→ Roadmap for the development of the UK SAF industry

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ICF

An ICF Report for UK Sustainable Aviation

SUSTAINABLE AVIATION

1 Foreword

The UK has built an exceptional aviation industry, contributing more than £22 billion directly to GDP, and an additional £34 billion from the export of aerospace components. Further economic and social value is catalysed, with overseas visitors spending almost £30 billion in the UK each year, and UK residents benefiting from the connectivity to every corner of the world.

The need for decarbonisation has been recognised across the UK aviation value chain. Targets have been established and significant progress has already been made. More efficient aircraft, engines, and operations have decoupled growth from emissions, with passenger numbers in the UK growing by nearly 200% between 1990 and 2019, while aviation emissions grew by just 125%. However, reducing the rate of emissions growth is not enough; aviation must fully decarbonise to avoid the worst impacts of climate change.

The ATAG Waypoint analysis estimated that decarbonizing aviation fuel (the source of almost all emissions from the sector) will require annual consumption of 400 million tonnes of low carbon aviation fuels by 2050. With negligible production today, this represents a considerable opportunity for countries to create economic value and jobs, attract investment, and bolster the resilience of the energy sector with domestic alternatives. Unlocking investment is the key challenge, with the cost of production higher for the innovative but unproven SAF technologies compared to the mature fossil fuel industry. Policies that recognise the additional environmental value of SAF are critical to create a level playing field.

This analysis shows that the UK has sufficient feedstock – biological and other – to fully decarbonise the aviation sector. It also shows that relying on imports will be challenging, with a global shortfall in announced capacity compared to targets of almost 4 million tonnes of SAF by 2030, equal to over three times the UK's projected 2030 demand. Attracting the scarce supply over other demand sources would require UK consumers to pay a meaningful premium and would contribute nothing to the UK economy or energy resilience.

Utilizing UK feedstock requires new conversion technologies to be commercialized. The Hydroprocessed Esters and Fatty Acids (HEFA) pathway dominates the trickle of current production, but the waste fats and oils this approach requires are limited in their availability. To achieve the necessary growth, SAF producers must commercialise technologies such as Fischer-Tropsch, Alcohol-to-Jet, and others. These technologies hold great promise but will not be feasible without additional support. The high capital costs, uncertain revenue, and complex technologies prevent investments until the level, type, and longevity of policy support is known and sufficient. The Advanced Fuel Fund has set the groundwork, but additional support is urgently needed. Time is running short to get these complex facilities built and commissioned by 2030.

The United States and EU have recognised this opportunity. The US has historically been a large producer of renewable fuels through the federal RFS and BTC policies, augmented by several state-level programs. This has been supercharged by the Inflation Reduction Act (IRA), attracting over 70% of announced SAF capacity to the US. The EU is also progressing, with the Fit for 55 policy package including several complimentary supply and demand side mechanisms. Notably, the EU has paired the ReFuel mandate with a contract-for-difference style mechanism, funded through revenue from the ETS program. Within this context, UK-based airlines have devoted significantly more investment and offtake agreements for SAF outside their home country.

The UK has a narrow opportunity to develop domestic SAF production and sustain the aviation industry in a low carbon future. This report comprehensively shows that the UK has the resources to achieve this and highlights the urgent need for policy to unlock the opportunities.

2 Key findings

- **Aviation context:** Aviation is a key pillar of the UKs economic and social prosperity, contributed more than £22 billion to GDP each year and directly employing over 230,000 people. As a hub for the global industry, the UK operates almost 8.4% of global capacity, despite representing just 0.8% of the global population. While UK terrestrial emissions halved between 1990 and 2019, aviation growth resulted in sectorial emissions increasing by 137%. The industry has committed to net zero carbon emissions by or before 2050 at the global, sectoral, regional, and individual levels. All mechanisms will be important to achieve this target, with SAF likely to make the largest contribution by decarbonising the energy required.
- **UK Energy context:** The UK has made significant progress to decarbonise. Low carbon electricity provided 54% of UK electricity in 2021, equivelent to 24% of primary energy. In just a decade, wind and solar generation in the UK has increased by 417% and reduced in cost so much that wind and solar are frequently the cheapest form of generation available. The RTFO (Renewable Transport Fuel Obligation) supports reduces 5.25 MT of on-road CO2e (2020). The more stringent sustainability expectations for SAF and need to avoid substitution of these fuels from road to sky means the SAF industry will require new technologies and policy approaches to succeed.
- **UK aviation emissions:** The UK Government Jet Zero Strategy forecasts aviation emissions of 39 MT (million tonnes) of carbon dioxide equivalent in 2030, decreasing to 29.5 MT in 2050. The remaining CO_2e must be addressed using in-sector (SAF) and out-of-sector (carbon removals) mechanisms to achieve net zero.
- **SAF Requirement:** 1.2 MT of SAF will be required in 2030 to meet the government ambition, increasing to 7.0 MT by 2050 to achieve net zero (in a central case with 75% of residual carbon addressed through SAF).
- **Current Outlook:** Achieving 1.2 MT in 2030 will require additional facilities. Announced SAF capacity in the UK is c. 0.6 MT, so at least 0.6 MT remains to be met by unnanounced capacity or imports – and more if the announced facilities encounter delays or difficulties during development. Support policy mechanisms which incentivise investment in SAF production will be required to scale up capacity.
- **Feedstock opportunities:** There is adequate SAF feedstock in the UK. In the central estimate, this study conservatively estimates feedstock availability for 3.5 MT SAF from waste and advanced feedstocks, and 1.9 MT from renewable electricity. The combined range is estimated at 2.7 MT to 9.3 MT. Alongside SAF, almost 3 MT of renewable diesel and naphtha co-products would be produced, accelerating the decarbonisation of the UK road, chemicals, and other sectors.
- **Feedstock specifications:** This study identifies and quantifies potential feedstocks, with strict sustainability criteria excluding any crops or food. The feedstocks assessed include agricultural, woody, and municipal wastes, advanced feedstocks such as algae, and renewable electricity. Most identified feedstocks are not currently in use, as the technology to convert them to fuels has not yet been commercialised. The availability of waste-based and advanced feedstocks is estimated at 0.48 EJ (exajoules), and rapid expansion of renewable electricity generation could make 50 TWh/yr available for PtL (Power-to-liquid) SAF.
- **Job creation:** Building a SAF industry has significant potential to create jobs and economic growth. Production of 0.6 MT SAF SAF in 2030 could create 10,350 jobs, including operators, construction, and upstream. By 2050, this could increase to 60,000 jobs in the UK. By decarbonising aviation, a SAF industry could sustain a further 210,000 aviation jobs in a carbon-constrained economy.
- **Economic growth:** By 2030, this analysis estimates that a SAF industry could contribute £1.8 billion in Gross Value Added (GVA) for the UK, with much of this in the upstream activities. By 2050 this could increase to £10.1 billion, of which £1.7 billion is direct/construction and the remainder in the upstream value chain.

Recommendations

- **Ensuring Supply:** The upcoming UK SAF mandate will stimulate demand, but this must be matched with policies to ensure the feasibility of production. The ambition to supply this SAF without substitution from on-road renewables or the use of feedstocks that compete with foods will constrain production to using technologies that are still in the early stages of commercialisation. The cumulative technology, feedstock, and revenue risk prevents investment, even with a mandate. Mechanisms to ensure revenue stability will be essential to commercialise the emerging technologies the UK requires.
- **Ensuring access to feedstocks:** Renewable electricity underpins the energy transition. Aviation must encourage and support the deployment of low-carbon electricity, particularly from wind, solar, and nuclear. A rapid build-out will increase the potential for PtL SAF and reduce the diversion of bio-feedstock for electricity production. Airports, airlines, and other companies in the value chain should stimulate the market, for example by purchasing REGO certificates, or building generation on site – as many UK airports are doing.
- **Short term scaling using waste fats and oils:** HEFA and Co-processing technologies draw from a finite feedstock pool but are commercially proven and will be important to kick-start the UK SAF industry. The UK is current projected to suffer a severe shortage of SAF compared to the mid/mid-term mandate volumes. No HEFA facilities have been announced in the UK at the time of writing. This stands in stark contrast to the rest of the world, with HEFA representing over 70% of global announced SAF capacity. An important factor is the proposal for a cap on the contribution HEFA can make to the UK SAF mandate. Ensuring any HEFA cap is initially set sufficiently high will be important for the early industry deployment and will be highly unlikely to 'squeeze-out' other SAF production technologies before 2030.
- **Catalysing the advanced ethanol industry:** The global Alcohol-to-Jet (AtJ) industry has significant ambition to scale, initially by leveraging the considerable 1st gen corn and sugarcane ethanol industries in the US and Brazil. 2nd generation ethanol from non-food cellulosic material offers improved sustainability attributes but is challenging to produce. The exclusion of feedstocks that compete with food would limit UK SAF to only 2nd gen ethanol, compounding the technical challenge of cellulosic ethanol production with the difficulty of AtJ production. Targeted measures could decouple the risk. Supporting the cellulosic ethanol co-product revenue streams (such as biochar) reduces the dependence on SAF revenue for cellulosic ethanol production. Allowing small volumes of 1st gen ethanol feedstock to be used in exceptional circumstances would reduce price spikes for cellulosic ethanol, for example if several facilities reduce production during maintenance. Ethanol from waste industrial gases has been shown as viable, but the limited calendar viability proposed in the EU will hold back investment. The UK has an opportunity to improve on this by linking the feedstock eligibility to a reasonable period after each facilities' commissioning.
- **Supporting Fischer-Tropsch technologies:** The UK has significant availability of Municipal Waste and other solid biomass that could be used for FT facilities. These require considerable capital investments, and revenue support policies will be particularly critical to seize this opportunity, alongside policies such as capital grants and loan guarantees to support the investments (as used in the US). Accessing the relevant feedstocks requires the support of local governments, which should be incentivised to facilitate feedstock contracts. Recognising the balance between progress and perfection is important, and regulations across the CI requirement and waste-based/non-waste-based measurement should be structured with gradually increasing stringency to ensure the industry faces a manageable set of challenges to address.
- **Facilitating deployment:** The UK SAF industry is developing from a low base and will need to build up many capabilities across the value chain, from construction to insurance and financing. This will take time, and emphasises the need to implement a robust, clear policy environment to accelerate efforts and attract international resources as soon as possible.

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3 Introduction and UK Context

3.1 Introduction

Aviation is currently responsible for 2.1% of all human-induced carbon dioxide (CO_2) emissions[1] and up to 3.5% of global warming with additional effects such as contrails[2]. Aviation has significantly reduced fuel consumption per passenger kilometer travelled by improving efficiency, but this will not be sufficient to decarbonise the industry. More must be done to avoid the worst impacts of climate change.

Recognising the need to accelerate efforts, the global aviation industry has committed to achieving net zero by 2050. Achieving this target will only be possible by decarbonising the fuel produced and consumed. Decarbonising the fuel will require SAF to take the leading role. However, there is a long journey ahead with commercial SAF only just starting production and no dedicated facilities currently under construction in the UK.The UK will need to support a diverse range of feedstocks, technologies, and approaches. The country has plentiful waste and residue feedstock, supported by globally leading knowledge, expertise, and the strong renewable energy industry offering potential to scale power-to-liquids (PtL) SAF in the longer-term.

This document describes the context, evaluates the resources available, and shows several potential roadmaps for the deployment of a UK SAF industry.

3.2 The UK has built a world leading aviation industry

The aviation industry underlies modern society, **connecting over 1.5 people globally, with the UK acting as a crucial hub.** It enables businesses to conduct international operations, friends to come together over long distances, and tourists to travel and explore.

The relative size and value of the UK aviation industry is far greater than the global average. In 2019, UK aviation delivered over 843 billion Available Seat Kilometres (ASK)[3], equivalent to almost 8.4% of global capacity despite representing only 0.8% of the world's population. By contrast, the aviation activity per person is almost double in the UK compared to similar European countries, with 12,700 ASK per person per year in the UK, compared to 7,000 in France.

The industry brings considerable value to the country. The UK Jet Zero Strategy calculates that before COVID-19, the aviation sector contributed more than £22 billion to UK GDP each year and directly employed at least 230,000 people[4]. Alongside a vibrant airline industry, the UK also has a leading aviation manufacturing industry, with more than 13,000 aircraft worth up to £195 billion produced in the country over the last decade[5]. Key manufacturers, such as Rolls-Royce, Airbus, GKN, Thales, Boeing, BAE, and many other aerospace firms operate in the UK.

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[1] Air Transport Action Group (ATAG) – Facts & Figures

[2] Study published in 2020 in the Atmospheric Environment journal

[3] OAG

[4] UK Jet Zero Strategy

[5] UK manufacturing statistics

Mobility and connectivity are fundamental to a sustainable economy. Over a third of the UK's ex-EU trade by value is sent by air, with air transport essential for perishable and time-sensitive goods such as food and medical supplies[6]. Developing a sustainable way for the aviation industry to continue serving communities and businesses will provide significant environmental, economic, and social benefit for the UK.

The value provided by the industry is expected to increase as the UK aviation industry continues to grow. Strong demand for flights to and from the UK will compound the global demand for aircraft, systems, and technologies manufactured in the UK. For example, the introduction of the Manchester to Beijing service in 2016 increased export values from Manchester Airport to China to £1.29 billion, created 11 inward investment projects, and increased inbound tourism by 38%[7].

3.3 The industry must decarbonise to reach its full potential

If no action is taken, aviation will contribute an increasing portion of emissions. Global carbon emissions increased by 62% between 1990 and 2019[8], while global aviation carbon emissions increased by 146%[9]. In the UK, the inequality is even larger; UK terrestrial emissions decreased by 49.7% over the same period, while UK international aviation bunkers increased by 137%[10]. As other, easier to abate sectors reduce their emissions, it is feasible that if no further action is taken aviation could become one of the largest sources of GHG emissions in the UK.

There is considerable social pressure to decarbonise. There is a growing recognition that while aviation is a small percentage of global emissions, it represents the greatest source of emissions for some individuals. To illustrate, the average per-person emissions reported by the UK to the UNFCCC[11] was 7 tCO_2e per capita in 2019[12] (for all domestic sources but excluding international aviation and marine), while IATA estimates[13] that a single return economy-class trip LHR–SFO will emit 0.9 tCO_2. This means that a passenger could create as many emissions on a22-hour flight as they would in 1,130 hours of other activities. Additionally, a few international trips can emit more carbon than the average UK resident in a year.

This pressure is translating to behaviour change. The Flygskam, or flight-shame movement, originated in Sweden in 2018 and has quicklygained traction, encouraging people to use more sustainable alternatives to aviation. Causality is difficult to assess, but there are few robust alternative explanations for the 4% decrease in passenger numbers flying through Swedish airports and 9% decrease in domestic travel[14], particularly as the main train operator in Sweden announced 1.5 million more tickets sales in 2018 compared to the previous year[15].

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[6] Airlines UK

[7] The China Dividend

[8] Global CO2 emissions from fossil fuels & industry

[9] European Parliament: Emissions from planes and ships

[10] 2020 UK Greenhouse Gas Emissions, Final Figures

[11] 'Territorial emissions', which include emissions created within the UK border. It excludes international aviation and shipping, and the consumption emissions from UK use of goods produced in other nations.

[12] 2020 UK Greenhouse Gas Emissions, Final Figures

[13] ICAO carbon emissions calculator

[14] Sweden sees rare fall in air passengers, as flight-shaming takes off

[15] How Greta Thunberg and 'flygskam' are shaking the global airline industry

Pressure is also growing from a finance perspective, with HSBC Bank reporting in 2019 that mentions of climate change increased from 1.5 sentences per earnings call in 2018 to 6.5 in 2019[16].

Airport expansion ambitions have been materially impacted. Airport expansion proposals at Heathrow, Bristol, and other UK airports have been challenged in the courts on sustainability grounds[17,18].

The UK aviation industry has recognised the challenge. Targets have been established at the global, national, and organisational scale, supported with varying levels of detail and initiatives. In February 2020, UK Sustainable Aviation was the first aviation industry coalition to commit to net zero by 2050. At the global level, IATA, representing the airline industry, has committed to net zero carbon emissions by 2050 in October 2021. This was supported by the detailed Waypoint 2050 analysis and the associated study *Fuelling Net Zero* on SAF by ICF. Representing the airport industry, ACI has committed to a long-term carbon goal of net zero by 2050. At the national level, the UK Government announced the UK Jet Zero strategy in July 2022, which details the country's approach to achieving net zero aviation by 2050. The UK has enshrined the aviation emission reduction target into law and has shown leadership by incorporating the UK's share of international aviation emissions into the sixth Carbon Budget[19].

The targets are translating into initiatives. The global and national targets have been endorsed by the whole UK aviation industry. These targets are increasingly supported by well-considered plans to achieve them, and capital, resources, and prioritisation given to sustainability initiatives.

Decarbonisation and growth are not incompatible. The technical, economic, and operational challenges are daunting, but these challenges must be considered in the context of the value generated by the industry. ATAG estimates that in 2019, aviation directly and indirectly enabled $3.5 trillion (£3.1 trillion) in global GDP and emitted 915 million tonnes of CO_2 in the same year, suggesting an extraordinary economic benefit of $3,800 (£3,300) per tonne of carbon emitted. In the UK, the Jet Zero strategy estimates £22 billion in direct GDP contributions and the CCC estimate 39.6MT CO_2e in 2019, suggesting a direct benefit of £555 (around $600) per tonne of carbon emitted – not including the further £34 billion of aerospace exports from the UK. This provides a strong rational for the growth of aviation but can only be justified if the industry can demonstrate a credible path to decarbonise. Given the difficulty and uncertainty, the path will require evidenced by near-term achievement.

3.4 Efficiency is not enough – aviation must decarbonise the energy used

The aviation sector has continuously recorded significant efficiency gains, driven by the strong alignment of financial and environmental incentives; with fuel costs representing around a third of total airline costs, fuel economy is critical to profitability. Recognising this, manufacturers have invested over £120 billion in research and development since 2009[20], and airlines have spent over £9.25 million on newer, fuel-efficient aircraft over the same period. This has enabled fuel consumption and CO_2 emissions per seat kilometre to reduce by 54% between 1990 and 2019[21].

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[16] Climate issues becoming material for airline investors

[17] Heathrow expansion blocked

[18] Bristol airport expansion blocked

[19] UK enshrines new target in law to slash emissions by 78% by 2035

[20] Waypoint 2050

[21] ATAG fact sheet 3: Tracking aviation efficiency

These efficiency improvements are visible in the elegant curves of newer aircraft representing improved aerodynamics, and the high bypass ratios of modern engines improving propulsive efficiency. Many further material, structural, system, and other improvements further contribute. There are considerable opportunities to sustain these incremental improvements, as seen by announced future aircraft, engine, and research programs. While some of the easier opportunities have already been addressed, the growing size of the industry has also increased the reward for improvements, allowing greater capital to be focused on sustaining efficiency improvements. Sustainability considerations will also play a role, with increasing carbon costs and sustainable fuel mandates further incentivising fuel efficiency. As the reward for fuel efficiency increases, it may allow engineering firms to take on the development risk for more advanced configurations, such as open rotor engines, truss-braced wings, or blended bodies.

These technical improvements can be augmented by operational changes, such as cruising at lower speeds, saving fuel but increasing block times. Other operational improvements require investment in infrastructure, such as air navigation service providers (ANSPs) and airports, to allow more efficient routings, smooth ascent and descent into airports, better taxiing, and many other changes. In a white paper by the UK CAA for COP26, these improvements were estimated to offer emission reductions of up to 8%[22].

The potential contribution from improved technology and operational efficiencies can be seen in the analysis by the UK Jet Zero Strategy. Coupled with a slight reduction in growth due to the higher cost of aviation resulting from the cost of carbon, this analysis shows around a 45% reduction in UK aviation industry emissions[23] by 2050, compared to the baseline.

Research also clearly shows the limits to the extent that we can rely on efficiency improvements to decarbonise the industry, particularly in the context of sustained growth and the long industry asset turnover cycles. Even with reduced growth and efficiency improvements, slightly over half of the UK industry emissions remain, which must be addressed through lower-carbon fuel use or out-of-sector measures. Adoption of more efficient operations, aerodynamics, propulsion, and systems will make the task to decarbonise manageable but cannot solve it alone. A key contributing factor will be the decarbonisation of the energy used. .

3.5 SAF must be part of a portfolio approach to decarbonise aviation

There are four major approaches that can be used to decarbonise the energy used by aviation: electricity, hydrogen, bio-SAF, and Power to Liquid SAF (PtL). A summary of the main advantages and disadvantages of each is given below, which illustrates the key role SAF will play in the decarbonisation of UK aviation.

Electric aircraft will predominately impact short range aircraft in the mid/long-term. The regional market represents a significant number of flights, but a low portion of emissions. Research commissioned by the UK Government and UK Climate Change Committee (CCC) stated that larger (>71 seats) all-electric aircraft are unlikely to be in service until after 2050, and thus cannot offer meaningful emission reductions in the short or medium term[24]. A key challenge is the battery weight; while jet fuel provides over 40 MJ of energy per Kg of weight, the best batteries today provide less than 1 MJ of energy per Kg weight. This impact is compounded as conventional aircraft get lighter during the flight as they consume fuel, while the weight of batteries remains the

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[22] Equipping Aviation Regulators to Decarbonise Air Transport and Tackle Climate Change

[23] This varies by scenario. These values use the average of Scenarios 2, 3 and 4, which represent the scenarios modelling a ‘do something’ outlook.

[24] Understanding the potential and costs for reducing UK aviation emissions

same. This limits their mid-term application to regional, short-haul and novel applications, such as air-taxis. In the UK, the 2ZERO project received a share of £30m from Future Flight Challenge to demonstrate hybrid-electric aircraft on regional routes in the South-West[25]. This will see an electric aircraft being based at Cornwall Airport, Newquay, and energy used to charge batteries generated by an adjacent solar farm. The same project saw Ampaire, a leader in electric aviation, demonstrating the first hybrid electric flights in Scotland during summer 2021[26]. Virgin Atlantic have partnered with Vertical Aerospace, based in Bristol, to purchase up to 150 electric zero emission vertical take-off and landing (eVTOL) aircraft[27].

Hydrogen will become increasingly important as supply and demand challenges are solved. Approximately 100 million tonnes of hydrogen are currently consumed by refineries, fertiliser production, steel, and other industries, with almost all produced from natural gas, creating approximately 9 Kg of CO2 per 1 Kg of hydrogen. Decarbonising existing and future demand will require a significant build-out of renewable electricity and electrolyser production (Green), and Carbon capture and sequestration (Blue), alongside new infrastructure for transport, storage, and distribution.

Currently there are no hydrogen aircraft in commercial production, although several companies are working towards this goal. British Airways partnered with ZeroAvia in the UK to speed up the switch to hydrogen-powered passenger aircraft, and recently completed the world's first hydrogen fuel cell powered flight of a commercial-grade aircraft[28]. Rolls-Royce and easyJet announced a partnership to develop hydrogen combustion engine technology, aiming to demonstrate the use of H_2 to power a range of aircraft from the mid-2030s onwards[29]. Developing and deploying hydrogen aircraft will take time.

Bio-SAF is SAF produced from biological feedstocks, such as waste oils, fats, agricultural, woody and municipal residues. The low weight and volume required to store energy as kerosene make SAF ideal for flight. As a drop-in fuel, SAF can be used with no change to the infrastructure and to the aircraft used today. The production technologies are proven to be safe, and need to be commercially scaled.

Power to Liquid SAF is a production approach using renewable electricity and hydrogen as the feedstocks. This could alleviate constraints on bio-feedstock availability, although is currently more expensive. Conversion into SAF uses the same technologies as bio-feedstocks, allowing PtL to leverage cost reductions achieved alongside the scaling of bio-SAF, cost reductions in direct air capture (DAC), and green hydrogen production.

3.6 Quantifying the role for SAF in the UK

Reduced use of jet fuel will be critical to reduce the challenge for SAF. Sustainable fuels are no silver bullet and will be challenging to scale. Accelerating the deployment of more efficient aircraft and zero-carbon aircraft (such as hydrogen and electric) is a pre-requisite, but these solutions are forecast to leave considerable emissions unabated.

In sector emissions: The UK Jet Zero Strategy allocates 38.1 million Tonnes CO2e (MT CO2e) from civil aviation in 2019, with a further 1.1-1.2 MT CO2e from military aviation. While the Jet Zero strategy excludes military, this

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[25] 2ZERO - Towards Zero Emissions in Regional Airline Operations

[26] Ampaire Demonstrates First Hybrid Electric Aircraft in Scotland

[27] Virgin Atlantic partners with Vertical Aerospace

[28] British Airways & ZeroAvia partnership

[29] easyJet and Rolls-Royce partner on hydrogen technology demonstrator programme

analysis has broadened the scope to include them as the RAF has committed to Net Zero by 2040[30], and their initiatives will interact with the civil sector; from trials with electric aircraft[31] to consumption of sustainable fuels[32]. Assuming no change to military emissions[33] and no improvements above the continuation of current trends baseline, aviation emissions would increase to 52.2 MT CO2e in 2050 (+ 36%), while passenger numbers increase from 275 million in 2019 to 465 million in 2050. The Jet Zero Strategy models three improvements to abate emissions below this level:

1. **Reduced demand due to carbon price:** The strategy assumes the aviation carbon price increases to £346/tonne CO2 in 2050. While this supports the adoption of more efficient aircraft and low carbon fuels, it also increases the cost of flying and therefore reduces demand. As a result, the assumed carbon emissions in 2050 are forecast to reduce by 13.9 MT CO2e (27% of the 2050 abatement).
2. **More efficient aircraft:** The Jet Zero strategy assumes slightly greater aircraft efficiency improvements, reducing emissions by 7.9 MT in 2050 (15% of 2050 abatement).
3. **Zero-emission aircraft:** Hydrogen and electric aircraft enter the commercial fleet in 2035, gradually replacing aircraft where viable. These reduce 2050 emissions by 2.1 MT CO2e (4% of 2050 abatement).

