Vertical Take-Off?

Cost Implications and Industrial Development Scenarios for the UK SAF Mandate

Dr Cato Sandford and Dr Chris Malins

July 2024

Acknowledgements

This work was supported by the International Council on Clean Transportation. Cover image by Jane Robertson Design.

Disclaimer

Contents

Glossary

Abbreviation	Description
AFF	Advanced Fuels Fund (UK)
ASTM	American Society for Testing and Materials
ATI	Aerospace Technology Institute (UK)
AtJ	Alcohol-to-jet fuel
BAU	Business as usual
BtL	Biomass-to-liquid fuel
CCS	Carbon capture and sequestration
CCU	Carbon capture and use
CI	Carbon intensity
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation (ICAO)
DAC	Direct air capture
DESNZ	UK Department for Energy Security and Net Zero
DfT	UK Department for Transport
DoE	U.S. Department of Energy
ETS	EU Emissions Trading System
EUR	Euro, €
FOA	Funding Opportunity Announcement
FT	Fischer-Tropsch
GBP	British pound, £
GHG	Greenhouse gas
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-hour
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydro-treated vegetable oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Authority
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
ILUC	Indirect land-use change
JFK	John F. Kennedy Airport (U.S.)
kt	Kilotonne (metric)
ktoe	Kilotonnes of oil equivalent
kW	Kilowatt

kWh	Kilowatt-hour
LCA	Lifecycle analysis
LCFS	Low carbon fuel standard
LHR	London Heathrow Airport (UK)
LHV	Lower heating value
MJ	Megajoule
MSW	Municipal solid waste
Mt	Megatonne (metric)
Mtoe	Megatonnes of oil equivalent
MW	Megawatt
MWh	Megawatt-hour
PJ	Petajoule
PtL	Power-to-liquid fuel
R&D	Research and development
RFNBO	Renewable fuel of non-biological origin
RTFC	Renewable Transport Fuel Credit (UK)
RTFO	Renewable Transport Fuel Obligation (UK)
SAF	Sustainable aviation fuel
SIP	Synthetic iso-paraffin
t	Tonne (metric)
toe	Tonne of oil equivalent
UCO	Used cooking oil
USD	U.S. dollar, $
WEF	World Economic Forum

1. Introduction

1.1. Background

1.1.1. The UK Jet Zero Strategy

In 2022, the UK Department for Transport (DfT) launched its Jet Zero Strategy (UK Department for Transport, 2022b). This set out proposals for the UK's aviation sector to reach 'net zero' emissions for domestic flights by 2040 and for all flights by 2050[1]. Under a net zero target, residual greenhouse gas emissions from the aviation industry may be offset by action in other economic sectors or by carbon removals. Residual emissions are estimated at 35.4 Mt in 2030, declining to 28.4 Mt in 2040 and 19.3 Mt in 2050, following Jet Zero's default 'High Ambition' scenario.

Achieving these kinds of emissions reductions is envisioned to depend heavily on so-called 'sustainable aviation fuel' (SAF), which encompasses a number of drop-in replacements for fossil fuels. Alternative fuel deployment will work in tandem with other measures, notably improvements to aeroplanes' energy efficiency, investment in negative carbon technologies to offset emissions, and, ultimately, the development of electric- and hydrogen-powered aircraft[2] (UK Department for Transport, 2022b).

A significant portion of the warming impact from aviation is associated not with CO_2 emissions from fuel combustion, but with non-CO_2 effects: principally the trapping of heat by aviation-induced clouds. The Jet Zero Strategy notes that about two thirds of the warming from aviation is due to non-CO_2 effects, consistent with a report commissioned for the DfT (Lee, 2018)[3]. Meeting the UK's net zero target for CO_2 emissions would not, therefore, eliminate the aviation sector's climate impact.

1.1.2. Incentivising alternative aviation fuels

The Jet Zero Strategy identifies a number of existing, developing, and planned regulatory instruments to guide the aviation industry's UK operations. Foremost among these, at least in the medium term, is the UK's SAF Mandate, which will obligate the suppliers of aviation fuel to bring a minimum fraction of alternative fuel to the market. Two stakeholder consultations on

[1] https://www.gov.uk/government/speeches/jet-zero-strategy-our-approach-for-achieving-net-zero-aviation-by-2050

[2] At present, only small, short-haul electric aircraft have been developed, and production has not been commercialised. For now, only liquid fuels used in conventional jet engines offer the specific energy (energy per unit mass) needed to power commercial passenger or freight aeroplanes for longer trips. Most aviation decarbonisation will therefore have to be delivered by reducing the carbon intensity and/or consumption of liquid fuels, at least for the next two decades.

[3] The warming effects of CO_2 and aviation-induced clouds have different lifetimes, so any comparison of the two will depend on the timeframe considered.

the design and implementation of the SAF Mandate have already been completed by DfT: one in 2021 (UK Department for Transport, 2021a), and another in 2023 (UK Department for Transport, 2023b), where the latter included an impact analysis detailing the Government's expectations and modelling decisions (UK Department for Transport, 2023e).

Final decisions on the consultation questions have now been released, alongside an updated impact analysis (UK Department for Transport, 2024a, 2024b). For the purposes of this report, we take these documents to establish the design and parameters of the SAF Mandate, though these will only be truly finalised once an official regulatory text is adopted into law. As of now, the essential points are as follows:

- The SAF Mandate will obligate suppliers of jet fuel to blend a growing fraction of alternative aviation fuel.
- The policy value of a given litre of fuel will be scaled in proportion to the reportable emissions savings of the fuels used.
- A range of alternative fuel production pathways will be eligible, provided they meet sustainability criteria such as the exclusion of crop-based feedstocks, and a minimum emissions-saving of at least 40% compared to fossil aviation fuel.

1.1.3. Existing programmes: RTFO, CORSIA, and the UK ETS

Three existing programmes incentivise the use of alternative aviation fuel in the UK. As these will be referred to in future sections, we briefly introduce them here.

The first is the UK's Renewable Transport Fuels Obligation (RTFO), which started in 2008; elements of this system are to be used as a template for the SAF Mandate. Under the RTFO, suppliers of transport fuels in the UK must demonstrate that a percentage of the fuel they supply comes from renewable sources, and meets specified minimum sustainability criteria (UK Department for Transport, 2022c). This percentage is adjusted each year by the DfT; in 2023 it was 13.078%.

Under the RTFO, obligated parties – i.e. fossil fuel suppliers[4] – buy Renewable Transport Fuel Certificates (RTFCs) from renewable fuel suppliers to fulfil their quota. Of course, it is quite possible that a given fossil fuel company will also be in the business of supplying renewable fuels, in which case that company can redeem its own RTFCs. RTFCs are awarded in proportion to the number of litres of compliant fuel supplied, and the market determines RTFC prices depending on the balance of availability and demand. Obligated parties also have the option of 'buying out', so that if there is a shortfall in RTFC availability in a given year, they can pay a set fee to the DfT to meet their RTFO obligations.

Aviation and maritime transport fuels are not obligated fuels under the policy, meaning that fossil fuel supplied to these sectors incurs no obligation to acquire or generate RTFCs. However, renewable fuels used in aircraft and 'renewable fuels of non-biological origin'[5] used in maritime applications have been eligible to generate RTFCs, which can then be traded with

[4] More specifically, companies that supply at least 450,000 litres of fuel per year for use in road transport, and in certain non-road applications such as mobile machinery and tractors.

[5] These include electrolytic hydrogen powered by renewable electricity, and fuels derived from this hydrogen – see Section 1.3.3.

fuel suppliers in the road and off-road sectors. The interchangeability of aviation and road RTFCs will cease once the SAF Mandate is enacted, so there will be no direct interaction between the two credit markets.

The second fuels policy relevant to aviation is CORSIA, the Carbon Offsetting and Reduction Scheme for International Aviation[6]. This is a global credit market managed by the International Civil Aviation Organisation (ICAO), designed to offset a certain quantity of CO_2 emissions from international flights. Under CORSIA, aeroplane operators[7] in participating countries must compensate for emissions above their 2019 baseline by buying carbon offsets, by investing in technological and operational efficiencies, or by using renewable fuels with lower lifecycle greenhouse gas emissions than fossil jet fuel.

CORSIA is voluntary for ICAO members until 2027, but the UK signed up to participate in its pilot phase from 2021 onwards. The SAF Mandate will run in parallel with CORSIA, meaning that producers of renewable aviation fuel may benefit from both systems, provided they meet the eligibility criteria.

Finally, the UK's Emissions Trading Scheme (UK ETS) is a cap-and-trade system modelled on the EU ETS. It covers airlines as well as companies involved in power generation and heavy industry: companies in these sectors must report their direct emissions, and buy emissions allowances on the ETS market. The total number of allowances available is capped at a level which decreases each year. Only domestic flights and flights to and from the European Economic Area (EEA) are included; other flights are exempt[8]. Airlines have historically been granted a number of free emissions allowances, but these are being phased out from 2026 onwards.

Airlines using alternative fuels on relevant flights can report lower emissions and hence reduce the burden of buying emissions allowances[9]. This gives extra policy value to alternative fuels in aviation, which is felt directly by airlines and passed through to alternative fuel producers. The SAF Mandate will run in parallel with the UK ETS, so fuel producers can stack the benefits of both to enhance project viability. A flip-side of this is that SAF Mandate support will reduce aviation's demand for UK ETS credits; if the cap is not adjusted, this will increase the number of credits available to other ETS sectors, lessening the pressure for them to decarbonise (this is dubbed the 'waterbed effect' (UK Department for Transport, 2024a)). It would be appropriate, therefore, for the UK Government to consider tightening UK ETS caps in response to the SAF Mandate.

1.1.4. Government support to industry

In 2022, the UK Government signalled a commitment to have at least five commercial-scale alternative jet fuel plants under construction by 2025 (UK Department for Transport, 2022a). A

[6] https://www.icao.int/environmental-protection/CORSIA/pages/default.aspx

[7] Cf. the RTFO and the SAF Mandate which applies to fuel suppliers.

[8] While the UK Government has agreed to include international shipping and aviation in the UK's carbon budget (UK Parliament, 2024), this does not necessarily mean inclusion in the UK ETS.

[9] Qualifying alternative fuels are automatically assigned zero greenhouse gas emissions. The UK ETS Authority has stated an intention to explore the use of the fuels' estimated lifecycle emissions instead (UK Parliament, 2024).

few measures have been put in place or proposed for stimulating investment in the aviation fuels space, but the feasibility of fully achieving the goal is at this point still to be determined.

Alternative fuel grant programmes in the UK started with the 2014 Advanced Biofuels Demonstration Competition[10], which allocated £25 million among three projects turning wastes and residues (including from whisky distilleries) into road fuels. Two of these projects appear to have been successful, and one has disappeared from view. Similar government initiatives have followed, focussed more specifically on aviation fuels: the Future Fuels for Flight and Freight Competition[11], launched in 2017; and the Green Fuels, Green Skies Competition[12], launched in 2021. Total funding earmarked for these two initiatives amounted to £37 million, spread between 15 projects[13]. Most recently in 2022, the Advanced Fuels Fund[14] (AFF) made £135 million available for grants to first-of-a-kind and demonstration plants aiming to produce alternative aviation fuels. The grants have now been awarded, over the course of two 'funding windows'; grantee projects are planning to build fuel production plants with capacities ranging from 2.7 to 179 kt/year[15].

Table 1 Recipients of funding through the UK Government's alternative fuels competitions

Government Programme	Grantee	DfT Grant (£ million)	Feedstock	Conversion Technology
Advanced Biofuels Demonstration Competition (2014)	Celtic Renewables	10.9	Whisky by-products	Fermentation
	Advanced Plasma Power	11.0	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Nova Pangaea	3.0	Forestry residues	Pyrolysis
Future Fuels for Flight and Freight Competition (2017)	Rika Biogas Technologies	5.1	Agricultural residues	Anaerobic digestion
	Johnson Matthey	0.2	Municipal solid waste	Gasification + Fischer-Tropsch synthesis

[10] https://www.gov.uk/government/speeches/advanced-biofuels-demonstration-competition-grant-award

[11] https://www.gov.uk/government/news/government-funding-boost-for-low-carbon-fuels-development

[12] https://www.ricardo.com/en/news-and-insights/campaigns/gfgs

[13] The Future Fuels for Flight and Freight Competition was to award grants in two phases: an initial £2 million round allowed companies to develop proposals for a £20 million capital investment round. Four projects were short-listed for the second round, and announcement of the grant amounts was scheduled for early 2019. However, it has not been possible to ascertain whether the full £20 million has been allocated.

[14] https://www.ricardo.com/en/news-and-insights/campaigns/aff

[15] https://www.gov.uk/government/publications/advanced-fuels-fund-competition-winners/advanced-fuels-fund-aff-competition-winners

Government Programme	Grantee	DfT Grant (£ million)	Feedstock	Conversion Technology
	Standard Gas	0.2	Refuse derived waste and woody residues	Pyrolysis
	Lanzatech	0.4	Industrial off-gas	Alcohol-to-jet
	Progressive Energy	0.2	Municipal solid waste and woody residues	Gasification + Fischer-Tropsch synthesis
	Kew Projects	1.8	Woody residues	Gasification + Fischer-Tropsch synthesis
	Velocys	0.4	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
Green Fuels, Green Skies Competition (2021)	Fulcrum	1.4	Refuse derived waste	Gasification + Fischer-Tropsch synthesis
	Advanced Biofuel Solutions	2.1	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Lanzatech	3.2	Agricultural waste and flue gas	Alcohol-to-jet
	Green Fuels Research	1.9	Sewage	Hydrothermal liquefaction
	Velocys	2.4	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Nova Pangaea Technologies	0.5	Woody residues	Pyrolysis and alcohol-to-jet
	Alfanar	2.4	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Lanzatech and Carbon Engineering	0.3	Industrial off-gas	Alcohol-to-jet
Advanced Fuels Fund (2022)	Abundia Biomass-to-Liquids	4.5	Forestry residues	Pyrolysis
	Alfanar Energy	19.7	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Arcadia e-Fuels	12.3	Biogenic CO_2	Power-to-liquid
	Carbon Neutral Fuels	1.4	Direct air capture CO_2	Power-to-liquid
	Esso Petroleum Company	6.1	Refuse derived waste	Alcohol-to-jet
	Nova Pangaea Technologies	9.1	Agricultural and wood waste	Pyrolysis and alcohol-to-jet
	OXCCU Tech	2.8	Biogenic CO_2	Power-to-liquid

Government Programme	Grantee	DfT Grant (£ million)	Feedstock	Conversion Technology
	Willis Sustainable Fuels	4.7	Point-source CO_2	Power-to-liquid
	Zero Petroleum	3.5	Direct air capture CO_2	Power-to-liquid
	Fulcrum BioEnergy	16.8	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Lanzatech	25.0	Industrial off-gas	Alcohol-to-jet
	Velocys	27.0	Municipal solid waste	Gasification + Fischer-Tropsch synthesis
	Velocys	2.5	Point-source CO_2	Power-to-liquid

Note: Grants awarded over multiple funding rounds to a single company have been summed.

Facilities for testing and certifying UK-produced aviation fuels have been established at the University of Sheffield's SAF Clearing House[16], with £12 million investment from DfT (UK Department for Transport, 2022a).

One further initiative under development by the DfT, in collaboration with industry through the Jet Zero Council[17], aims to strengthen the investment case for UK-based fuel production and may link directly to the SAF Mandate. The idea[18] is to establish a Government-backed minimum price guarantee on renewable jet fuel produced in the UK. Possible mechanisms include: (i) an obligation for the Government to buy SAF Mandate certificates at a guaranteed minimum price; and (ii) a contracts-for-difference system, where the Government pays (or is paid) the difference between the prevailing market price for alternative aviation fuel and a pre-determined price point. Although nothing has been decided at the time of writing, such guarantees would help to de-risk investments, and allow projects to secure loans on easier terms. Moreover, if credit prices are consistently high (above the floor price / contract for difference target price), there would be no need for the Government to make any pay-out. We will return to this in Section 5.

In parallel with fuels investment, the UK Government has publicised its support of the aerospace industry's R&D into novel technologies such as hydrogen- and battery-powered aeroplanes through its Aerospace Technology Institute (ATI) Programme. In 2022, it was announced that £685 million of Government money (over £1 billion with industry match) would be committed over a three-year period[19]. UK Research and Innovation's Future Flight

[16] https://www.safclearinghouse.uk/

[17] https://www.gov.uk/government/groups/jet-zero-council

[18] https://www.gov.uk/government/news/new-measures-to-support-sustainable-aviation-fuel-industry

[19] https://www.gov.uk/government/news/green-aerospace-tech-to-receive-record-government-funding

Challenge also encompasses elements of low-emission flying technology, with a government budget of £125 million[20].

1.1.5. This report

This report examines the UK government's proposed SAF Mandate targets from the perspective of industrial development, asking what the Mandate entails for the scale-up of alternative fuel production capacity in the UK. Various novel fuel production pathways are introduced in Section 1.3, and are characterised in terms of the required up-front investment in fuel production facilities and their expected cost per unit of fuel supplied to buyers in Section 2.3.

The additional fuels required by the SAF Mandate will have implications for resource demand. Feedstocks considered in this study are waste and residual lipids, ligno-cellulosic wastes and residues, and renewable electricity. The implied greenhouse gas emissions and emissions savings from alternative fuel use will be a key result of this study.

Five scenarios are presented, covering the period 2025-35. These are intended to illustrate how Government targets might be met through prioritisation of one fuel production technology over others and explore the wider ramifications of such choices. Together, the scenarios show that, irrespective of the technology pathway assumed, an exceptional level of ambition for industrial development will be needed to deliver on Government commitments.

1.2. The UK SAF Mandate

1.2.1. Mandate mechanism

A pillar of the JET Zero Strategy and the SAF Mandate is a blending quota for alternative fuels in the aviation fuel pool. The UK Government has committed that 10% of aviation fuel demand will be met by non-fossil alternatives by 2030: this is to be achieved through placing blending obligations on suppliers of jet fuel[21]. The obligated 'supplier' is in this case the entity that owns the fuel as it passes the fuel duty point: this means the point at which fuel leaves the warehouse or production facility for fuels produced in the UK, and the point of import otherwise[22] (UK Department for Transport, 2024a). The fuel may then be bought by and transferred to downstream users like airports and airlines. Suppliers which provide eligible alternative fuel will be rewarded with 'SAF certificates', issued in proportion to the number of litres of SAF supplied.

A novel feature proposed for the SAF Mandate is the use of an emissions-based weighting system, which adjusts the compliance value of a fuel batch depending on its reported lifecycle greenhouse gas emissions intensity (measured in gCO_2e/MJ). This can be seen as a compromise between a solely volume-denominated target (as is currently applied under the RTFO) and a greenhouse-gas-reduction denominated target (as in regulations such as

[20] https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/future-flight/

[21] Suppliers of fossil hydrogen and aviation gasoline ('avgas') are free from such obligations.

[22] This aligns with existing rules under the RTFO. Although jet fuel is not liable for energy tax, the duty point is still defined.

California's Low Carbon Fuel Standard, or in the UK's past implementation of Article 7 of the EU's 2009 Fuel Quality Directive (European Union, 2016)).

More precisely, supplying a litre of a given fuel may be counted as more or less than a one litre towards the blending target, depending on whether its reportable emissions reduction is higher or lower than a set baseline. The 2023 DfT consultation offered two options for the calculation – either using a continuous linear weighting function or banded classes (UK Department for Transport, 2023b). This has now been decided in favour of the former option, such that a given physical volume of fuel (measured in litres) will generate certificates based on the following formula:

$$\text{SAF certificates (l)} = \text{Physical volume (l)} \times \frac{\text{GHG emissions reduction (\%)}}{70\%} \tag{1}$$

where 'GHG emissions reduction' is calculated with respect to the fossil jet fuel carbon intensity, fixed at 89 gCO_2e/MJ[23]. Under these conditions, a litre of fuel delivering a 70% greenhouse gas reduction would generate one SAF certificate, while a litre delivering a 90% greenhouse gas reduction would generate 1.29 certificates.

Hence, in the context of the SAF Mandate, we can talk about a 'physical volume' or 'physical energy' content of a quantity of fuel, or about its 'regulatory volume' or 'regulatory energy'; regulatory quantities have been weighted with respect to their greenhouse gas emissions intensity following Equation (1). For the remainder of the report, whenever quantities of fuel are discussed we will make clear whether we are talking about physical or regulatory quantities.

