduction in global GHG emissions that is achieved when policy mandates the consumption of an additional megajoule of alternative aviation fuel?

The first of these questions is about the attribution of emissions from individual intermediate processes to a final product. The second of these questions is about assessing the wider consequences of a policy decision.

The attributional question is an easier one to define, has a narrower scope, and is less ambiguous to assess. It is possible in principle to find the farm on which a batch of biofuel feedstock was produced, the fertiliser factory where the fertiliser used was produced, identify the types of tractor used and the fuel they consume, find the biofuel plant and assess the amount of natural gas and electricity consumed etc. Even in the attributional framework some subjective decisions may need to be taken – for example if a process produces two outputs, what fraction of the emissions should be allocated to each one – but it is relatively clear what sort of data is needed to undertake the assessment.

The consequential question is harder to pin down. Given that the question asks about global emissions changes, the scope of the analysis is potentially very broad. It asks us to consider the series of consequences that follow when consumption of a given alternative fuel is increased by a mandate. Does production of that particular fuel increase, and if so by how much? Are batches of that fuel diverted from other possible uses? If production increases, is more feedstock produced or is it diverted from other applications? If feedstock production increases, is this associated with land use change? Is overall consumption of fossil fuel reduced, and if so by how much? Data collection to answer this question is not limited to the supply chain for a single fuel batch but instead extends into the global economy, and consequential LCA requires relatively complex models to be developed.

In the attributional analysis we don't have to worry about whether emissions in a specified system have actually changed. For example, a farm producing wheat as biofuel feedstock may have been producing the same amount of wheat every year on the same area of land for decades. If a batch of that wheat goes to a local biofuel plant we would include that farm in the attributional LCA, even though its output is the same as it has been for years. In the consequential analysis, in contrast, we are only interested in things that are changed compared to a hypothetical 'counterfactual' universe, so we are interested only in farms where wheat production has been increased to meet additional demand rather than the farms that are physically supplying a biofuel facility.

There are two main reasons for the dominance of the attributional approach to LCA – a good reason and a bad reason. The good reason is that using attributional LCA is a way to indicate to producers what they could do to reduce the GHG footprint of their activities. Producers have control of operations at facilities they own, and can exert influence with their suppliers. It makes sense to make the alternative fuel industry accountable for things it can actually change. The bad reason is that attributional LCA is easier and looks like it offers precise answers – tools already exist for attributional LCA that any producer can use to generate a number specific to their process, whereas detailed consequential analysis can only be undertaken by expert modellers using complex economic modelling tools. Because it is hard to produce a good answer, it's easy to fall back on an easy answer that looks plausible, even if it might be entirely misleading.

In alternative fuel policy, it is normal to hear claims made about the 'GHG saving' delivered by using a quantity of some type of alternative fuel. This is a claim about a change in emissions, consistent with asking the second, consequential, LCA question – and yet these claims are most commonly based on the results of the attributional form of lifecycle analysis, which has become dominant in alternative fuel regulation. Rather than attempt to develop consequential models, these claims about GHG savings are made by simply comparing two attributional LCA values against each other – one for the alternative fuel pathway, and one for a conventional fossil fuel.

It's useful to consider a few of examples of alternative fuels that might score well on an attributional LCA but rather less well on a consequential view. First, take the case of palm oil HEFA biojet[4]. The EU's Renewable Energy Directive (RED) reports a typical GHG reduction value of 53% for this fuel pathway based on attributional LCA[5], but there is extensive evidence (see e.g. Malins, 2019) that the increased consumption of palm-oil-based fuels drives land use change emissions from deforestation and peat drainage. When these indirect land use change emissions are taken into account, it is likely that increasing consumption of palm oil biofuels increases rather than reduces net GHG emissions.

A second case is HEFA biojet from rendered animal fats. These animal fats are produced by rendering (heat treating) livestock carcasses, and the amount of fat produced is driven by the demand for meat rather than demand for fat. The rules in the RED allow for by-products of this sort to be treated as having zero production emissions in the attributional LCA, and the typical GHG saving compared to fossil kerosene is reported as 83%. However, these animal fats would still be 100% utilised in the absence of the biofuel market, meaning that when they are used for biofuel production they must always be displaced from some other existing uses such as pet food and oleochemicals (Malins, 2023). The most chemically similar replacement materials for animal fats are vegetable oils like palm and soy oil – so there is a considerable risk that

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[4] Produced with the 'hydroprocessed esters and fatty acids' (HEFA) technology.

[5] Strictly speaking the RED only contains a value for hydrotreated road diesel, but the process for biojet is very similar.

when animal fats are displaced into biofuel use then we increase demand for palm oil anyway. The consequences of that would include an indirect increase in palm cultivation emissions and ILUC emissions from palm expansion.