Despite these measures, this leaves a further 29.5[34] MT in-sector CO2e that must be abated in 2050.

Out-of-sector emissions: The UK Jet Zero Strategy accounts for fossil jet fuel emissions using the Greenhouse Gas Protocol (GHGp), allocating tank-to-wake emissions (from the combustion of the fuel) to aviation, and the well-to-tank emissions (from the extraction, transport, refining of fuel) to the sectors in which they are emitted. Carbon accounting for the UK aviation sector must recognise these upstream emissions – and the role that each mechanism can contribute to abate them. Carbon pricing and more efficient aircraft are equally effective at reducing the upstream emissions. Zero-emission aircraft will only contribute zero upstream emissions if zero-carbon electricity/hydrogen is used.

The upstream emissions have been estimated using the ICAO global benchmark of 89 gCO2e/MJ jet fuel, which implies that in the base case an additional 12.7 MT CO2e is emitted from upstream sources in 2050, reducing to 7 MT CO2e after the impact of carbon price, aircraft efficiencies, and Zero-emission aircraft are included.

The Jet Zero Strategy diverges from the GHGp when accounting for the emissions reduction of SAF. The GHGp currently recommends that renewable fuels are assumed to have 0 in-sector (tank-to-wake) emissions, with the residual emissions recorded separately. To reconcile more closely with reality, the Jet Zero Strategy assumes the in-sector emissions are reduced by the average GHG reduction of the SAF. This difference is important as it means the upstream emissions reduction from SAF is not captured in the Jet Zero Strategy. To align with the Jet Zero Strategy, the same approach has been used in this analysis, with the full emissions scope illustrated below.

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[30] A Net Zero RAF by 2040

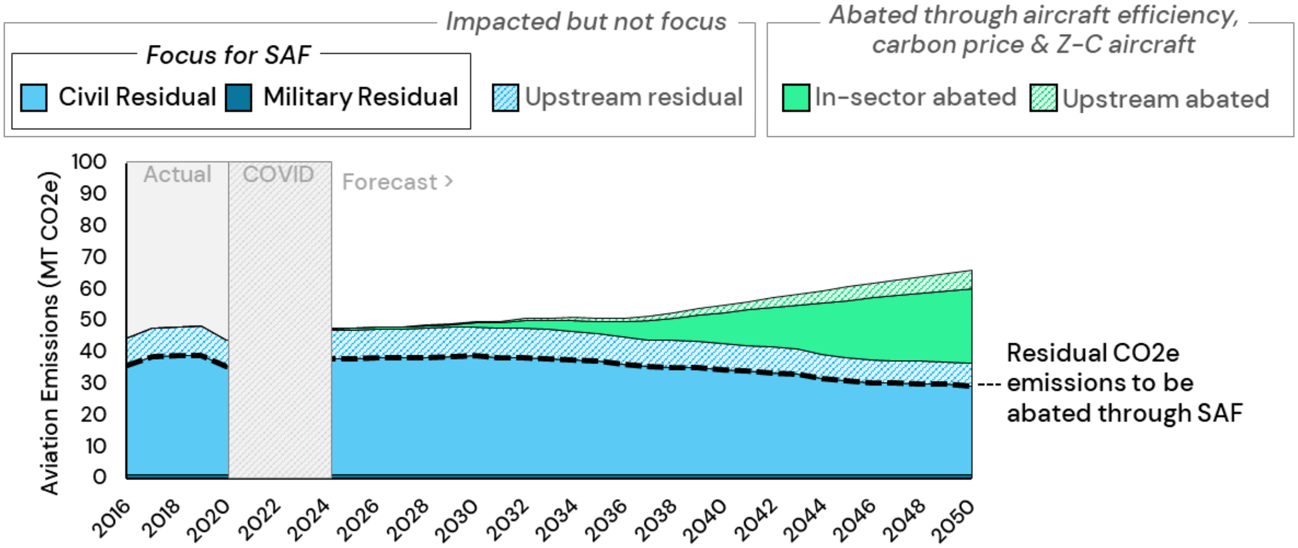
[31] RAF takes key step on path to Net Zero 2040 with electric aircraft trials

[32] Project MARTIN - Defence goes green

[33] The UK RAF has committed to Net Zero emissions by 2040. This analysis has assumed that delivering capabilities is prioritised over decarbonisation, leaving the RAF to focus on renewable drop-in fuels (SAF). This may be conservative, as some military aircraft such as trainers my be able to use zero carbon technologies.

[34] 28.4 MT from civil aviation, 1.1 MT from military aviation

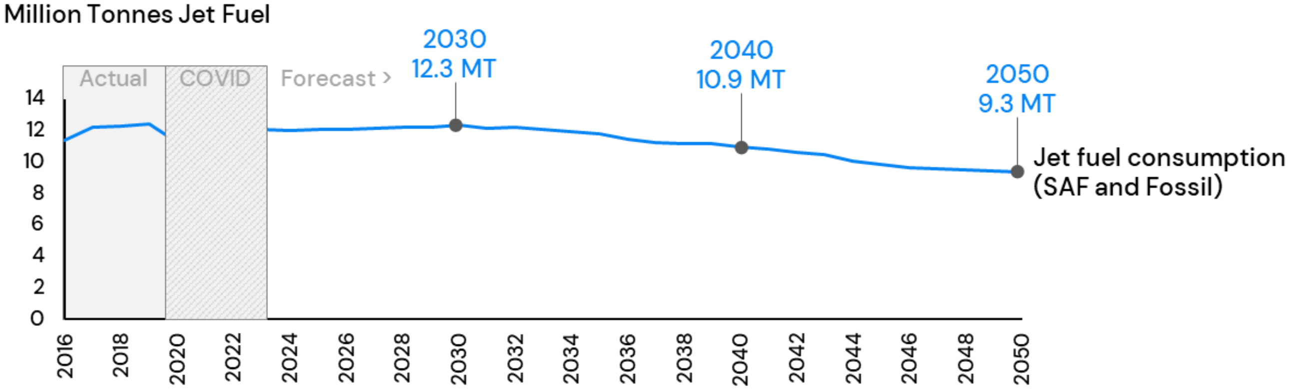
The UK aviation in-sector emissions remaining after carbon impacts, fleet efficiencies and zero-carbon aircraft is 39 MT in 2030, decreasing to 30 MT in 2050



Source: UK Jet Zero Strategy, aligned to Scenario 3(High Ambition, SAF).
Notes: Military is not included in the Jet Zero Strategy, but has been added as a source of demand for SAF. Total emissions calculated assuming jet fuel emission intensity of 89 gCO2e/MJ, aligned to ICAO

The measures outlined in the Jet Zero Strategy will reduce the demand for aviation fuel. While 12.4 million tonnes of aviation fuel were consumed in 2019, the carbon impacts, fleet efficiencies and zero-carbon aircraft are forecast to reduce the demand for fuel over the next decades. Applying the decrease to the jet fuel volumes reported by the DfT implies a reduction in demand to 12.3 MT in 2030 and 9.3 MT by 2050.

UK Aviation Fuel demand is forecast to decrease from 12.4 million tonnes in 2019 to 9.3 MT in 2050, reducing the volume of SAF required to decarbonise aviation



Source: UK Department for Transport Statistics, National Atmospheric Emissions Inventory (NAEI) team. Extrapolated using the Jet Zero Strategy.
Notes: Including Military. Jet fuel only; excludes energy use from zero-carbon aircraft

A greater reduction may be possible, as the impact of COVID-19 is not fully captured; the Jet Zero strategy records a 10% drop in CO2e in 2020 vs 2019, compared to the 60% drop in fuel consumption reported by the DfT. Reducing the scope to exclude military fuel use would further reduce the calculated jet fuel demand.

The UK context - implications:

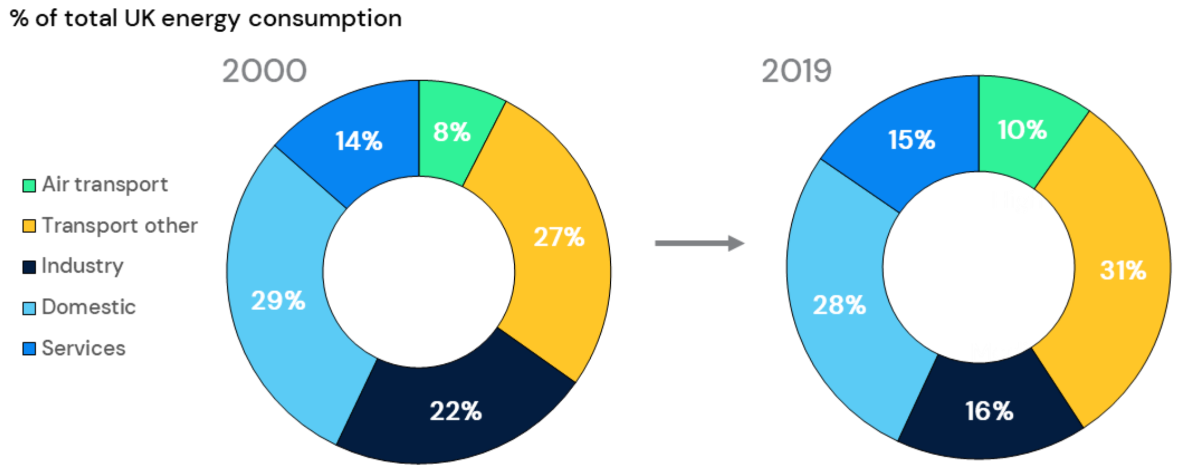
- Aviation is a key pillar of the UKs economic and social prosperity, contributing more than £22 billion to GDP each year and directly employing over 230,000 people. As a hub for the global industry, the UK operates almost 8.4% of global capacity, despite representing just 0.8% of the global population. The value provided by the industry will continue to increase as the industry grows.
- Aviation represents 2.1% of global carbon emissions. While UK terrestrial emissions halved between 1990 and 2019, the strong growth of the aviation sector resulted in emissions increasing by 137% over the same period. The UK aviation industry must decarbonise for the country to achieve its climate ambitions.
- The industry has stepped up to this challenge, committing to net zero carbon emissions at the global, sectoral, regional, and individual levels.
- There is no silver bullet, and all mechanisms are crucial, including efficiency improvements, electric, hydrogen and hybrid aircraft, and sustainable aviation fuel. To avoid the most catastrophic impacts of climate change, SAF must play a significant role.
- Many companies have implemented sustainability initiatives, but the use of SAF in the UK continues to be extremely limited. Several UK airlines, including British Airways and Virgin Atlantic, have made commitments and investments to purchase SAF in the US, building on the supportive federal and state policy schemes. The domestic industry in the UK must be catalysed through additional policy mechanisms and clarity.

4 The UK Energy context

4.1 Energy must be considered in the wider context

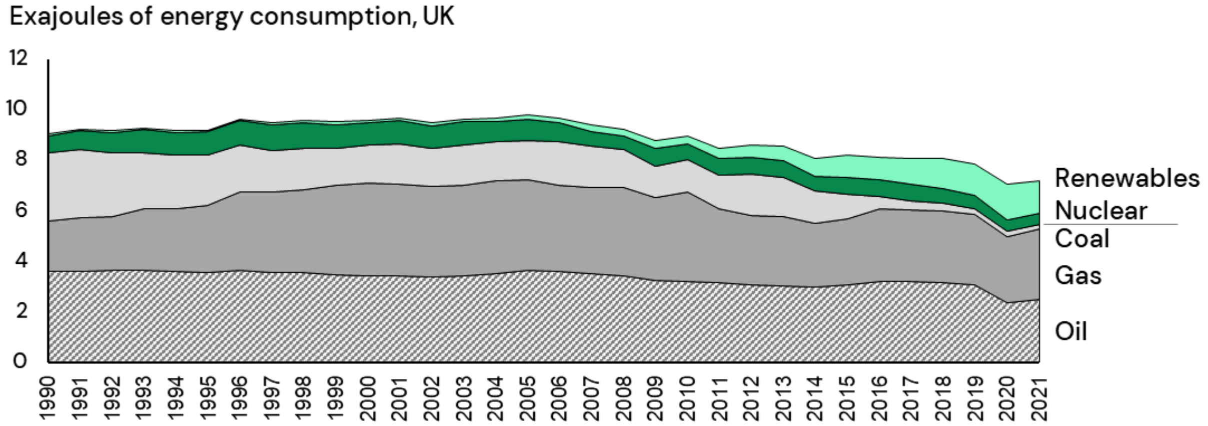
While aviation represents only 2.1% of global carbon emissions and a similar portion of global energy consumption, it represents a much higher portion of energy consumption in the UK – both because the UK has a relatively carbon-efficient, service economy, and because the UK is the hub for a large aviation industry. Since 2000, the portion of energy consumption by aviation has grown from 8% to 10%, driven by the increased efficiency in other sectors and aviation growth.

UK energy consumption in 2000 and 2019, by sector



The UK has made significant progress to decarbonise the energy consumed, becoming a world leader in wind power. In 2021, low carbon electricty (renewables and nuclear) provided 54% of electricity consumed, but just 24% of primary energy in the UK. To fully decarbonise the UK, more industries must transition to use electricity (e.g., through electric vehicles and heat pumps) and the electricity used must be decarbonised. This compounding challenge makes it crucial to ensure the best approaches are used for each industry.

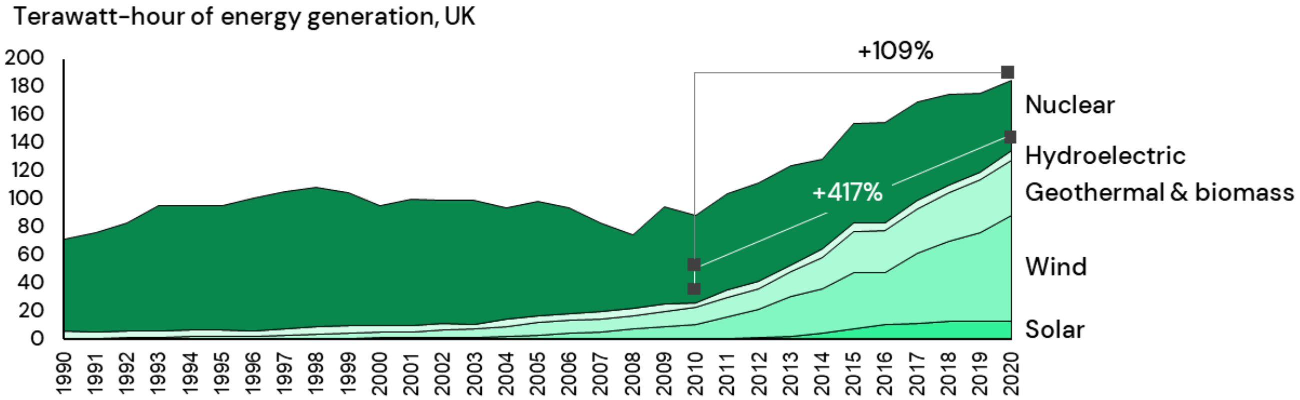
Considerable gas and oil consumption must be displaced by renewables



Source: BP Statistical Review of World Energy June 2022
Note: Renewables are measured on an input-equivalent basis, i.e., the EJ of input fossil energy that would be required to generate the equivalent amount of energy

When viewed independently, the rapid scaling of low carbon electricity is clear. Since 2010, the total generation of low carbon energy in the UK (including nuclear and hydroelectric) has increased by 109%. Excluding nuclear and hydroelectic, the other renewables have increased by an incredible 417% over the same decade.

The UK has rapidly scaled zero-carbon energy, particularly wind generation



Source: BP Statistical Review of World Energy June 2022

The use of energy is crucial. The majority of renewable energy in the UK is used to decarbonise the electricity grid, primarially due to the ease of substitution and economic advantages. Other sectors have seen a much slower transition to clean energy, for example the road sector, which has many more hurdles to substitution (complete asset replacement of ICE cars to electric vehicles), lower incentives (road is currently not covered by the ETS, although this may change[35]), and less structured buying decisions of the public compared to corporations. As a result, the UK emissions from transport overtook the UK emissions from the power sector in 2016[36], and have continued to grow faster since (although this temporarially reverted during COVID).

The UK already has several policies to decarbonise the road sector, particularly through electric vehicles (EVs) and on-road biofuel use. The UK Renewable Transport Fuel Obligation (RTFO) mandates that an increasing portion of renewable fuels must be blended into road fuels. In 2020, the required blend rate was set at 10.637% of fossil and renewable fuels used in road transport , and will gradually increase each year.

A significant volume of the feedstock used to produce fuels for road under the RTFO are also feasible feedstocks for SAF production. In 2020, Used Cooking Oil (UCO) was the largest feedstock for RTFO fuel production, contributing 50.5% of supply, while no other feedstock contributed more than 7% of the supply. UCO is widely used and desirable for SAF production due to the low technical risk for conversion to renewable fuel (Hydro-processed Esters and Fatty Acids, HEFA, or co-processing pathways), high carbon reduction potential, and ease of transportation. Ethanol can be blended directly with petrol (e.g., E10), and is also an important feedstock for SAF, with considerable announced capacity using the AtJ pathway (particularly by producers such as LanzaJet and Gevo). As the SAF market develops this will be advantageous to ethanol producers as it will provide an additional market to sell into, however, it will also require SAF producers to be able to offer higher value (or offtake security) compared to the road market to gain a supply of ethanol. Supplying the volume of UCO and ethanol to meet the RTFO obligation (particularly as it continues to increase) exceeds the supply available in

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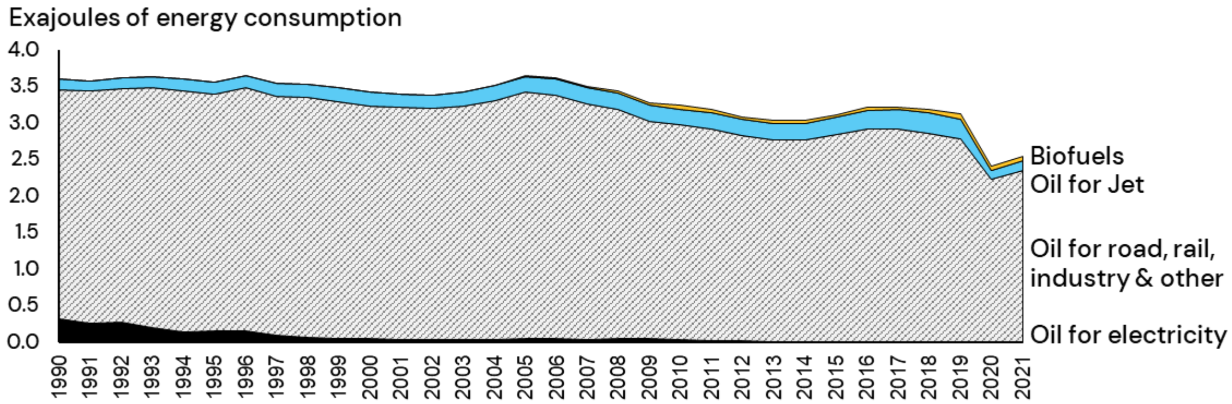
[35] Developing the UK ETS

[36] Transport and environment statistics

the UK, requiring significant imports. In 2020, just 12% of renewable fuels were supplied by the UK, with other top supplying countries including China, USA, Spain, and France.

These challenges emphasise the difficulty to scaling the biofuels industry, particularly in the context of total oil use in the UK. As shown below, the current biofuel use is a fraction of the oil used for on-road transport, which itself is a small portion of oil used for all modes of transportation, materials, and other industries. Even with increased efficiency and technologies to utilise a wider range of feedstocks it will not be possible to scale biofuels to displace all oil use in the UK. The feedstocks and fuels must be targeted to the sectors where they can have the most impact.

Renewable liquid hydrocarbon fuel represents a fraction of total UK oil consumption



Source: BP Statistical Review of World Energy June 2022

Policies to decarbonise other sectors that may look to biofuels but have access to economic and feasible alternatives are therefore indirectly crucial to decarbonise the aviation industry. It is particularly encouraging to see the development of UK policy to ban the sale of new petrol and diesel cars from 2035 and the accelerating of EV sales. In 2021, 190,000 battery powered EVs were sold in the UK, more than the five previous years combined, representing almost 1 in 8 new cars sold[37].

The SAF industry is also linked to the road sector by many facilities producing fuels for use in several markets. Hydrocarbons such as naphtha, petrol, jet fuel, and diesel contain many different types of molecules, with a range of properties. Two particularly important properties are the carbon chain length and the boiling point, with the carbon chain length and boiling point of jet fuel overlapping somewhat with petrol, and significantly with diesel. This overlap means that every facility will produce a blend of products, which must then be separated. Due to the considerable overlap with diesel, it is generally possible for a facility to produce diesel with no jet fuel, but rarely jet fuel with no diesel. This also impacts the economics. If a facility aims to maximise the production of jet fuel, then it must shift the production distribution to shorter carbon chain lengths than diesel, which also results in more naphtha and light ends. These have a lower market value and are sometimes not eligible for incentives. Separating and processing jet fuel also requires some additional infrastructure, which together with the product distribution dynamics means that in the absence of regulatory value, renewable diesel

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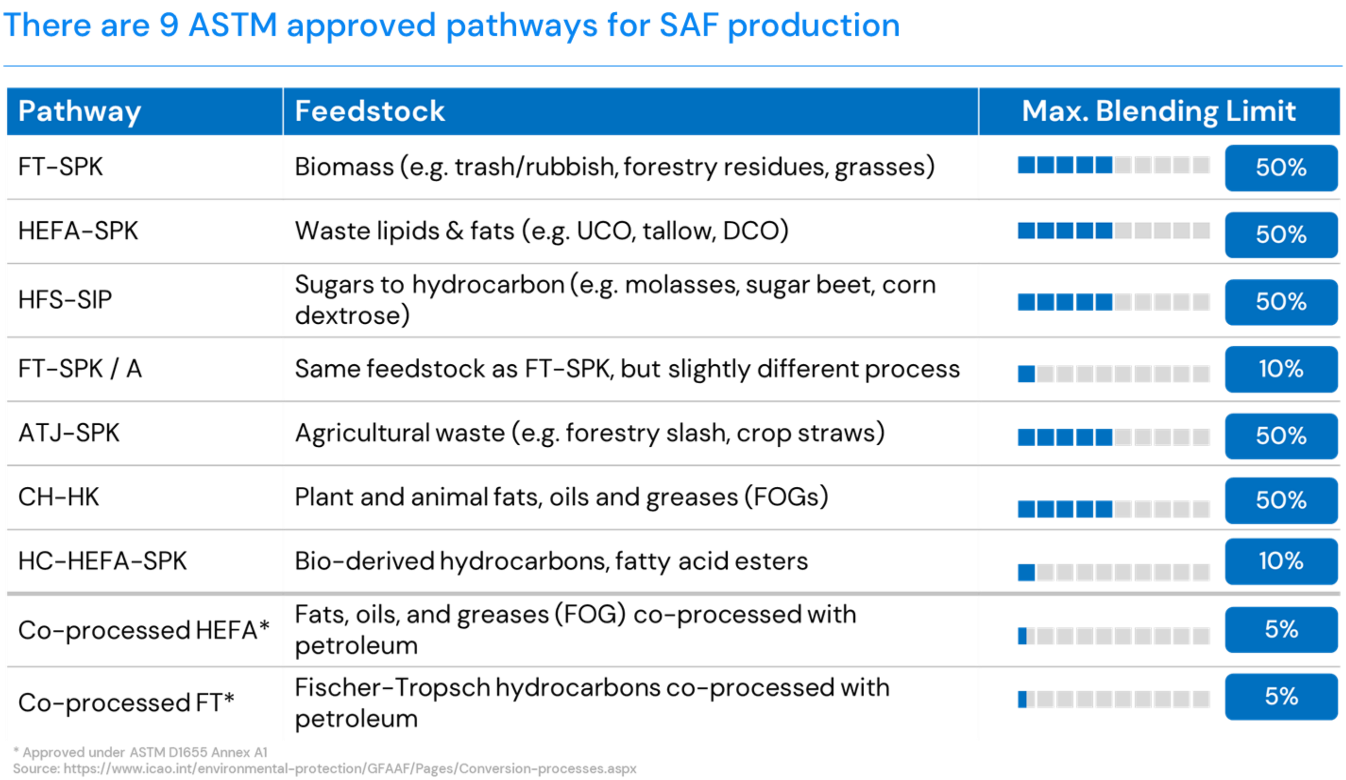
[37] Taking charge: the electric vehicle infrastructure strategy

is always more profitable to produce than SAF. As a result, the renewable diesel market today is quite developed, while the SAF market is nascent.

Building a SAF industry is incremental to the existing UK renewable fuel industry and must consider this context. In the absence of regulation or a meaningful premium by offtakers, other renewable fuels will always be more profitable, and (as today) very little capacity will produce any SAF. While UK SAF production is increasing from almost zero, demand for the most desirable feedstocks is significant. The UK already imports considerable feedstocks to meet the RTFO and it is reasonable to expect that the competition for these feedstocks will rapidly increase; for example, as the EU ReFuel mandate diverts feedstocks to the EU, as the US Inflation Reduction Act increases the desirability of US domestic production and use of SAF, and as other facilities (such as the Neste SAF refinery in Singapore) increasingly use feedstocks closer to their source.