1.2.2. Targets

The DfT anticipates the SAF Mandate coming into force in 2025; its consultation (UK Department for Transport, 2023b) presented three possible trajectories for the mandate level in the period to 2040, as shown in Figure 1. By 2030, the target is for 10% of aviation fuel to be classified as SAF; if this were to offer a (modest) 70% greenhouse gas emissions saving compared to an equal energy of fossil fuel, then all else being equal we would expect to see the emissions intensity of aviation reduced by 7%.

Progress towards the chosen target will be calculated as the regulatory volume – i.e. the number of SAF certificates issued – divided by the total fuel volume. This means that the same target could be satisfied with a lesser quantity of lower-emissions fuel, or a greater quantity of higher-emissions fuel. To be precise, 'lower' and 'higher' are relative to the baseline (i.e. a 70% saving, see Equation (1)). The actual volume of alternative fuel supplied may therefore not be exactly 10% of the total.

[23] This is the fossil jet carbon intensity adopted by ICAO (ICAO, 2021). Under the RTFO, the fossil fuel comparator is 94 gCO_2e/MJ (UK Department for Transport, 2021b).

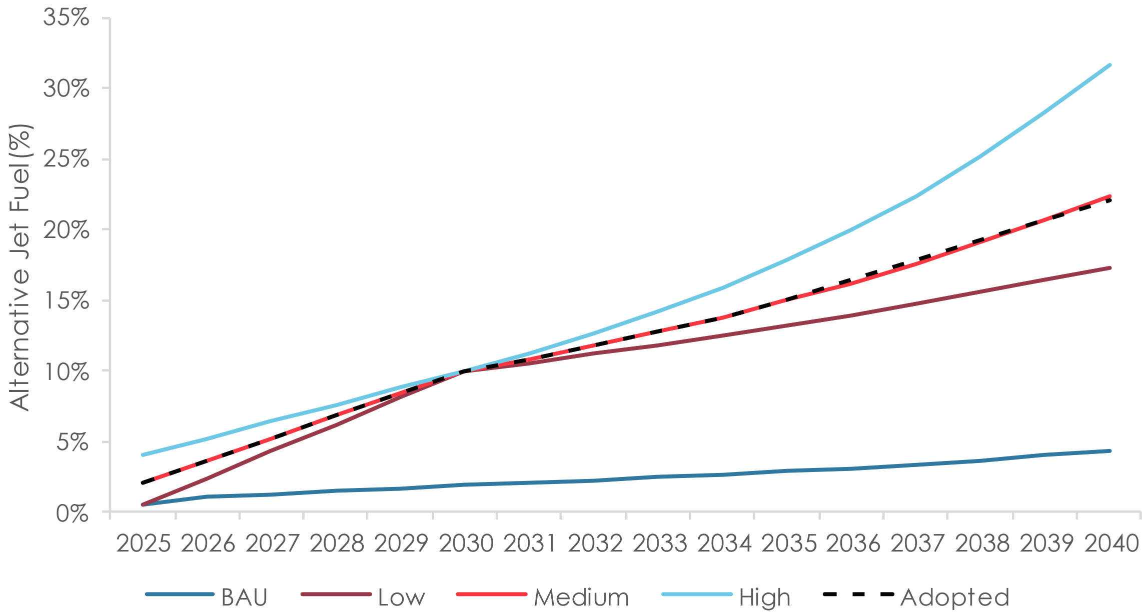


Figure 1 **Options for the main SAF Mandate target to 2040, indicating the adopted pathway**

Note: 'BAU' stands for 'business as usual'.

Following the DfT's projections for the UK's aviation fuel demand (UK Department for Transport, 2024b), the adopted percentage target is translated into implied volumes of fuel in Table 2 (for consistency with the rest of the report, we quote volumes of fuel in units of toe – see Section 2.4.1 on energy units).

Table 2 **Regulatory fuel volumes (in ktoe) required by the SAF Mandate options**

SAF Mandate Target	Unit	2025	2030	2035	2040
Low	%	0.5%	10.0%	13.2%	17.3%
	ktoe	57	1,238	1,683	2,297
Medium	%	2.0%	10.0%	15.0%	22.4%
	ktoe	230	1,238	1,912	2,965
High	%	4.0%	10.0%	17.8%	31.6%
	ktoe	460	1,238	2,274	4,194
Adopted	%	2.0%	10.0%	15.0%	22.0%
	ktoe	230	1,238	1,918	2,918

Note: The percentages in this table correspond to those in Figure 1. These are translated into regulatory fuel volumes using DfT's jet fuel demand projection. The corresponding physical fuel volume will depend on the greenhouse gas weighting factor (see Equation (1)).

A number of fuel technology pathways are under development, as outlined in Section 1.3 below. At present, the only commercially mature technology is the production of hydro-treated esters of fatty acids (HEFA). As will be discussed in greater detail below, concerns have been raised about the sustainability of HEFA production, inspiring the imposition of a cap on the use of HEFA towards the compliance with the Mandate. Figure 2 shows the maximum cap level suggested by DfT in the second consultation, and the cap which has now been adopted since then which is significantly higher. The official rationale for departing from the initial proposal invokes a number of factors (UK Department for Transport, 2024a), but this is likely to come as a disappointment to members of the environmental community which have argued for a complete exclusion of HEFA from the SAF Mandate on the grounds that, from an environmental perspective, the required feedstock resources would be better used in other sectors (e.g. UK Department for Transport, 2023b).

By design, the SAF Mandate target can be entirely met with HEFA for the first two years (2025-26), and mature HEFA pathways are expected to continue to dominate until 2035 when the HEFA cap would still comprise 52% of the overall target. Operationally, suppliers of HEFA will generate 'HEFA certificates' rather than the standard SAF certificates. These will be redeemable against the overall obligation as normal, but only up to a maximum limit calculated annually for each supplier on the basis of the volume of fossil and alternative fuel they bring to market (UK Department for Transport, 2023b). A fuel supplier will be allowed to redeem HEFA certificates in proportion to the amount of fuel they deliver.

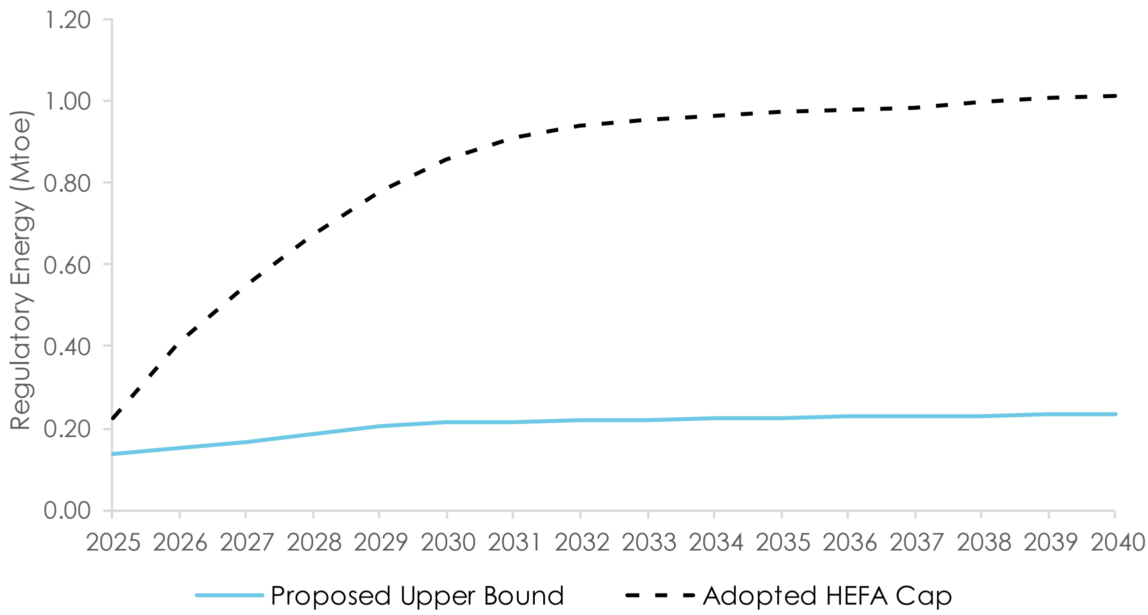


Figure 2 **Adopted HEFA cap, and the previously proposed upper bound, to 2040**

Note: The adopted HEFA cap is expressed as a percentage of supplied aviation fuel and has been translated into regulatory energy following DfT's projected jet fuel demand. The previously proposed cap was expressed as an absolute energy content of fuel; the regulatory and physical energies would be equal if HEFA has an average lifecycle greenhouse gas saving of 70%.

The main alternative to HEFA and other bio-based liquid jet fuels is 'power-to-liquid' (PtL) jet fuel, also referred to as electro-jet, e-jet, or RFNBO-jet[24]. A separate sub-target will be set to

[24] RFNBO stands for 'renewable fuels of non-biological origin', already mentioned in Section 1.1.3 in the context of the RTFO. Strictly speaking, RFNBOs could also include fuels produced using energy from

stimulate the production of PtL jet fuel; the consultation options and the adopted schedule are shown in Figure 3 (UK Department for Transport, 2023b, 2024a). Suppliers of PtL will be awarded 'PtL certificates', which count towards both the main SAF obligation and the PtL sub-mandate.

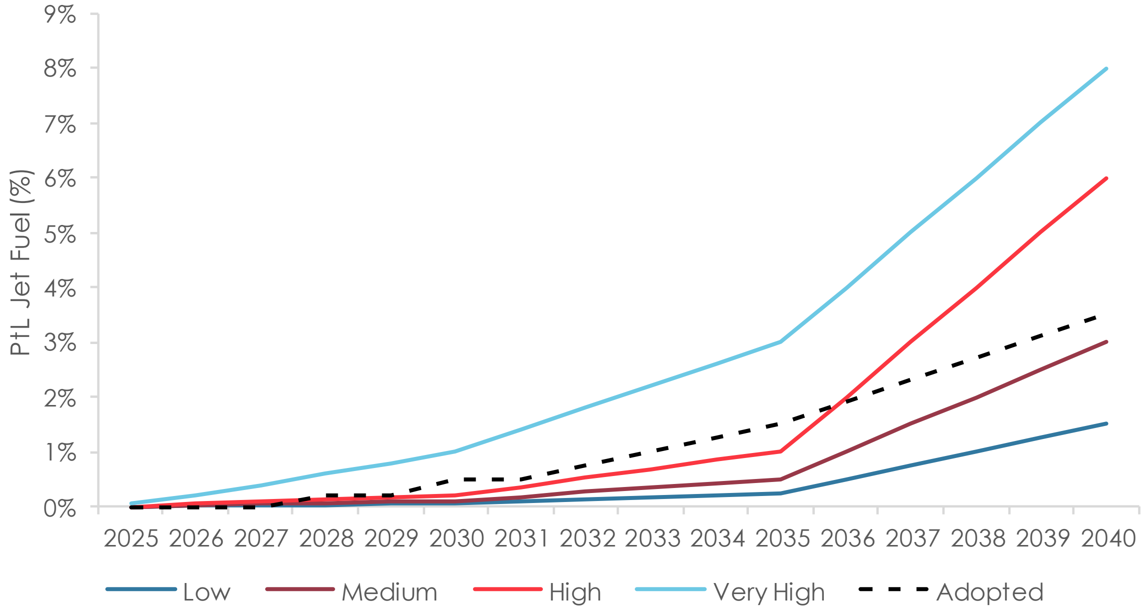


Figure 3 **Adopted PtL sub-target and consultation options, to 2040**

The implied regulatory volume of fuel required is shown in Table 3. As in Figure 1, we have assumed that future fuel demand follows DfT's projection (UK Department for Transport, 2024b).

Table 3 **Regulatory fuel volumes (in ktoe) required by the SAF Mandate's PtL sub-target**

PtL Sub-target Trajectory	Unit	2025	2030	2035	2040
Low	%	0.0%	0.1%	0.3%	1.5%
	ktoe	0	6	28	154
Medium	%	0.0%	0.1%	0.5%	3.0%
	ktoe	0	12	55	309
High	%	0.0%	0.2%	1.0%	6.0%
	ktoe	0	23	110	618
Very High	%	0.1%	1.0%	3.0%	8.0%
	ktoe	6	116	331	823
Adopted	**%**	**0.0%**	**0.5%**	**1.5%**	**3.5%**
	ktoe	**0**	**58**	**166**	**360**

Note: The percentages in this table correspond to those in Figure 3. These are translated into regulatory fuel volumes using DfT's jet fuel demand projection. The corresponding physical fuel volume will depend on the greenhouse gas weighting factor (see Equation (1)); for PtL, this factor is likely to be larger than 1,

heat or directly from sunlight, but in practice all commercial RFNBOs are expected to be PtL in the period to 2040.

in which case the physical volume of fuel supplied will be lower than the regulatory value in the table.

The aviation industry in the UK will likely wish to maximise its use of HEFA up to the cap, while simultaneously seeking to satisfy the PtL sub-mandate of Figure 3. The remainder of the obligation would have to be satisfied using other bio-based fuels, which we refer to as biomass-to-liquid (BtL) fuel – described more fully in Section 1.3.2. The balance between use of HEFA, PtL, and BtL will define the model scenarios used in the report; we discuss the scenario definitions in Section 3.4.

As a final note, the DfT has confirmed that excess certificates generated or gained by a fuel supplier in a given year can be used to fulfil up to 25% of their obligation in the following year (UK Department for Transport, 2024a). This applies to both the main target and the PtL target, and is consistent with the RTFO system. Similarly, a supplier's excess HEFA certificates can be carried over to fulfil up to 25% of the following year's HEFA cap.

1.2.3. SAF criteria

The technical standards body ASTM International has established certification standards for a number of alternative aviation fuels (Pavlenko & Searle, 2021), including fossil, biogenic, and other renewable feedstocks. Only ASTM-certified fuels will be eligible to count towards the SAF Mandate.

The first alternative fuel pathway to be approved in 2011 was lipid-based HEFA, for which production technology is already mature. Now the approved list includes synthetic kerosene made using other processes on lipid feedstocks, alcohol-to-jet (AtJ) processes, Fischer-Tropsch (FT) synthesis, and processes to produce iso-paraffins from sugars (SIP). At the time of writing, 11 production pathways had been approved, and a further seven (including pyrolysis) were under evaluation[25]. The resultant fuel can be blended with fossil jet fuel up to a specified limit depending on the technology used – the highest limit so far is 50%, which applies to HEFA, FT, and AtJ. The blend restriction is primarily due to the lack of aromatic molecules in the currently certified alternative fuels: aromatics are associated with increased air pollution and contrail formation, but existing jet engines and fuel delivery systems were designed to operate with a minimum 8% aromatic content. One consequence of the ASTM's blend limits is that no commercial flight running entirely on alternative fuel is possible at present[26].

In order to be eligible for the UK SAF Mandate, alternative aviation fuel[27] must satisfy a number of sustainability requirements. First, SAF must have a greenhouse gas emissions intensity score at least 40% below the standard fossil kerosene value of 89 gCO_2e/MJ; DfT have left open the possibility that the threshold may be strengthened over time (UK Department for Transport, 2024a). The threshold can be compared with the minimum 10% saving for CORSIA, 50% for the U.S. SAF Tax Credit (U.S. Internal Revenue Service, 2023), and 65% for the RTFO and the EU's

[25] https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

[26] In November 2023, it was announced that the first transatlantic flight using 100% bio-jet was achieved (see, e.g., this press release https://corporate.virginatlantic.com/gb/en/business-for-good/planet/fuel/flight100.html). This was a demonstration flight with no paying passengers, which was granted special permission to surpass the ASTM limit.

[27] Both avtur (jet fuel) and avgas (piston-engine fuel).

Renewable Energy Directive[28]. Lifecycle emissions for SAF Mandate fuels will be calculated according to the RTFO methodology; this means that fuel producers can use default parameters for listed fuels or provide their own values (with adequate justification), or a combination of both. At present, no default emissions values are provided for alternative aviation fuels in the relevant appendix (UK Department for Transport, 2023b). Values for hydrotreated vegetable oil (HVO), which is a bio-based replacement for road diesel, do appear, though, and comparable values for HEFA would be expected.

The RTFO allows a range of feedstocks, including crop feedstocks, whereas under the proposed definitions only residue-and-waste-based fuels will be eligible for the SAF Mandate[29]. Road HVO made from used cooking oil (UCO) and tallow is awarded relatively low lifecycle emissions of 16.0 and 21.6 gCO_2e/MJ respectively (an 82% and 76% reduction compared to the SAF Mandate comparator). This is largely because greenhouse gas emissions from the production of wastes and residues are assumed to be zero.

In the second SAF Mandate consultation (UK Department for Transport, 2023b), the DfT re-stated its commitment to following the RTFO's waste assessment framework[30], which is already associated with an extensive list of wastes and residues (UK Department for Transport, 2024c)[31]. The feedstocks eligible for use under the SAF Mandate will therefore be the same as those eligible to be double counted under the RTFO. New feedstocks are assessed for inclusion by DfT in response to industry applications, and the status of feedstocks currently on the list may be reviewed in light of developing evidence.

In 2022, 47.6 million litres (38.3 ktoe) of waste-and-residue-based HEFA were credited under the RTFO (no other aviation fuel types were supplied). Figure 4 shows the quantities of HEFA fuel originating from different source countries, along with the reported carbon intensities (UK Department for Transport, 2023c). The vast majority (99.6%) was made from UCO.

[28] These systems use a slightly different fossil fuel baseline, but the general conclusion is unaffected.

[29] DfT appears to be keeping its options open: "We will monitor developments in SAF technologies and feedstocks and keep under review broadening the list of eligible fuel types and feedstocks, for example, to include sustainable crops and cover crops" (UK Department for Transport, 2024a).

[30] The consultation document specifically notes that no change is proposed to this waste assessment framework and therefore there is no consultation question related to it.

[31] For reference, the equivalent list in EU legislation would be Annex IX of the Renewable Energy Directive (see European Union, 2018).

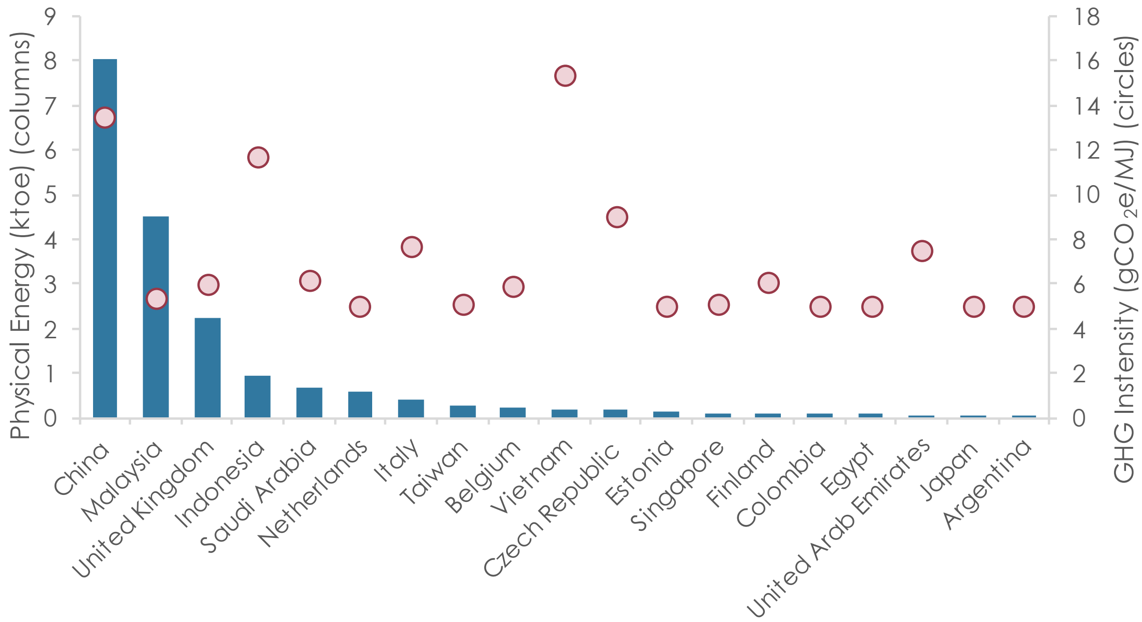


Figure 4 **Volumes (columns) and greenhouse gas intensities (circles) of alternative jet fuel reported under the RTFO in 2022, by feedstock source country**

Note: The fossil fuel comparator for fossil kerosene is 89 gCO$_2$e/MJ (off the scale of the graph). The top 19 countries by supply are included in the figure; a further 17 are not shown, but the combined volume from these is very low. The only aviation fuel supplied was HEFA. Volumes reported under the RTFO may be double-counted depending on feedstock, but here we show physical, single-counted energy.