A third case is the production of e-fuels using renewable power from a pre-existing windfarm. On an attributional LCA, the GHG intensity of the consumed electricity would be very low (zero in an LCA system that doesn't account for construction and maintenance emissions), and as the electricity is the main energetic input for e-fuel production the e-fuel would also be assessed as having low emissions. This would ignore the fact that if the windfarm had previously supplied power to the grid, that power would need to be replaced. That replacement power could be of fossil origin; if so, an e-fuel that was identified as very low emissions on an attributional basis would be shown to cause a significant net-emissions increase if assessed on a consequential basis.

There is no simple, universal resolution to these consequential problems, but there are many partial solutions that can be used to make regulatory frameworks more robust and to boost the likelihood that alternative aviation fuel policy actually delivers net emission reductions. Part of the answer is to address these indirect effects directly through other parts of regulation. For example, EU biofuel policy is phasing out support for palm-based biofuels for road use, and all food-based fuels will be excluded from support under REFuelEU from the start. The EU has also introduced rules for e-fuels so that they can only be counted as renewable if they meet certain conditions – for example, power from a direct connection to a windfarm could only be used if the windfarm came into operation around the same time as the e-fuel plant.

Elements of consequential thinking can also be brought into attributional LCA systems, creating what are sometimes referred to as hybrid LCAs. For biofuels and land use, this has been done in CORSIA through the use of ILUC factors: emissions terms calculated with consequential modelling tools that are then added to attributionally-calculated GHG scores. For RCFs, LCA rules adopted by the European Commission include an idea of feedstocks with 'rigid' or 'elastic' supply (European Commission, 2023). If the production of a feedstock can be increased to meet extra demand, its supply is elastic and it should be assessed using normal attributional LCA. If, however, the production of a feedstock is set and will not change if demand increases, then the supply is rigid and the rules require operators to consider the emissions to produce materials to replace it in any existing use. For e-fuels, EU rules tie the LCA to the assessment of renewability, so that electricity sourced from existing renewable resources cannot automatically be treated as low carbon. These hybrid measures are not perfect, and do not necessarily result in a precise estimate of the real net GHG impact of using any of these fuels, but they are used to make the attributional result less misleading and to help policies drive better outcomes.

3 Uses of waste

Turning waste materials into alternative fuel has been seen as a potential win-win, simultaneously allowing reductions in consumption of fossil fuels and contributing to waste management goals. Both recycled carbon fuels (RCFs) and biofuels are seen as potentially worthy of policy support, the preference for wastes as biofuel feedstocks being further strengthened in the context of concerns about the impact on food markets of using food commodities as biofuel feedstock.

UK waste policy is built on the waste hierarchy, within which the most favoured solution is to avoid generating waste in the first place, and under which recycling of wastes into new materials is given a higher priority than energy recovery. To the extent that the UK can reduce waste generation it will also reduce the resource available as feedstock for fuels. Currently, the UK has several waste management targets that, if successful, will reduce both total waste generation and the non-recyclable fraction of waste. The UK Resources and Waste Strategy calls for the elimination of 'avoidable' plastic waste by 2042, and aims for all plastic packaging to be reusable, recyclable or compostable by 2025 (DEFRA, 2018). There is a target to reduce food waste generation by 20% between 2015 and 2025 though it seems this target is unlikely to be achieved, and a target to eliminate food waste from going to landfill by 2030, hinging on the distribution of segregated food waste bins. There is a general target across municipal waste for 65% to be recycled and no more than 10% to be landfilled by 2035, to achieve the 'near' elimination of biodegradable material being sent to landfill, and to eliminate all 'avoidable' waste by 2050. There is a general intention to reduce other waste to landfill but no specific landfill elimination target.

At present, UK waste policy identifies anaerobic digestion and recycling as the preferred dispositions for biodegradable material diverted from landfill. This is in line with the waste hierarchy, but leaves key pathways for producing alternative aviation fuel from biodegradable waste with a secondary status. Given that the UK Government now sees alternative aviation fuel production as a priority area, it seems plausible that aviation fuel production from biodegradable resources may in future be given a more equal footing with these uses.

Material that would otherwise be sent to landfill, without even energy recovery being practiced, might be characterised as a 'true waste' – a material the value of which is entirely wasted on disposal – but there are other secondary products that have been grouped with wastes in the biofuel discourse that have alternative uses and would not be landfilled. These are sometimes referred to as by-products or residues. There are no universally applied definitions for these terms, which has led to disagreement and sometimes ambiguity about how resources should be treated in alternative fuel policy if extra incentives are granted for the use of 'wastes and residues' as feedstock. Something that these materials have in common is a rigid supply – meaning that the amount of waste, residue or by-product that is produced is determined by the level of demand for the main product (European Commission, 2023). If more of one of these materials is used as aviation fuel feedstock it will not stimulate further production; if the material in question has an existing use then diverting it to into aviation fuel will force either a scale-back of production or the use of alternative feedstocks.