4.2 Additional pathways will allow access to wider feedstock opportunities

Current biofuel production almost exclusively uses fats, oils, and greases. Expanding the industry will require the commercialisation of additional pathways to widen the feedstock pool that can be accessed. The American Society of Testing and Materials (ASTM) has certified pathways for 7 pathways and 2 co-processing pathways, which allow hundreds of combinations of feedstocks, pre-processing, and conversion for SAF production. Commercialising all available pathways will be crucial to ensure the industry can access sufficient feedstock to sustainably grow.



There are 9 ASTM approved pathways for SAF production

Pathway	Feedstock	Max. Blending Limit
FT-SPK	Biomass (e.g. trash/rubbish, forestry residues, grasses)	50%
HEFA-SPK	Waste lipids & fats (e.g. UCO, tallow, DCO)	50%
HFS-SIP	Sugars to hydrocarbon (e.g. molasses, sugar beet, corn dextrose)	50%
FT-SPK / A	Same feedstock as FT-SPK, but slightly different process	10%
ATJ-SPK	Agricultural waste (e.g. forestry slash, crop straws)	50%
CH-HK	Plant and animal fats, oils and greases (FOGs)	50%
HC-HEFA-SPK	Bio-derived hydrocarbons, fatty acid esters	10%
Co-processed HEFA*	Fats, oils, and greases (FOG) co-processed with petroleum	5%
Co-processed FT*	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

* Approved under ASTM D1655 Annex A1

Source: https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

The UK energy context - implications:

- The UK has made significant progress to decarbonise energy by becoming a world leader in wind power. In 2021, low carbon electricty provided 54% of UK electricity consumed, equivelent to 24% of primary energy.
- In just a decade, wind and solar generation in the UK has increased by 417% and reduced in cost to the extent that such as wind and solar now the cheapest form of generation available.
- The UK has developed a vibrant on-road biofuel industry, but this represents a fraction of total liquid hydrocarbon use in the UK. Future decarbonisation will require additional technologies to be commericalised to allow the feedstock pool to be expansed, and policies to ensure limited resources are used to decarbonise the industries where direct electrification is not possible – including aviation.

5 Market outlook and UK requirement

Image credit: NASA

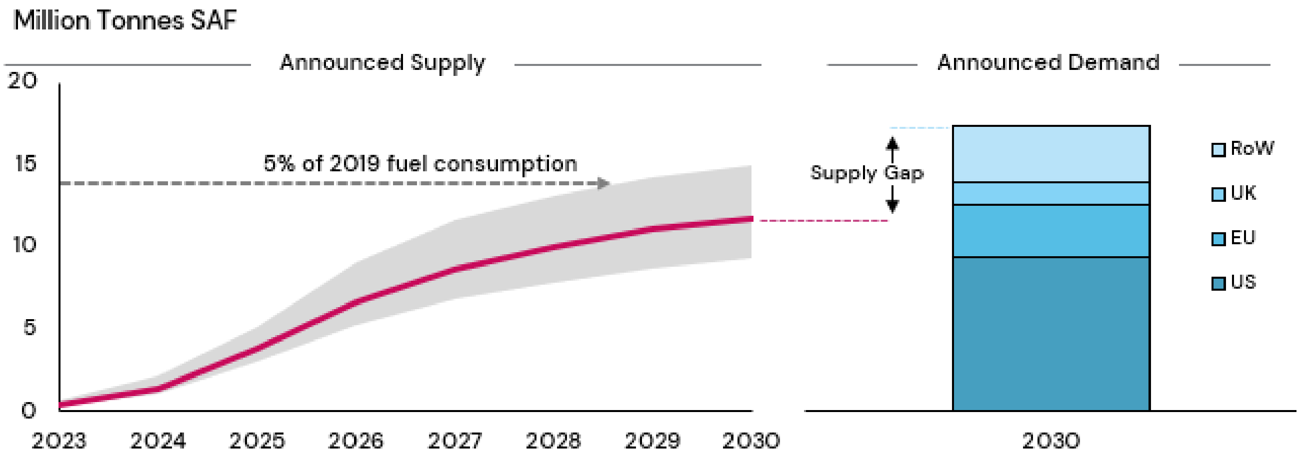
5.1 Global market outlook

In 2022, global SAF production was less than 0.1% of jet fuel, with just 240,000 tonnes of production[38]. The Net Zero carbon emissions from aviation target established by IATA, set into law by the UK, and adopted by the airlines operating from the UK will require approximately 400 million tonnes of SAF globally by 2050. This will in return require extremely rapid deployment, compounded by technical, economic, and policy uncertainty. There is an expectation that slow initial growth in SAF production capacity will accelerate as technologies are de-risked and become more affordable. As a result, 2030 ambitions have universally been set with the assumption of accelerated growth in the subsequent two decades. For example, the EU are discussing 6% SAF by 2030 through ReFuel, the US has set a 2030 goal for 3 billion gallons of SAF (c. 15%), and the UK is developing policies to achieve 10% SAF by 2030.

The market outlook is complicated by multiple contributing factors, so this report has focused on a comparison between announced facilities and announced targets. At the time of writing, meeting the ambitions in the US, EU, and UK will require c. 14 million tonnes of neat SAF by 2030, with the expectation that this will significantly increase as many more countries look to scale use of SAF. For example, it seems likely that Turkey, Australia, New Zealand, Japan and others will make commitments in the near future.

The volume of announced SAF capacity is currently much lower than this. Production should expand as additional facilities are announced over the coming years, however the long lead times for new facilities means that most capacity operating by 2030 will have been announced by 2025-2027. Equally, many announced facilities may not achieve operation, with a myriad of possible technical, commercial, and other challenges that each must overcome.

Global SAF demand far exceeds announced SAF production



Source: ICF Tracking of public announcements, Discussions with producers

This comparison suggests that ambitions for SAF currently exceed the announced capacity, and that a very rapid build out of SAF capacity will be required for sufficient facilities to be commissioned to achieve these targets.

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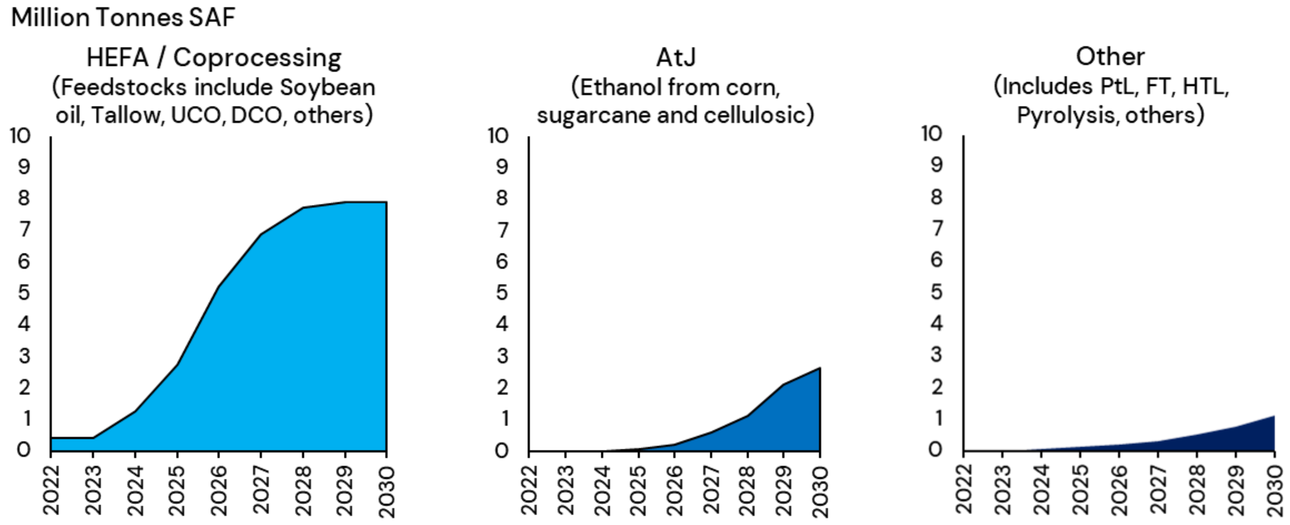
[38] https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/

Announced global capacity for grouped SAF technologies suggests rapid scaling of HEFA, followed by AtJ later in the decade



Source: ICF Analysis

The announced capacity is dominated by production from HEFA facilities. This technology offers comparatively low technical risk and capital costs, and existing fossil-based facilities can be retrofit to use this process. However, global feedstock for this pathway is constrained, with much demand from other industries and limited potential to expand supply, which will constrain the growth of the HEFA pathway.

There is significant Alcohol-to-Jet (AtJ) production capacity expected to come online mid-decade. Essentially all this capacity will use ethanol derived from crops such as corn and sugarcane. The UK RTFO development fuel classification and EU RED II Annex IV exclude feedstocks that compete with foods, so this announced growth is almost entirely in the US. Cellulosic ethanol (biofuel produced from lignocellulose found in plants) presents a more sustainable alternative (and would be eligible for SAF in the RTFO and RED II), although very limited capacity is currently operational. The combined technical risk to develop both cellulosic ethanol and the AtJ process are likely to result in cautious deployment in the UK, although this may accelerate as the AtJ pathway is de-risked using corn ethanol in the US.

Other pathways, particularly Fischer Tropsch (FT), HTL, Pyrolysis, and PtL, have less announced capacity by 2030. This is driven by three factors: the technical risks remaining, the high capital cost, and the small size of each facility. The contribution of FT SAF is expected to accelerate as the technical challenges are reduced and as the policy environment increasingly supports the large requirement for capital investments.

With the UK policy capping the contribution from HEFA and excluding the use of crop-derived ethanol for AtJ, the focus is on this ‘other’ group, which represents a fraction of global production, and presents unique challenges to growing the UK market.

Global market outlook summary

- The HEFA pathway will dominate global capacity by 2030. The comparatively low technology risk, capex investment, and ability to retrofit obsolete fossil facilities make this a viable investment in an uncertain market. The large facility sizes and known technology enable significant capacity to quickly come online.
- The AtJ pathway is likely to be proven in the US using corn ethanol. While the UK and EU regulations are not supportive for this approach, both regions may be able to leverage the de-risking conducted in the US and scale AtJ at a more conservative pace using cellulosic ethanol.
- FT and other pathways hold significant promise but require further development and support to offer viable risk-adjusted returns. The technical challenges and small facility sizes limit the contribution from these approaches by 2030.
- The PtL pathway is an emerging technology and will likely augment the waste and advanced feedstocks over the mid/long term. Very little capacity has currently been announced due to the high cost of production, technical challenges, and policy uncertainty.

5.2 UK market outlook

5.2.1 SAF demand

Section 3 illustrates the UK demand for jet fuel evolving from 12.4 MT in 2019 to 9.3 MT in 2050. There are two main approaches to decarbonise the emissions from this fuel:

1. Use of SAF to reduce in-sector and upstream (TTW and WTT[39]) emissions, which will depend on the volume of SAF consumed
2. Out-of-sector measures, such as carbon removals.

The most likely situation will be a blend of both approaches, with the contribution determined by policy, economics, technologies, and potential scaling constraints. Given the critical role of policy, this analysis will align SAF demand to the UK Jet Zero Strategy ambition of 10% SAF in 2030 and 75% SAF in 2050, as shown in the following graph. The residual emissions will be addressed through out-of-sector measures.

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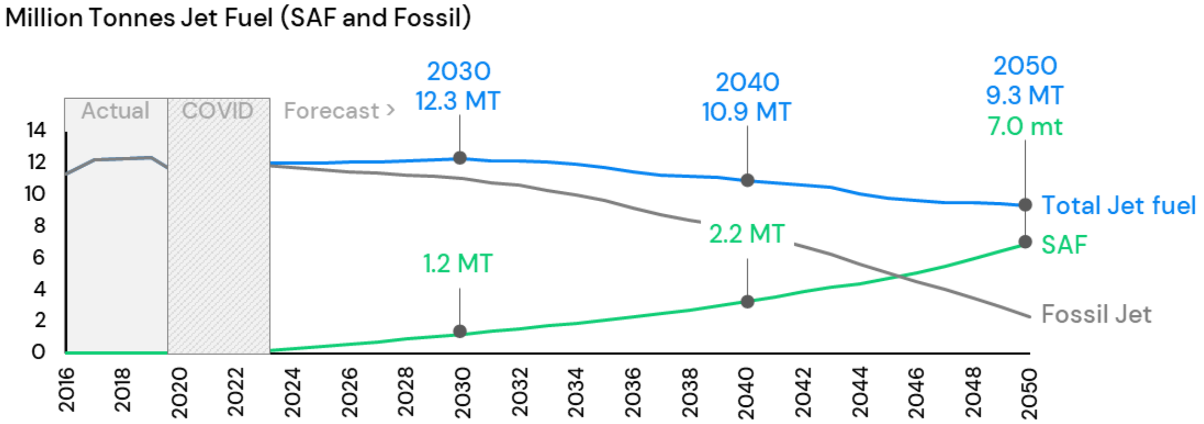
[39] TTW = Tank-to-wake emissions, i.e. those produced during combustion. WTT= Well-to-tank, i.e., during the refining and transport of fuel.

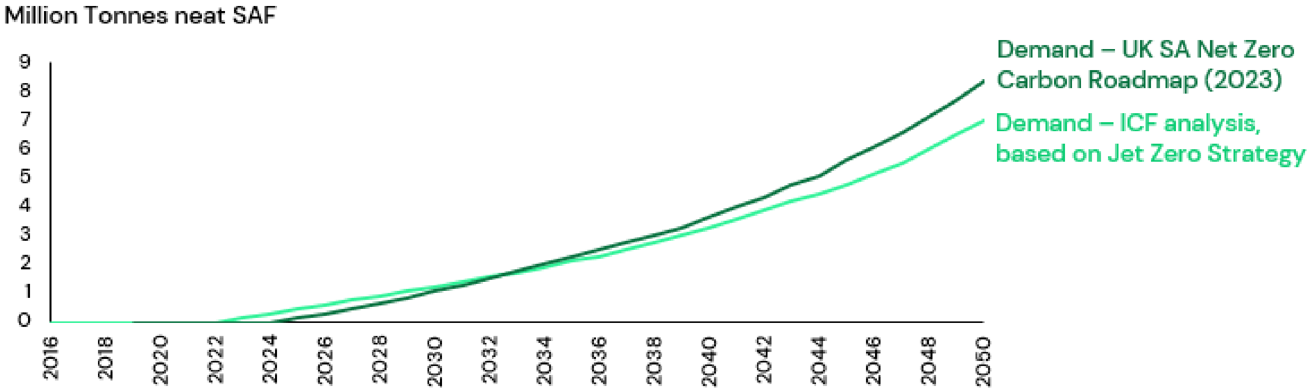
This analysis forecasts SAF demand at 1.2 MT in 2030, increasing to 7 MT by 2050



Note: This ICF analysis is based on the UK Jet Zero Strategy, with adjustments to include military aviation

This analysis has leveraged the UK Government's Net Zero strategy, which uses different assumptions to the UK Sustainable Aviation (SA) Net Zero Carbon Roadmap, including differences on the industry growth rate, efficiency of new aircraft, and deployment of zero-carbon aircraft. Both analyses assume a similar role for SAF compared to out-of-sector mechanisms. The following diagram compares the SAF requirement calculated from these two approaches, and shows that while the results closely reconcile, the UK SA Net Zero Carbon Roadmap does show a slightly slower ramp rate but higher peak in 2050. The supply-side calculations show both sets of results to facilitate comparison.

The analysis in this report closely reconciles to the UK Sustainable Aviation Roadmap, although with a slightly flatter ramp-rate and lower peak



		2030	2035	2040	2045	2050
🟩	This report	1.2	2.1	3.3	4.7	7.0
🟩	UK SA Roadmap (2023)	1.1	2.3	3.6	5.6	8.4
	Difference	-0.1	0.1	0.3	0.9	1.4

Note: SA = Sustainable Aviation. The remainder of the report focuses on the UK SA Net Zero Carbon Roadmap to align with the higher requirement.

5.2.2 SAF Carbon Intensity

The volume of carbon removals will be determined by the carbon intensity of the SAF. This represents the emission reduction of the SAF compared to fossil fuels, where the fossil fuel baseline was assumed to be 89 gCO_2e/MJ[40]. Fuel emissions are measured across the lifecycle, from the well to wake, with the final emissions calculated as the sum of the sources and sinks created during the fuel origination, production, transport, consumption, and other processes. In addition to the feedstock and pathway used, there are many approaches to drive up the emissions reduction from SAF, including:

- **Emissions intensity of process inputs**: The energy used to produce SAF can be lower emissions if renewable electricity is used, if natural gas is substituted with renewable natural gas, and any hydrogen used is green or blue hydrogen.
- **Process efficiencies:** Reducing the inputs required to produce SAF will reduce the CI of the product. Efficiencies can be gained at many points through the process and may also include fewer emissions from the transport of feedstock or product, for example by using ship, pipeline, or rail instead of road.
- **Feedstock growth:** Reducing the emissions associated with feedstock will further reduce the SAF CI, for example through an increase in soil carbon from contributions associated with feedstock growth.
- **Carbon capture:** Process emissions can be captured and sequestrated to significantly reduce emissions.

The carbon reduction from SAF can vary from a small reduction to significantly over 100%, i.e., a carbon negative fuel. Carbon negative fuels are already feasible, and several SAF facilities in the development process are expecting to achieve this. Two examples have been given below to illustrate the calculations:

1. A SAF facility using Municipal Solid Waste: The emissions reduction for a facility is typically measured against the baseline emissions if no facility is built, i.e., how the waste would otherwise be managed. In the feedstock analysis, this study has only counted organic municipal waste currently sent to landfill, which would degrade in the absence of oxygen to produce methane. Although most methane is captured, it is virtually impossible to capture all landfill gas, resulting in fugitive methane emissions. The much higher warming effect of methane compared to carbon dioxide means that a significant emissions reduction can be achieved by building a SAF facility to convert the MSW into SAF, avoiding the methane emissions. In many cases, the avoidance of methane can result in an emissions reduction significantly over 100%.
2. A SAF facility capturing process emissions: Many SAF production processes are catalytic, resulting in incomplete conversion of the feedstock into products. As a result, it is often practical to separate the carbon that is not converted and sequester it. As the carbon stream is often highly concentrated, this process is much cheaper than capturing the carbon from the atmosphere. During the carbon accounting process, the carbon sources and sinks are allocated to the end product, so the carbon sequestered is recorded as a reduction to the SAF carbon intensity (mirroring the accounting of process sources such as fossil electricity use to increase the SAF CI). If significant carbon is captured and sequestered during the production process, then the SAF can also be significantly net negative.

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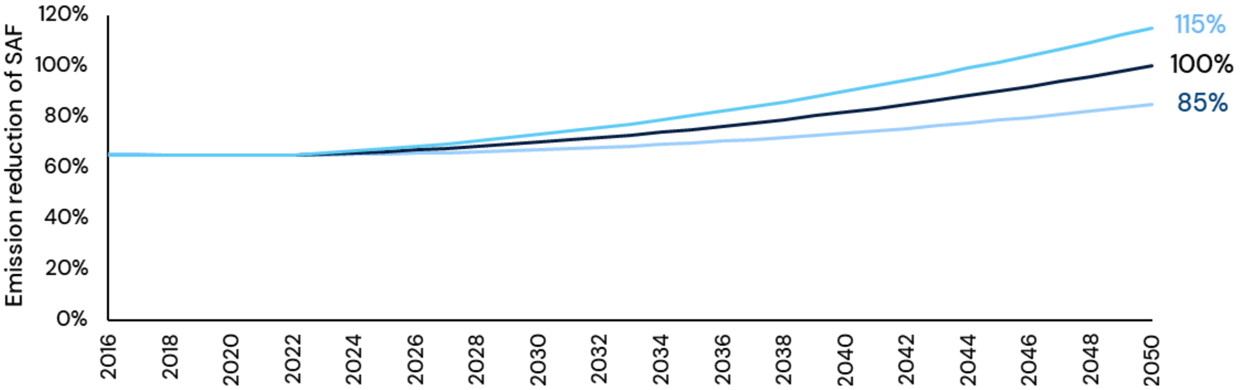
[40] Sustainable aviation fuels mandate: A consultation

It is crucial that policy recognises the variability of the SAF CI and rewards producers that achieve a greater emissions reduction. For example, capturing and sequestering process emissions requires investment in additional infrastructure, carbon transport, and sequestration site permitting, and if there is little or no incentive then the producer may choose to emit the process carbon to the atmosphere, resulting in a higher CI but cheaper fuel.

In this analysis, a central case for the CI has been modelled with an emissions reduction starting at 65% which aligns with the most selected minimum required SAF carbon intensity reduction in the SAF mandate consultation responses (question 12[41]). Emissions reductions increase over time, with the low SAF emissions reduction being 85% in 2050, the average 100%, and a more ambitious scenario increasing reductions to 115%, as outlined below. As these are averages, the scenarios will include a portion of carbon negative SAF to compensate for any with residual positive emissions.

The SAF carbon intensity is assumed to increase from 65% to 100% by 2050



The SAF carbon intensity is measured across the full lifecycle (Tank-to-Wake), meaning that both the emissions during combustion and the upstream (out of sector) emissions are reduced by this factor. The carbon abated by SAF, and the residual emissions are shown in the following diagram, with the upstream emissions illustrated to provide context.

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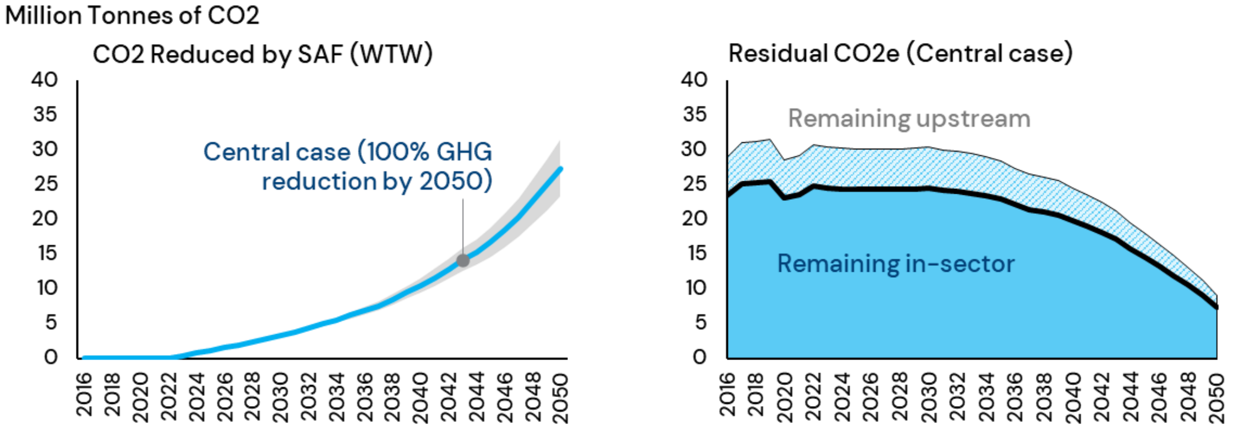
[41] Sustainable aviation fuels mandate consultation

In the central case (75% SAF % 100% GHG reduction by 2050) the residual in-sector emissions are 7.4 MT CO2e, with over 27 MT CO2e abated by SAF



Notes: While this shows a further 1.8 MT CO2e created upstream, this assumes no emission reduction in the energy sector. There are a great many initiatives to reduce the upstream emissions, and given the Net Zero commitments by energy companies these upstream emissions should taper to zero. This analysis has retained them to emphasise the need for all industries to contribute to the energy transition.

5.2.3 Announced UK supply

As of August 2022, there are at least 9 SAF projects under development in the UK, accounting for publicly announced facilities and Green Fuels, Green Skies (and subsequent Advanced Fuels Fund) competition winners[42]. The majority of the announced projects use the Gasification + Fischer-Tropsch (Gas+FT) and Alcohol-to-Jet technologies.

- Projects planning to use Gas+FT will be developed by Velocys, Fulcrum, Advanced Biofuel Solutions Ltd (ABSL), and Alfanar. These four facilities will be converting waste into syngas, then syngas to SAF via the Fischer-Tropsch process.
- The second most common technology for announced SAF production in the UK is AtJ, with the supply chain including Nova Pangaea Technologies (producing cellulosic ethanol), LanzaTech (producing ethanol and SAF from waste carbon gases) and Carbon Engineering (capturing carbon from the atmosphere). LanzaTech has announced two projects, one using ethanol from biogenic wastes and industry flue gases to produce SAF, and the other using direct air captured CO_2 and hydrogen. The latter will be in collaboration with Carbon Engineering, a leading Direct Air Capture (DAC) company. Nova Pangaea Technologies will use woody residues to produce SAF.
- Although HEFA is the most common production pathway today, there are no announced projects in the UK using this pathway, driven by the policy uncertainty around a cap on the volume of HEFA production that will be eligible. Only the ongoing Phillips 66 production by co-processing used cooking oil is doing anything similar, and this has been approved under a different ASTM annex. The FIREFLY project by Green Fuels, Petrofac and Cranfield University will explore feasibility of a novel pathway to produce SAF from sewage sludge through hydrothermal liquefaction (HTL), which is currently under development and requiring ASTM certification.