1.2.4. Electricity and additionality

Electricity is the primary energetic input for the production of PtL jet fuel, and electrolytic hydrogen could in principle be used in bio-jet production too. The DfT has decided that the rules governing the use of electricity as source of fuel energy should follow those already laid down in the RTFO (UK Department for Transport, 2024a). Only the low-carbon share of the electricity – that is, the share from renewable power (excluding biomass) or nuclear power – is deemed eligible to count towards SAF Mandate targets. The carbon intensity of the renewable batch is then calculated based on the national grid average carbon intensity, unless the fuel production site: (i) uses electricity from a regional grid; or (ii) can demonstrate that it uses additional low-carbon electricity – renewable electricity capacity brought or kept online in order specifically to power the PtL facility. Under these circumstances, the percentage of low carbon electricity and the emissions intensity of the electricity may differ from the national grid values.

This means, for example, that if grid electricity which is 30% low-carbon is used to make 100 litres of PtL, then 30 litres of the resulting fuel would be treated as renewable and therefore be potentially eligible for the SAF Mandate. The carbon intensity of these 30 litres will be based on the grid average carbon intensity rather than that of the low-carbon sources, meaning that the batch would struggle to meet the 40% emission reduction threshold (see Section 1.2.3).

1.2.5. Buy-out

Fuel suppliers may comply with the SAF Mandate targets by blending eligible alternative fuels or by buying certificates from other suppliers who have already done so. If insufficient alternative fuels or certificates are available in a given year, there is a mechanism for the obligated parties to 'buy out' of their obligation by paying a fixed fee per missing certificate. The buy-out price, decided well in advance by DfT, effectively caps the cost of compliance with the SAF Mandate because if the cost of acquiring eligible alternative fuel exceeds this price, it is economically rational for suppliers to just buy out instead. It follows that when the supply of compliance options is tight relative to demand, one would expect the certificate price to rise closer to the buy-out level – in other words, for a stretching policy target the buy-out becomes an indicator of the cost that will be incurred by fuel suppliers[32]. Failure to comply through supplying alternative fuels, purchasing certificates, or buying out, will result in a punitive penalty.

The DfT proposed three options for the initial level of the buy-out price, denoted 'Low', 'Medium', and 'High' in Table 4[33] (UK Department for Transport, 2023b). Following this, revised estimates in the response to the second consultation showed that alternative fuels' future availability would likely be lower than previously expected, and their price higher; this led to the adoption of a buy-out price considerably higher than what was consulted upon (UK Department for Transport, 2024a). The buy-out price for PtL is larger than for other fuels, reflecting particularly high expected costs and the extra incentive needed to achieve the PtL sub-mandate. For the main obligation, the adopted buy-out price equates to a carbon abatement cost of 2,267 £/tCO_2e for a fuel delivering a 70% greenhouse gas saving (assuming that each physical unit of alternative fuel will displace one physical unit of fossil fuel).

[32] As a side note, stretching targets which result in sustained high credit prices will give investors more confidence in the viability of the next generation of fuel technologies. This is important for nudging the industry out of the first-generation rut that may otherwise persist.

[33] Note that this report's modelling results are expressed in units of tonnes of oil equivalent (toe) rather than tonnes of jet fuel: these differ by about 2%.

Table 4 **Proposed and adopted buy-out price options, per unit of regulatory volume and regulatory energy**

Option	Explanation	£/litre	£/toe
Main mandate			
Low	RTFO development fuel buyout price	1.60	1,992
Medium	Pessimistic production costs	2.00	2,490
High	Pessimistic production costs plus margin	3.00	3,735
Adopted	Stimulate investment given revised production costs	4.75	5,914
PtL mandate			
Low	Recommended option for main mandate	2.00	2,490
Medium	Pessimistic production costs	2.75	3,424
High	Pessimistic production costs plus margin	4.15	5,167
Adopted	Stimulate investment given revised production costs	5.00	6,226

The high buy-out price adopted by DfT sends a strong value signal compared with price caps in other systems, and will make the UK an attractive market for alternative fuels. Another major market for alternative fuel in the coming years will be the EU, where the 2023 ReFuelEU Aviation Regulation has already set targets for the use of alternative aviation fuels (European Union, 2023). Fuel suppliers which fail to comply must pay a "proportionate and dissuasive" penalty to be set by the Member State authorities, which should be at least twice the price difference between conventional and alternative fuel (Ibid., Article 12). This penalty is different from a buy-out in that it does not clear the deficit: any fuel shortfall in one year must be compensated in the following year (Ibid., Article 4.7). We shall present a quantitative comparison with the SAF Mandate buy-out in Section 5.3 of the Discussion.

We can also compare with value signals from national regulations currently in force (though for EU Member States, we can expect these to be updated to align with the ReFuelEU Aviation Regulation). In Germany, fuel suppliers failing to comply with the emissions reduction schedule must pay a penalty of 600 €/tCO_2e (Government of Germany, 2023, §37c (2)), which translates to about 0.5-1.0 €/l of alternative jet fuel. A penalty of 70 €/GJ is also levied on obligated jet fuel suppliers who miss the target for blending PtL; this translates to about 2.50 €/l, significantly less than the SAF Mandate's 5 £/l.

Sweden has also enacted greenhouse gas reduction targets, differentiated between petrol, diesel, and kerosene pools. Penalties for non-compliance are expressed in terms of SEK/kgCO_2e (Government of Sweden, 2021, §11), and equate to about 1.10 €/l for diesel, 1.20 €/l for petrol, and 1.50 €/l for kerosene. Data from the Swedish Energy Agency (Energimyndigheten, 2023) shows a substantial volume of jet fuel obligation is paid through penalties rather than alternative fuel deliveries: clearly this is the cheaper option.

Finally, in the UK's RTFO (Section 1.1.3), the buy-out price is currently set at 0.50 £ per physical litre for single-counted liquid fuels contributing to the main obligation, 1.00 £/l for double-counted fuels, and 1.60 £/l for fuels contributing to the 'development' sub-target (UK Department for Transport, 2023d, Section 3.18). Again, the value signal for the RTFO pales in comparison to the SAF Mandate, meaning that a greater diversity of fuels (i.e. fuels with greater production costs) can be supplied to the UK's aviation sector, and also that any SAF

Mandate-compliant fuels which are currently supplied to the road sector (i.e. residue-and-waste-based HVO/HEFA) are likely to be shifted to the aviation sector where they can command a higher price for the same level of emissions reduction.

DfT acknowledges that higher fuel prices could raise fares for aeroplane users, and that a shortage of compliant fuel may lead to extensive buy-out. DfT's final consultation response commits to reviewing and altering SAF Mandate parameters if there are "significant unexpected increases in … price, and potential buyout, … to ensure price rises do not happen, and consumers are not adversely affected" (UK Department for Transport, 2024a). This may include "broadening the list of eligible fuel types and feedstocks, for example, to include sustainable crops and cover crops", depending on developments in fuel technologies.

1.3. Alternative aviation fuels

Burning alternative jet fuel in aircraft engines instead of fossil fuel is intended to reduce the net greenhouse gas emissions of flying. For biofuels, combustion emissions are conventionally reported as zero due to the understanding that an equivalent amount of carbon dioxide was removed from the atmosphere when the feedstock was grown, and the expectation that an identical amount of carbon dioxide will be re-absorbed when the biogenic feedstock re-grows in future. When following this carbon accounting shortcut, emissions arise only from the production of feedstock, feedstock conversion into fuel, fuel processing, transport and distribution, and indirect effects such as feedstock displacement (Pavlenko & Searle, 2020) and indirect land-use change (ILUC).

In the case of PtL fuels, combustion emissions are assumed to be cancelled out by the upstream capture of carbon dioxide used in the fuel synthesis process. This capture may be either from the atmosphere or from point sources (and both are permitted under the SAF Mandate). PtL emissions are therefore comprised of emissions arising from electricity generation, hydrogen production, fuel synthesis, transport and distribution, and possible displacement effects of diverting electricity from other uses.

Each of the technology pathways for production of alternative aviation fuel can be categorised according to the feedstock used (e.g. lipids, biomass, electricity), the type of production process (e.g. chemical, bio-chemical, thermo-chemical), and the maturity of the technology (e.g. commercial, demonstration, pilot). Each of these pathways seeks to produce a synthetic replacement for conventional fossil fuel – one that mimics the key physical and chemical characteristics such as density, flash point, freezing point, heating value, and viscosity (Holladay et al., 2020). However, there are two important differences.

First, the concentration of complex hydrocarbons such as aromatics is naturally lower in current alternative fuels than in fossil jet (Shahriar & Khanal, 2022, Table 2). Pure alternative fuels generally consist of relatively simple paraffinic and iso-paraffinic (branched) hydrocarbons, whereas refined fossil jet fuel has an aromatics content between 8% and 22% by mass (Anuar et al., 2021). This has implications for the operation of aircraft engines and fuel systems built to specifications that assume the presence of aromatics with certain chemical and physical properties (Fantuzzi et al., 2023). It also has implications for non-CO_2 emissions, as soot formed from burning aromatics is associated with planet-warming contrail formation (Moore et al., 2017; Voigt et al., 2021)[34].

A second general difference between alternative and fossil aviation fuel is sulphur content. For bio- and electro-fuels, sulphur levels are close to zero, whereas in finished jet fuel it is allowed to be up to 3,000 parts per million. Blending alternative fuels may therefore help to reduce the overall sulphur content of blended jet fuel and thereby reduce air pollution (although alternative fuel blending could also facilitate the use of a dirtier fossil blendstock, such that the overall sulphur level is unchanged).

The remainder of this section covers the major production technologies considered in this study.

1.3.1. HEFA

As discussed in Section 1.2.2, HEFA stands for hydroprocessed esters and fatty acids. It is the aviation version of hydrotreated vegetable oil (HVO), otherwise known as renewable diesel. HEFA and HVO can be produced either in oil refineries through co-processing biogenic lipids with petroleum, or in dedicated stand-alone facilities[35]. It is currently the only commercially mature technology for alternative aviation fuel, and the UK already reports HEFA consumption under the RTFO (see Figure 4).

HEFA produced in dedicated facilities from 100% bio-oils has been approved by ASTM for blending up to 50% in jet fuel. There is also an approval for partially renewable fuel produced by co-processing of up to 5% bio-oils with fossil kerosene at oil refineries. Given the proposed SAF Mandate trajectories in Figure 1 and Figure 2, hitting this co-processing maximum could theoretically make a significant contribution to targets in early years of the Mandate; the DfT has projected that by 2030, 50 ktoe/year of co-processed HEFA could be available (UK Department for Transport, 2021a, Annex A). As for the second route, at present no dedicated HVO/HEFA facilities exist in the UK and none have been announced (Blanshard & Gibson, 2023, Section 5.2.3), so high-HEFA blends would have to use imported fuel.

HEFA is made from lipid feedstocks, meaning vegetable oils such as soy and sunflower oil, animal fats from the livestock industry, algal oil, and waste oils like used cooking oil[36]. Use of virgin vegetable oil is associated with higher direct and indirect greenhouse gas emissions (Pavlenko & Searle, 2021), and is not permitted under the SAF Mandate. At-scale algal oil production has yet to materialise, and algal oil is not expected to make a significant contribution for the foreseeable future. Use of feedstocks classed as wastes, such as UCO, is generally expected to have lower associated emissions (Hamelinck et al., 2021), but the resource is limited (O'Malley et al., 2021) and may have existing uses (Malins, 2017a; Malins & Sandford, 2022).

[34] Contrail reduction could also be achieved (possibly more cheaply) through targeted treatment of fossil jet fuel, by modifications to jet engines (Kelesidis et al., 2023), and/or by altering flight paths in real time to avoid contrail-forming regions.

[35] These are sometimes converted oil refineries.

[36] Indeed, 41.6% of renewable fuel volume reported under the RTFO in 2022 was UCO-based, including double-counting (UK Department for Transport, 2023c).

The high value of lipids in other applications means that HEFA tends to have higher feedstock costs than other alternative fuels (Pavlenko et al., 2019). There are also concerns that the risk of fraudulent mis-labelling of virgin vegetable oils as wastes has not been adequately addressed by current supply chain monitoring systems (European Court of Auditors, 2023; Suzan, 2023).

1.3.2. Biomass to liquid

Biomass to liquid (BtL) encompasses a range of methods for producing drop-in hydrocarbons from (relatively) low-value cellulosic and ligno-cellulosic feedstocks (Maniatis et al., 2017). Here we focus on three representative technologies: gasification with Fischer-Tropsch synthesis, pyrolysis with catalytic upgrading, and alcohol to jet (AtJ).

Gasification with Fischer-Tropsch synthesis is a thermo-chemical BtL pathway. Biomass is gasified by subjecting it to high temperatures, whereupon it gives off 'syngas' – a mix of hydrogen, carbon monoxide, and carbon dioxide (Landälv et al., 2018). The natural ratio of hydrogen to carbon atoms in biomass feedstocks is lower than is needed to synthesise liquid hydrocarbons, and so it is tuned using a 'water-gas shift' reaction, or through the addition of hydrogen from an external source. After this, the Fischer-Tropsch synthesis step converts the gas into a range of hydrocarbons (Yugo & Soler, 2019, Figure 2). Of the three BtL technologies discussed here, gasification is considered the least sensitive to the feedstock type, meaning that inhomogeneous, 'dirty' feedstocks like municipal solid waste (MSW) can potentially be used.

Pyrolysis refers to heating of biomass (to around 500 °C) in the absence of oxygen to produce a liquid mixture of organic compounds called 'pyrolysis oil', along with solid biochar. There are a number of uses for pyrolysis oil, one of which is as a feedstock for hydrocarbon synthesis through the catalysed addition of hydrogen (to remove impurities and oxygen content). An advantage of pyrolysis over gasification is that the pyrolysis oil production facilities can be smaller (potentially feeding a centralised oil-upgrading location), which reduces the up-front cost and the required catchment area for feedstock.

The third BtL technology is alcohol-to-jet, a biochemical pathway[37]. Common alcohols include methanol, ethanol, and butanol, made through microbial fermentation of sugar and starch (in the case of first-generation crop-based biofuel) or of hydrolysed cellulose (in the case of second-generation biomass-based biofuel)[38]. Alcohols may be chemically 'oligomerised' into hydrocarbons, of which the jet fuel fraction can be as high as 70% (van Dyk & Saddler, 2021). The AtJ plants that we consider in this study are modelled using cellulosic feedstocks, as crop-based fuel is not eligible under the existing SAF Mandate proposals (there are signs that corn-derived ethanol-to-jet fuel will be more readily accepted in the USA[39]).The biological agent is more sensitive to the feedstock profile than the thermo-chemical technologies are – for

[37] Thermo-chemical AtJ production methods also exist, but we do not consider these here.

[38] Alcohols can also be produced from energy-rich waste industrial gases, using modified bacteria. We do not consider these fuels here.

[39] https://www.bloomberg.com/news/articles/2023-09-26/sustainable-aviation-fuel-a-lifeline-for-america-s-corn-farmers#xj4y7vzkg

instance, the lignin content and the balance of sugars will affect the performance of the agent.

Other technologies exist – for instance, hydrothermal liquefaction, aqueous phase reforming, and fermentation of non-alcohol platform molecules – but for the purposes of this study we model the industrial development of only the three introduced above.

1.3.3. Power to liquid

Power to liquid (PtL) is also known as electro-fuel, e-fuel, or RFNBO. Electricity – more specifically for the SAF Mandate, low carbon electricity – is used to split water into hydrogen and oxygen. Some of the hydrogen is reacted with carbon dioxide captured from the atmosphere or from a concentrated point source to produce carbon monoxide, which can be reacted together with the remaining hydrogen in a Fischer-Tropsch process. The resulting hydrocarbons are upgraded to meet the required characteristics of jet fuel and road fuels – an FT synthesis process will produce a range of molecules only some of which are suitable for aviation fuel use. The process has an energy conversion efficiency from electricity to liquid fuel of about 50%; this efficiency should improve over time, for example by transitioning from low-temperature to high-temperature electrolysers (Malins, 2017b).

Operating costs for PtL facilities will be dominated by the cost of electricity for electrolysis (to produce hydrogen) and the capital costs to construct the facility. A review found that the first factor may constitute 40-50% of the total (Malins, 2017b); but how costs stack up in practice will be sensitive to a number of developments outside the transport sector: the price of electricity, the evolving mix of grid generation sources, and/or on the ease of establishing additional low-carbon electricity generation (see Section 1.2.4). The wide range of applications foreseen for green hydrogen – from fuel production to chemical synthesis to steel-making – has galvanised policy efforts to facilitate investment. For instance, the U.S.'s Energy Earthshot aims to reduce the cost of using low-carbon hydrogen to 1 $/kg by 2030[40] (the $ 1 figure is implicitly bundled with government support and so does not reflect the actual production cost). In Europe, the EU's Fuel Cells and Hydrogen Joint undertaking is expected to bring EU-backed investments of over €1.3 bn in the period 2014-24 (Erbach & Jensen, 2021); while the 2020 Hydrogen Strategy foresaw 6 GW of green hydrogen capacity in 2024 increasing to 40 GW in 2030 (European Commission, 2020b), with a quarter of renewable electricity being used for hydrogen production in 2050. It remains to be seen whether an expanding base of supply sources will be capable of keeping up with rapidly diversifying demand in the decades to come; and if not, what impact this will have on hydrogen prices.

Another cost for PtL is carbon dioxide. This cost is expected to be smaller than electricity and capital but can nevertheless vary considerably depending on whether the carbon dioxide comes from a concentrated point source (e.g. a power station, incinerator, or a cement kiln), or is drawn from the atmosphere (direct air capture, DAC). Collecting waste CO_2 from concentrated sources is easier and more energy efficient; but there are concerns that reliance on point source CO_2 may run into scalability issues as economy-wide decarbonisation leads to a dwindling supply of concentrated CO_2 streams in the long term.

[40] The cost is currently 3-6 $/kg, compared with 1.5-2 $/kg for fossil-derived hydrogen (European Commission, 2020b).

The second potential source of carbon is DAC. For practical purposes, the atmosphere has an unlimited supply of carbon dioxide, but extracting and purifying it is expensive. A recent study (World Economic Forum, 2021a) suggests a cost of around 220 $/t$CO_2$ in 2030, at least double the cost of point-source carbon. DAC cost estimates in the range 100-300 $/t$CO_2$ are prevalent in the literature, but concerns have been raised that these rely on overly optimistic assumptions – in particular, on the aggressive rollout of renewable electricity generation going hand-in-hand with steep falls in the cost of electricity[41]. Most projections for the cost of industrial electricity assume moderate increases in the medium term, not significant reductions. Besides, a very particular set of economic conditions would be necessary to stimulate large investment in the power sector while the simultaneously ensuring that returns from electricity sales fall sharply. A more plausible price-point for DAC CO_2 in 2030 might be around $600-1000 $ per net tonne of CO_2 captured (Herzog, 2022).

The availability of DAC-CO_2 is another issue: while the theoretical potential is almost unlimited, in 2021 there were 18-19 operational plants globally, with combined capacity of only around 8 ktCO_2/year (International Energy Agency, 2022; Ozkan et al., 2022). For the UK to meet a 1% PtL mandate by 2030, it would require around 700 ktCO_2 per year (Fantuzzi et al., 2023)[42]. In order to accelerate technology development, in 2022 the UK's inter-departmental 'direct air capture and greenhouse gas removal programme' announced disbursal of £60 million towards 15 projects[43], many of which are developing DAC technology and use cases (though none intend to directly produce liquid fuel for transport). It remains to be seen what effect this will have on DAC rollout in the UK.