Consider the case of animal fats from rendering of animal carcasses. The supply of rendered fat as a whole is determined by demand for meat, so rendered fat can be considered as a by-product or a residue – but it cannot be considered a true waste as essentially all of it is already used as an input for (depending on the grade) animal feed, pet food, oleochemicals, and if nothing else for energy recovery (Malins, 2023). Again, displacing these existing uses means that some alternative material will be needed, and so the environmental advantages of using them for aviation fuel versus the incumbent disposition must be examined carefully. Under the UK RTFO all but the most contaminated animal fats are treated as 'products' and excluded from the double counting incentives reserved for wastes and residues – this includes 'Category 2' animal fats. Under EU biofuel policy, however, Category 2 animal fats are treated as residues eligible for double counting. As a side note, there is some evidence that incentives to use lower quality animal fats may have led to suppliers relaxing segregation protocols in their production and supply chains to increase the amount counted as low quality, or perhaps even to mislabelling fraud (Malins, 2023). This illustrates the potential for market distortion when classifying a certain feedstock as a waste or residue results in it having more value than a higher quality alternative material.

The firm posture against landfill in the UK and EU waste hierarchies has a particular significance for RCFs made from non-recyclable and non-biodegradable plastics. The longevity of plastics is often seen as problematic, but it does mean that, were they sent to landfill, their fossil carbon would remain sequestered for centuries if not millennia. Policy that prioritises energy recovery – either through incineration or through RCF production – in effect promotes the release of this carbon into the atmosphere as CO_2 in order to displace grid electricity or liquid fossil fuels. This contributes to waste management goals but may not contribute to climate goals. This has implications for understanding the net emission impact of producing RCFs. Proposed UK treatment of RCFs would take incineration with energy recovery as the counterfactual, in which case there is no net change in emissions from combustion, but because RCF production is expected to be more energy efficient than incineration this approach assumes RCFs displace more fossil energy and therefore achieve net GHG savings. If instead zero-emission landfill was taken as the counterfactual, you would not identify any significant climate benefit. If the 'true' counterfactual includes some reduction of landfill, as waste policy implies, then the current UK proposal overstates the climate benefit of developing RCF production.

4 Alternative fuels and the pathway to lower carbon flights

Alternative aviation fuels have been identified by the aviation industry and by many governments as a key tool to deliver GHG emission reduction from aviation, in the hope that continued aviation growth will be compatible with climate change targets. The EU has set a 70% target for alternative aviation fuels by 2050, and the UK has proposed a 50% target. Meeting those targets at the same time would require about 37 million tonnes of oil equivalent of alternative aviation fuel production. At present, the only commercially available alternative aviation fuel technology is hydrotreating of vegetable oils and animal fats, but the availability of these resources is limited, and diverting them into aviation use would put pressure on markets for vegetable oils for food. The only scalable and potentially sustainable options to deliver the quantities of alternative aviation fuel required rely on more advanced processing technologies – conversion of cellulosic biomass into fuel, and production of fuel from renewable electricity. Cost assumptions in the REFuelEU impact assessment imply capital expenditures of the order of €1 billion per year from now until 2050, and the need to deliver capacity growth rates through the 2030s similar to those delivered by the U.S. corn ethanol industry in the 2000s. Achieving this for technologies that are not yet in successful commercial operation will be highly challenging.

The UK has recognised that making these technologies successful is key to delivering on long-term policy goals for alternative aviation fuels, and has therefore proposed to strictly limit the quantities of hydroprocessed biofuels that will be allowed to contribute to UK SAF mandate targets. EU policy is less confident on this point – while the impact assessment on REFuelEU anticipates the deployment of more advanced biofuels, there is considerable risk that the largest contribution to 2030 targets will come from diverting by-product and residual oils and fats out of other productive uses (including out of use as feedstock for on-road biodiesel), delivering minimal (if any) net climate benefit. With the U.S. potentially counting hydroprocessed from soy and rapeseed oil towards its alternative aviation fuel goals, the UK may find itself offering the clearest value signal in the world for cellulosic biojet deployment in the period to 2030. This gives the UK a genuine opportunity to become a leader in this area, stimulating the development of production both domestically and overseas.