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[42] https://ee.ricardo.com/gfgs

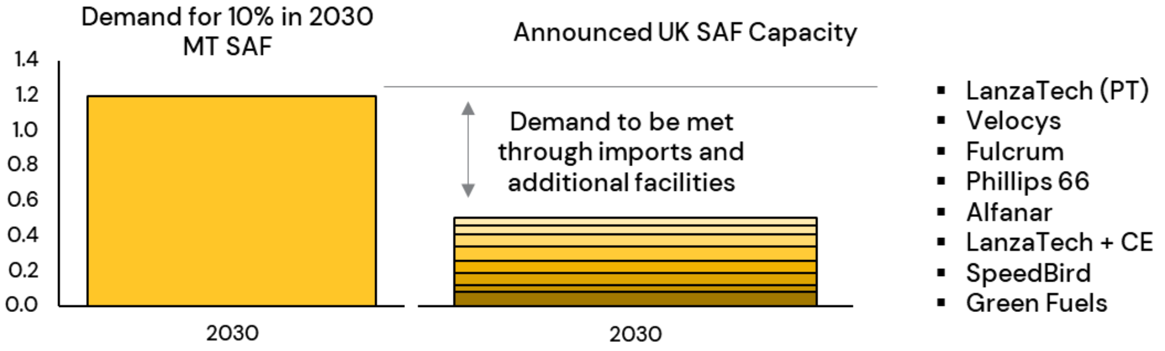
There are several SAF projects at different stages of development in the UK, mostly focused on the AtJ and FT pathways

	Approved pathways				Under certification
	HEFA/Co-processing	AtJ	Gas+FT	PtL[3]	HTL
# of projects in the UK[1]	1	3	4	0	1
Project developer(s)	Philips 66 (Co-processed HEFA)	1. Lanzatech 2. Carbon Engineering 3. Nova Pangaea[2]	1. ABSL 2. Alfanar 3. Fulcrum 4. Velocys	Note ambitions: 1. ScottishPower and Storegga 2. Acorn Project	Green Fuels Research
Intermediate inputs	Waste lipids	Alcohols	Syngas	Hydrogen, Carbon	-
Example Feedstocks	Used cooking oil, inedible tallow, other waste fats, oils, and greases	Biogenic wastes, woody residues, industry flue gases, DAC, water (hydrogen)	MSW, residual waste and industrial waste	Renewable electricity	Sewage sludge

Notes: (1) Including GFGS competition winners (2) Nova Pangaea produce cellulosic ethanol which will be processed by LanzaJet. (3) PtL has been shown stand-alone, but would use the ASTM certified AtJ or FT-SPK pathways for SAF production. PtL may also use the methanol route, which is not yet certified.
Sources: https://ee.ricardo.com/gfgs,

Only one facility in the UK is currently producing SAF (Phillips 66, using co-processing in the Humber). Eight more facilities have been publicly announced for the UK, and are set to begin production over the coming years. In total, the announced facilities have the potential capacity for up to 0.6 million tonnes of SAF produced nationally per year by 2030. This represents a shortfall of 50% compared to the expected 2030 requirement, which must be met through imports of additional facilities.

C. 50% of a 10% SAF mandate in 2030 needs to be met with unannounced capacity



Source: ICF Analysis, Press announcements

The market outlook and UK requirement – implications:

- The UK Government Jet Zero Strategy forecast that UK aviation emissions remaining after carbon impacts and fleet efficiencies will be 39 MT in 2030, decreasing slightly to 29.5 MT in 2050. An aggressive uptake of hydrogen and electric aircraft could reduce this to 17.1 MT in 2050, although this scenario stands out from the IATA and ICAO modelling and is assumed to be of limited likelihood.
    - This analysis will assume 39 MT in 2030 and 29.5 MT in 2050 of aviation CO_2e must be addressed
    - Global emissions from aviation are expected to increase over the same time period, meaning that % SAF targets represent a slower ramp-rate for the UK than globally (i.e. an increase in SAF from 10% in 2030 to 50% in 2040 would represent a slower growth rate in the UK than globally)
- The remaining CO_2e must be addressed through both in-sector (SAF) and out-of-sector (carbon removals) mechanisms.
- This study assumes a central case that 75% of CO2e is addressed by SAF, in-line with the UK Jet Zero Strategy. The remaining CO_2e will be addressed with out-of-sector mechanisms
- The carbon reduction of SAF varies with different feedstocks types and production, logistics, operational decisions, and use of energies
- This study assumes in a base case that the carbon reduction of SAF increases from 65% today (estimate) to 100% by 2050. In the high case, it is assumed that SAF could reduce carbon emissions by 115%, representing an aspirational case with supportive regulation. The low case assumes 85% in 2050.
- The central case estimate (29.5 MT of in-sector CO2e in 2050, 75% addressed by SAF, with a 100% GHG reduction) gives a SAF requirement of 7.0 MT in 2050.
    - Achieving the 2030 mandate will require an estimated 1.2 MT SAF
    - This requires a high comparative ramp over the next decade, but less rapid growth 2030-2050 than many other analyses assume (less of a 'hocky stick' curve).
- Achieving this increase to 2030 will require additional facilities. Announced capacity in the UK is c. 0.6 MT, so a further 0.6 MT remains to be met by unnanounced capacity or imports.

6 The feedstock opportunity for the UK

Image credits:
UK Department for Business & Trade (top right)
pxfuel (center)
Dalibor Danilovic (bottom-right)
Rolls-Royce (bottom-left)

This section has been separated into three sub-sections: The first investigates the wastes and advanced feedstock available to scale SAF production in the UK, while the second investigated the opportunity to scale use of Power-to-Liquids, including the underlying renewable electricity and electrolyser capacity required. The third sub-section consolidates these to construct feedstock combinations for the UK.

6.1 Sustainability criteria

The development of a SAF industry creates an opportunity to build on the experience gained during the development of previous biofuel production and to further refine the sustainability of the fuels. The UK already has an extensive biofuel industry supported by the Road Transport Fuel Obligation (RTFO), which consumes a significant volume of potential feedstocks. This feedstock analysis has been conducted to ensure that there is minimal divergence of these feedstocks to SAF production, ensuring that the resulting SAF drives additional emission reductions. As the road sector adopts electric and/or hydrogen vehicles, some of the feedstock may become surplus for the road sector demand, creating potential upside to the feedstock estimated in this section.

While existing biofuel production for the road sector does use feedstocks that compete with food or feed, there is no expectation that SAF production will use these feedstocks. The feedstocks evaluated in this section do not compete with food, either as a produce, or for the arable land.

6.2 Wastes and advanced feedstock opportunities

The amount of waste-based and advanced feedstock available to the UK has been assessed, considering sustainability criteria, use by other industries, and the potential for growth or imports. This assessment is based on a top-down analysis of several macro studies by government, academia, and non-profits, complimented by a bottom-up analysis of specific data on individual feedstocks. These have been used to build-up a low, central, and high range for the wastes and advanced feedstock energy available for SAF production in the UK:

- The **Low scenario** estimates that 0.30 EJ of wastes and advanced feedstock would be available for aviation, sufficient for approximately 2.2 MT of SAF production.
- The **Central scenario** estimates that 0.48 EJ of wastes and advanced feedstock would be available for aviation, sufficient for approximately 3.5 MT of SAF production.
- The **High scenario** estimates that 0.67 EJ of wastes and advanced feedstock would be available for aviation, sufficient for approximately 4.9 MT of SAF production.

6.2.1 Review of existing studies on UK feedstock availability

Feedstock availability is often calculated with different framing, assumptions on sustainability, competing uses, and economic/logistical factors. ICF uses a framework to consider feedstock according to four definitions, as described below:

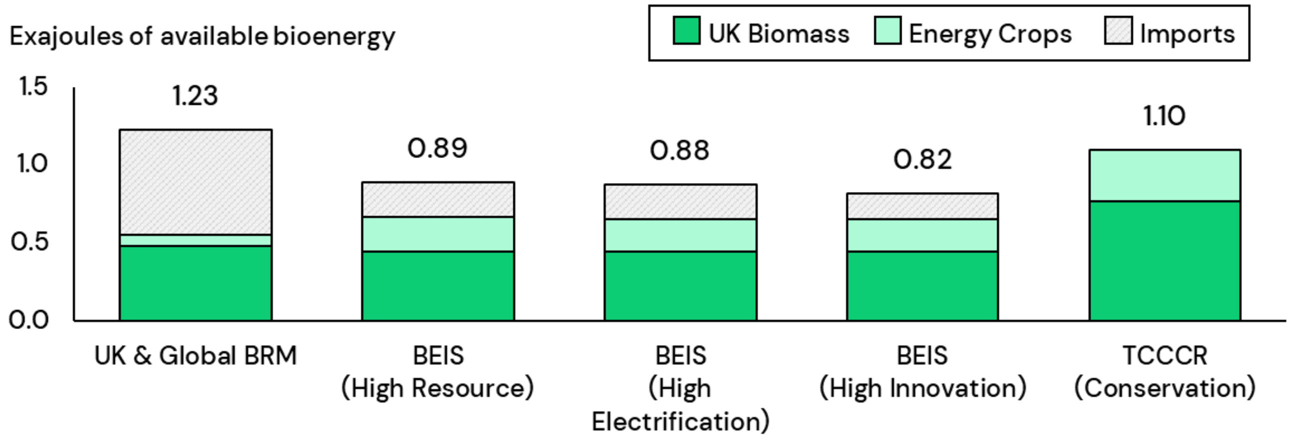
- Total availability of a feedstock refers to total amount of potential feedstock available in a region. This includes availability for SAF production, as well as other potential uses, such as biodiesel or energy. Depending on the environmental dynamics of the region, technically available feedstock vary greatly.

- Sustainable availability refers to accounting for sustainable practices, for example leaving some biomass residue in the field to protect soil quality. This helps to ensure a sustainable feedstock supply in the future, whilst also protecting against erosion and associated loss in carbon and nutrient content. As a result, the amount of feedstock available for SAF production is reduced.
- Availability for biofuel production refers to utilisation of feedstock by competing fuel industries. For most of the feedstocks, SAF production is just one possible use as other applications include alternative fuel production (biodiesel), chemicals industry (naphtha), and energy production.
- Only a portion of the sustainably available feedstock for biofuel production would be allocated to the aviation industry, which would refer to net feedstock availability for SAF production. The values for these have been considered to produce High, Central, and Low outlooks. These outlooks include a proportion of imported feedstock.

This report aims to build on existing literature and has considered feedstock studies by the UK Government (using the Bioenergy Resource Model, BRM), UK Department for Business, Energy and Industrial Strategy (BEIS) for the Net Zero studies, and the University of Manchester Tyndall Centre for Climate Change and Research (TCCCR) who undertake research to deliver insights on energy and climate change. Each of these studies estimate the sustainably available feedstock and do not allocate specific portions to aviation. The International Council on Clean Transportation (ICCT), an independent organisation providing research to benefit public health and mitigate climate change, has published estimates on the availability to aviation in the UK, and specific data sources, for example on crops and municipal wastes, complement these studies.

Comparing the studies, the UK Government, BEIS, and TCCCR suggests that approximately 0.45 EJ of biomass feedstock is sustainably available, which could be increased with energy crops and imports. The BRM suggests a significant role for imports, while the TCCCR suggests additional biomass could be sourced domestically. Energy crops are crops which are solely grown for the purpose of use for bioenergy production. The role of energy crops have not been modelled in this analysis as focus is placed on the use of energy from waste-based products for SAF production.

Studies estimate c. 0.45 EJ of feedstock, which can be supplemented with energy crops and imports. More aggressive scenarios suggest potential upside.

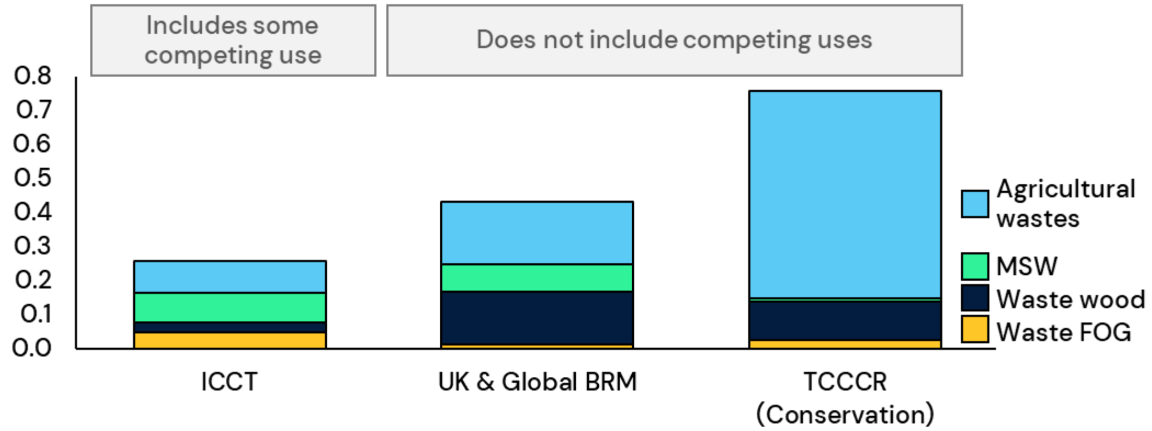


Source: The UK Government Global Bioenergy Resource Model (BRM), the Tyndall Centre for Climate Change Research (TCCCR) at the University of Manchester, BEIS Net Zero by 2050 scenarios

The studies can be assessed in more detail to understand the specific feedstocks driving the different estimates. The BEIS Net Zero by 2050 does not provide a breakdown so has been excluded. The ICCT has been included, although it should be recognised that scope is different as it includes alternative uses for some of the feedstocks. The greatest difference is driven by agricultural waste assumptions, followed by MSW and wood.

UK Biomass feedstock is reasonably well diversified, although analyses differ on the availability, particularly for agricultural residues, and somewhat on MSW and wood

Exajoules of available domestic UK bioenergy (excluding energy crops)



Sources: The International Council on Clean Transportation, The UK Government Global Bioenergy Resource Model (BRM), the Tyndall Centre for Climate Change Research (TCCCR) at the University of Manchester

6.2.2 Analysis of each feedstock category

Agricultural wastes

In 2021, the potential area of the UK for crops was 6.1 million hectares (ha), and as 1.2 M ha and 0.7 M ha were left as temporary grassland and uncropped arable land, 4.635 M ha was used for crops[43]. Most of this was used for wheat (1.7 M ha) and barley (1.3 M ha), with the rest spread between oats, potatoes, oilseeds, horticulture, and other. To estimate the residues available, yield and residue percentage should be calculated. In the UK in 2019, the yield was 7.6, 6.1, 4.9 and 3 T/ha for wheat, barley, oats, and oilseed respectively. The Residue-Product-Ratio (RPR) can be estimated by different relationships, and using these RPR of 83% for wheat, 73% for barley and 70% for other crops was estimated[44]. This gives total residues of 23.6 MT, and (assuming 10% moisture content) 21.2 MT of dry residues. Applying LHV for each crop gives an estimate of 0.33 EJ total. This must be reduced by the volume that will remain on the fields to ensure soil health, and a further portion which is economically or logistically uncollectable. Estimating a range of 40%-60% that must be left on the field and an additional range of 10%-25% that remains uncollected gives an estimated range of 0.1-0.18 EJ.

The TCCCR feedstock study estimates feedstock availability from agriculture to be much higher than estimated by the other studies (0.60 EJ Vs. 0.09 and 0.14 EJ). An explanation for this is that waste, fats, oils, and greases

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[43] Agriculture in the UK Evidence Pack

[44] Crop residues are a key feedstock to bioeconomy but available methods for their estimation are highly uncertain

are not separated from animal agriculture as feedstock categories, unlike in the other studies. It is likely that a portion of feedstock from animal agriculture could constitute waste, fats, oils, and greases, and thus values appear to be higher when compared. Based on the top-down and bottom-up calculations, this analysis uses a central estimate of 0.14 EJ available from agricultural wastes.

Municipal waste

The UK produced 27 MT of waste from households in 2020[45], of which 44% (11.9 MT) was recycled and 42% (11.4 MT) was sent to incineration[46]. 6.1 MT of total municipal waste was derived from biological sources and was sent to landfill. This fraction represents the core opportunity for conversion into SAF as its use as a feedstock would generate a considerable emissions reduction (due to the avoided fugitive methane emissions), reduce the land needed for landfill, and create economic value.

The energy contained in this waste stream will vary with the materials and moisture content. The IEA suggests an average range of 8-12 MJ/KG for the biological fraction of MSW[47], and using a lower heating value (LHV) of 10 MJ/Kg gives an estimation of 0.06 EJ energy availability from this feedstock. The ICF analysis assumes that in the Low scenario 80% of this energy can be diverted to SAF production, in the Central scenario 90% can be used for SAF, and 100% in the High case.

This energy may be complimented by additional bioenergy diverted from waste incinerators as the facilities reach end-of-life[48]. While it may be environmentally beneficial to build SAF capacity faster than the incinerator asset replenishment cycle, this would result in a high cost of stranded incinerator assets and lost capital. This analysis assumes that in the low case there is no diversion from incinerators to SAF production by 2050, in the central case there is 10% diversion (+0.01 EJ), and up to 25% in the high case (+0.03 EJ).

Combining the values for the waste-based and advanced feedstock fraction (diverted from landfill and end-of-life incinerators) results in estimated energy availability of 0.05 EJ, 0.07 EJ, and 0.09 EJ in the Low, Central, and High scenarios respectively. This approximates results provided by the UK government, which gives 0.08 EJ of availability for all industries, reconciling to this slightly lower availability for SAF production only.

Sustainably available wood

Waste wood includes wood that has previously been used as a resource or the unwanted by-product of a process such as branch pruning. Examples include shavings, sawdust, and residues from forestry production. It is deemed a sustainable resource as it may otherwise end up in landfill where it would decompose and emit GHGs. The studies reviewed estimate waste wood availability between 0.03 EJ (ICCT) to 0.21 EJ (UK Government). The low estimate by the ICCT may be explained in part by not considering waste that is recovered for any useful purpose other than biofuel as available for feedstock. Additionally, the ICCT provides less granular feedstock breakdowns, and only includes categories for forestry residue production and wood wastes. By comparison, the UK Government includes six sub-categories, and the TCCCR includes four sub-categories. It is possible that wood feedstock types that are included in the UK Government and TCCCR studies are not considered in the ICCT study, appearing to reduce availability.

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[45] UK statistics on waste

[46] Response to call for evidence on inclusion of EfW in the UK ETS

[47] Municipal solid waste and its role in sustainability

[48] ICF recognise that a small proportion of non-biodegradable waste may end up being mixed with biodegradable waste, however, owing to large uncertainty around this data and the fact that this proportion is likely to be very small, it has been excluded from calculations.

5 million tonnes of waste wood are generated in the UK every year, with half of this weight sent to UK biomass facilities[49]. Assuming 20 MJ/Kg, the remaining 2.5 MT would offer 0.05 EJ of feedstock, comparable to the ICCT estimate of 0.03 EJ feedstock from waste wood. This analysis has aligned to the wider scope of the UK government and TCCCR calculations, using the central estimate of 0.12 EJ.

Waste industrial gasses

Waste industrial gases are only considered by two of the three studies: TCCCR and ICCT. These estimate 0.01 EJ and 0.05 EJ availability respectively. To better understand these values, availability was independently assessed using data on emissions from cement, steel, iron, and ammonia production from the UK Government. Data was provided in MT emissions (CO_2), and International Energy Agency (IEA) high, medium (sustainable growth), and low (net zero) growth outlooks were applied to these values for 2030. Values were then converted to energy units, utilising assumptions of energy content. Research showed that this was 5.6 MJ/KG for cement production[50], 22.7 MJ/Kg for steel and iron production[51], and 18.8 MJ/Kg for ammonia production[52]. Analysis demonstrated that between 0.05 and 0.07 EJ could be produced from this resource, informing the Low, Central, and High output scenarios. With 50% of this feedstock calculated as available to aviation, between 0.02 EJ (Low) and 0.03 EJ (High) is available.

Innovative/advanced feedstocks

Analysis includes a wedge for innovative and advanced feedstocks. This contribution is represents the significant innovation expected on the feedstocks alongside the conversion technology developments. Many of these novel feedstocks that are in advanced stages of commercialisation, and hold significant promise, despite only being nascent today. Considerable innovation is expected over the next three decades, which may lead to the use of feedstocks that are not considered today. Sewage sludge and algae have been chosen to illustrate the potential contribution:

- **Sewage Sludge** is produced as a solid mass during the process of wastewater treatment. Approximately 1.5 MT of sewage sludge is produced in the UK each year[53]. The energy content of this material is variable (likely depending on moisture ratio), with studies suggesting 11-22 MJ/Kg[54], matching discussions with industry that suggested a range of 10-15 MJ/Kg. Using an input volume of 1.5 MT and energy content assumptions of 10-15 MJ/Kg, 0.015 to 0.023 EJ could be produced. This approach has the advantage of providing a better disposal route for wastes, but is challenged by the meaningful proportion currently locked into long-term energy contracts or for fertilizer provision. In addition, thermochemical conversion of sewage sludge into energy involves several processes requiring high temperatures, posing a challenge to large-scale application[55].
- **Algae & cover crops** may further augment the energy available. Utilising algae for energy has high potential in the UK due to its abundant coastal regions and nutrient-rich seas. However, there is uncertainty around production potential due to the requirement for technological development to

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[49] Wood recyclers' association

[50] Concrete and embodied energy

[51] Energy use in metal production

[52] Ammonia for power

[53] Biomass and Biofuel Production - Comprehensive Renewable Energy

[54] Sludge-to-energy recovery methods – a review

[55] A review on turning sewage sludge to value-added energy and materials via thermochemical conversion towards carbon neutrality

maximise output. The ETC estimates total global resource of algae for energy at up to 7 EJ. A conservative approach is taken, assuming just 50% of this is realised, 10% of the realised global volume is available in the UK, and half of this is used for fuel production (i.e., 2.5%, 0.17 EJ).

- This analysis assumes no additional contribution from cover crops, although any shortfall that materialises below the algae assumptions could be met through cover crops. The BEIS scenarios estimate 0.21 EJ to 0.22 EJ of energy crops are available, and the average of the UK Government and TCCCR calculations (0.20 EJ), suggesting that excluding cover crops is highly conservative.

Availability of imports

A certain percentage of global feedstocks will be available to the UK via imports. UK Government and BEIS are the only studies analysed to assess import potential. The UK Government study assumes that the UK would be able to acquire 7% of the global surplus of bioenergy, calculating that 0.68 EJ would be available. This value is quite high as there is likely to be strong demand for bioenergy from the U.S. and EU as the globe undergoes societal decarbonisation, and so additional research was reviewed. BEIS have developed three different outlooks in their 2021 Net Zero Strategy[56]. These are High Resource, High Electrification, and High Innovation scenarios, estimating 0.22 EJ, 0.22 EJ, and 0.17 EJ of biomass imports respectively for the purpose of bioenergy. Considering demand for bioenergy from other countries, an average of the BEIS values was selected for the Central scenario (0.20 EJ). 50% of this value has been included in the Low scenario, and 150% in the High scenario. As described in the next section, these values were then reduced to 50% to represent the amount of biomass imports directed to aviation.

6.2.3 Availability to aviation

There is competition for feedstock resource from other industries, and only a portion of the available feedstock will be directed towards aviation. Previous global research by the ETC has estimated that 14%-30% of available feedstocks will used by the aviation industry[57]. This is based on their report *Bioresources within a net-zero emission economy* which calculates that 15 of 50-110 EJ feedstock per year can be assigned to aviation. The IEA estimates a similar value of 15%, based on 15 of 102 EJ feedstock per year assigned to aviation[58]. The ICCT provides a more granular assessment by feedstock, estimating that 31% of agricultural residue feedstock will go towards biofuel production and 22% of forestry residues.