DfT's first SAF Mandate consultation (UK Department for Transport, 2021a) implied that both DAC carbon dioxide and biogenic carbon dioxide captured from point sources and would be eligible for use in PtL jet fuel (provided that the point source that had not been deliberately created for fuel production). The second consultation considered only DAC-enabled PtL pathways in its impact assessment (UK Department for Transport, 2023e), but the final Government publication explicitly left the door open to point source carbon dioxide – both from biogenic and from fossil sources (UK Department for Transport, 2024a). It is worth noting that carbon capture and utilisation (CCU) activities such as PtL will come into competition with carbon capture and sequestration (CCS), which will increase the price of captured carbon. It is also worth noting that as a carbon abatement strategy, capturing carbon to produce low-lifecycle-emissions PtL fuels is inefficient compared with simply using fossil fuels in conjunction with CCS (Malins, 2017b). A comparison in the academic literature concluded that decarbonising a given flight with DAC+PtL (using zero-carbon electricity) required 2.25 times more energy than offsetting the flight emissions with DAC+CCS (Gray et al., 2024). Based on their results, the emissions abatement cost for substituting fossil jet fuel with PtL would be 370-3,120 €/tCO_2e, while for CCS it was 160-1,300 €/tCO_2e.

[41] Studies have been known to assume that electricity costs follow the levelised production cost of renewable electricity, rather than the expected grid sale price.

[42] The cited study estimates 83-104 MtCO_2 would be required to meet 100% of the UK's demand with PtL jet fuel; assuming a greenhouse gas emissions reduction of 90% (meaning each litre of PtL fuel earns 1.28 litres of certificates), satisfying a 1% PtL sub-mandate would require 0.65-0.81 MtCO_2 in 2030.

[43] https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition

1.3.4. Energy and feedstock consumption

Table 5 re-caps the fuels considered in this study and shows the standard colour assignments that will be used in charts throughout this report.

Table 5 Key to fuel technology pathway names and the standard colours used in this report

Short Name	Longer Name	Colour Code
AtJ	Alcohol-to-jet	
Gasification	Gasification with Fischer-Tropsch synthesis	
Pyrolysis	Fast pyrolysis with catalytic upgrading	
HEFA	Hydro-processed esters of fatty acids	
PtL	Power-to-liquid via Fischer-Tropsch synthesis	

Note: Biomass-to-liquid or BtL jet fuel encompasses the first three technology pathways.

The efficiency of a fuel-producing process can be thought of in terms of its yield from a given quantity of feedstock, its energy conversion efficiency, and/or the specific output of target molecules (here, molecules in the jet kerosene range) versus other less valuable products.

Table 6 characterises the processes using illustrative results from the literature. The first two – feedstock yield and energy efficiency – consider all biorefinery products including jet fuel, distillates, naphtha, and lighter hydrocarbons (Shahriar & Khanal, 2022), while the final column gives the maximum percentage (by energy) of the final product that is jet fuel (Pavlenko et al., 2019).

Table 6 Yields from common SAF production pathways

SAF Production Pathway	Mass Yield ($t_{total\ fuel}/t_{feedstock}$)	Energy Efficiency ($GJ_{fuel\ output}/GJ_{input}$)	Maximum Specificity ($GJ_{jet\ fuel}/GJ_{total\ fuel}$)
HEFA	0.75–0.83	0.71–0.77	0.55
Gasification	0.13–0.22	0.91	0.50
AtJ	0.56	0.40–0.53	0.74

Note: Following the original source (Shahriar & Khanal, 2022), the feedstock yield and energy efficiency values incorporate all liquid fuel fractions resulting from the process in question. The energy efficiency denominator includes energy input from external sources such as hydrogen and natural gas. PtL relies on Fischer-Tropsch synthesis and so its aviation fuel specificity is expected to be similar to the value for gasification.

1.3.5. Hydrogen consumption

Besides the biomass feedstock requirement for biofuels, another key input is hydrogen[44] – this is used, for example, in the cracking of Fischer-Tropsch waxes and in the deoxygenation of pyrolysis oil. The DfT's second SAF Mandate consultation (UK Department for Transport, 2023b) distinguishes two categories of hydrogen use: as a 'feedstock'; or as a 'process input'. When hydrogen is used as a feedstock, it adds to the final energy content of the fuel – for example, in the refinery process of hydrocracking which increase the ratio of hydrogen to carbon atoms in the finished fuel. When hydrogen is used as a process input, its role is typically to remove impurities (for example by reacting with atoms of sulphur and oxygen in the refinery feed to form hydrogen sulphide and water). To be eligible for the SAF Mandate, the consultation proposes that hydrogen used as a feedstock should be from 'low-carbon' sources, whereas process input hydrogen can be from any source (provided of course that the final fuel meets the greenhouse gas reduction threshold). We note that currently RTFO rules define HVO as 100% renewable even if fossil hydrogen is used, and therefore if the rules for HEFA supplied under the UK SAF Mandate require low-carbon hydrogen this could imply an inconsistency in treatment between the different transport modes.

Low-carbon hydrogen includes "renewable or nuclear electrolytic hydrogen, [and] biohydrogen from wastes or residues" (UK Department for Transport, 2023b)[45]. The vast majority of hydrogen produced today comes from reformation of fossil natural gas (with a smaller contribution from gasification of coal). Using compliant biomethane instead of fossil methane may reduce net emissions from combustion, though whatever the source of methane, leaks along the supply chain can easily negate the greenhouse gas savings from using biofuel[46]. For some BtL plant configurations, hydrogen may be generated on-site through gasification of some portion of the fuel feedstock. This adds to the complexity of the plant, and significantly increases feedstock consumption (with knock-on effects for sourcing, transport and handling); but on the other hand, there may be greenhouse gas and cost advantages from using biomass as the hydrogen source. Production of hydrogen from electrolysis has already been discussed in Section 1.3.3.

Refining of fossil petroleum also requires hydrogen for hydrotreating, and at some refineries, hydrocracking. This has traditionally come from on-site reforming of fossil methane or refinery off-gases. The precise level of hydrogen consumption per unit of fuel depends on the refinery complexity and configuration, as well as the quality of the crude oil input (with 'light' and 'sweet' crudes requiring less hydrogen than 'heavy' and 'sour' crudes). A sampling study performed by the Argonne National Laboratory (Elgowainy et al., 2020) suggests that in the U.S., a value of 5-10 kgH_2 per tonne of crude oil would be representative of common setups (Elgowainy et al., 2020). The hydrogen intensity of finished fuel will be higher than this if petroleum co-products like bitumen, waxes, and refinery off-gases are allocated a lower share of the total hydrogen consumption. On the other hand, European refineries tend to process lighter, sweeter crude, and hence be lower complexity, than U.S. refineries (MathPro, 2011). Given the lower stringency on sulphur content, fossil jet will consume less of the total hydrogen

[44] For PtL fuels, all the hydrogen needed is produced through electrolysis.

[45] Hydrogen produced from recycled carbon fuels (RCFs) is also eligible, but we do not consider RCFs in this report.

[46] This interactive web-tool allows users to explore the climate impacts of different hydrogen production technologies and configurations, and includes methane leakage rates as a primary input: https://www.catf.us/hydrogen-lifecycle-analysis-tool/.

input than road-sector distillates. Taken together, the hydrogen intensity a gasification or AtJ pathway (Hannula, 2016, Table 7; Park et al., 2022) will very likely consume more hydrogen per unit than fossil jet fuel production. HEFA may consume twice the hydrogen of gasification/AtJ (Maniatis et al., 2017; World Economic Forum, 2021b), and pyrolysis four times this (Elgowainy et al., 2012). It is therefore safe to conclude that substituting fossil jet fuel with bio-jet will entail higher hydrogen demand.

1.3.6. Carbon capture and storage

Finally, some fuel production processes are associated with significant on-site CO_2 emissions, for example CO_2 from fermentation in AtJ processes. In principle this CO_2 can be captured and permanently sequestered in a process called 'carbon capture and sequestration' (CCS). If implemented and appropriately verified, this allows fuel producers to register a lower lifecycle emissions score. However, we do not consider CCS in this report.

1.4. Fuel production

1.4.1. Historical global trends

Current production of alternative aviation fuel is modest, serving less than 0.1% of total global demand in 2022, as shown in Figure 5 (Owens Thomsen et al., 2023). This was predominantly HEFA. In 2025, the UK SAF Mandate will require volumes of alternative fuel comparable to 2022's global production; by 2035, this requirement will grow by an order of magnitude.

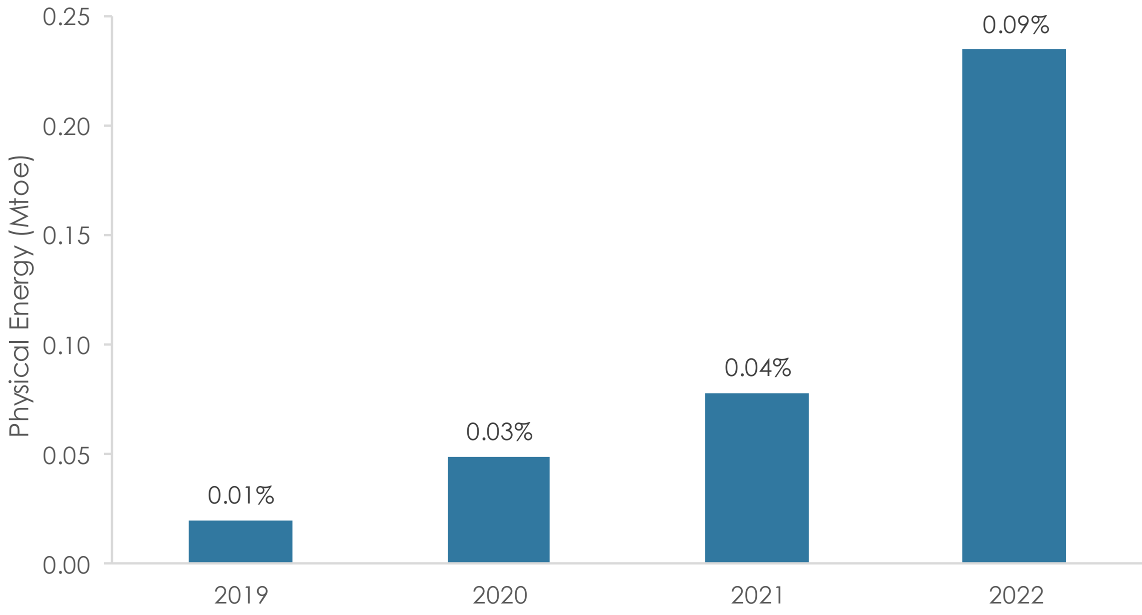


Figure 5 **Historical global production of alternative aviation fuel (in physical energy units), indicating percentage of global demand**

1.4.2. UK fuel production

DfT's final cost-benefit analysis features estimates of the growth in UK fuel production (UK Department for Transport, 2024b). These have been developed based on assumed success rates for Advanced Fuels Fund (AFF) projects, and capacity growth of 15% per year for HEFA and BtL, and 21% per year for PtL. The results can be compared against the fuel volumes required by the SAF Mandate, as well as the modelling results presented below.

For HEFA, DfT's estimate (characterised as a maximum) predicts high levels of fuel imports until the late 2030s. Figure 6 shows DfT's anticipated UK production of HEFA fuel, using both domestic and imported lipid feedstock. Figure 7 complements this by showing DfT's estimates for the availability of domestic lipid feedstocks for fuel production (HVO plus HEFA). The main thing we can take from the figure is that even in the late 2030s when domestic HEFA production is projected to overtake demand, the UK will still have to import a significant portion of the feedstock – especially if there is also still a strong market for road-sector HVO.

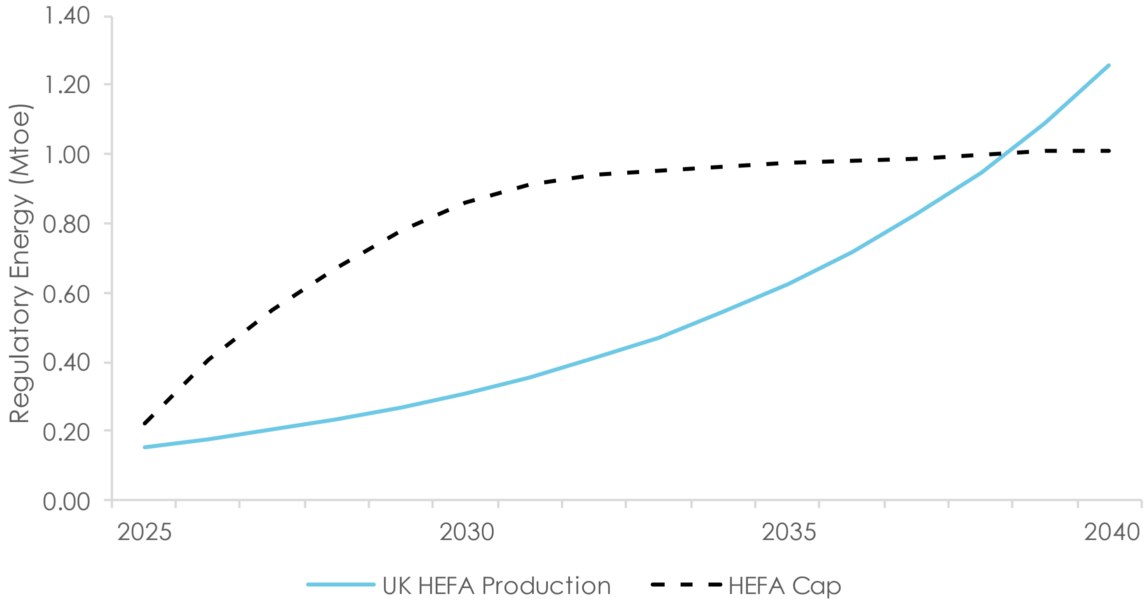


Figure 6 **Predicted domestic HEFA production compared with the SAF Mandate's HEFA Cap**

Note: Targets and caps are set in terms of regulatory energies, while estimated production volumes from DfT's cost-benefit analysis are physical energies. In order to present them on the same graph, we have assumed a 70% lifecycle greenhouse gas emissions saving from HEFA.

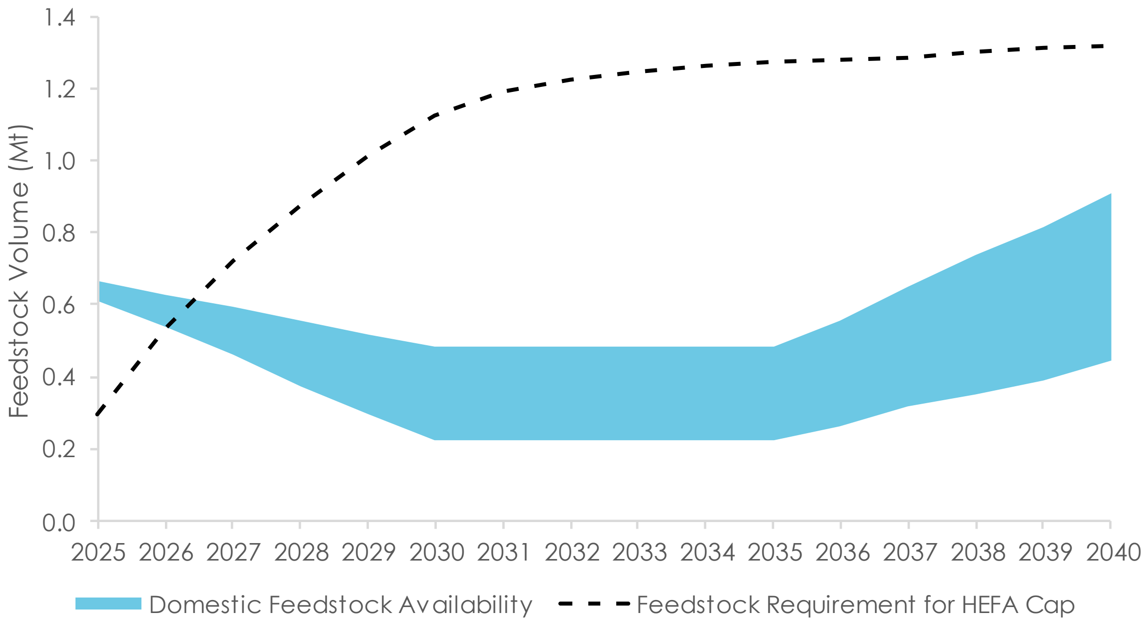


Figure 7 **Predicted availability of UK lipid feedstocks for HVO & HEFA production, compared with estimated feedstock demand under the HEFA cap**

Note: Feedstock availability encompasses compliant lipids used for HVO and HEFA. The feedstock requirement shows the volume of lipids that would be needed to meet the SAF Mandate's HEFA cap, assuming a standard fuel conversion efficiency.

For PtL, DfT considers indicative scenarios where 25% ('Low') or 50% ('High') of AFF capacity comes online. The adopted PtL target starts out consistent with Low and then rises to the approximate level of High – see Figure 8. Under the High scenario the UK would be a net exporter of PtL jet fuel, whereas under the Low scenario it would need to import about half of the PtL required to fulfil the target.

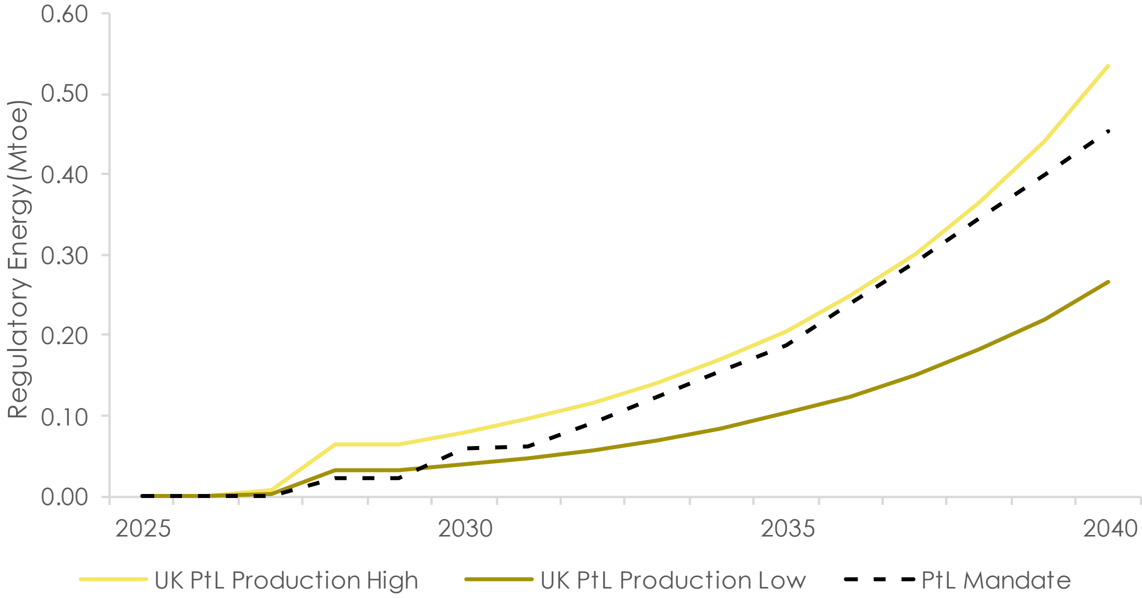


Figure 8 **Predicted domestic fuel production compared with SAF Mandate targets; left: HEFA; right: PtL High and Low scenarios**

Note: See the note under Figure 6. We have assumed a 95% lifecycle greenhouse gas emissions saving for PtL.

Putting the above together with DfT's projections for BtL, we see in Figure 9 that according to the DfT's scenarios, approximately 50-70% of the SAF Mandate target could be satisfied with domestic fuel production in 2035, and the remainder would have to be either imported or bought out. By 2040, only the 'High' scenario approaches fulfilment of the Mandate with domestic production. We shall use this as a benchmark for developing our fuel deployment scenarios in Section 3.5.2.