Offering a clear value signal will be vital, as the development of advanced alternative fuel production has been plagued in the past by the use of incentive systems that have not delivered long-term value confidence, and the cost of production of all types of alternative aviation fuel is likely to remain significantly higher than the cost of production of fossil jet fuel (not including explicit or implicit carbon pricing) for the foreseeable future. For hydroprocessed fuels the main expenditure is operational, the cost of feedstock purchase. For cellulosic biojet, feedstock costs will tend to be lower but capital costs for more complex processing steps are increased. For e-fuels, the main cost is the electricity itself. About half of the input electricity is lost in an e-fuel production system (though this loss should be reduced over time) meaning that for every one unit of fuel energy produced, two units of electricity input are needed. This is a difficult equation to make work commercially given that the wholesale price of electricity per unit of energy is often higher than that price of fossil jet fuel, implying that successful e-fuel production will be dependent on sourcing low-cost electricity. That might be achieved by using electricity only during periods of low demand for other sectors, but reducing the operational hours of electrolysers (and perhaps fuel synthesis units) will increase the effective capital cost per unit of fuel produced. It might also be achieved by developing low-cost renewable power generation in areas that are remote from existing grids and where there is therefore no competition with other potential power consumers. Neither of these business models will be easy to make work.

For both biojet and e-jet, there is a higher level question to answer – is it proportionate to devote limited biomass resources and electricity that could be used to decarbonise other sectors to sustaining the scale of the aviation industry, when aviation is a high energy-intensity activity massively skewed towards wealthier people and which is associated with significant additional climate impact due to non-CO_2 effects (in particular warming associated with aviation induced cloudiness)? It is certainly possible that governments will decide that the volumes of alternative aviation fuel production implied by current policy are not sensibly achievable, and that it is appropriate to use policy to curtail growth in aviation demand.

While alternative fuels seem to have broad support in the aviation industry at the moment, it remains to be seen how long this will last in the context of a growing cost burden. Looking forward, we can anticipate that there will be renewed discussion about the relative merits of alternative aviation fuel use versus simply offsetting aviation emissions through CO_2 capture and storage. If e-fuel production remains very costly airlines are likely to become increasingly resistant to meeting ambitious deployment trajectories and look to lower cost alternatives. For a given quantity of captured CO_2, the emission benefit of storing it underground will be comparable to that from using it for e-fuel production, probably at significantly lower cost.

5 Considerations for policy design

Debate is likely to continue for the foreseeable future about the best way to deal with the climate impact of aviation. The industry will inevitably seek to assert its right to grow, focussing on the benefits delivered by air travel. Those whose primary concern is mitigating climate change will continue to identify aviation as a luxury activity that could be scaled back. In a recent report for the UK Government (New, 2023), Phillip New argued that there is a degree of consensus at the intersection of these opposed priorities that there is an opportunity to scale up alternative aviation fuels in a way that is sustainable and delivers real net GHG emission reductions.

In fact, however, many environmental groups are sceptical about whether alternative fuels offer a genuine pathway to decarbonisation or whether the attention these fuels are now commanding is providing unhelpful cover for airlines and aircraft manufacturers to continue with their current business model, rather than investing in more radical new energy options. To the extent that these fuels have a role to play in the mix of solutions for tackling aviation emissions, it is essential for policymakers to ensure that any desire for rapid commercialisation of alternative fuels does not lead them to compromise on the environmental integrity of these fuels. There are many concerns to consider in designing effective policy, but in this field two challenges stand out:

1. Design policy that identifies and supports alternative aviation fuel pathways that deliver net GHG emission reductions without undue negative impacts in other areas of sustainability;
2. Design policy that provides the value confidence needed to stimulate investment while delivering alternative fuels at the lowest achievable cost.

Achieving the first of these goals requires the appropriate use of lifecycle analysis tools to provide a meaningful characterisation of the relative merits of different fuel pathways. Given the potentially significant indirect emissions associated with many alternative fuels, this should include the use of hybrid LCA tools, using ILUC modelling and displacement emissions analysis where appropriate. For fuels produced from woody material and agricultural material it requires a careful assessment of the changes in standing carbon stocks in biomass and soils implied by additional material harvesting. It requires setting appropriate sustainability criteria to govern the gathering of agricultural and forestry residues, and of applying principles of sustainable forestry if additional wood is harvested from existing forests. For wastes as feedstocks, it requires a careful consideration of whether use for fuel production is the best environmental outcome or whether alternative options such as recycling are available that deliver greater climate and/or other environmental benefits. For electricity used for e-fuels, it means guaranteeing that additional renewable power deployment is funded through the price of the e-fuel produced so that power capacity isn't taken away from other (potentially more efficient) uses.

Achieving the second of these goals implies providing predictability, some level of value certainty, and making sure that producers of sustainable fuels that are needed in the long-term are not forced to compete on price with producers of less sustainable fuels that have no place in the long-term. The UK is looking to introduce a tightly defined SAF mandate, capping the contribution of hydroprocessed fuels and including a specific sub-target to accelerate the deployment of more expensive e-fuel technology. This is a promising basis for progress. There are further options available to enhance the value of this package as an investment driver, such as the potential to offer producers contracts for difference to guarantee revenue (Calderbank & Malins, 2021) and the use of grants to support new projects through the Advanced Fuel Fund (Ricardo, 2023).

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