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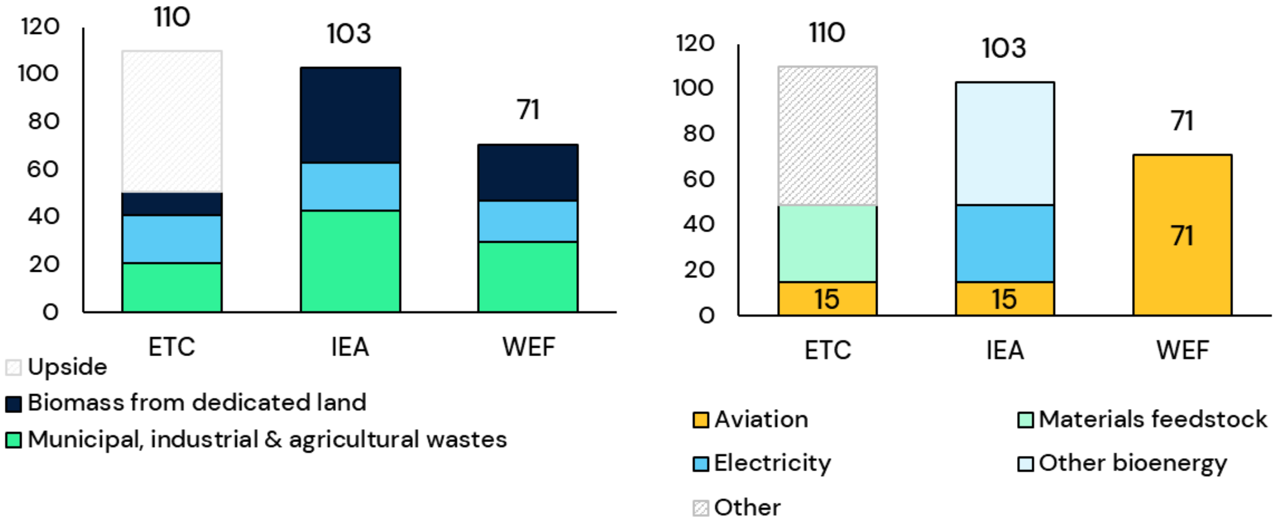
[56] BEIS 2021 Net Zero Strategy

[57] Energy Transition Commission: bioresources within a net zero economy

[58] IEA Net Zero by 2050. A roadmap for the global energy sector

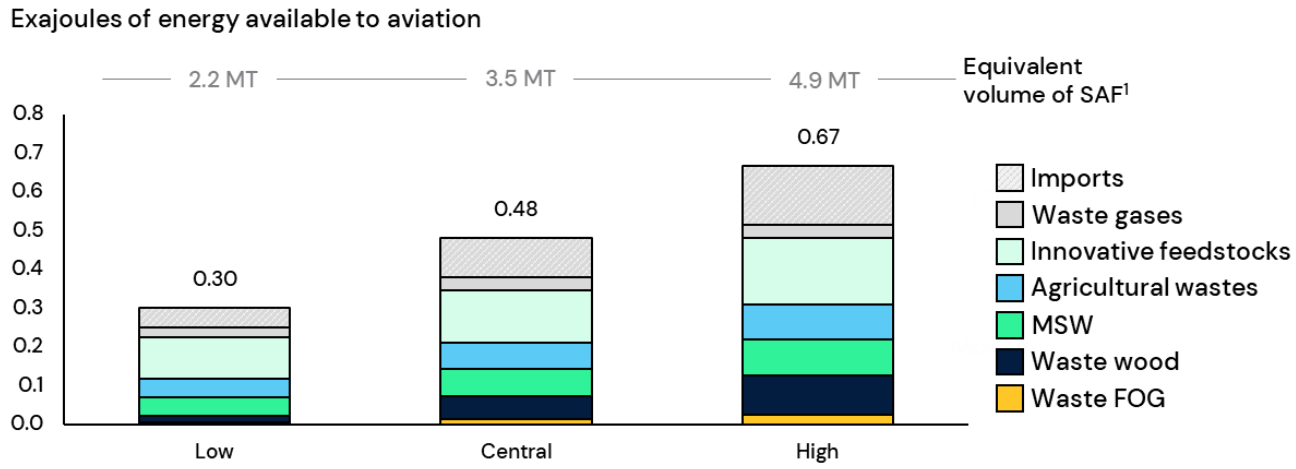
Feedstock availability and use, by publishing body and industry, EJ



The analysis presented here has already accounted for some of the alternative uses for feedstocks, for example, with a portion of agricultural residues remaining uncollected or uneconomic to collect, continued incineration (EfW) for significant volumes of MSW and similar assumptions across the other feedstocks. It is also assumed that the UK is able to allocate wastes and advanced feedstock to more optimal uses than is done at a global scale, resulting in a higher share available for aviation. This optimistic assumption is not a foregone conclusion, and it is notable that due to current policies and available technologies, almost all available feedstock is either uncollected or used by other industries. The UK has made binding commitments to achieve net zero by 2050, supported by a variety of policies from energy efficiency to the electrification of the road sector. Only if this system-wide transition is achieved will this feedstock become reasonably available to aviation. Based on this context, 50% of the estimated remaining availability of feedstocks was allocated to aviation, with the other 50% used across other industries.

A significant volume of the energy assumed for aviation will still end up in other sectors, as every SAF facility will produce a portion of renewable diesel and naphtha alongside SAF; the energy assumed for aviation is used as the input to SAF-focused facilities, while the output will include RD, naphtha, and fuels used by other industries.

The energy available for UK SAF production is distributed across multiple waste-based and advanced feedstocks, with uncertainty on magnitude and the allocation to aviation



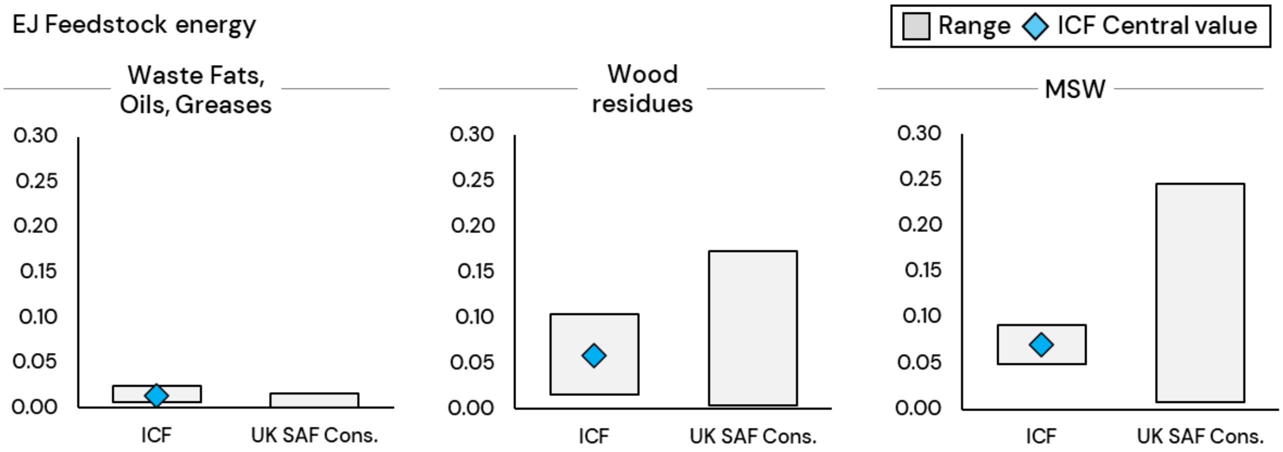
Source: ICF Analysis of multiple sources

Notes: (1) Approximate, varies with production pathway and product slate

6.2.4 Reconciliation to the second UK SAF mandate consultation

In March 2023, while this analysis was in the final stages, the UK published the Second SAF mandate consultation "*Pathway to net zero aviation: Developing the UK Sustainable aviation fuel mandate*". This analysis included a high-level analysis of the UK feedstock opportunities, with an estimate of the upper and lower range from multiple input studies. These ranges have been compared to the ICF estimates in the following illustration.

The ICF estimates are aligned to the ranges provided in the UK SAF Mandate consultation, with conservative central values



Source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147350/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate.pdf

The upper and lower ranges for the ICF values match the upper (0.67 EJ) and lower (0.30 EJ) estimates, with the central value (the blue diamond) matching the central 0.48 EJ estimate. The 2040 values for the UK SAF Consultation have been used, assuming that any facility built today would be operating through this period.

This reconciliation shows that the ICF estimates reasonably approximate the UK SAF Mandate consultation estimates, with the central values typically sitting at the lower end of the range, representing conservative estimates. As illustrated by the much higher range for waste wood and MSW, additional feedstock could be available for SAF production if more aggressive assumptions are used.

6.3 Power-to-Liquid feedstock opportunities

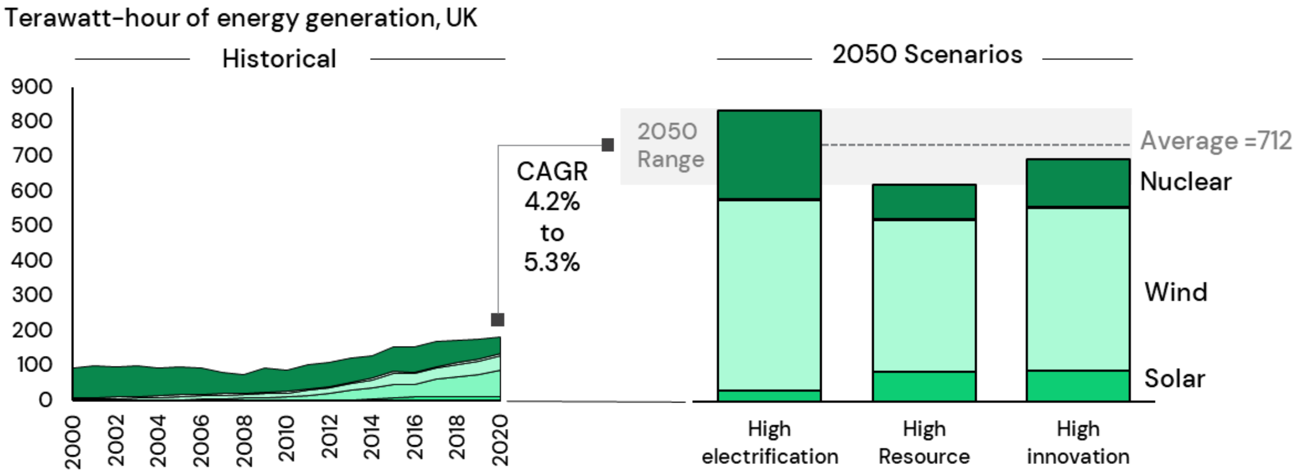
Power-to-liquids is a technology combination to convert renewable electricity into SAF. The renewable energy is typically used for electrolysis of water to produce 'green' hydrogen. This can be combined with a sustainable source of carbon and synthesised into a liquid fuel, for example through the FT or AtJ technology. The carbon will initially be sourced from concentrated point sources, although many companies are developing direct air capture which could allow the carbon to be sourced directly from the atmosphere in the mid/long term.

The complete technology stack is expensive but appealing as the volume of production is not constrained by access to a waste feedstock whose supply cannot be increased. Low carbon electricity from the wind, tide, sun, and other sources is virtually infinite, and instead the active constraints are more likely to be economic and practical limitations on how quickly renewable electricity generation can be built.

This study assumes that policy measures can be implemented to make SAF production economically viable, meaning that the key constraint for PtL SAF will be the rate of renewable electricity capacity build-out. SAF production should not cannibalise renewable energy from alternate uses (such as EVs, heat pumps) if this would require fossil generation plants to remain online; instead, the renewable energy for PtL production should be additional. This means the required rate of renewable electricity deployment is the sum of the rate required to decarbonise other industries and for PtL production, making this an acute constraint.

The UK Net Zero Strategy (NZS) provides an excellent analysis of the renewable electricity required to decarbonise the UK, including the domestic aviation industry, but only includes a small volume of hydrogen. It is assumed that any hydrogen available from the NZS is used as a fuel directly in aircraft combustion or fuel cells, or as an input to wastes and advanced feedstock SAF facilities. Therefore, renewable electricity capacity for PtL production isn't included in the scenarios but can be assumed to be incremental to the growth projected by the BEIS NZS scenarios, which show a requirement of 712 TWh by 2050.

The UK NZS includes limited electricity for aviation, suggesting most PtL will require incremental generation



Source: BP Statistical Review of World Energy June 2022, UK BEIS NZS

Increasing low carbon electricity generation to 712 TWh by 2050 requires a compound annual growth rate (CAGR) between 4.2% and 5.3%. As the demand for PtL is incremental to this value, any PtL generation will also require an increased CAGR.

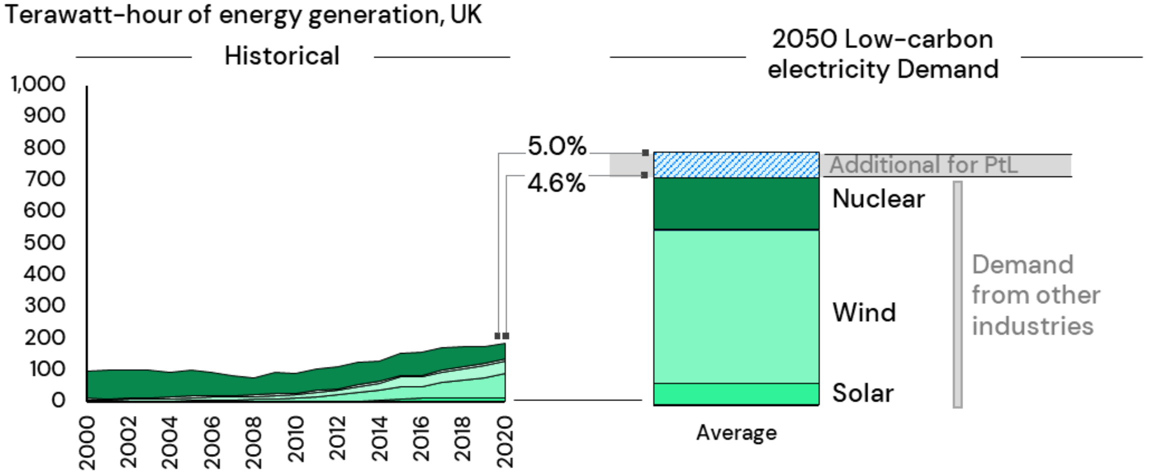
While the potential for PtL SAF is theoretically unlimited, real-world limitations to renewable electricity deployment, location, and cost constrain the actual amount of PtL that can accessed. This analysis proposes three scenarios for potential renewable electricity that could be accessed for SAF production:

- Low: 30 TWh (+4% total renewable electricity in 2050)
- Mid: 50 TWh (+7% total renewable electricity in 2050)
- High: 80 TWh (+11% total renewable electricity in 2050)

These scenarios are purposefully set at reasonably high aspirations. Firstly, not all of this energy might be incremental to the generation, as some might represent electricity that would otherwise be curtailed. Secondly, hydrogen and SAF production may be beneficial as it can be (relatively) flexibly located and may allow some of the demand to be situated near to the electricity supply; in contrast to current generation which is often some distance from cities/demand. Finally, aviation represents a high-value use of electricity, and may allow some of this value to pull incremental capacity into the renewable electricity market. These three scenarios represent a modest increase in the CAGR for UK renewable electricity, with an increase from 4.2% – 5.3% to 4.6% – 5.0%.

The scenarios for additional low-carbon electricity demand for aviation increase the required CAGR from 4.6% by up to 5.0%

Terawatt-hour of energy generation, UK

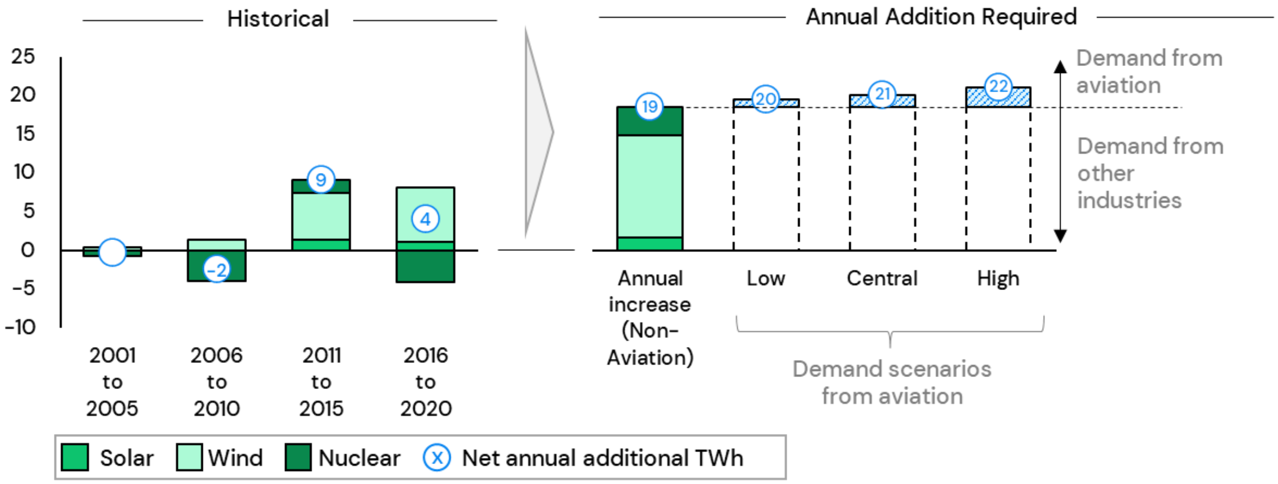


Source: BP Statistical Review of World Energy June 2022, UK BEIS NZS, ICF Analysis

However, this does still represent a meaningful increase in absolute terms, given the increasing size of the industry – each year the annual growth in renewable electricity generation must increase from 19 TWh to a central case of 20.7 TWh, and a high case of 21.7 TWh.

Decarbonising the UK requires a sharp acceleration of low-carbon energy. The additional requirement for PtL further increases the challenge

Annual additional Terawatt-hour of low-carbon energy generation, UK



Source: BP Statistical Review of World Energy June 2022, UK BEIS NZS, ICF Analysis

6.3.1 Can renewable energy scale fast enough to produce PtL?

The growth of PtL SAF concurrent to the decarbonisation of the UK electricity grid requires prodigious renewable electricity. This section discusses the possibilities, looking at the scaling potential for the two main drivers identified by the UK BEIX Net Zero Strategy: wind and nuclear.

Wind energy production technology in the UK has rapidly grown, increasing by 715% from 2009 to 2020[59], and contributing to 24% of the UK's electricity generation.

The UK has enormous potential for additional wind power. The country already has the most installed capacity of offshore wind power generation of all countries[60], and over 11,000 miles of coastline provides significant potential to scale this approach, particularly as offshore wind technologies develop.

The UK set a record for installed capacity in 2022, adding 3.5 GW of new capacity, sufficient to power more than 3.4 million UK homes. Almost all (3.2 GW) of this was built offshore. The UK has set 2030 Government Energy Security Strategy targets for 50 GW of offshore wind energy, including 5 GW of floating wind[61].

The wind industry is facing economic and supply chain issues, partially fuelled by increased material costs, and partially as demand for components has accelerated. Other considerations, including the time taken for permitting, and onshore public perception present additional challenges.

Curtailment is becoming increasingly important as the portion of non-dispatchable generation has grown. Hydrogen and PtL SAF may have an important role to address this, with the ability to overproduce and store hydrogen when excess energy is available and reducing power use when there's a scarcity. This will become increasingly viable as electrolyser costs continue to decrease, reducing the importance of high utilisation.

Nuclear generation has varied over the past decades, but UK BEIS is looking for a resurgence. This will only be possible if the capital costs can be reduced. The Levelized Cost of Energy Comparison (LCOE) for nuclear is estimated at $200/MWh[62], compared to $45/MWh for wind, although nuclear providers additional benefits as a baseload contributor. To increase affordability, Rolls-Royce are leading a consortium in the UK developing Small Modular Reactors (SMR) for electricity generation[63]. The Government has also launched funding to accelerate supply[64], targeting 8 new nuclear reactors by 2030 and 24 GW by 2050[65]. In October 2022, it was announced that the UK's first fusion energy plant will be in Nottinghamshire and built by 2040 with £220 million support from Government funding. The Nuclear Fuel Fund will provide £75 million to unlock investment, reducing reliance on imports and ensuring greater energy interdependence[66].

Nuclear Lifecycle emissions are some of the lowest across renewable energy technologies at 12gCO_2e/kWh, second only to onshore wind (11gCO_2e/kWh)[67]. However, public perception is likely to be a key barrier, with

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[59] Wind energy in the UK

[60] Offshore wind: part of the UK's energy mix

[61] British energy security strategy

[62] Lazard's levelized cost of energy comparison

[63] Rolls-Royce: Small nuclear power stations

[64] Government fund to accelerate nuclear fuel supply opens

[65] British energy security strategy

[66] Nuclear energy: What you need to know

[67] Annex III. Technology-specific Cost and Performance Parameters

misconceptions about risks. The Institution of Mechanical Engineers (IMechE) reporting that just 42% of people support the use of nuclear energy for producing electricity in Britain (plummeting to 27% when asked if they would support a facility in their local area), compared to 84% who support production from other renewable sources[68]. The report notes low level awareness among young people that nuclear is a low carbon energy source, demonstrating a need for stronger messaging about its benefits to a low carbon society.

The BEIS analysis anticipates a limited role for solar PV, with a maximum contribution from solar in 2050 is 88 TWh, compared to 542 TWh from wind. However, solar has exceeded many analysts' expectations, scaling and reducing in cost more rapidly over the last decade than almost any forecasts calculated. While the UK weather is not particularly favourable for Solar PV, the diversification from wind may be beneficial to balance the grid, and it has particular potential for co-location with (or on) infrastructure, such as airports and car parks.

Other forms of generation may increasingly contribute. Over the next three decades there will be significant innovation, and perhaps technologies such as wave, tidal, and other novel concepts will succeed.

The UK feedstock opportunity - implications:

- This study shows that sufficient feedstock is available to meet SAF volume trajectories
- Waste-based and advanced feedstock estimates vary from 0.30 EJ to 0.67 EJ, with a central estimate of 0.48 EJ
    - Equivalent to 2.2 to 4.9 MT SAF (central 3.5 MT) after accounting for conversion efficiencies and jet fuel allocation
- Waste-based/advanced feedstock availability is spread across multiple categories, with no dominant source. Additional technologies must be developed to realise potential, both to allow processing and ensure supply
- While renewable electricity availability is theoretically unlimited, real world factors – including cost and deployment, will constrain the availability for PtL
- This analysis estimates that between 30 TWh and 80 TWh of renewable electricity is available for PtL, with a central estimate of 50 TWh. These figures will be highly dependent on the rapid build-out of renewable energy generation.
- The volume of SAF produced from these feedstocks will depend on operational decisions and policy that will support a focus on road fuels (RD) or SAF
- In the central estimate, this is sufficient for 3.5 MT SAF from bioenergy and 1.9 MT from renewable electricity. In the high case estimates for both sources SAF could be as high as 9.3 MT, and if both fall short then the estimate is 2.7 MT (although clearly zero production is also possible).

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[68] Public Perceptions: Nuclear Power

7 Building a UK SAF industry

Image credit: Pexels, Louis

7.1 Total SAF and co-products opportunity

7.1.1 Catalysing SAF alongside other renewable fuels

The SAF industry cannot be considered in isolation of other renewable fuel industries, with many feedstocks applicable to produce several types of fuel, and many other renewable fuel possible intermediaries for SAF production (such as ethanol and bio-methane).

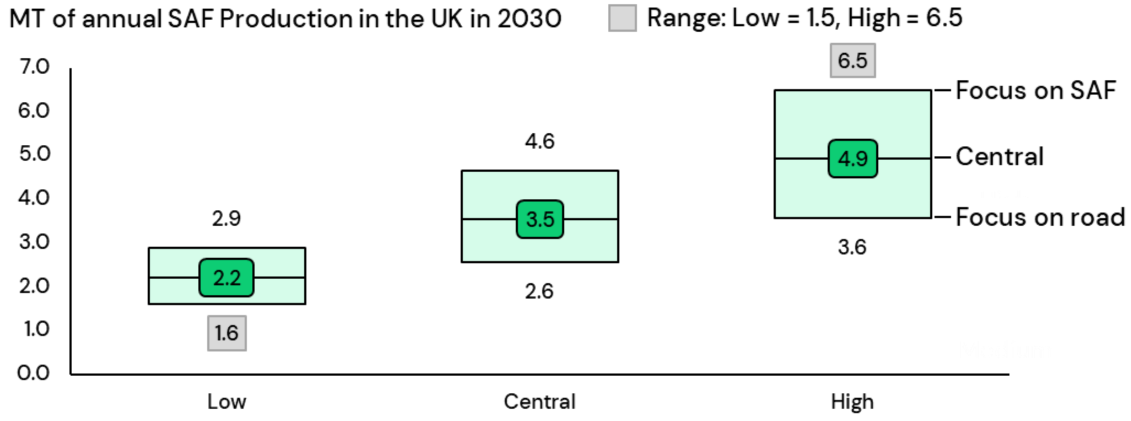
This analysis recognises the importance of decarbonising all sectors in parallel, and the feedstock assumptions have been conservatively developed to ensure resources are reasonably distributed to the highest-value end uses. The central estimates shown above (0.48 EJ of bioenergy, 50 TWh renewable electricity) are the estimated resources that could be available for use by SAF facilities and could produce 5.4 MT of domestic SAF (range 3.3 - 7.9 MT), significantly greater than the requirement for 1.2 MT SAF to meet the 10% mandate by 2030.

However, a significant portion of the feedstock energy used by SAF-focused facilities would also be embodied in co-products, typically renewable diesel, and naphtha. This is a result of the catalytic processes used, which typically result in a range of products of different carbon chain lengths. While these processes can be focused to produce higher portions of specific fractions, technical and policy factors often make it more economic to produce several products.

Policy is a key factor to incentivise different types of production. As an example, while many renewable diesel facilities could produce SAF with only a small piece of additional infrastructure, the current economic/policy environment typically provides a greater level of support for RD, resulting on the considerable volumes of global RD production and negligible SAF production.

Ensuring an appropriate yet balanced blend of production is a key. The following analysis shows the range of potential SAF production from waste and advanced feedstocks depending if policies are designed to focus on decarbonising road or aviation

Renewable fuel facilities will optimise production to the highest value market, shifting production between road and aviation fuels



Source: ICF Estimates

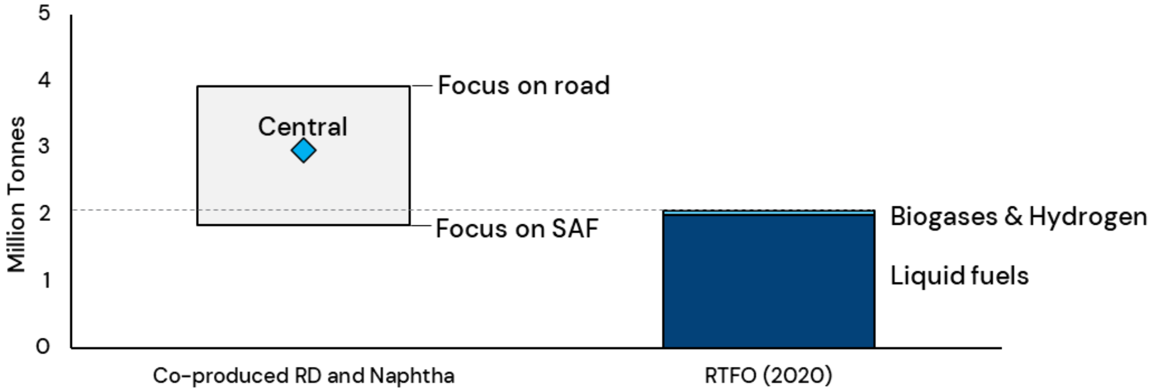
This shows that under conservative assumptions the resources (0.48 EJ of bioenergy) could produce 3.5 MT of SAF, but this could be as high as 4.6 MT if SAF facilities focus on SAF over alternative fuels. Conversely, if SAF receives little support then SAF production could be far lower, or (as currently) effectively zero, with all resources remaining unused or consumed by other sectors.