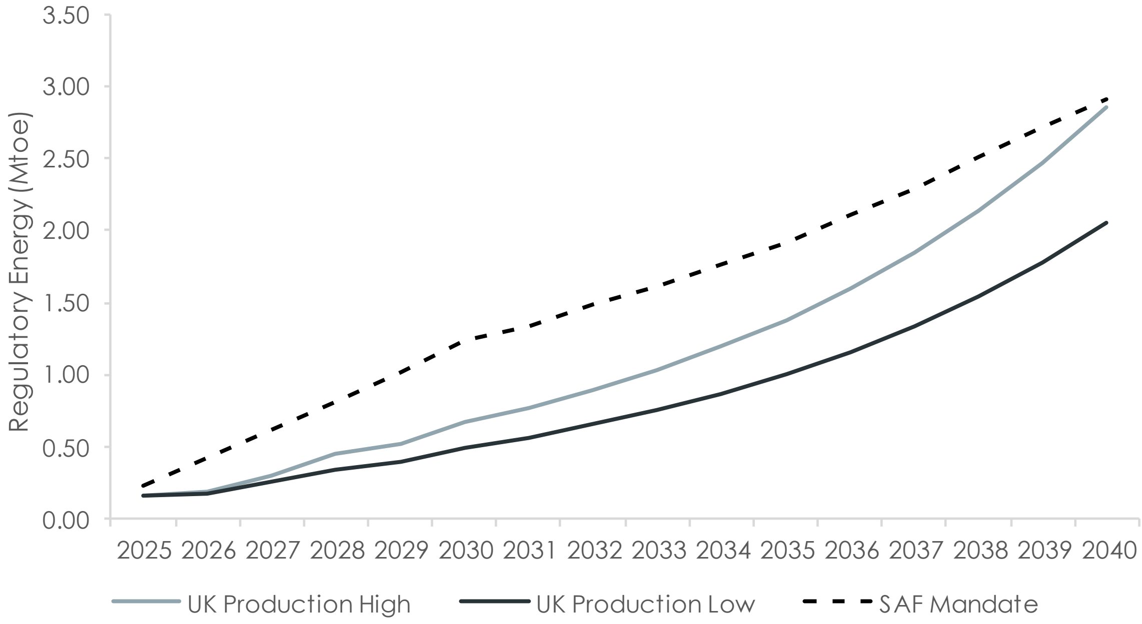


Figure 9 **Predicted domestic fuel production compared with the overall SAF Mandate target, High and Low scenarios**

Note: See the note for Figure 6. For the purposes of this graph, we have assumed BtL jet fuels offer an 80% reduction in lifecycle greenhouse gas emissions.

1.4.3. EU comparison

The EU provides a point of comparison for both SAF Mandate targets and projected rates of plant construction. Figure 10, which is based on the ReFuelEU Aviation report for the European Commission (Giannelos et al., 2021), shows a developing share of fuels consumed to 2050.

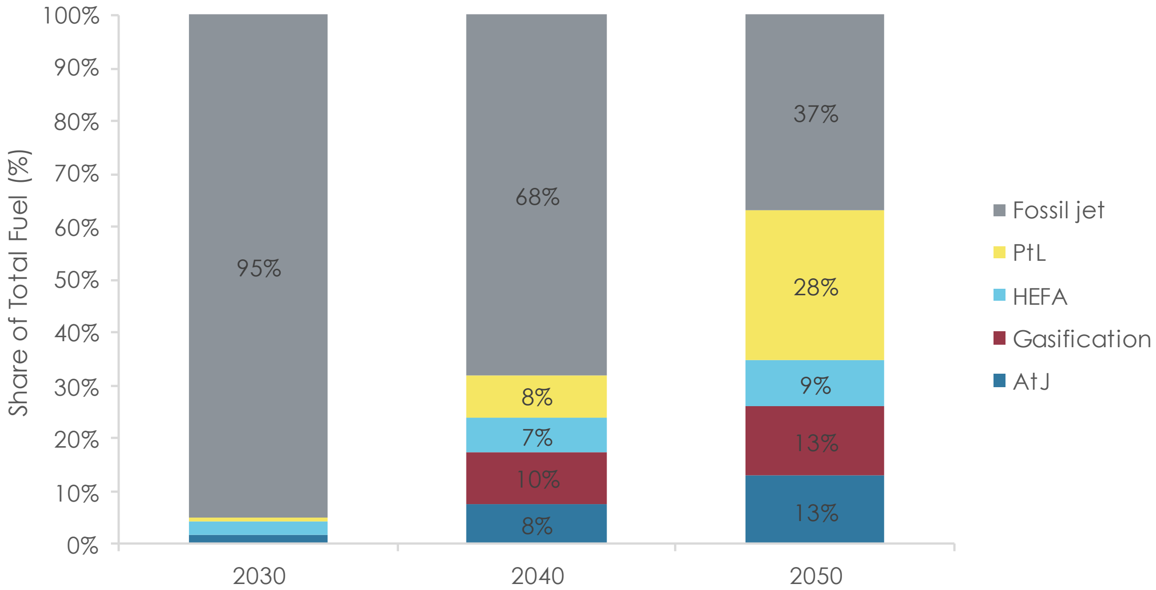


Figure 10 Predicted share of EU aviation fuel from different technology pathways

Given the 32% alternative fuel fraction for the EU in 2040, the overall trajectory in Figure 10 may be compared to the 'High' scenario in the UK's SAF Mandate consultation (see Figure 1 and Table 2). In percentage terms, the overall target that was actually adopted by DfT is slightly more ambitious in early years and less ambitious in later years (cf. Figure 1); its HEFA cap is comparable (cf. Figure 2); and the PtL mandate is about half as high (cf. Figure 3).

It would be an understatement to say that Figure 10 implies a rapid rate of technology and industrial development – 58 new commercial-scale plants by 2040 (Giannelos et al., 2021). It has been argued that this is an underestimate, as it was published before the final target was adopted, it assumes uniform capacities without taking into account the smaller size of early-generation plants, and it doesn't cover imported fuel. A revised estimate found that over 80 new plants would be needed in 2040 for the EU + UK (Malins, 2023). At the time of writing, 25 commercial-scale projects have been announced globally just for production of PtL jet fuel, but none of these have yet been given the final go-ahead and some are still in early stages of planning (Mutrelle, 2024).

1.4.4. Challenges in plant construction

In practice, there are many stages between the first decision to build any large-scale industrial facility and the finished facility reaching its name-plate production capacity: iterations of engineering design and siting, permissions, construction, infrastructure integration, testing and commissioning, and finally a ramp-up of production to a commercial operating state (Miller et al., 2013). Advanced fuel production is no different, and historically it has taken years and sometimes more than one operator to get plants up and running. Few have reached production targets; many have closed[47]. Thus there is justification for caution when assessing claims of rapid scale-up of the alternative aviation fuel industry.

[47] Taking cellulosic ethanol as an illustrative example, persistent technical and financial issues continue to hinder development (Padella et al., 2019; Pavlenko, 2018). Plants have experienced delays in construction and ramp-up, changes in management, idling, or closure.

2. Model Description

The model used in this study is a 'bottom-up' model, which models the construction of fuel-producing plants as each technology matures, and aggregates their output into the fuel pool. The fundamental modelling question posed here is 'What industrial development trajectory would be necessary in order to reasonably achieve SAF Mandate policy targets?'. This modelling question is answered by adjusting model parameters and constraints, as described below, to achieve the desired outcome in terms of produced volumes.

2.1. Advanced fuels deployment

2.1.1. Fuel production

The core purpose of the model is to project the development of fuel production capacity for the technologies introduced above (with BtL disaggregated into AtJ, gasification with Fischer-Tropsch synthesis, and pyrolysis with catalytic upgrading). This is framed as a growing fleet of fuel production plants, spanning four 'generations' with different nameplate capacities. The modelling framework we use builds on previous Cerulogy work for Transport and Environment (Malins, 2021); this was in turn based on a model developed by E4Tech (Sustainable Aviation, 2020).

Each modelled fuel technology is characterised by a build rate (i.e. the number of plants successfully built per year, for each generation), typical plant size (output toe per year, for each generation) and the date at which the first plant comes into operation. We assume that HEFA is already available at volume (see below), and that the other technologies' first plants become operational in 2027 to coincide with the first year in which the SAF Mandate target exceeds the HEFA cap.

From 2027 onwards, BtL and PtL technologies go through a sequence of 'generations': 1, 2, 'N', and 'N+1'. The rate of progression is parameterised in the model, and depends on the time elapsed in the current generation as well as the number of plants that have been built. Build rates are slower and typical plant sizes smaller in early generations. Table 7 shows the average plant size we assume for each generation of plants; the generation N nameplate capacities are aligned with modelling by E4Tech (Sustainable Aviation, 2020).

Table 7 Average plant capacity used in the model, by fuel production technology and generation, expressed in thousand toe per year and million litres per year

Fuel	Plant Capacity (ktoe/year)				Plant Capacity (Ml/year)			
	1	2	N	N+1	1	2	N	N+1
AtJ	70	92	140	210	56	74	112	169
Gasification	43	57	86	129	35	46	69	104
Pyrolysis	32	42	64	95	26	34	51	77
HEFA	171	226	343	514	138	182	275	413
PtL	43	56	85	128	34	45	68	103

In Section 1.4.4, we alluded to the fact that building an industrial fuel production facility takes a long time, and that many past projects have failed during the inception/construction phase or after the plant has become operational. As such, when a plant is built in the model and begins production, we must imagine that the process was initiated years beforehand: in other words, we are ignoring all those plants that were started and not finished. It is important to bear this in mind when we consider near-term fuel supply targets – if a swathe of construction is not initiated by 2027, say, there is little hope of meeting even modest production targets for non-HEFA aviation fuel in 2030.

Once built and commissioned, we model each plant as experiencing a gradual ramp-up in output until it achieves its final operating capacity[48]. The production development follows an S-shaped trajectory, levelling off after about three years (Pavlenko et al., 2019).

2.1.2. Fractions and attribution

Oil refineries produce a range of outputs, or 'fractions', the relative proportions of which depend on the crude oil input as well as the refinery configuration. These include 'light ends' like propane, naphtha (which can be upgraded to petrol or used as a chemical industry feedstock), diesel, kerosene, fuel oils, and heavy fractions such as tar (MathPro, 2011). Refineries can be optimised to favour the yield of one fraction over another (e.g. maximise jet kerosene output), but there are upper limits on what is possible and economical, and an over-optimised plant may require higher inputs of energy and hydrogen while achieving a lower overall yield of liquid fuel.

A similar dynamic is at play for the alternative fuel production technologies considered here – cf. Table 6. We assume for the purpose of this study that fuel production facilities are set up to maximise jet fuel yield, but will also produce other products. Unless otherwise stated, in this study when we quote plant sizes and total capital investments associated with deployment of the facilities required to produce the desired amount of jet fuel those numbers include the production of other hydrocarbons. There are markets for these other products (for example through the RTFO) and therefore we would expect the capital costs for a facility to be recouped by the combination of jet fuel sales and other fuel sales – and therefore when we quote costs per unit of output (e.g. £/toe) we assume that those costs are spread equally across the product slate. Similarly, when we quote feedstock demand associated with the SAF Mandate we quote only the fraction of feedstock input that is attributed to the jet-compatible output on an energy allocation basis.

2.1.3. Linear mandates and target feedback

The bottom-up modelling approach to plant construction and fuel production trajectories implies a fundamental tension when considered against the regulatory targets proposed by the UK government. A gradual ramp-up of building rates and plant capacity results in fuel production that accelerates over time. This sort of quasi-exponential growth can often be seen with the initial phases of deployment of a new technology. On the other hand, the SAF Mandate trajectories shown in Figure 1 bend in the wrong direction, with a smaller rate of

[48] For the sake of the modelling, we assume 100% utilisation of the nameplate capacity in Table 7. In reality, this is rarely achieved. Imposing a lower utilisation would result in lower levels of fuel production and hence a higher requirement for construction of new plants.

growth in later years. The model is constrained to generate a result more consistent with the target trajectory by reducing the rate of plant construction in years that the mandate targets are already being fulfilled – SAF demand will be mandate-driven and there is no point building a new plant if there is no demand for the produced fuel.

Nevertheless, in early years of the SAF Mandate, targets increase relatively quickly while modelled fuel production from relatively small and tentatively-built generation 1 plants ramps up gradually. The ensuing shortfall could be plugged if the UK industry outbids alternative fuel consumers in other regions and is able to import fuels from plants that were built with the expectation of servicing other markets.

We shall return to the matter of imports in the Discussion section (Section 5): we do not include the import option in our modelling, and model instead that the buy-out option would need to be used to fulfil the SAF Mandate until domestic production suffices. This decision yields an upper bound on the price increment arising from SAF Mandate compliance, which could be reduced if there are ready sources of appropriate alternative fuel that can be diverted to the UK from other markets.

2.1.4. Price-induced demand change

In practice, we expect a SAF Mandate to impose costs on fuel suppliers, and for these costs to be passed on to fuel buyers (i.e. airports and airlines), and thence to flyers. These costs could either be due to SAF purchases or to paying the buy-out price – either way, economic theory suggests that when costs to consumers increase we should expect a marginal consequent reduction in demand. This effect is not modelled in this study, though other analyses of aviation sector regulations do incorporate it (e.g. Pavlenko & Zheng, 2024).

2.2. Input parameters

The parameters used in the modelling are listed in Table 8.

Table 8 Description of model input parameters

Parameter	Type	Description
First plant (per technology)	Capacity development	Calendar date that the first generation 1 plant begins production
Plants per year in generation N (per technology)		Number of plants built per year in generation N (build rates in earlier and later generations are also determined by this parameter)
Plant nameplate capacity in generation N (per technology)		The nameplate production capacity (measured in ktoe/year) of a generation N plant of the technology in question; other generations' capacities are scaled from this
Years between generations (per technology)		Years that elapse before the plant generation is automatically upgraded, from 1 to 2 to N
SAF Mandate trajectory	Regulatory decisions	DfT's evolving target for the fuel compliance schedule (2025-40); selected from options presented in the consultation
PtL Mandate trajectory		DfT's evolving target for the PtL fuel compliance schedule (2025-40); selected from options presented in the consultation
HEFA Cap		Determines the absolute cap on HEFA's share of the fuel mix: can be zero, the DfT's proposed maximum, or an intermediate value
CCS Regime		In this report we assume CCS does not contribute negative terms to fuels' emissions intensity scores
Buy-out price		Sets the level of the buy-out price for both the main mandate and the PtL mandate; measured in £/litre, and selected from DfT's consultation options
Refinery optimisation	Industry economics	Assume refineries are optimised for production of jet fuel rather than for overall liquid fuel production
Fuel cost regime		Choice of fuel cost projection from the literature
Cost pass-through		Assumed pass through of cost increments to fuel buyers, as a percentage

2.3. Costs

For this report, financial values are quoted in 2023-GBP, denoted £. Where source data is quoted for earlier years, we use standard inflation rates and standard exchange rates to convert from other currencies (EUR/€ and USD/$). All future costs are quoted in 2023-GBP without accounting for potential inflation.

The DfT's buy-out price is applied as a nominal price per litre of fuel. We do not expect the SAF Mandate to include any mechanism to make annual adjustments to maintain the real value of the buy-out price, as there is no such mechanism in operation under the RTFO. This means that the buy-out price will diminish over time in real terms unless DfT adjusts it upwards. We do not model this gradual devaluation of the buy-out price, and consequently we may slightly overstate the relative cost of buying out in later years. We do not expect this to significantly affect the results, however: especially since in the time-frame under consideration, the buy-out route is used only in early years of the SAF Mandate when inflationary effects will be limited (see Section 4).

2.3.1. Production cost

Future costs of unproven technologies are difficult to predict. Even the cost of HEFA production, the most mature of the fuels considered, is highly sensitive to the cost of its feedstock. In the context of the SAF Mandate, the supply of such lipids is significantly restricted by eligibility criteria, and is prone to competition from other markets (such as the EU) vying for the 'most sustainable' feedstocks. Price fluctuations are therefore to be expected for HEFA, and the uncertainties for other more speculative technologies are greater still.

Figure 11 and Figure 12 below show cost estimates for the period 2025-2040 for gasification + Fischer-Tropsch and PtL jet fuel respectively. The estimates derive from a number of sources, discussed briefly in the following paragraphs, and represent possible options for use in the modelling work.

The DfT's original impact analysis (UK Department for Transport, 2023e, Appendix 7.3) provided cost trajectories out to 2050 for a specified set of fuel-feedstock combinations[49]. The updated analysis (UK Department for Transport, 2024b), on the whole estimates considerably higher costs than the original analysis; this gives some context for the raised buy-out prices discussed in Section 1.2.5. These trajectories were modelled by the Aviation Impact Accelerator[50] (see UK Department for Transport, 2024b, Sections 3.11-3.15). The range in scenario estimates reflects uncertainties in the cost of inputs like biofuel feedstock and low-carbon electricity, and the cost of plant construction. In the case of PtL fuel, DfT consider only DAC as a CO_2 source, which raises the production cost relative to point-source-derived CO_2 (see Section 1.3.3).

A dedicated analysis of alternative aviation fuel costs for the World Economic Forum (WEF) presented a cost break-down for selected fuel-feedstock combinations[51], modelled out to 2050 (Soubly & Riefer, 2020). Based on optimistic forecasts for electricity prices, they concluded that PtL jet fuel shows the greatest potential for cost reduction: in 2020-25 it is by far the most expensive fuel, but by 2050 is cheaper than BtL. For AtJ, feedstock costs stay constant and other cost factors decrease gradually, while in the case of MSW gasification, modelled feedstock costs are shown as rising over time, indicating competition for this waste resource. These BtL pathways end up with a levelised cost of 1,500-1,800 \$/tonne in 2050 (approximately 1400-1700 £/t).

[49] Namely: HEFA made from UCO or tallow; gasification with Fischer-Tropsch fuel made from forestry residues or MSW; AtJ made from forestry residues; pyrolysis made from forestry residues or MSW; and PtL using carbon dioxide from DAC and electricity from wind or nuclear sources.

[50] https://aiazero.org/

[51] Namely: HEFA made from UCO; gasification with Fischer-Tropsch made from MSW; AtJ made from sugarcane bagasse; and PtL made from industrial point-source CO_2 and solar-PV electricity.

Somewhat less dynamism is on display in a 2022 report for the European Parliament's Transport Committee (Neiva et al., 2022). Changes in the cost of HEFA and gasification-plus-Fischer-Tropsch fuel are negligible in the period 2020-50, while AtJ and PtL jet fuel costs fall by 25%. More remarkable is the suggestion that fossil jet prices will more than double. For this report, we have opted to keep the fossil jet fuel price constant.

We show cost projections for 2025-35 in Figure 11 and Figure 12; in the modelling we use the 'DfT Central' values[52]. DfT's adopted buy-out prices are included in the figures as these cap the cost of compliance. The buy-out price is larger than estimated costs for gasification-based jet fuel (with the exception of the Pessimistic 2025 value): this signals to investors that it should be viable to produce this fuel for the UK, provided cheaper options cannot meet all demand. It is a similar story for PtL fuel, though at the upper end of cost estimates (where electricity costs are high), buy-out will be increasingly attractive.

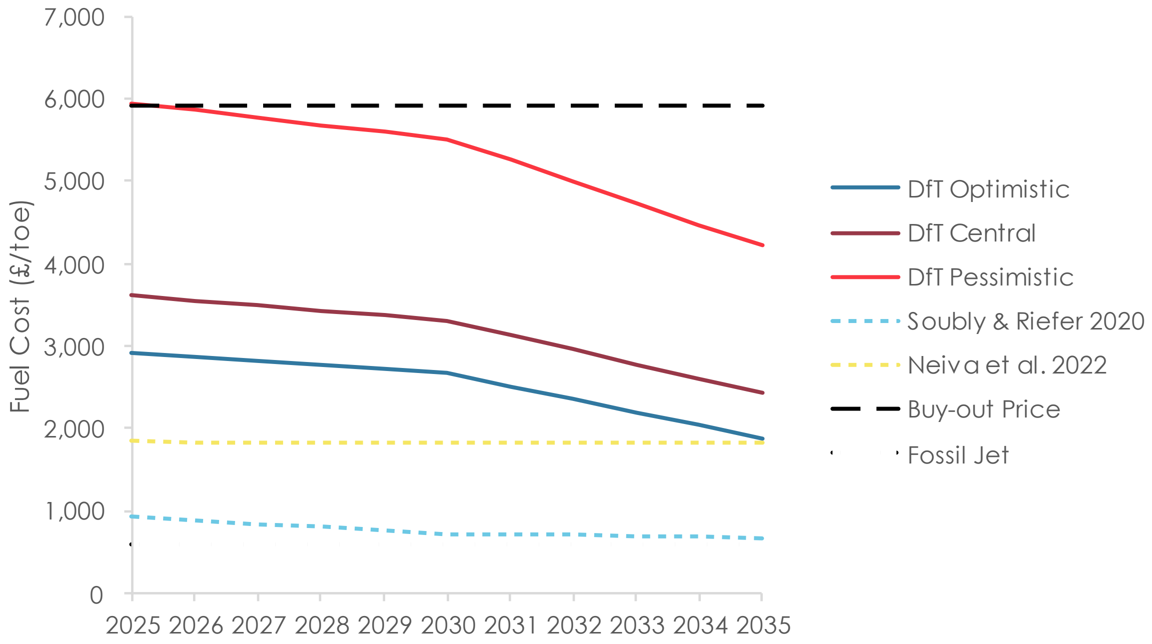


Figure 11 **Cost projections for jet fuel made through biomass gasification with Fischer-Tropsch synthesis**

Note: The buy-out levels, shown for reference, do not change in time but all other series do. We have linearly interpolated decadal/quinquennial points to annual.

[52] The DfT's final cost-benefit analysis (UK Department for Transport, 2024b) did not include updated estimates for pyrolysis-based fuel costs. The values that we use are those from the second consultation cost-benefit analysis (UK Department for Transport, 2023e), scaled according to the new estimates for gasification-based fuels.

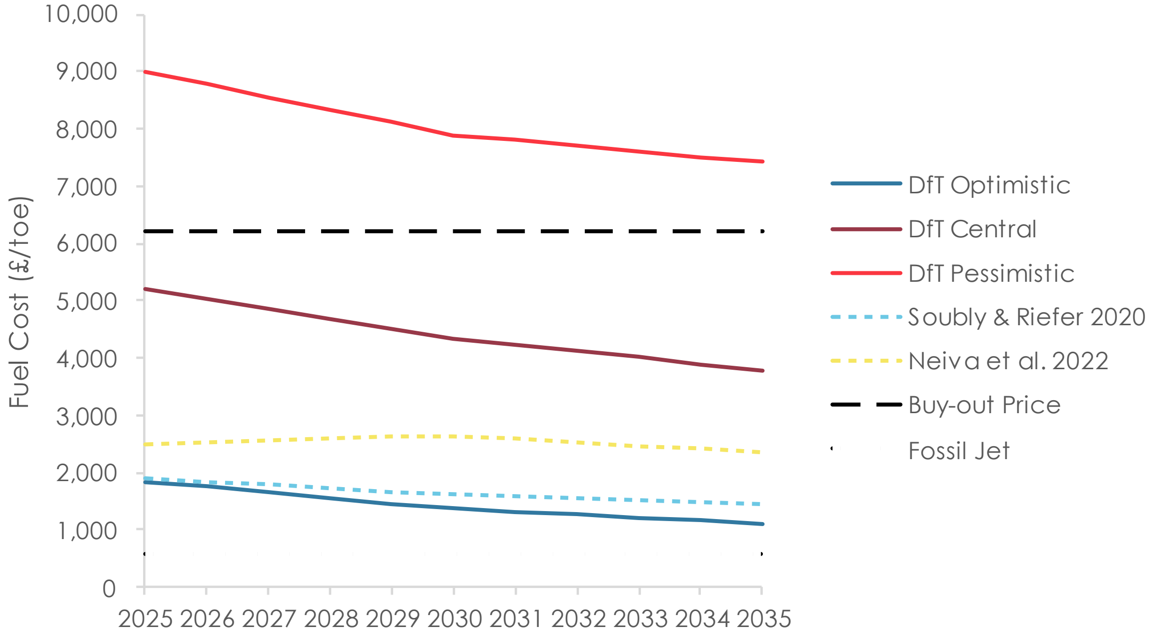


Figure 12 Cost projections for PtL jet fuel

Note: The buy-out levels, shown for reference, do not change in time but all other series do.

The range in estimates in Figure 11 and Figure 12 above results from the variety of technology configurations and feedstocks that can be used for each fuel production pathway, coupled with significant uncertainty over the future costs of each one. This is investigated at a more granular level in a review of bio-jet cost estimates in the academic literature (Shahriar & Khanal, 2022); the results are shown in Figure 13[53]. Note that while the review finds consistently that the estimated costs of pyrolysis pathways are lower than those of FT pathways, this is based on a limited dataset and it remains uncertain which pathway will offer the lowest cost fuel production when commercialised.

The break-down of these totals into various contributing factors of feedstock, CapEx, process energy, chemical inputs, etc. depends on the technology pathway, plant design, and the feedstock used. For BtL facilities relying on woody biomass (purpose-grown or residual), feedstock costs have been found to dominate, at 30-50% of the total (Atsonios et al., 2015; Crawford et al., 2016; Yang et al., 2018). On the other hand, feedstock for BtL fuels made from energy crops and agricultural residues, was estimated to comprise only 20-25% of the total cost, with the largest share (50-80%) coming instead from capital costs (Pavlenko et al., 2019). Indeed, a report for the European Commission remarks that feedstock choice can change gasification-based BtL production cost by 20-30%, and AtJ by even more than this (Giannelos et al., 2021).

[53] Fuels considered also included lignin-to-jet and SIP pathways which we omit here.

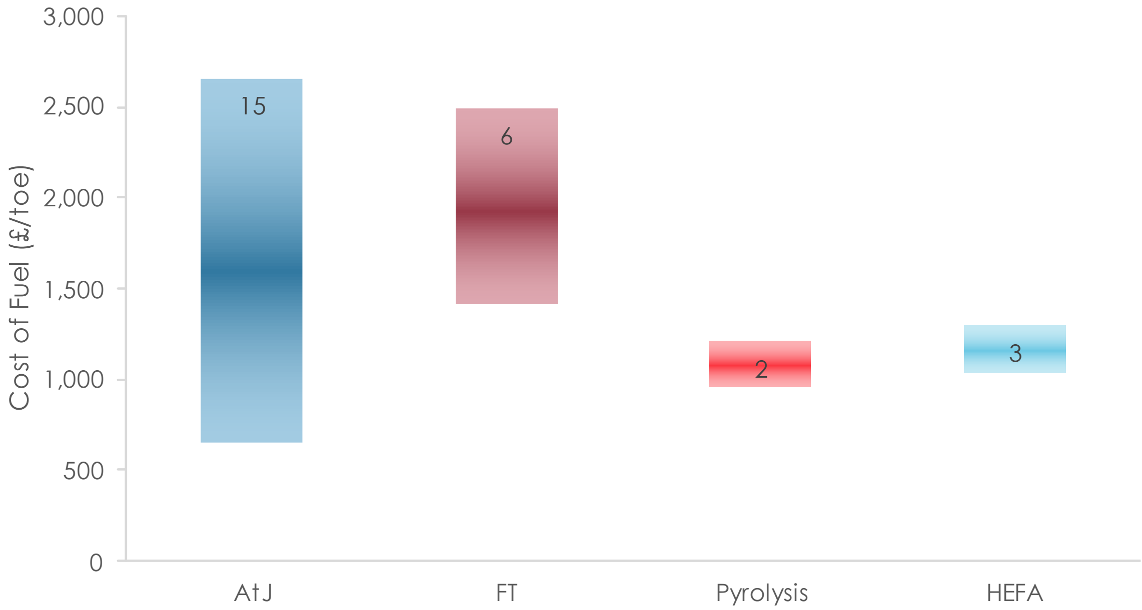


Figure 13 **Bio-jet cost ranges from a review of the literature, labelled with the number of contributing estimates (Shahriar & Khanal, 2022)**

Note: The low uncertainty on pyrolysis bio-jet is an artefact of the small number of estimates. This applies also to HEFA, though as a more commercialised technology it would be expected to show a smaller range of estimates; the future availability and price of HEFA feedstocks is, however, far from certain. For HEFA we consider 'traditional' feedstocks only, omitting data-points for jatropha.

2.3.2. Capital cost

Capital costs may comprise more than half of the total costs of alternative aviation fuel production (Cantarella et al., 2023). As discussed in Section 1.3, the most scalable solutions are not commercially mature, and some technologies may prove to be dead ends; investment therefore carries all the risks associated with an early and developing market. Initiatives such as the U.S.'s SAF Grand Challenge, the EU's ReFuelEU Aviation Regulation, and the UK's SAF Mandate, aim to drive investment by convincing the private sector that a lucrative market is forming and that the price at which SAF can be sold will be enough to cover operational and capital costs and deliver returns to investors.

Different fuel production technologies each require a suite of specialised equipment and plant integration / co-location arrangements, as well as transport networks for collection and consolidation of cellulosic / lipid feedstocks (in the case of bio-jet), and carbon dioxide and electricity (in the case of PtL). The cost of construction naturally depends on the plant location, the existence of nearby infrastructure and services, the capacity of the plant, and the number of additional processing steps (for instance, an AtJ plant may make cellulosic ethanol on-site rather than bringing it in from outside).

Estimates of the expenditure per unit of annual production capacity, measured in £/(toe/year) are shown in Figure 14. The coloured bars represent the range of estimates collated in a review of the techno-economic literature from 2022 (Shahriar & Khanal, 2022), while the points show estimates from standalone reports (Giannelos et al., 2021; Pavlenko et al., 2019) – these are seen to inhabit the low end of the range given by the first source.

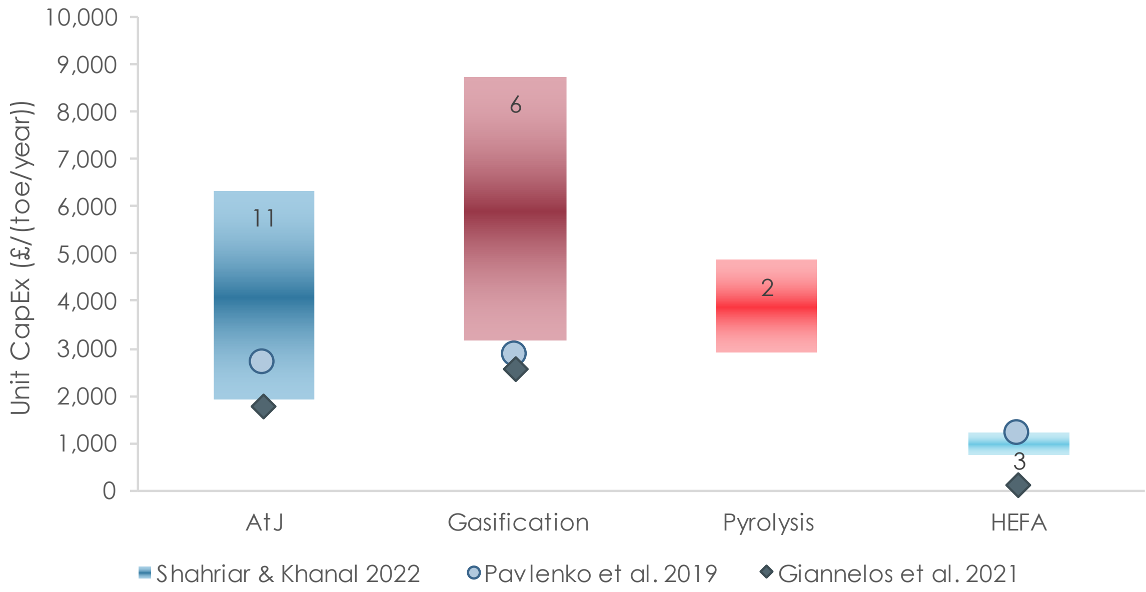


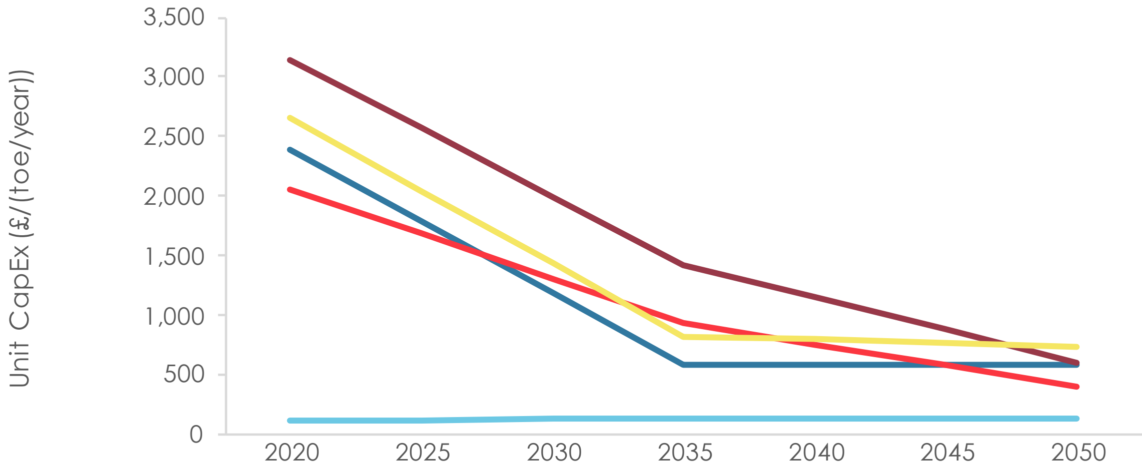
Figure 14 CapEx estimates for bio-jet facilities, in GBP per unit of annual output capacity

Note: No pyrolysis CapEx estimate was given in the latter two sources. See also the note for Figure 13 above.

As fuel production technologies mature, we expect facilities coming on-line to get larger in size (Section 2.1) – partly because the up-front investment has more certain pay-off. At the same time, development of best practices in plant design and economies of scale in procurement bring unit costs down. Taken together, this means that the average cost of plant construction my increase, but the unit CapEx will decrease – a fact that is not captured by Figure 14's static snapshots.

The European Commission impact study for ReFuelEU Aviation (Giannelos et al., 2021) provides a basis for estimating how construction costs may evolve in future. These are the values we shall use in this report, presented in Figure 15[54].

[54] The ReFuelEU Aviation impact study (Giannelos et al., 2021) presents conspicuously low HEFA CapEx estimates. This is partly explained by the emphasis on optimisation and retro-fitting of existing facilities – something that is discussed critically in a techno-economic assessment by ICCT (Pavlenko et al., 2019).



	2020	2025	2030	2035	2040	2045	2050
AtJ	2,387	1,785	1,184	583	583	583	583
Gasification	3,145	2,569	1,993	1,417	1,146	874	603
Pyrolysis	2,060	1,682	1,305	928	750	573	395
HEFA	108	113	118	124	124	124	124
PtL	2,651	2,040	1,429	818	790	762	734

Figure 15 **Projected development of unit CapEx (in £/(toe/year)) for the alternative jet fuel technologies considered**

Note: For comparison, typical unit CapEx for a petroleum refinery would be around 610 £/(toe/year) (Favennec, 2022), but there is lots of variation on this number depending on refinery complexity.
Note: The data from the original study (Giannelos et al., 2021) implies that unit CapEx for AtJ rises rather than falls in the 2040s. We have over-ridden this result.

2.3.3. Compliance cost

A fuel supplier may encounter two sources of extra costs introduced by the SAF Mandate: the cost of buying alternative fuel (including transporting it to where it is used in the case of segregated supply chains), and the 'buy-out' cost that applies when Mandate obligations are not met (this was covered in Section 1.2.5). Both of these scale with the volume sold by each fuel supplier.

The impact on fuel prices depends on whether additional costs imposed upon fuel suppliers are passed through in their entirety to buyers (that is, airports and airlines) or whether some portion is absorbed, perhaps temporarily, by the fuel supplier. In this report, we shall assume full pass-through, such that 100% of the costs of the SAF Mandate are felt in the year that they occur. This follows past work from Cerulogy (Malins & Sandford, 2021); we believe this gives the clearest indication of the programme's high-level impacts, without invoking speculative economic reasoning which may limit the applicability of the results.

Generally speaking, the question of how upstream costs trickle down to the fares paid by flyers is non-trivial: it depends on existing profit margins, the size and duration of changes in costs, the elasticity of demand for flying, and the level of competition in the sector (or indeed at specific airports). A study for the European Commission settled on a pass-through range of 74-

82%, depending on the duration of the flight and the airports involved (European Commission, 2020a). The DfT's SAF Mandate cost-benefit analysis (UK Department for Transport, 2023e, Annex 7.4) adopts a 'medium' assumption of 75%, but notes that airport capacity constraints can result in pass-through as low as 0% at congested airports and as high as 100% and airports with latent capacity.

In this report, we do not model the market price of alternative fuel – what is passed through is simply the (pre-determined, evolving) production cost of the fuel consumed, plus any buy-out costs incurred. This neglects factors like fuel producers' profit margins or the cost of fuel transport. Another, more subtle, market reality under the SAF Mandate is the response of market prices to shortfalls in fuel supply: we may expect a supply gap to increase competition and therefore the price that can be charged by producers for the same batch of fuel. In the context of the SAF Mandate, this means that in years where the industry is forced to buy out of their obligation, the price of the fuel that does get supplied would likely float to just below the buy-out price.

Naturally, any hikes to ticket prices to reflect the new costs passed through to airlines will deter some flyers and reduce demand (recall the brief discussion in Section 2.1.4). From a climate point of view this would be a positive outcome in itself, quite apart from the incentivisation of renewable fuels, but we do not consider such feedback for this report. It is worth noting that airlines have some say in how they distribute costs among their customers; an application of the 'polluter pays' principle would mean price increase proportional to greenhouse gas emissions – meaning larger increases for long-haul flights and for business passengers.

2.4. Energy and emissions

2.4.1. Energy units

The technical specifications of aviation fuel are tightly regulated: aviation fuel produced through different technology pathways (fossil petroleum, HEFA, gasification, etc.) will therefore share all the basic physical properties like density and calorific value. This means that a given volume of any fuel will have the same mass and the same energy content, irrespective of the details of its production, and results about quantities of fuel can equally be expressed in units of litres or cubic metres (volume), kilograms or tonnes (mass), or megajoules or tonnes of oil equivalent (energy).

For this study, we generally to report fuel quantities in tonnes of oil equivalent (toe), which is a standard energy measure equivalent to 44.76 GJ. One tonne of jet fuel contains about 0.98 toe, so to a first approximation one can talk interchangeably about tonnes or toe. We use lower heating values (LHV) throughout.

2.4.2. Greenhouse gas emissions

The different fuel technologies and feedstocks are expected to be associated with different levels of climate benefit, and these are expected to improve over time (as processes become more efficient and society decarbonises). In the model, this is represented as an evolving emissions reduction percentage compared to the standard fossil kerosene comparator. The values used for this study are shown in the next section in Figure 17.

We compute the total emissions savings under the SAF Mandate[55] in a given year using Equation (2):

$$\text{GHG emissions savings } (\text{ktCO}_2\text{e}) = \text{Fossil comparator} \times \sum_{\text{fuels}} [\text{Energy supplied} \times \text{GHG emissions reduction}] \quad (2)$$

where,

'GHG emissions savings' is the total savings over all fuels, measured in $ktCO_2e$;

'Fossil comparator' is the fossil jet emissions intensity of 89.0 gCO_2e/MJ;

The sum is taken over all fuels contributing to the energy mix;

'Energy supplied' is the energy contribution of a given fuel, for the present purposes measured in PJ;

'GHG emissions reduction' is the percentage emissions saving for a given fuel, as in Equation (1).

The greenhouse gas reduction score for each fuel is based on comparing the estimated lifecycle emissions for the production of the fuel against the lifecycle emissions for production and combustion of fossil jet (the fossil fuel comparator). The combustion emissions for renewable fuels are treated as being exactly offset by CO_2 sequestered during plant growth (biofuels) or CO_2 captured for production (PtL fuels). The characterisation of emission reductions for SAF does not consider the non-CO_2 climate impacts of flights, for example through contrail formation.

[55] Note that the emissions savings in a given year are directly proportional to the number of SAF Mandate certificates.

3. Scenario Inputs

3.1. Time period

The second DfT consultation proposed four possible SAF Mandate trajectories covering the period from 2025 to 2040, and illustrated how these might evolve out to 2050. The trajectory to 2040 has now been finalised (Figure 1), with an indicative ambition to satisfy 50% of aviation energy demand with alternative fuel in 2050.

For this report, we consider the period 2025-35. Given the infancy of the regulation and of the technologies involved, and uncertainty over how the industry will respond, we consider that modelling further into the future would be speculative at this time.

3.2. Mandate trajectory and costs

The adopted blending mandate reaches a 15% alternative fuel contribution in 2035, and 22% in 2040, as shown in Figure 1 and Table 2 above. Section 2.1.3 introduced the tension between enacting a linear (or even convex-shaped) target for the overall SAF Mandate in light of the natural concave trajectory of industrial development, where slow progress in early years accelerates as an industry becomes better established. We shall see how this plays out when we come to the scenario results in Section 4. The proposed options for the PtL sub-target were all concave, and hence more consistent with industrial development pathways and the current modelling framework; but the adopted PtL sub-target is relatively linear (Figure 3). This study's model scenarios assume that the PtL target is more or less met.