The counterfactual to this is the considerable volumes of renewable diesel and naphtha produced alongside the SAF, with less produced when SAF is the focus, and more when road decarbonisation is the priority. The UK already has a considerable renewable fuel sector, with renewable fuels representing 5.9% of total (RTFO obligated) fuels in 2020[69].

Developing a domestic SAF industry would be highly complementary to the decarbonisation of the road sector. The RD and naphtha co-produced alongside the SAF could augment the existing production, facilitating the growth of the mandate (from 10.1% in 2021 to 12% of total fuel in 2030), and potentially increasing the sustainability and energy security of the scheme. For example, the SAF production is assumed to use waste and advanced feedstocks only, and the same sustainability attributes could allow the co-products to displace the some of the high ILUC feedstocks used to meet the RTFO, particularly with the reduction in the RTFO crop cap from 3.83% in 2021 to 2% in 2032. Only 12% of the RTFO renewable fuels were supplied by UK domestic producers/feedstocks, so the growth of domestic production would also greatly reduce the length of the supply chains, with a resulting increase in energy security and ease of auditing.

The renewable diesel and RD co-produced alongside these SAF volumes would significantly contribute to the decarbonisation of road and other sectors

Million tonnes of co-produced fuels (central feedstock scenario), compared to the 2020 RTFO volumes



Source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063075/renewable-transport-fuel-obligation-annual-report-2020-print-version.pdf
Notes: RTFO converted from volume to mass assuming diesel is 0.84Kg/l and ethanol is 0.78Kg/l. Gases are low mass but contribute more on an energy basis (biomethane 1.9x, hydrogen 4.58x). While co-produced RD is drop-in, naphtha must be blended, with alternative uses to decarbonise plastic production (via ethylene) and other industries

Comparing the volume of co-produced RD and naphtha to the RTFO volumes shows that if the central resources are available to aviation (0.48 EJ of bioenergy, 50 TWh renewable electricity), and using the central assumption on the split of SAF facility production between SAF and RD/naphtha, that the volume of co-products produced would be greater than the entire 2020 RTFO volumes – showing the considerable benefits the development of a UK SAF industry could bring to the decarbonisation of the road, chemicals, and other industries.

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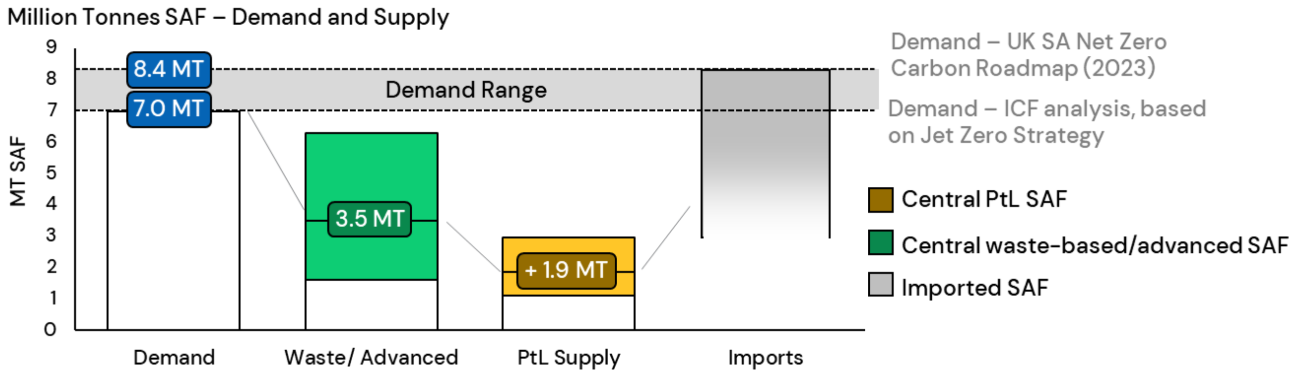
[69] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063075/renewable-transport-fuel-obligation-annual-report-2020-print-version.pdf

This further illustrates the conservative nature of this feedstock assessment; while the feedstocks have been estimated to minimise competition with road fuels, the contribution from SAF co-products towards the RTFO volumes has not been included beyond this qualitative analysis. The volume of SAF produced could consequently be higher, either as additional feedstocks currently used by the RTFO could be used for SAF production (e.g., the 1,367 million litres of UCO and tallow cat 1 used for RTFO-compliant biodiesel production), or because the SAF facilities could be focused more on SAF, shifting the central estimate from 3.5 MT toward the higher estimate of 4.6 MT (which the above illustration shows would still result in a volume of RD/naphtha almost equivalent to the entire 2020 RTFO volume).

7.1.2 The production opportunity from waste, advanced feedstocks, and PtL

The estimates and ranges for waste and advanced SAF can be combined with those for PtL to create a composite estimate of the total UK domestic SAF production potential.

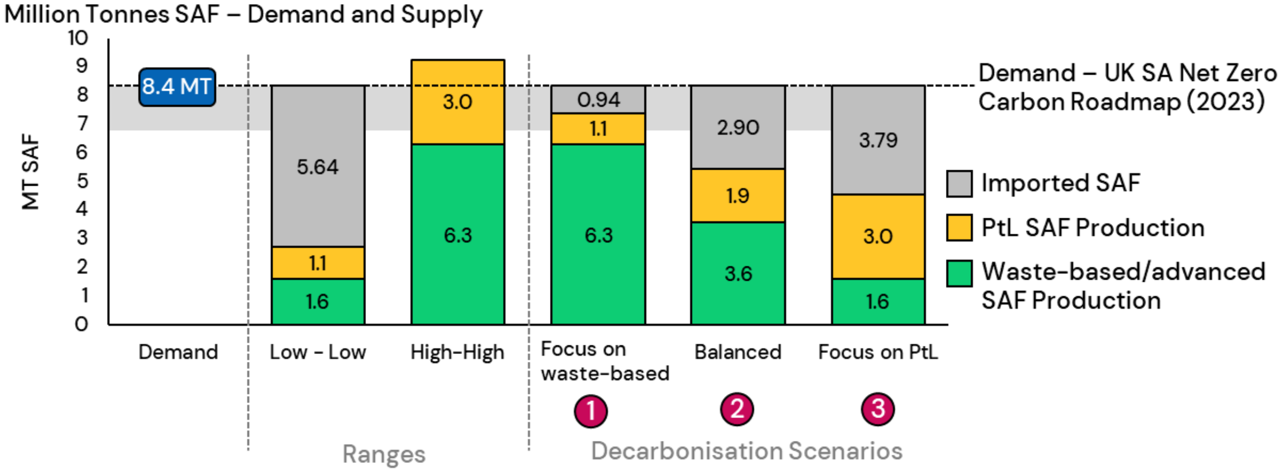
Demand of 8.4 MT in 2050 is met through 3.5 MT waste-based/advanced SAF, augmented with 1.9 MT of PtL SAF and 2.9 MT of imports



Note: The UK SA Roadmap demand of 8.4 MT is used to illustrate the requirement for the higher level of demand – the lower level of demand estimated by this roadmap (7.0 MT in 2050) would be achievable through a similar approach. In subsequent illustrations, only the higher level of demand is used.

This analysis illustrates that significant feedstock is available under reasonable assumptions, with small volumes of imports required to meet the central demand scenario of 7.0 million tonnes. The SAF industry can pursue different avenues to develop, with varying portions of waste-based/advanced, PtL SAF, and imports. Three scenarios have been illustrated below and will be further assessed in the section on deployment.

The potential 2050 production ranges bracket the demand scenarios. The meaningful potential for waste-based and PtL SAF allow a number of strategies to decarbonise



7.2 Industry scale-up rate

Economic viability is key to creating a SAF industry, although additional factors will shape the deployment rate. These include:

- **Limited organisational capacity:** The SAF industry is currently small, and few organisations have developed the capacity and knowledge to build SAF facilities. The industry will grow as these organisations increase in capacity, as additional start-ups enter the market, and as organisations in related markets pivot to SAF production. The time taken to achieve this will limit the rate of deployment.

- **Physical bottlenecks:** This includes the limitations on technical components, such as catalysts/reactors and building materials such concrete/steel.

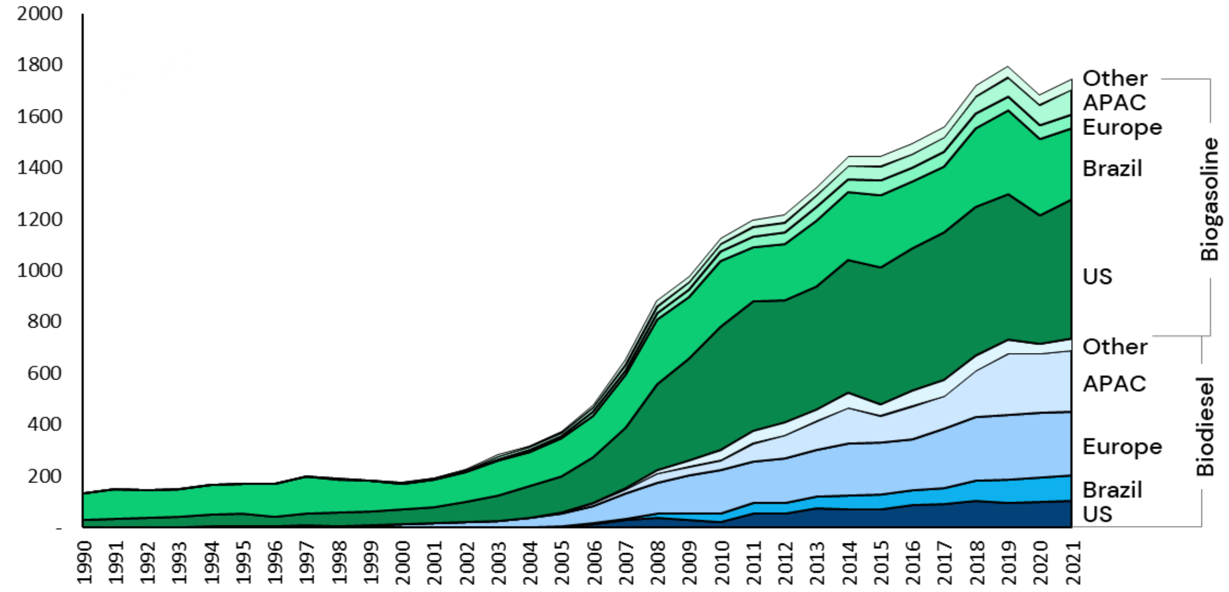
- **Permitting constraints**: Environmental permitting can take several years, as may the certification to sell fuel into the policy schemes.

- **Technology development and risk:** Some technologies have only been proven on a limited scale and/or duration. In some cases, producers and capital providers will wait to see the results of the early (FOAK) facilities before attempting to construct/fund additional facilities.

Deployment constraints have been modelled based on the historical rates for biofuels. This is an imperfect comparison, because the targeted SAF production technologies are more technologically complex than historical biofuel production, and historical deployment has (mostly) been driven by mandates so has not always been as fast as the market could deliver. The net effect is likely to drag potential SAF deployment to be slower than historical biofuel deployment, increasing the need to ensure additional constraints (such as the time for permitting) are reduced as much as possible.

Since 2000, global biodiesel production has grown by 722 Kboed and biogasoline by 850 kboed. 3,000 mmgpy SAF is approximately 185 kboed.

Biofuel production (Thousand barrels of oil per day equivalent)

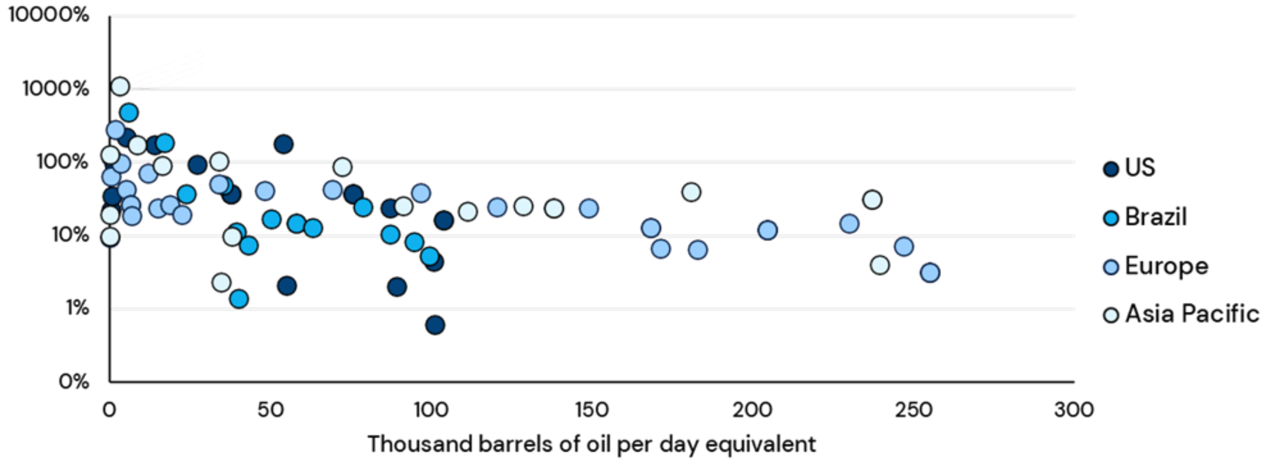


Source: BP Statistical Review 2020, ICF Analysis

The rate of capacity growth (%) declines with industry growth, although the increasing base results in larger absolute capacity additions per year. Early growth exceeded 1000% in some years, declining to c. 10% as the industry scaled, eventually reaching a maturity point in which production volume has scaled to meet market demand. Given the greater similarities with SAF production, biodiesel capacity deployment has been used for this analysis (biogasoline has been excluded).

The rate of capacity growth declines with total capacity

Annual biodiesel growth rate 2000-2020. Each point represents 1 year. Vertical (Y-axis) is logarithmic.



Source: BP Statistical Review 2020, ICF Analysis

The deployment scenarios are based on this historical analysis. When comparing projected SAF deployment to the historical biofuel deployment, there are two main differences that were considered:

1. Historical deployment has in some cases been driven by the need to meet mandates. This could have either accelerated deployment due to the need to meet the mandate or slowed the rate of deployment once the mandated volume had been achieved.
2. SAF production utilizes more complex technologies than biodiesel, particularly as the industry looks to shift to more sustainable feedstocks/pathways. This additional complexity may slow the rate of deployment for some pathways.

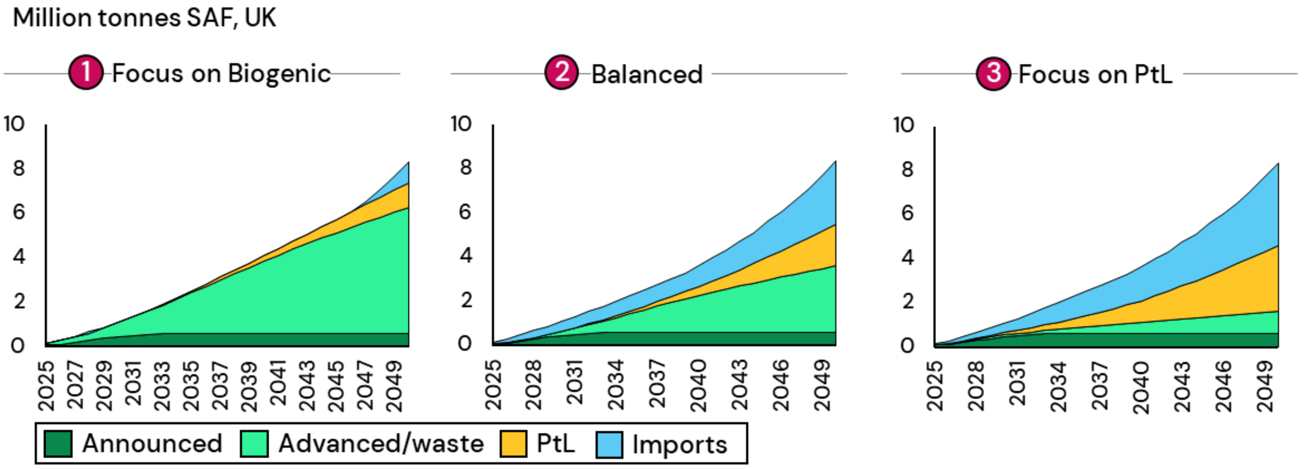
7.3 UK SAF industry deployment

Three deployment scenarios have been designed, mapping to the three production scenarios described in section 7.1.1: [1] Focus on waste-based/advanced, [2] Balanced, [3] Focus on PtL. For each, the deployment guidelines for each technology and existing announced capacity have been used to build illustrative deployment scenarios.

These scenarios are all designed to show what could be possible, and therefore an underlying assumption is that an appropriate policy environment has been established.

Given the rapid increase in capacity required to meet the 2030 target (1.2 MT in 2030), each scenario requires a small volume of imports in the near/medium term. These imports are assumed to be phased out, given the analysis has shown the sufficient availability of domestic feedstocks, the likely global scarcity of SAF for imports (and commensurate high price), and the greater energy security and economic benefits generated from domestic production.

Illustrative SAF deployment scenarios to meet the demand of 8.4 MT in 2050

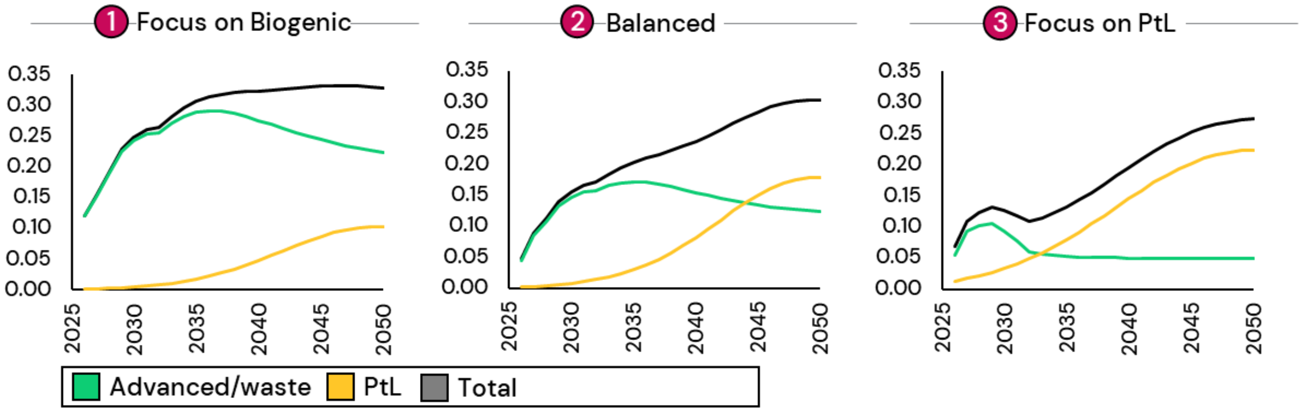


Notes: The deployment trajectories are highly dependent on the policy environment. These have been calculated assuming that policy is implemented to ensure the 2030 and 2050 targets are achieved (8.4 MT in 2050)

The comparatively greater technical maturity of waste-based feedstocks allows these to be scaled sooner, while PtL can only be deployed more gradually. Consequently, a focus on PtL requires a greater need for near-term imports to compensate, and delays much of the build-out, which potentially also reduces the UKs first-mover advantage.

Annual capacity addition peaks as the first generation of planned facilities comes online, and is then sustained through the transition to PtL capacity

Million tonnes SAF capacity added per year, UK



8 Costs and benefits

8.1 Costs

SAF production is currently limited, with the developing technologies, immature logistics, and emerging approaches driving high costs. As the industry matures and scales, the cost is expected to decrease; although this will be offset by the need to adopt more sophisticated technologies to access a larger and more sustainable set of feedstocks.

This analysis draws on several studies to estimate the global cost of production for each key pathway and apply the costs to the UK production mix.

8.1.1 Global SAF cost estimations

Estimating the cost of production

Analysis from four studies were combined to create aggregated cost estimates, including:

1. The ICAO Long term aspirational goal report[70]

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[70] https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx

2. The EU Destination 2050 analysis[71]
3. The Fuelling Net Zero report by ICF, for ATAG[72]
4. The World Economic Forum: Sustainable Aviation Fuels as a pathway to Net-Zero Aviation[73]

The cost data from each was consolidated into cost estimates for three 'categories' of SAF:

- HEFA and Co-processing
- Advanced/Waste technologies, including FT, AtJ, HTL, and others
- Power-to-Liquids

Given the limited resources available, this analysis was undertaken to provide a high-level estimate of the costs, but must be understood alongside a range of limitations, including:

- **Different modelling and macro assumptions:** Each study is composed of different approaches to the cost of production calculation and different macro assumptions (e.g., inflation). While imprecise, there is potential that averaging between the studies will develop a reasonable mid-point.
- **Location:** This study is focused on the cost of production in the UK, while the studies considered mostly evaluation the global cost. The cost in the UK will be different due to the national cost of land, materials, permitting, labour, feedstocks, and other categories. The high GDP of the UK may result in elevated costs compared the global average, although this may be somewhat offset, for example with the comparative legal/political stability encouraging a lower risk premium.
- **Technology specifications:** Every SAF facility is unique, and the studies are likely to have made different assumptions on factors ranging from the operating lifetime to the technology stack. Some pathways particularly variable, for example with some studies assuming the use of (more affordable) waste biogenic CO2 compared to Direct Air Capture. The use of global studies means the costs will not have been tailored to the expected facilities in the UK.
- **Technology blends:** Aggregating the costs into the three SAF categories reduces the analysis granularity, for example losing the difference in the cost of production between co-processed FOG and HEFA FOG.

These combined factors result in estimates that are useful to provide an indication of the cost-of-production but leave significant potential to be refined with calculations specific to the UK.

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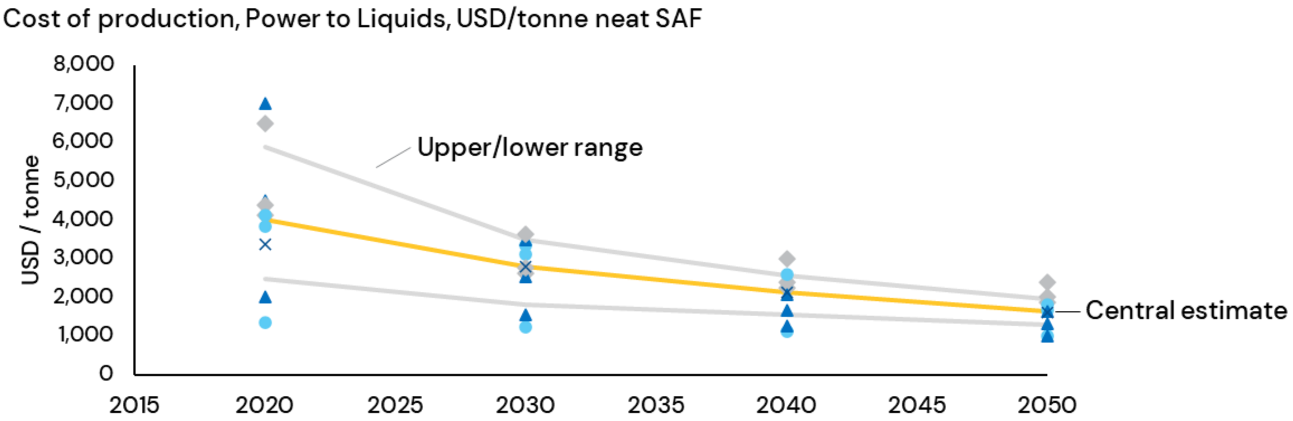
[71] https://www.destination2050.eu/

[72] https://www.icf.com/insights/transportation/deploying-sustainable-aviation-fuel-to-meet-climate-ambition

[73] https://es.weforum.org/reports/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation

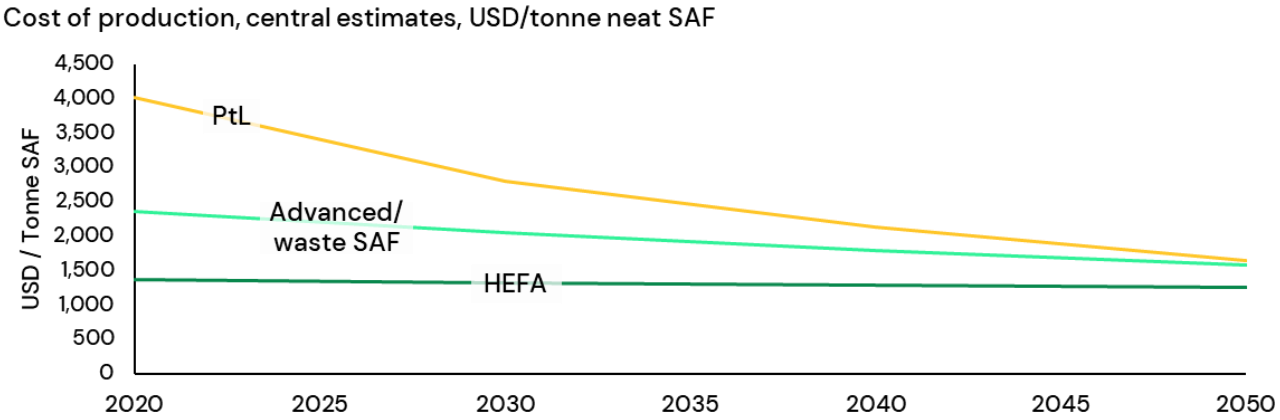
Illustrating the process to develop a central production cost estimate for PtL



Notes: Each point representing a value extracted from the four global studies

These values were combined to create central estimates for the cost of production for each SAF category. These showed a relatively flat trend for HEFA, a gradual decrease for advanced/waste SAF, and a rapid decline for PtL although from a far higher starting point.