As for fuel production costs, we presented in Section 2.3.1 a number of estimated cost trajectories, including a range from DfT's second consultation (UK Department for Transport, 2023b, Annex 7.2). Predicting future alternative fuel costs, and how they will compare with conventional fossil jet fuel, is non-trivial; even with technical breakthroughs in commercialising the technologies under examination, the ready supply of sustainable bio-jet feedstock and the availability of renewable electricity and captured carbon dioxide for PtL are not guaranteed. Sectoral stakeholders from industry and civil society may have an interest in presenting an optimistic or a pessimistic assessment – for instance as part of an argument that alternative fuels are a viable future option for aviation decarbonisation that can avoid the need to reduce fuel consumption more aggressively. For the purpose of this report, we adopt the DfT's moderate Central scenario for fuel costs[56].

Capital costs for plant construction were discussed in Section 2.3.2; in the present work, we use the values presented in Figure 15.

[56] Recall from Section 2.3.1 that the DfT's analysis of PtL production costs is based on DAC-sourced CO_2, though cheaper CO_2 from point sources will also qualify under the SAF Mandate. This will slightly inflate the cost of PtL fuel in the results.

3.3. Fuel emissions intensity

The second DfT consultation (UK Department for Transport, 2023b) included a range of estimates for the lifecycle greenhouse gas emission reductions offered by the different fuel production pathways. These reductions in some cases exceeded 100%, indicating that some form of carbon removal was bundled into the fuels' lifecycle analysis and that DfT's more ambitious scenarios were relying on negative carbon terms. Crediting flying with negative emissions is naturally controversial, (especially given that, as noted above, the warming impact of aviation induced cloudiness means that even planes running on nominally 'negative-emissions' fuel would be likely to contribute to global warming), and this may have contributed to the decision in the final Government response to cap emissions savings at 100% (UK Department for Transport, 2024b, Annex 7.3). The range of savings from this latter publication is shown in Figure 16, where we have selected the 2035 values. The optimistic end for some fuels (e.g. UCO-based HEFA) shows high emissions savings compared to what is typical today; this may be considered implausible.

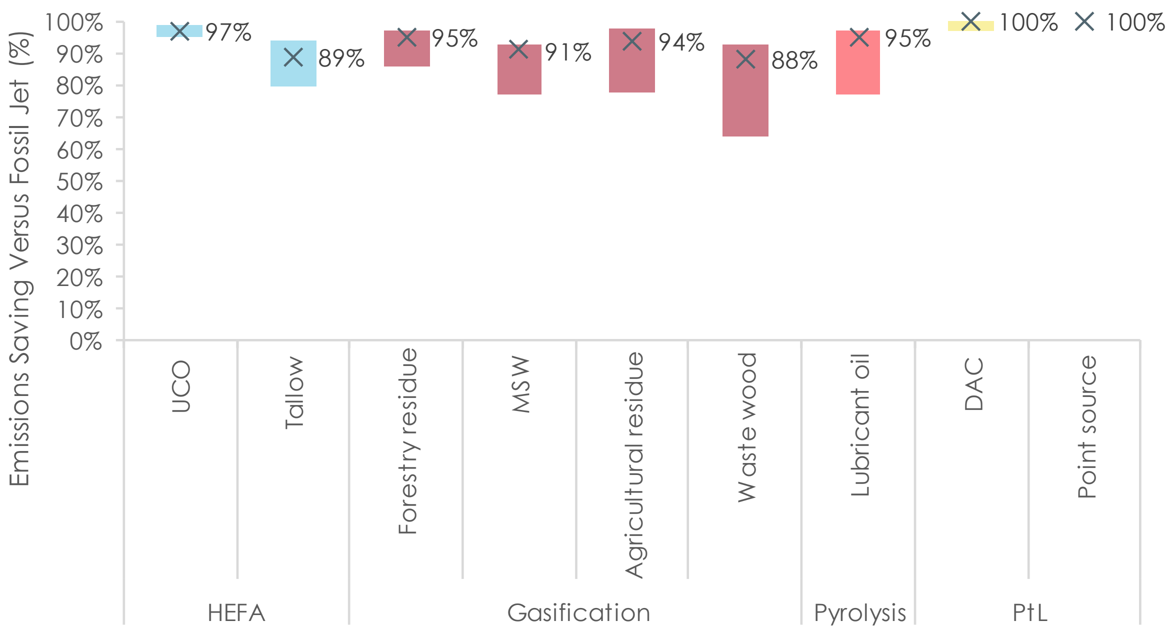


Figure 16 **Percentage emissions savings (range and central value) in 2035, from DfT**

Note: These are percentage savings with respect to the fossil jet fuel comparator of 89 gCO_2e/MJ.

We diverge from DfT's predicted savings to take into account other estimates from the literature, as well as the fact that the adopted 40% emissions threshold will allow suppliers more flexibility in feedstock sourcing and fuel production efficiency; so we assume actual greenhouse gas savings to be a little lower. Our average values are shown in Figure 17. We include gradual improvements for all fuels, with the exception of PtL which is a flat 95% saving. Of course, individual fuel producers may be able to register higher or lower scores, and it will become clearer what kind of emissions regime will apply to each technology pathway once they are further down the road to commercialisation. Since the number of SAF certificates issued per litre of physical fuel depends on its lifecycle greenhouse gas emissions score, the average savings used in the model will have implications for how much of each fuel is required to reach compliance.

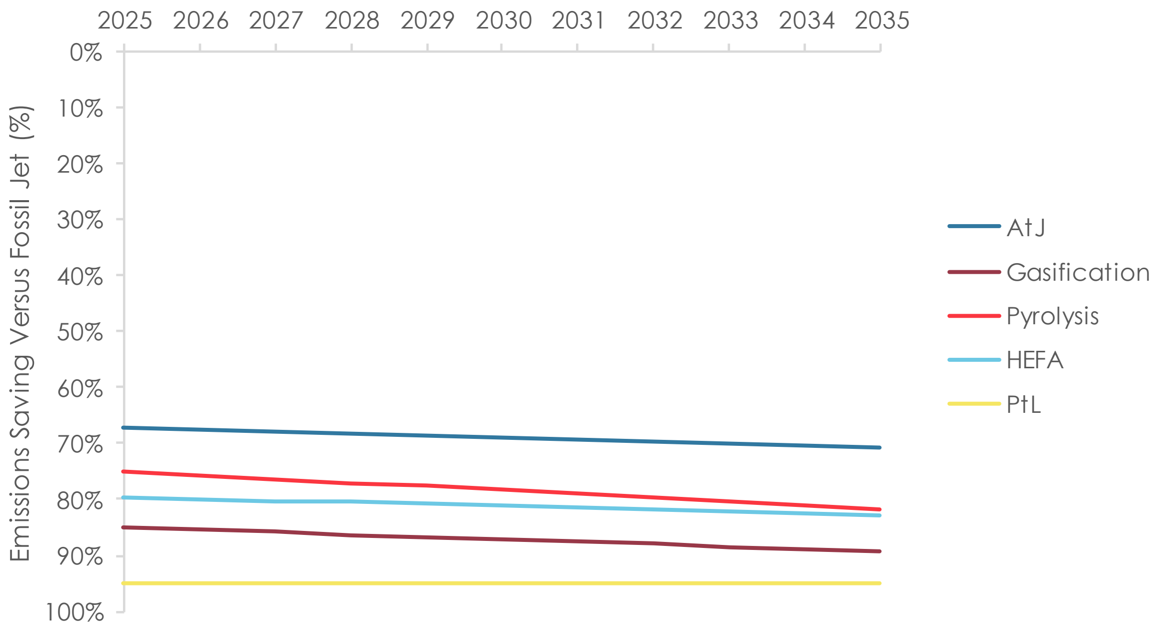


Figure 17 Percentage emissions savings of the fuel technologies over time

Note: These are percentage savings with respect to the fossil jet fuel comparator of 89 gCO_2e/MJ. No CCS is included.

The evolution of PtL emissions has three major influences: (i) the decarbonisation trajectory of electricity, both grid and non-grid; (ii) the energy efficiency of electrolytic hydrogen production; and (iii) the energy efficiency of carbon dioxide capture and transport. Since the expectation is that some renewable aviation fuel will be produced in the UK and some will be imported, calculating PtL's average carbon intensity in principle requires us to consider the relative volumes imported from different countries and their corresponding grid decarbonisation trajectories; we circumvent the cumbersome exercise by observing that grid-based PtL is unlikely to meet the SAF Mandate's CI threshold. We are therefore justified in that additional low-carbon electricity will be the primary input for PtL jet fuel production – this allows for the low carbon intensities shown in Figure 17.

Returning to Figure 17, we see that HEFA appears to register high emissions savings, comparable to biomass-based AtJ fuel. This is more optimistic than studies of residue-and-waste-based HEFA which show, for instance, a final fuel carbon intensity of about 24 gCO_2e/MJ (Hamelinck et al., 2021); but it is less optimistic than the values included in the DfT's cost-benefit analysis, which go up to 99% emissions reduction for UCO-based HEFA (UK Department for Transport, 2024b, Annex 7.3). As with the RTFO, indirect emissions are not included in the lifecycle analysis of these fuels – even though displacing waste or residual lipids from existing markets may lead to greenhouse gas impacts that reduce the net benefit of fossil fuel displacement (e.g. Malins, 2017a; Pavlenko & Searle, 2020). Indeed, the DfT's own analysis acknowledges that, under circumstances where the supply of lipid feedstocks is constrained, the use of HEFA in aviation will come at the expense of HVO in the road sector, and therefore that the declared emissions reductions will be at least partly compensated by increases out of scope (UK Department for Transport, 2024b, Paragraphs 4.14-4.17). For the purposes of this report, however, we put these issues to one side and adopt the emissions savings shown in Figure 17.

3.4. Hydrogen consumption

Following the discussion in Section 1.3.5, Table 9 presents the assumed hydrogen consumption per unit of transport fuel output, for each of our modelled technology pathways. For PtL, electrolysis is the sole source of hydrogen for building fuel molecules (stoichiometrically, around 10% of the mass of a jet fuel molecule is hydrogen[57]); we omit PtL from Table 9 because we account for its electricity usage elsewhere.

Table 9 External hydrogen consumption for the biofuel pathways, in tonnes of hydrogen required per toe of fuel output (all fractions)

Technology	AtJ	Gasification	Pyrolysis	HEFA
tH_2/toe	0.022	0.020	0.082	0.037

Note: Sources for these estimates are provided in Section 1.3.5.

Gasification warrants a special mention as the production of biogenic hydrogen is already at the core of the gasification pathway, and it may seem odd that more is needed. Following the gasification of biomass, the ratio of hydrogen to carbon monoxide in the syngas is optimised through the water-gas shift reaction before the reactants undergo Fischer-Tropsch synthesis into hydrocarbons. For the production of distillate-range hydrocarbons like diesel and jet fuel, the syngas must undergo a form of high-temperature synthesis, as this favours formation of long-chain waxes which can be upgraded into fuel through hydrocracking (Spath & Dayton, 2003, Section 7.3); but this hydrocracking requires extra hydrogen, hence the non-zero value in Table 9. As already touched upon in Section 1.3.5, the extra hydrogen may be derived from the biomass feedstock (which reduces the feedstock-to-fuel yield) or be provided from an external source. For this modelling, we report biomass feedstock consumption that covers the gasification and Fischer-Tropsch stages of fuel synthesis only, and we report the extra hydrogen consumption for upgrading as if it were external.

3.5. Scenario descriptions

3.5.1. The five scenarios

The five scenarios under consideration are presented in Table 10. Two characteristics are common to all of them. First, HEFA supply is modelled as the maximum allowed under the adopted cap (Figure 2). Consequently, detailed modelling of HEFA production facilities is not necessary – we simply calculate how much capacity would be required to meet the cap and assume that feedstock availability (domestic plus imports) is not a limiting factor. The second similarity between scenarios is that we assume no CCS is credited.

[57] This would imply a hydrogen requirement of order 0.1 tH_2/toe. Note that for the PtL process, efficiencies of only 39% electrolytic hydrogen being incorporated into hydrocarbon molecules have been reported (Rojas-Michaga et al., 2023).

In the first four scenarios, the model is set up to achieve (on average) mandated PtL volumes, as discussed earlier in Section 3.2. In the fifth scenario, PtL supply is assumed to surpass the mandated level. The remainder of the modelled fuel supply, after PtL and HEFA have been counted, is comprised of a varying mix of BtL technologies. In the AtJ Breakthrough scenario, AtJ constitutes the majority of BtL fuel, with token amounts from the other two BtL technologies (early plants are built, but do not progress past generation 1). Mutatis mutandis for the G+FT Breakthrough and Pyrolysis Breakthrough scenarios. For the BtL Mix and PtL Breakthrough scenarios, was assume that roughly equal regulatory volumes of fuel are delivered by the three BtL fuels.

Table 10 Scenario descriptions

#	Scenario	Description
1	BtL Mix	Maximum HEFA Fulfil PtL mandate Mix of BtL technologies No carbon removals
3	AtJ Breakthrough	Maximum HEFA Fulfil PtL mandate AtJ dominant No carbon removals
2	G+FT Breakthrough	Maximum HEFA Fulfil PtL mandate Gasification dominant No carbon removals
4	Pyrolysis Breakthrough	Maximum HEFA Fulfil PtL mandate Pyrolysis dominant No carbon removals
5	PtL Breakthrough	Maximum HEFA Surpass PtL mandate Mix of BtL technologies No carbon removals

3.5.2. Scenario construction

Our goal is to make meaningful comparisons between these scenarios – for example in terms of their cost and the emissions reductions achieved. This constrains somewhat how input parameters are chosen, as it would be misleading to compare, say, the emissions from two scenarios which deliver very different volumes of fuel.

The parameterisations used to construct scenarios aim to deliver the same SAF certificate generation in 2035 – more specifically, all are designed to match the SAF Mandate target in this year. This represents an accelerated schedule of project development compared to the DfT projections discussed in Section 1.4, and the resulting costs and industrial effort will be correspondingly ambitious. The rationale for this acceleration is that as global competition for alternative aviation fuel ramps up through the 2030s, reliance on persistent imports may not be viable and the UK may be forced to rely on domestic production. We will return to this point in Section 5.3 of the Discussion section.

Our 'bottom-up' modelling strategy for plant construction means that there will be some variations between scenarios in the period leading up to this, but these are small enough that all our scenarios can be freely compared with each other.

4. Results

This section presents results from the five scenarios introduced in the previous section. Full results are shown for the first scenario; for the sake of brevity only a restricted set of results is shown for subsequent scenarios. The final sub-section presents a cross-comparison of all scenarios.

4.1. Scenario 1: BtL Mix

4.1.1. Fuel supply

The contribution of alternative fuel to the jet pool is shown in Figure 18, against the target set by the SAF Mandate. Remember that the volume of alternative fuels that can be reported against SAF Mandate targets is weighted by a greenhouse gas emissions intensity factor (Equation (1)) – this means that the percentage of physical volume may be a little different to that shown in Figure 18. For all the scenario analyses that follow, fuel-related charts show weighted regulatory volumes rather than physical volumes unless explicitly stated. This makes them more relevant to the SAF Mandate discussion, but also more sensitive to our assumptions about the fuels' average lifecycle emissions.

Immediately obvious from Figure 18 is the supply shortfall which is only closed in 2035. This reflects the lack of existing operational fuel production facilities and the reality that facilities cannot be brought instantly online. Such a shortfall entails use of the buy-out mechanism. In 2035, production meets the Mandate target, and from then on it is plausible that the industry will be ready to grow at a rate faster than targeted. This could allow DfT to raise its targets, or the excess capacity could be used to supply other alternative fuel markets – either within the aviation sector, or in other transport sectors (e.g. increasing road fuel output to supply the UK's RTFO).

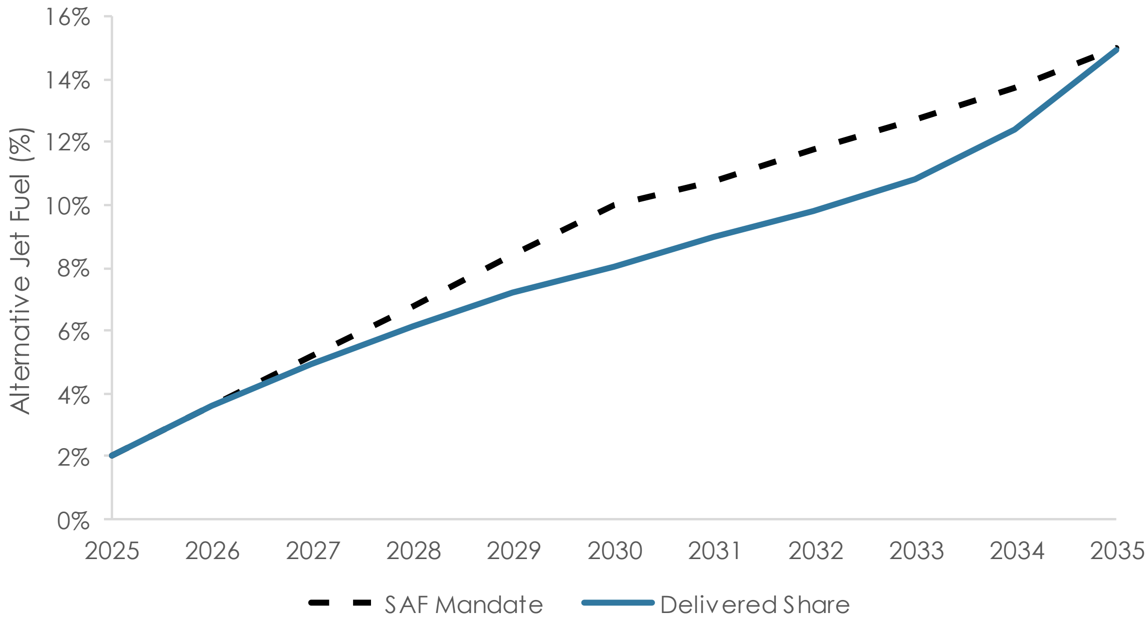


Figure 18 **Delivered fuel (regulatory volume with weighting factors) as a percentage of overall fuel demand, for the BtL Mix scenario**

Figure 19 shows the quantity of SAF Mandate certificates coming from each production pathway. By design, the first two years of Mandate targets are satisfied by HEFA alone, as is the case for all scenarios. In the BtL Mix scenario, the sub-target for PtL jet fuel is met, but PtL makes a modest contribution to overall SAF production in 2035. The three BtL technologies each make roughly comparable contributions to the total generation of SAF certificates. Both PtL and BtL exhibit the gradual ramp-up in production that would continue to accelerate after 2035.

As an aside, recall that Section 1.2.2 introduced the SAF Mandate targets and noted that the HEFA cap had been expanded considerably in DfT's final consultation response. Figure 18 shows that this has reduced fuel suppliers' exposure to buy-outs and uncertain imports, though it is not impossible that with a lower cap, UK BtL production would have had greater impetus to start earlier and ramp up faster than we have modelled in this report. Delivering the required rate of BtL deployment will still be highly challenging even with this expanded HEFA cap (see Section 4.1.2). The issue of the HEFA cap illustrates that the effort to decarbonise aviation while preserving sectoral growth inevitably leads to trade-offs – in this case, the consumption of large volumes of waste-and-residual oils which may have been put to better use elsewhere in the economy.