Central estimates for the cost of production for each SAF category



Estimating the market cost for imports – competing with the US value stack

However, the price that offtakers must pay for SAF is considerably different to the cost of production. This difference is driven by two key factors:

1. **Policy value:** In some regions, and particularly the US, SAF producers can access various sources of policy value. This allows the producers to sell the SAF at a lower net price to the offtakers.

2. **Market dynamics:** The demand for SAF is rapidly growing, but as the market is small and production capacity required several years to come online, there is currently far more demand than supply. This currently allows producers to charge a scarcity margin, pricing the SAF with a higher margin than a well-balanced market.

The UK will need to complete with other regions for SAF, particularly to access imported volumes. A producer based in (for example) Singapore, is expected to export production to the highest value market. As a result, the cost to offtakers in the UK may need to be higher than the cost of production to make the UK an attractive location for these volumes.

The US is currently both the largest and most lucrative SAF market and is therefore a key indicator of the market price for SAF. There are multiple policy schemes in the US, with significant complexity and interactions. This analysis will focus on three main sources of policy value:

- **The Renewable Fuel Standard (RIN):** This is a federal policy that requires a percentage of renewable fuels to be blended into the road market. While aviation (jet fuel) is not obligated by the RFS, SAF can generate compliance credits that can be sold to obligated parties. The RFS obligation is separated into several categories, according to their RIN, each with different sustainability criteria and required emissions reductions. Most SAF will claim the D4 RIN. The current value (March 2023) of the D4 RIN is $1.81, which is multiplied by an energy equivalence value of 1.7, to give a total value per gallon SAF of $3.08. As the compliance credits are traded in a market, they are volatile, and influenced by macro supply and demand trends.
- **The Inflation Reduction Act SAF-BTC:** The IRA introduced a federal SAF-BTC, with a base value of $1.25 for SAF that achieves a GHG reduction of over 50%, and an additional value of $0.01 for every CI point below this threshold. This BTC is available for 2023 and 2024, after which it is replaced by the CFPC. As the BTC can be claimed for fuel blended into the US fuel supply it is possible for importers to claim this value (although there are some other criteria that must be met). As the CFPC is only awarded to SAF produced in the US, importers would not be able to claim this value.
- **The California Low Carbon Fuel Standard (LCFS):** This is state policy requiring fuel sold in the state to achieve a declining GHG reduction. Fuel suppliers in surplus (selling more than the required percentage) can sell to those in deficit (selling less than the required percentage). The threshold is established based on the CI of the fuels, and the LCFS credits are traded in units of tonnes CO2e. Jet fuel is not obligated by the LCFS, but SAF uplifted in the state can generate credits. The LCFS credit value in March 2023 was $67.8/tCO2e, although it has historically traded closer to $180/tCO2e, and adjustments to the policy are expected to result in an increase above this currently low value.

These three sources of policy value can be claimed for the same gallon of SAF, with additional value to a producer for the physical value of the fuel and any premium paid by the airline. This value stack includes many assumptions, most importantly:

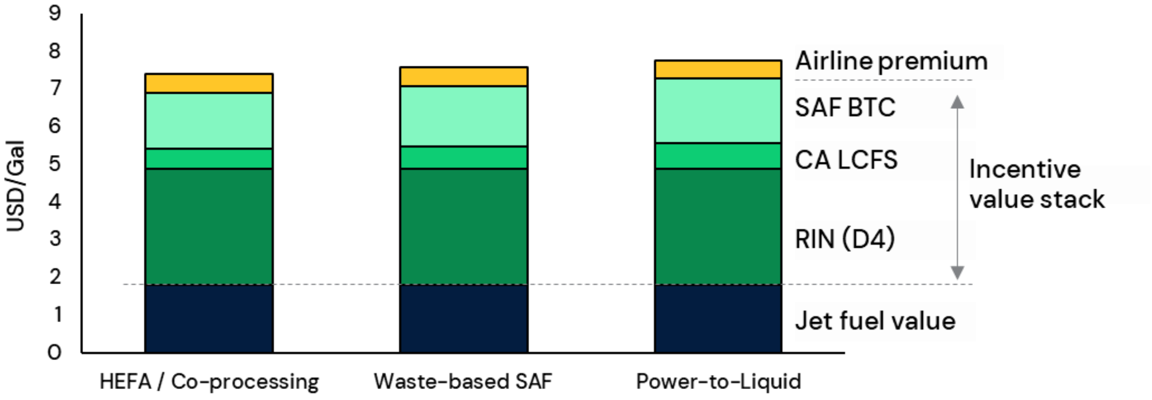
- **Other sources of value are not claimed.** There are multiple additional sources of value a US-based producer can sometimes access, including loan guarantees, capital grants, tax incentives for carbon capture, hydrogen production, and others. While an importer may not be able to access these sources of value, they may attract other scarce resources such as employees and finance, to establish production in the US rather than other locations.

- **Other state programs:** Only the California LCFS program has been shown, but several other state programs exist, including LCFS-style schemes in Oregon and Washington state, and a SAF credit in Illinois. Several other states are considering programs. While the LCFS value is currently particularly depressed, some of these other programs offer more value which means this may be an underestimate.
- **RIN value:** While the D4 RIN is claimed for the SAF produced, some facilities may claim more/less value depending on the inputs. For example, some ethanol facilities may only be able to claim D6 RINs, while some cellulosic feedstock facilities may claim the D3/7 RINs, which typically have a higher value than the D4s.
- **Airline Premium:** This analysis assumes, based on ICF market experience, that airlines are currently willing to pay a small premium for SAF offtakes. This additional value combines with the intrinsic value of the fuel and the policy value to create the full value-stack for producers. The premium is estimated at a minimum of $0.50/gal in 2020, tapering to $0.25/gal premium by 2030, and zero premium by 2040.

The combined value from the physical fuel, incentives, and airlines premium is shown below, with a small difference for each SAF category due to the different emissions reduction for each.

US SAF producers can access several sources of value to generate revenue of approximately $7.50 per gallon neat SAF produced

Value stack, March 2023, USD/tonne neat SAF



Notes: Assuming HEFA GHG Reduction of 75%, Waste-based of 85% and PtL of 95%.
Sources: EPA for RINS: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information , CARB for LCFS: https://ww2.arb.ca.gov/resources/documents/weekly-lcfs-credit-transfer-activity-reports, SAF BTC Value from the Inflation Reduction Act, Fossil Jet A/A1 price from EIA: https://www.eia.gov/dnav/pet/hist/eer_epjk_pf4_rgc_dpgD.htm

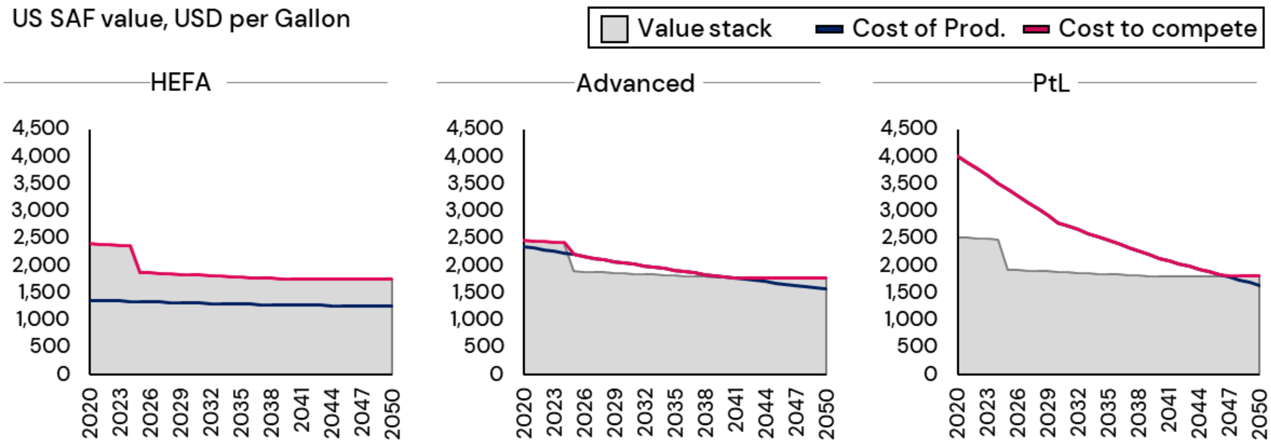
To project this value stack forward, the following assumptions were made:

- The SAF-BTC finishes in 2024, and is then replaced by the CFPC. As the CFPC can only be claimed for domestic US production, it cannot be accessed by international producers looking to export to either the US, EU, or UK. Therefore, this source of incentive value was removed from the value stack after 2024.
- The airline premium tapers to a minimum of $0/gal by 2040, as described above.
- The RIN and LCFS credit values remain constant. While several interacting factors drive these values, this assumption has been chosen as an effective and simple high-level approximation.

These assumptions are likely to be conservative. The California Air Resources Board (CARB) is currently considering an increase to the emissions reduction target which would support higher LCFS values, and other

US states are introducing programs that may offer higher value for imported SAF (e.g., Illinois). In addition, policies introduced to grow the SAF industry in countries including Canada, the EU, Turkey, Japan, and others will drive competition for scarce SAF production, which may further increase the price.

Imports to the US can access a considerable value stack. This is significantly above the cost of production, particularly for HEFA SAF



The cost to compete with the US is assumed to be the higher of either the imports incentive stack, or the cost of production. This assumption results in a significantly higher cost for imports of HEFA SAF, with the incentive stack meaningfully greater than the estimated cost of production. However, this dynamic has also resulted in greater value shared upstream, which is not reflected in the analyses used to estimate the cost of production as these were mostly calculated before this dynamic matured. This dynamic has driven a sharp increase in the cost of UCO, tallow, and other HEFA feedstocks, accentuated by the restaurant closures during COVID that cut UCO supply, and the supply chain challenges that impacted the international trade of these feedstocks. The result is that the gap between the incentive value and estimated cost of production is likely smaller than is shown, with these dynamics combining to increase the cost of production for all HEFA SAF.

The estimated cost of production is lower than the value stack for imported advanced and PtL SAF. Domestic US facilities are still viable through the CFPC (available 2025+ for US producers), other tax credits for carbon capture or green hydrogen production, and mechanism such as capital grants and loan guarantees. However, this dynamic is likely to restrict the appeal of importing advanced and PtL SAF into the US, unless the difference can be compensated through significantly cheaper production costs (perhaps where biogenic feedstock or renewable energy are affordable and plentiful).

Estimating the market cost for imports – competing with the EU Mandate

The policy combination in the EU provides significant pricing uncertainty, as many features of the policies are still to be confirmed at the time of writing, and the structures also lack defined prices. The key feature is likely to be the mandate established through EU ReFuel, which proposes an escalating requirement for SAF to be blended into the EU fossil jet fuel supply. This has both a 'main' mandate and a PtL sub-mandate and will not have a specific cap on HEFA-equivalent SAF (as defined by the feedstocks allowed in the RED II Annex IV), although the use of some of these feedstocks is capped for all renewable fuels.

Current expectations are for the price of SAF in the EU to be mainly driven by the supply-demand dynamics and the interaction with the buy-out price, alongside numerous smaller but important factors. The buy-out price is currently outlined as twice the difference between the fossil jet price and a relevant SAF price index, and potentially more as a deficit may need to be made-up the following year in additional to paying the penalty. If supply is scarce, then SAF may trade close to the buy-out price, i.e., close to the opportunity cost if the SAF cannot be accessed. If SAF is available in more significant quantities then SAF may trade at lower prices, although the value stack available in the US may establish an effective floor price. Given this pricing uncertainty, most SAF production announced in the EU has focused on the comparatively low-capex HEFA pathway.

The pricing uncertainty makes analysis of the import/export dynamics with the EU challenging, although it does highlight that if the SAF production capacity does not grow to meet the volumes required for the EU mandate then the market price for SAF could rise significantly (2-3x the SAF to fossil jet differential) above the cost of production.

A key factor is the lack of compatibility between a significant portion of the emerging global SAF production and the EU and UK sustainability/feedstock criteria, as the current European policies prohibit the use of feedstocks that compete with food or feed (such as SBO or corn ethanol), which may comprise a meaningful portion of production in other regions. As a result, parties obligated by the EU and UK mandates may only be able to access a fraction of the global market and incur elevated prices to meet the mandate volumes.

Developing a combined cost estimate for UK SAF

The different obligations, incentives, and criteria for SAF are likely to result in a fragmented market, with different price points depending on the policy regimes a given volume can access. As an approximation, this analysis will consider the three main categories of SAF described above, including:

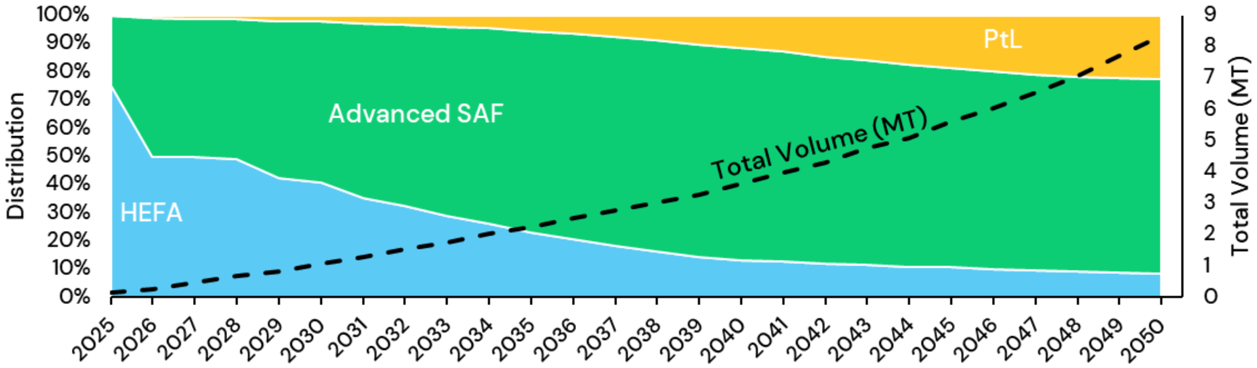
- **PtL SAF:** This SAF is assumed to be able to access the UK and EU PtL sub-mandates. Likely to be less prevalent in the US due to several headwinds in the current policy design.
- **Advanced SAF:** Eligible for the UK and EU main mandates, and typically able to claim significant value in the US due to a high GHG reduction potential. However, facilities require significant capex and while this SAF is likely to be widely applicable, advanced SAF only represents a small portion of announced production capacity. The global market is likely to be illiquid due to the low volumes, compounded because many facilities require long-duration offtakes to achieve financial close, so the fuel is already allocated to specific customers.
- **HEFA SAF:** Eligible for the UK mandate up to a SAF-specific cap, and eligible for the EU mandate (with some restrictions). HEFA SAF using waste feedstocks eligible for the EU and UK mandates is also highly valuable within the US policy structure due to the value the low CI can claim. Most announced capacity uses this approach, and volumes are expected to trade internationally.

A meaningful portion of global production will use feedstocks that compete with food or feed, but as these are not eligible for the UK mandate, they sit outside this analysis scope.

In the central UK SAF case, much of the initial volumes are HEFA, meeting the early mandate volumes with small volumes of domestic production (e.g., the P66 co-processing) and the majority through HEFA imports. The contribution of advanced SAF rapidly increases as the announced facilities start to come online, such as those that received funding through the AFF. The transition accelerates in the decade after 2030, augmented by the increasing PtL volumes. By 2050, most domestic production is assumed to be PtL and Advanced SAF (as described in the feedstock and deployment analysis), with imports split between HEFA and advanced SAF.

Initial volumes are dominated by HEFA imports, transitioning to advanced and PtL SAF as UK domestic production comes on-line

Left: Distribution of SAF category, % | Right: Total SAF volume, MT

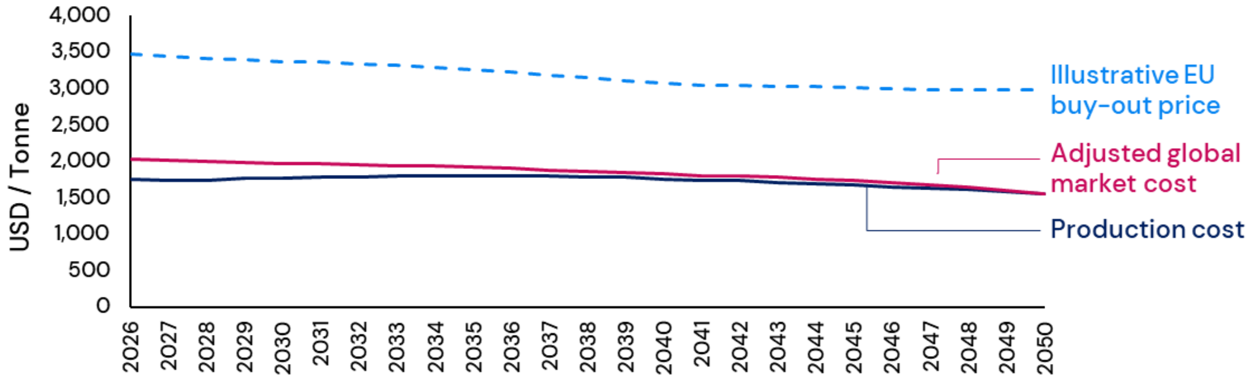


Notes: Almost all HEFA is assumed to be imported, with only minimal volumes produced domestically

Applying this distribution of SAF to the three cost estimate approaches (cost of production, cost to compete with the US, and potential EU buy-out price) generates three average costs of production per neat tonne SAF, as illustrated below. The adjusted global market cost assumes the market continues to be driven by the US value stack, although after discussions with stakeholders it was decided to taper the difference between this and the production cost to 0 between 2040 and 2050 to represent the market maturing.

The SAF price is likely to be elevated above the cost of production

Average USD per neat SAF tonne, composite for UK demand distribution, UK Central case



This illustrates the potential for some costs to be elevated in the near-term due to the competitive international dynamics, and a risk that prices may be significantly higher if scarcity drives prices close to the buy-out prices, with an estimate for the EU shown for context.

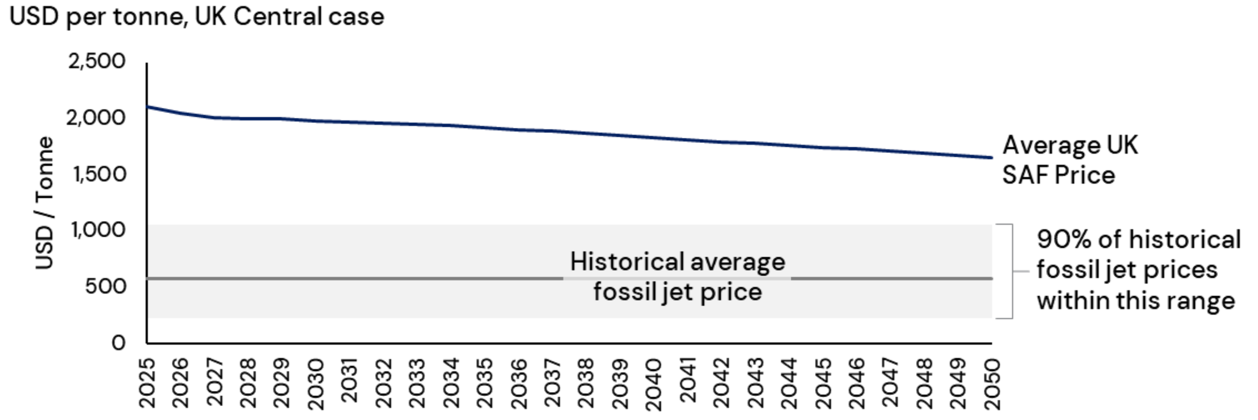
Mapping these to the UK is challenging due to the lack of policy clarity – both regarding the potential export of volumes produced in the UK, and the potential import from the US, EU, and other regions. Three simplifying assumptions were made:

1. **SAF produced in the UK is available at the cost of production.** This would require additional policy mechanisms such as a contract for difference that would limit the production to the domestic market and reduce the risk and uncertainty premia that producers would need to include.
2. **Imports at market price.** This assumes that SAF is available for import at the same price point as the US value stack, which would require that producers are indifferent between the markets. Additional costs may be required if the UK requires higher transport costs, or additional incentives are available in the US beyond those assessed here (e.g., some of the state-level policies under development).
3. **SAF is available in sufficient quantities**, allowing the market price to trade lower than the buy-out price. This requires policy to be implemented to catalyse a rapid build-out of capacity, with the current announced supply falling short of the announced 2030 demand.

Combining these assumptions and analysis gives the average SAF price. This shows a gradual decrease that is slightly offset by the transition to more expensive methods of production. The cost decrease is a result of decreasing SAF unit costs (as production costs decrease), and the reduced value stack in the US as federal policy shifts from a blenders credit (that importers can access) to a production credit (that requires SAF to be produced domestically). The reduction is tempered by the transition to more expensive production approaches, as advanced SAF production comes online, followed by PtL.

This analysis has been illustrated alongside the historical average and central 90th percentile of fossil jet fuel prices. While future fossil jet fuel prices are challenging to forecast, this shows the significantly reduced gap and residual premium.

The rapid decrease in unit SAF costs is offset by the transition to more sustainable but expensive approaches, with the average price remaining above fossil jet

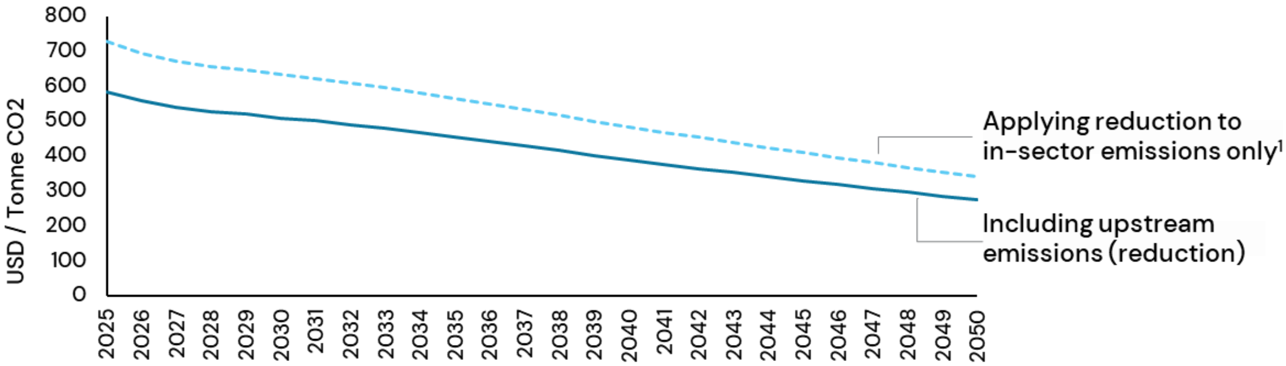


Source: Historical jet fuel price - https://www.eia.gov/dnav/pet/hist/eer_epjk_pf4_rgc_dpgD.htm

The reduction in average SAF costs combines with the increasing GHG reduction of the SAF to drive a rapid reduction in the SAF abatement cost. SAF reduces emissions over the fuel life cycle, so the emissions reduction over the full life cycle is typically used; however, the UK government reports emissions based on the sectoral approach but adjusts this by applying the GHG reduction of SAF to the in-sector emissions only (to recognise that SAF does not fully reduce emissions). This differs from other reporting approaches (e.g., the EU) that follow the Greenhouse Gas Protocol sector approach by modelling 0 tank-to-wake emissions for SAF, and reporting the residual emissions (e.g., from transport, refining) in the relevant sectors. While the physical volume of CO2 abated remains the same, the difference between the approaches is the sector that reports the reduction, and to capture this difference both the full (lifecycle emissions reduction[74]) and in-sector (UK government) approaches have been illustrated.

A rapid decrease in abatement cost is driven by the reduced cost of production and the increasing GHG reduction

USD per tonne CO2e, UK Central case



Note 1: While all SAF emission reduction (excluding non-co2 impacts) is upstream of combustion in the life cycle, some analyses by the UK Government consider the tank-to-wake ("in-sector") emission of SAF only, and apply the GHG reduction to this portion only, resulting in lower emission reduction and therefore higher abatement cost

These both show the rapid reduction in abatement cost achieved, with the initially high costs decreasing over the assessment period. However, the residual premium must still be addressed, and the next section estimates some of the non-co2 benefits that could be addressed through the development of a domestic UK SAF industry.

8.2 Economic and security benefits to the deployment of a UK SAF industry

8.2.1 Economic & employment growth

Investing in SAF production is highly effective in creating jobs, with labour required to gather, process and transport feedstock, as well as design, construct and operate facilities. The development of the full value chain can create many jobs, particularly in more rural areas[75].

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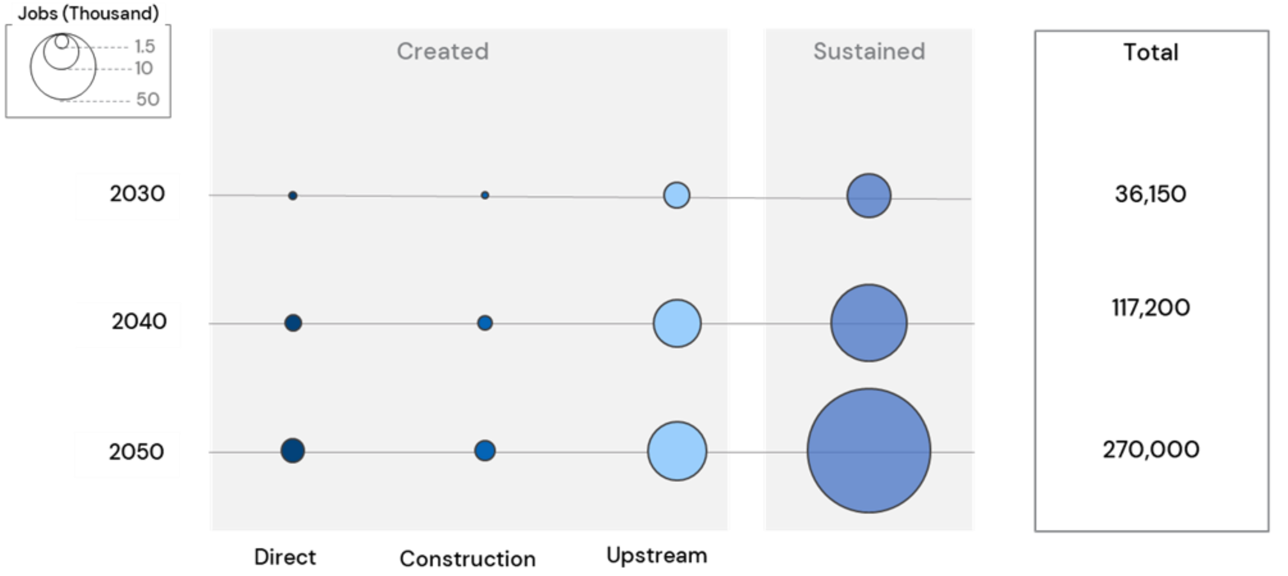
[74] Using the ICAO average fossil jet fuel emissions baseline of 89gCO2e/MJ

[75] Bioenergy Technologies Office, Sustainable Aviation Fuels

Job creation can be split by employment type; jobs that are directly created as a result of SAF production, temporary jobs in construction, and jobs created in the value chain/upstream. Direct jobs are linked to the long-term, direct operation of SAF production facilities, whilst construction jobs are substantial but temporary. There will also be jobs created or sustained along the SAF value chain, for example upstream agricultural or waste management jobs. Significant employment would also be sustained within the aviation industry with SAF allowing continuing operation of the sector in a carbon-constrained future.

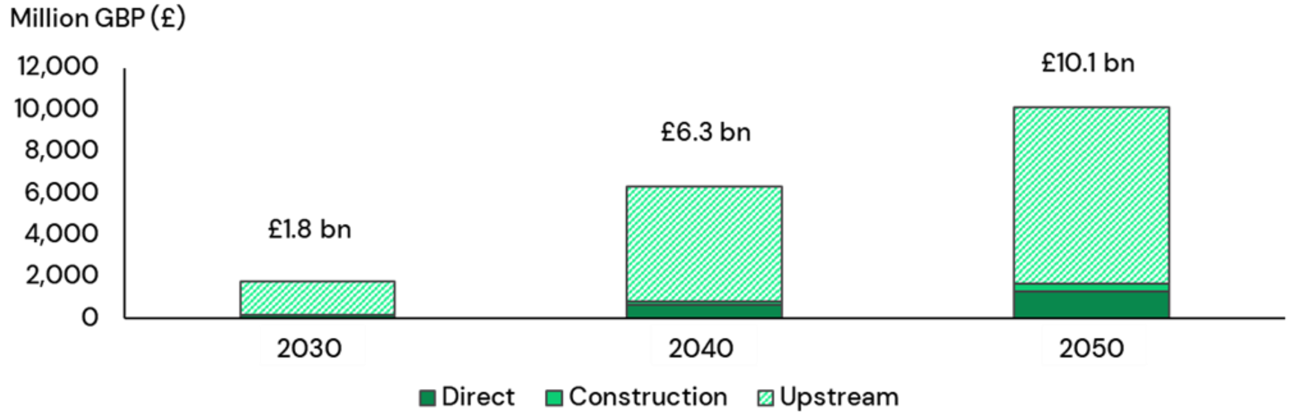
This report estimates job creation using the central UK SAF production ramp rate which calculates that 0.6 MT SAF will be produced in the UK in 2030, increasing to 5.5 MT in 2050. As detailed in this report, this will be supplemented by imported supply to meet the 10% SAF mandate by 2030 (equivalent to 1.2MT SAF) and a demand scenario of 8.35 MT SAF in 2050. In 2030, ICF estimates that ~10,350 jobs could be created by the UK SAF industry (approx. 800 direct, 600 construction, 8,950 upstream), with the potential for an additional ~25,800 jobs sustained/safeguarded across the aviation industry (calculated as the percentage of the industry employment decarbonised by SAF in that year). In 2040, ~37,000 jobs are created (approx. 3,500 direct, 2,500 construction, 31,000 upstream) and ~80,200 safeguarded, whilst in 2050, estimated job creation increases to 60,000 (approx. 7,350 direct, 5,150 construction, 47,500 upstream), with an additional 210,000 aviation jobs sustained.

Developing a UK SAF industry will create and sustain up to 270,000 jobs by 2050



Building a domestic SAF industry has the potential for substantial economic growth, measured as gross value added (GVA). In 2030, ~£1.8 billion could be generated in GVA as a result of UK SAF production, increasing to ~£10.1bn in 2050. This is linked to direct, FTE construction, and upstream employment from the industry, with the latter driving the greatest employment and consequently GVA. Direct jobs generate ~£148 million in 2030 and ~£1.3 billion in 2050. While the construction roles contribute less overall, these would be front-loaded as the industry is built out.

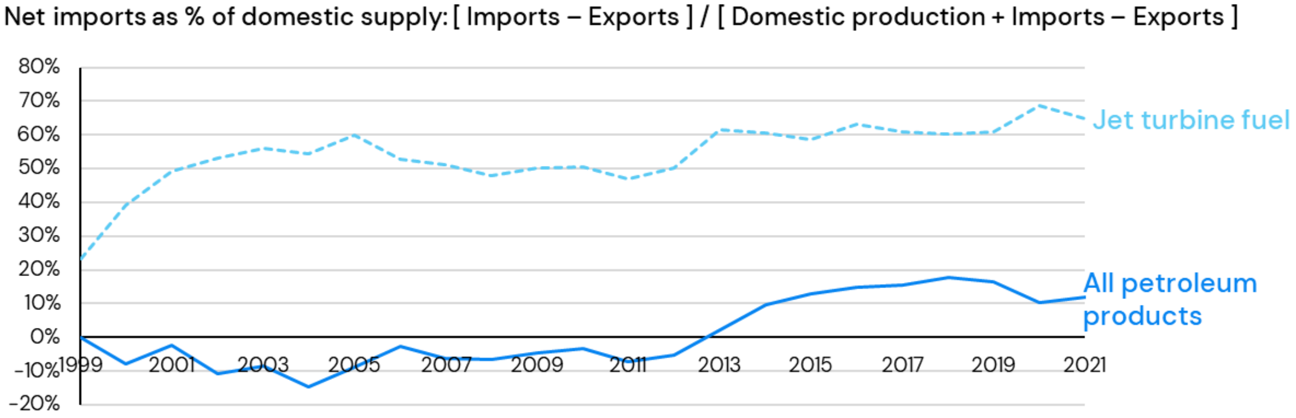
Gross Value Added by a UK SAF industry, central case



8.2.2 Energy security & resilience

The UK currently imports around 64% net jet fuel, creating a significant dependence on the production and political goodwill of other countries. The interconnected global economy will always require cross-border flows of energy, but additional domestic production can be an important tool to increase resilience and improve the UK's negotiating position with countries whose values do not align with those of the UK.

The UK has transitioned from a net exporter to a net importer of oil products, and particularly imports the majority of UK jet turbine fuel



The UK has historically been a net importer of jet turbine fuel but was a net exporter of other oil products (petroleum) until 2013. Domestically produced SAF could present an opportunity for the country to reduce their reliance on imports and make steps to restore a more balanced exchange of energy.

9 Conclusions and next steps

Decarbonising the UK's aviation industry in less than three decades is challenging but achievable. Commercial aviation has barely existed for a century, and yet in that time has progressed at a frenetic pace, with Whittle inventing the jet engine just 27 years after the first powered flight, and Concorde carrying passengers at supersonic speed only 46 years later. Recent improvements have been less noticeable but perhaps more revolutionary, with efficiency improvements making flight affordable to millions more people and decoupling emissions from the industry growth.

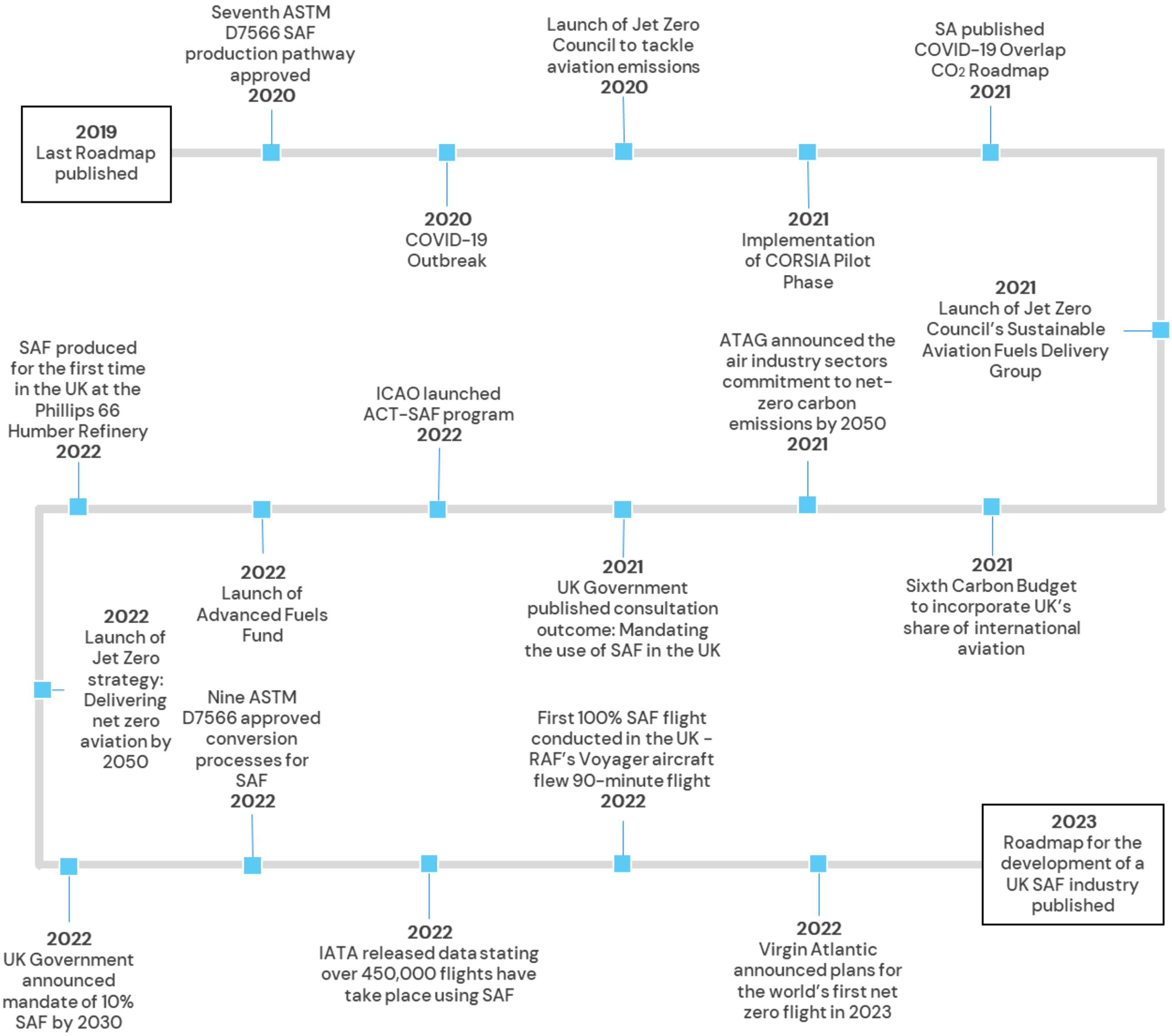
The industry must continue to evolve. In just 27 years, by 2050, aviation should replace the polluting fuels currently used with clean energy to avoid the worst impacts of climate change. Accelerated efficiency improvements will be critical to ensure as little energy as possible is required, but this must be matched by a very rapid build-out of the SAF industry.

This analysis shows that considerable feedstock can be accessed in the UK, sufficient to produce 6.5 million tonnes of SAF in the central case and perhaps more if other sectors decarbonise more rapidly. This is adequate for UK aviation to fully decarbonise, succeeding through a portfolio of efficiency, net zero aircraft, SAF, and out-of-sector measures. While SAF is currently more costly to produce than fossil fuels, it also provides much more value – most prominently through reduced emissions, but also by enabling job and economic growth, and increasing the resilience of the UK's energy supply. This additional value could be considerable, with an estimated 60,000 full-time jobs created through the construction, operation, and logistics of SAF production, and many more sustained in the aviation industry. The gross value added to the UK economy could be in excess of £10 billion.

The nascent SAF industry will require many technologies to be developed and commercialized, and this presents opportunities far wider than the UK market. The Waypoint 2050 report by the Air Transport Action Group estimates that the global aviation industry will require approximately 400 million tonnes of SAF by 2050, and the companies and IP required to achieve even half this volume will be titans of the future economy. This is an area the UK has shown leadership in previously, with exports of aerospace components bringing £34 billion to the UK every year. A UK market has the potential to provide the sandbox to develop SAF companies for global growth ambitions.

The global SAF policy environment is developing at pace, led by the US and EU. The UK has a solid foundation to join these pioneers, with adequate feedstocks, expertise, and abundant enthusiasm. Efficient and transparent policies to support both the demand and supply side of the industry represent the final catalyst to develop SAF in the UK and their evaluation and implementation represents the most important next steps for the industry.

10 Key changes since the 2019 Sustainable Aviation Roadmap



2019
Last Roadmap published

Seventh ASTM D7566 SAF production pathway approved
2020

2020
COVID-19 Outbreak

Launch of Jet Zero Council to tackle aviation emissions
2020

2021
Implementation of CORSIA Pilot Phase

SA published COVID-19 Overlap CO_2 Roadmap
2021

2021
Launch of Jet Zero Council's Sustainable Aviation Fuels Delivery Group

2021
Sixth Carbon Budget to incorporate UK's share of international aviation

ATAG announced the air industry sectors commitment to net-zero carbon emissions by 2050
2021

2021
UK Government published consultation outcome: Mandating the use of SAF in the UK

ICAO launched ACT-SAF program
2022

2022
Launch of Advanced Fuels Fund

SAF produced for the first time in the UK at the Phillips 66 Humber Refinery
2022

2022
Launch of Jet Zero strategy: Delivering net zero aviation by 2050

2022
UK Government announced mandate of 10% SAF by 2030

Nine ASTM D7566 approved conversion processes for SAF
2022

2022
IATA released data stating over 450,000 flights have take place using SAF

First 100% SAF flight conducted in the UK – RAF's Voyager aircraft flew 90-minute flight
2022

2022
Virgin Atlantic announced plans for the world's first net zero flight in 2023

2023
Roadmap for the development of a UK SAF industry published

Technical Appendix

Feedstock availability

The data primarily used in this study published by the UK Government[76], ICCT[77], TCCCR[78], and BEIS[79]. Each source published different forecasts for feedstock availability within the UK. To provide what we deem to be a more accurate reflection of these values, independent analysis and verification has also been completed.

The UK Government model estimates the potential bioenergy resource available to the UK from domestically sourced and imported feedstocks, from 2010 through to 2050. Availability is split by resource with and without imports, and thus both values were considered in ICF's analysis. The study also makes sustainability and competing use considerations, and ICF used figures produced by selecting a competing use price level of £4/GJ, assuming supply barriers will be overcome. Values representing accessible resource are provided in PJ.

The ICCT study assesses the availability of feedstocks in each EU member state and the United Kingdom to understand the extent to which the country can rely on domestically available low carbon biofuels to decarbonise their transport sector. The ICCT provides three scenarios, splitting feedstock resource availability by the total availability, sustainable availability, and availability for use for biofuel production. This means that sustainability and competing use considerations are made. Feedstock resource is provided in weight value, and so is converted to energy by ICF through assumptions made on the amount of energy available per weight of specific feedstock (MJ/Kg), listed in a table below.

The TCCCR study provides data from a Biomass Resource Model, reflecting key supply chain dynamics and the interactions that determine resource availability, including sustainability considerations. Four scenarios are modelled, reflecting focus on feedstock for food, economic, conservation and energy purposes. The conservation scenario places emphasis on enhanced conservation and preservation of biodiversity and resources. As sustainability is also a focus of this report, values from this scenario were utilised.

UK Government values on waste industrial gases were provided in weight of emissions (CO_2) from cement, steel & iron, and ammonia production in 2019. High, medium (sustainable growth), and low (net zero) growth assumptions from the International Energy Agency (IEA) were applied to these values to the year 2030. Values were then converted to energy units as per the assumptions below, with High, Central, and Low outputs of jet fuel.

The final feedstocks assessed in this study are as follows; wood (domestic & imported), municipal waste, waste fats, oils, & greases (domestic & imported), agricultural wastes, sewage sludge, algae, cover crops, and waste industrial gasses.

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[76] Biomass Feedstock Availability

[77] Waste and residue availability for advance biofuel production int he European Union and the United Kingdom

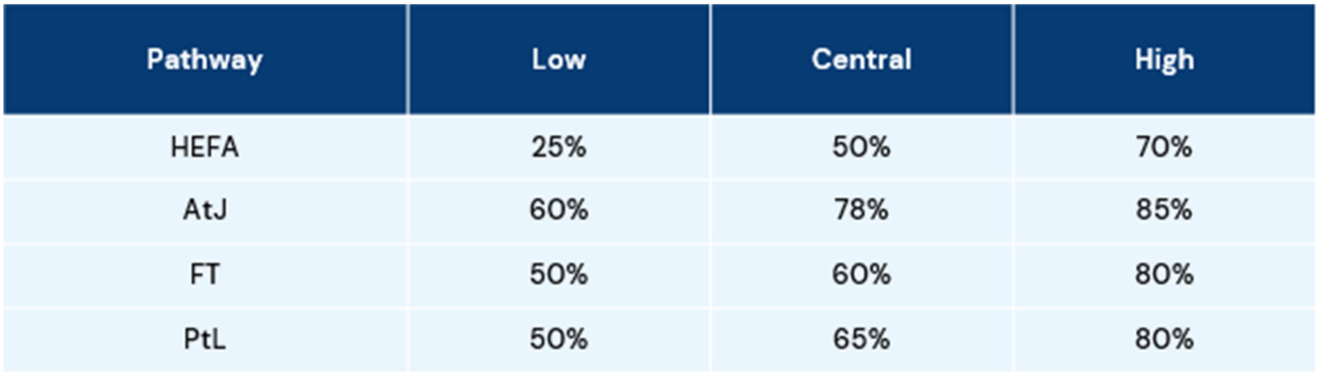
[78] Securing a bioenergy future without imports

[79] Net Zero Strategy: Build Back Greener

Assumptions

While ranges at both extremes are possible and likely for specific facilities, these assumptions have been developed to reflect moderate values across the full UK industry. If policy is particularly supportive of SAF over other fuels then higher percentages are feasible, and equally, many facilities can produce no SAF.

ICF assumptions, % of jet fuel produced by facilities by SAF production pathway



Pathway	Low	Central	High
HEFA	25%	50%	70%
AtJ	60%	78%	85%
FT	50%	60%	80%
PtL	50%	65%	80%

ICF assumptions, energy per weight of feedstock (MJ/Kg)

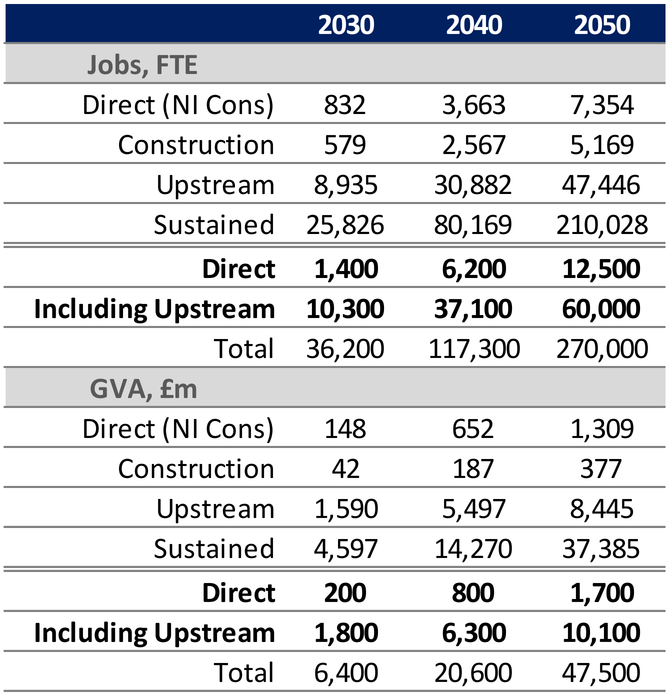
Feedstock	Assumption (MJ/Kg)
UCO	42
Tallow	42
Animal & mixed food waste	42
MSW	10
Cement Production	5.6
Steel & Iron Production	22.7
Ammonia Production	18.8
Waste wood	20
Agricultural residues	15
Perrenial energy crops	20
Cellulosic cover crops	19

Supply & demand

Supply and demand for SAF has been calculated by comparing publicly announced SAF production facilities against publicly announced country-level SAF targets/mandates. Information gathered on SAF production facilities includes facility name, location, production start date, feedstock used, and production volume. Estimated yield was then calculated, accounting for efficiency losses dependent on production technology used. Information on demand accounts for SAF targets by country and is aggregated regionally. The date of the target is also noted, and then plotted against supply.

Job creation

Job creation from UK SAF production has been estimated through to 2050. As an initial top-down analysis of job creation from a UK SAF industry, a number of facilities which have publicly announced values for job creation were assessed. The published values were scaled to 1 MT equivalent as facilities are often small. Full-time direct jobs, construction jobs, and upstream jobs could then be calculated based on the UK SAF production outlook. Construction jobs were transferred to full time equivalent numbers. For example, if 500 construction jobs were said to be created, it was assumed that these jobs will last for 3 years for a facility lifetime of 25 years, equalling 60 full time equivalent construction jobs. The average number of jobs created was calculated across the facilities, split by employment type and production pathway, producing an average number of jobs created per million tonnes SAF.



	2030	2040	2050
Jobs, FTE			
Direct (NI Cons)	832	3,663	7,354
Construction	579	2,567	5,169
Upstream	8,935	30,882	47,446
Sustained	25,826	80,169	210,028
Direct	**1,400**	**6,200**	**12,500**
Including Upstream	**10,300**	**37,100**	**60,000**
Total	36,200	117,300	270,000
GVA, £m			
Direct (NI Cons)	148	652	1,309
Construction	42	187	377
Upstream	1,590	5,497	8,445
Sustained	4,597	14,270	37,385
Direct	**200**	**800**	**1,700**
Including Upstream	**1,800**	**6,300**	**10,100**
Total	6,400	20,600	47,500

A bottom-up analysis was also done by calculating the number of jobs that could be created per facility, based on facility size and production pathway. The number of jobs per facility was then multiplied by the number of facilities that could be created, based on production volumes per facility and total calculated production volume in 2030 and 2050.

These values were then applied to the ramp rate scenarios for UK SAF production that ICF had previously developed to calculate job production from SAF from 2025 through to 2050.

An additional 15% was applied to the number of direct jobs created at facilities from 2030 through to 2050 to account for management roles such as sales and marketing. A 20% reduction (linear from 0 today and 20% in 2050) was then applied to account for job automation over the coming years.

To calculate employment sustained in the aviation industry through the deployment of SAF, an initial value of 230,000 direct jobs from aviation in the UK, quoted by the Jet Zero Strategy, was used. This value was applied to a calculated net change in employment, accounting for increased passenger numbers and job automation. Factors based on a proportion of emissions reductions being achieved through other measures, as well as SAF ambition, were then applied, producing values for total jobs sustained through SAF.

GVA

Figures published by the Office of National Statistics' Annual Business Review on GVA by role type were applied to the number of jobs created by a UK SAF industry in 2030, 2040, and 2050. GVA per job in direct and value chain roles is calculated as £178,000, compared to a lower GVA value for construction roles of £73,000.

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