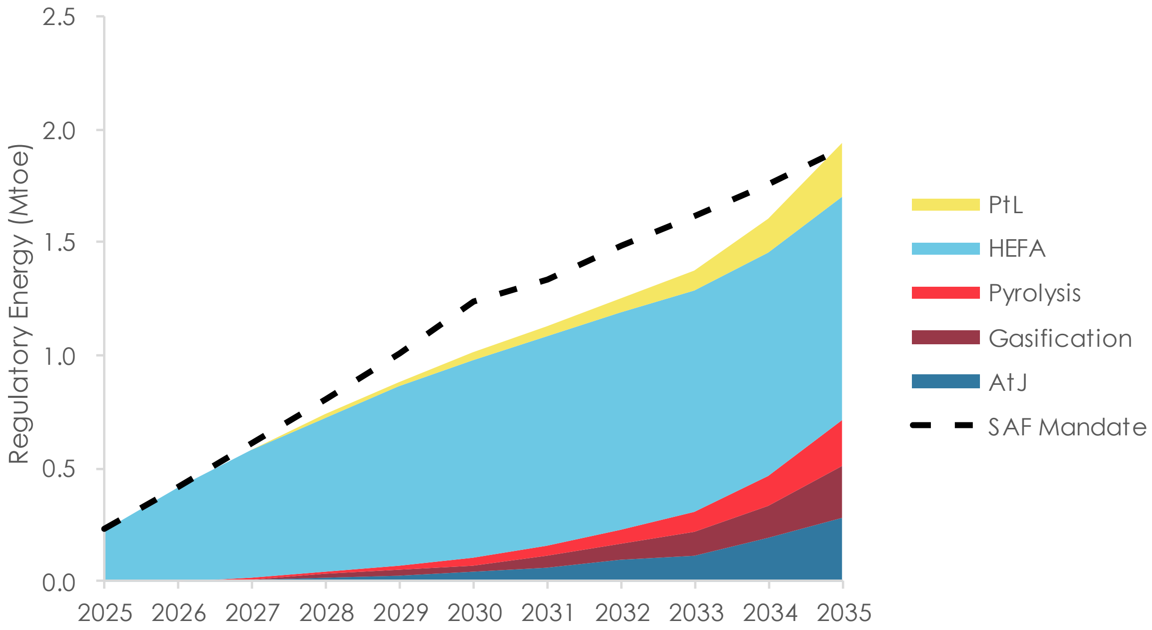


Figure 19 **Delivered fuel (regulatory volume with weighting factors) by type for the BtL Mix scenario**

In the left panel of Figure 20, PtL supply is tuned to keep pace with the mandate on average, though as already seen with the main target, this may lag behind or advance beyond the target. The right panel of Figure 20 shows the HEFA supply to the UK aviation sector. For all scenarios in this report, we assume the regulatory cap is met.

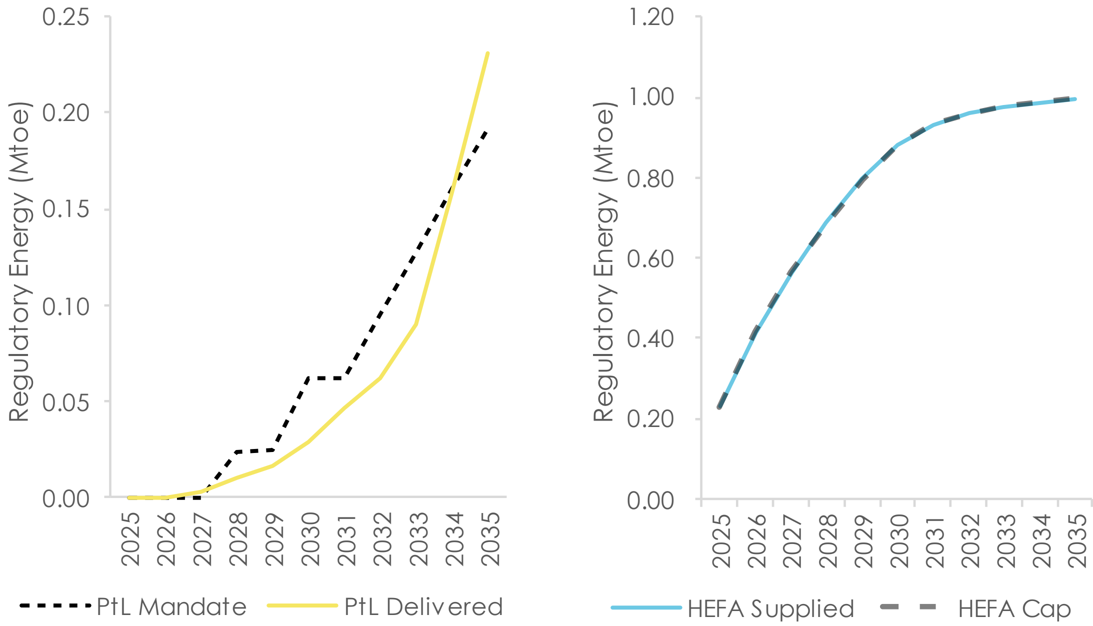


Figure 20 **Left: delivered PtL fuel under the sub-mandate, for the BtL Mix scenario; right: HEFA supply compared with the cap; weighting factors included in both**

Note: In the right-hand plot, the two lines are coincident as we assume in the modelling that maximum HEFA is supplied to the UK, up to the imposed cap.

4.1.2. Plant construction

The number of plants in operation over time is a key output of the model. The number of plants built in a given year emerges from the combination of assumed build rates in each generation, the time taken to advance between generations, and the level of current fuel production with respect to SAF Mandate targets. The growing population of plants for the BtL Mix scenario is shown in Figure 21; the columns are clustered rather than stacked to make it easier to see the growth for each technology type.

As HEFA demand is assumed to adhere to the maximum cap, Figure 21 simply shows the number of plants required to supply the desired quantity of fuel from Figure 20. Four HVO/HEFA refineries (optimised for jet fuel production) would be able to produce enough output to meet UK demand under the cap in 2035; this is why plant construction ceases after 2030. The difference in numbers between the BtL technologies reflects the different assumptions on typical plant size – for the same level of fuel supply one needs more pyrolysis plants compared to AtJ plants.

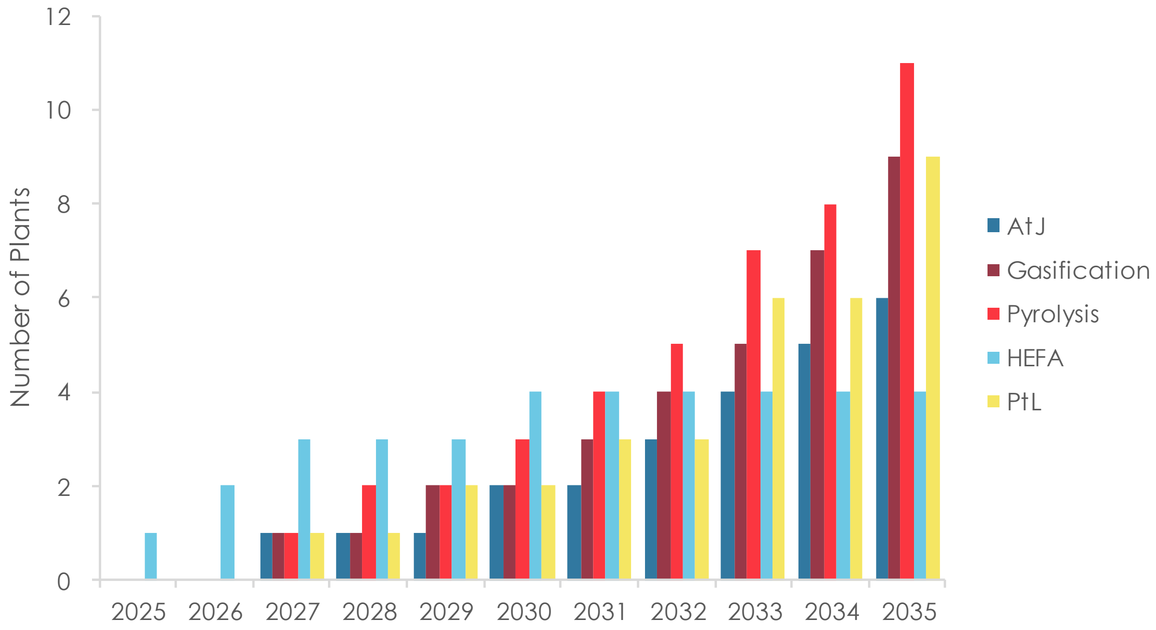


Figure 21 Number of plants in operation, split by technology, for the BtL Mix scenario

The spree of facility construction pictured in Figure 21 comes at a cost, and the implied invested CapEx is shown in Figure 22. Capital expenditures are counted as if they were incurred wholly in the year in which a plant enters production. If there is no new plant of a given technology coming online in a given year there would be no CapEx shown.

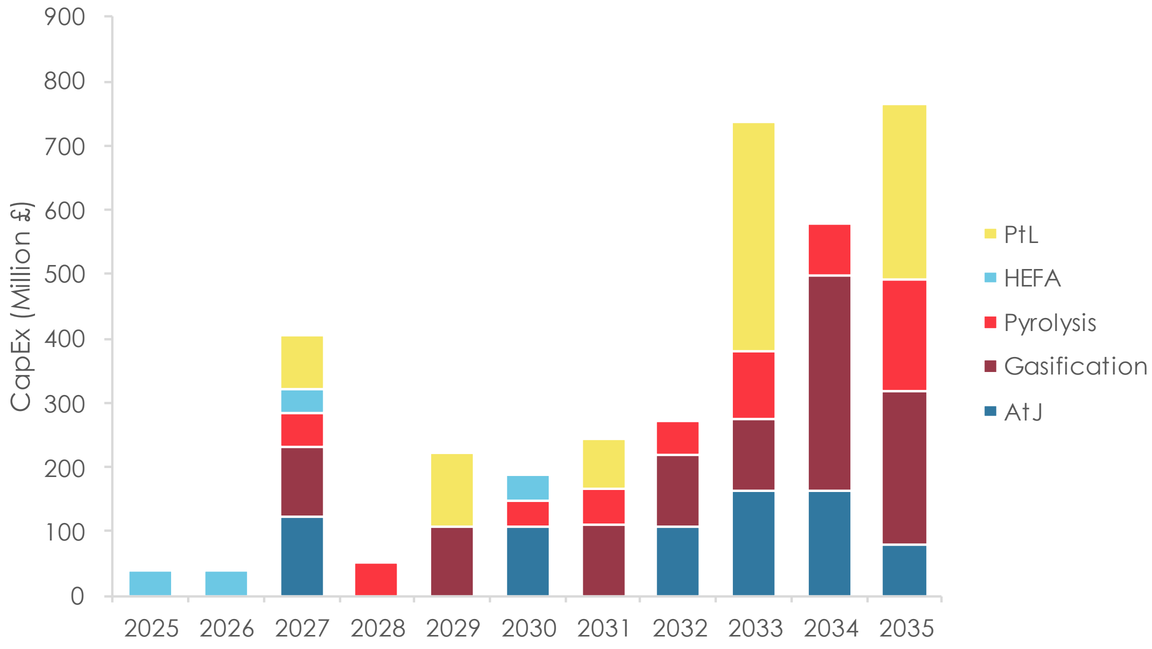


Figure 22 **Annual CapEx investment required, for the BtL Mix scenario**

4.1.3. Fuel cost

Figure 23 shows the impact of the SAF Mandate on the cost of jet fuel from the perspective of fuel purchasers (e.g. airlines and airports). The cost of fossil jet fuel (solid grey) is assumed fixed in time, at 583 £/toe (about 720 \$/toe). To this is added the marginal cost of buying alternative fuel (dark blue-grey) and the cost of buying out of unfulfilled obligations when alternative fuel is not available (shaded grey). As expected, in the Mandate's early years the dominant increment comes from buy-out certificates, until sufficient volumes of compliant fuel become available. In 2033, the additional cost arising from the SAF Mandate surpasses 200 £/toe (about 0.16 £/l)[58].

[58] Recall that this – and respective conclusions for the other scenarios – is predicated on our use of DfT's fuel cost results. See Section 2.3.

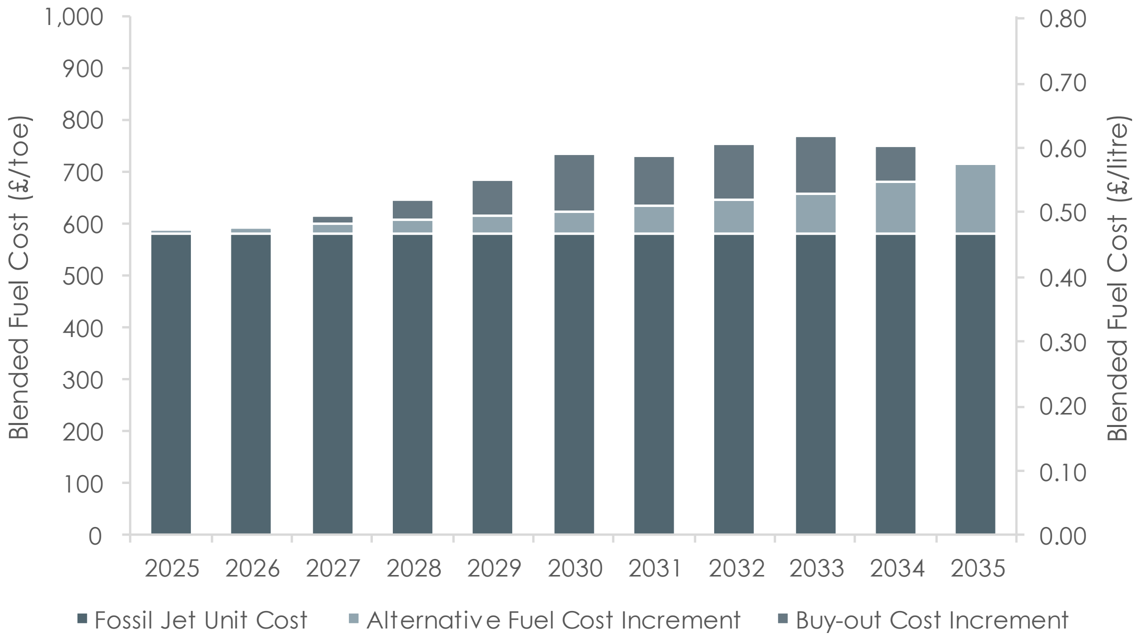


Figure 23 **Average cost of blended jet fuel for the BtL Mix scenario, showing increments to the baseline (fossil jet) which arise from purchase of alternative fuel and from buying out of SAF Mandate obligations**

4.1.4. Feedstock consumption

The overall demand for different feedstocks naturally depends on the slate of fuels used for the mandate: HEFA requires lipids and hydrogen, BtL fuels require cellulosic/ligno-cellulosic biomass and hydrogen, and PtL requires electricity and a source of carbon dioxide. Figure 24 shows the demand for lipids and biomass, where lipid use is determined by the HEFA cap (this will also be the case for all subsequent scenarios).

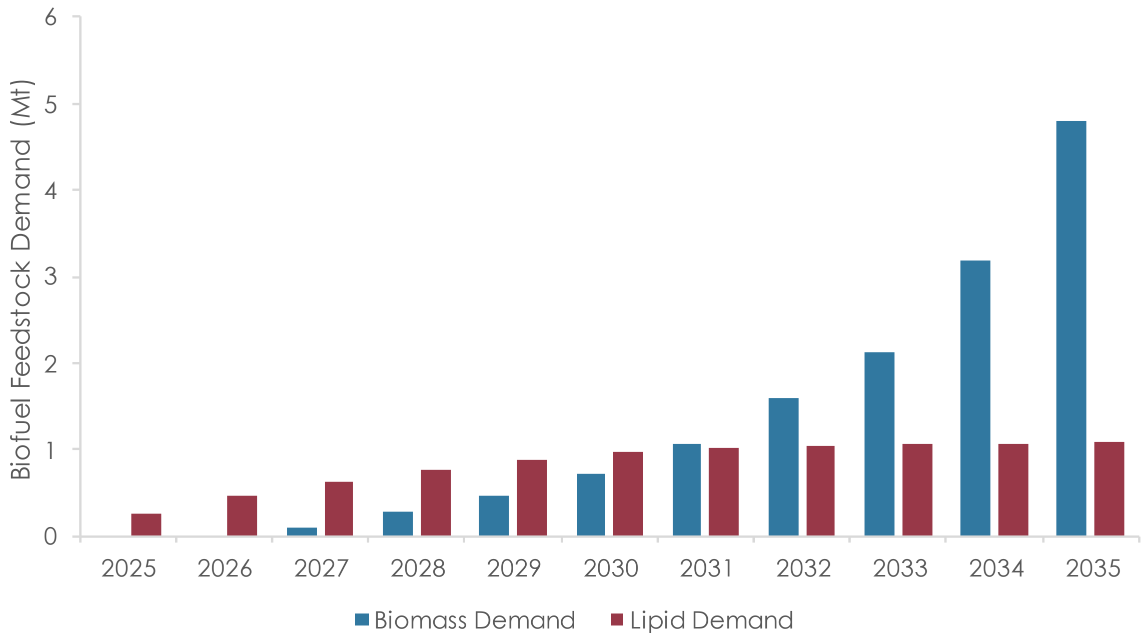


Figure 24 **Biofuel feedstock consumption for the BtL Mix scenario (jet fraction only)**

Note: As discussed in Section 2.1.2 and elsewhere, fuel facilities produce a range of molecules. The "jet fraction only" in the figure label indicates that we have pro-rated the feedstock consumption to consider only the portion required to produce jet fuel. An actual refinery will consume more feedstock than this and produce a larger slate of outputs.

Figure 25 shows the hydrogen consumed for biofuel production. As already discussed in Section 1.3.5, BtL facilities may include units for generating hydrogen via feedstock gasification. However, we present hydrogen consumption as if it is sourced externally: this is for transparency, and for consistency with the parameterisation of greenhouse gas emissions and feedstock demand which has been used elsewhere in the modelling (e.g. in Figure 24 above).

The gasification and AtJ technologies have similar hydrogen requirements per unit of physical fuel output (see Table 9), and so the difference in hydrogen consumption in Figure 25 is mostly down to the differing production levels and the different regulatory weighting factors. Pyrolysis, on the other hand, has significantly higher hydrogen requirement per unit of jet fuel produced, and this is reflected in the results.

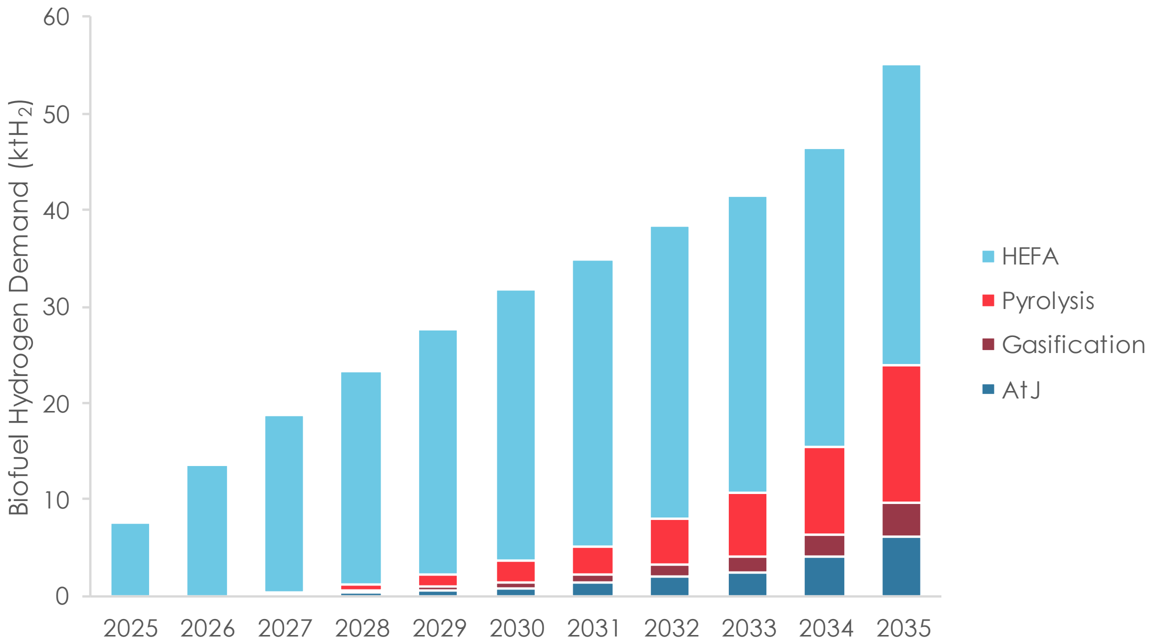


Figure 25 Biofuel hydrogen consumption, for the BtL Mix scenario (jet fraction only)

Note: See the note for Figure 24.

Figure 26 shows the growing power demand from PtL, contextualised as a share of UK national demand. However, some jet fuel will be imported so it is not necessarily the case that UK electricity will be used for the production of all SAF Mandate PtL (indeed, the DfT has stated that "much of the increased demand for electricity and hydrogen will be met through production outside of the UK" (UK Department for Transport, 2024a, Paragraph 6.5)). What is shown in the graph is only the electricity required to run the electrolyser – energy used for the carbon capture unit, feedstock transport, Fischer-Tropsch synthesis, fuel upgrading, and distribution to airports, is not included.

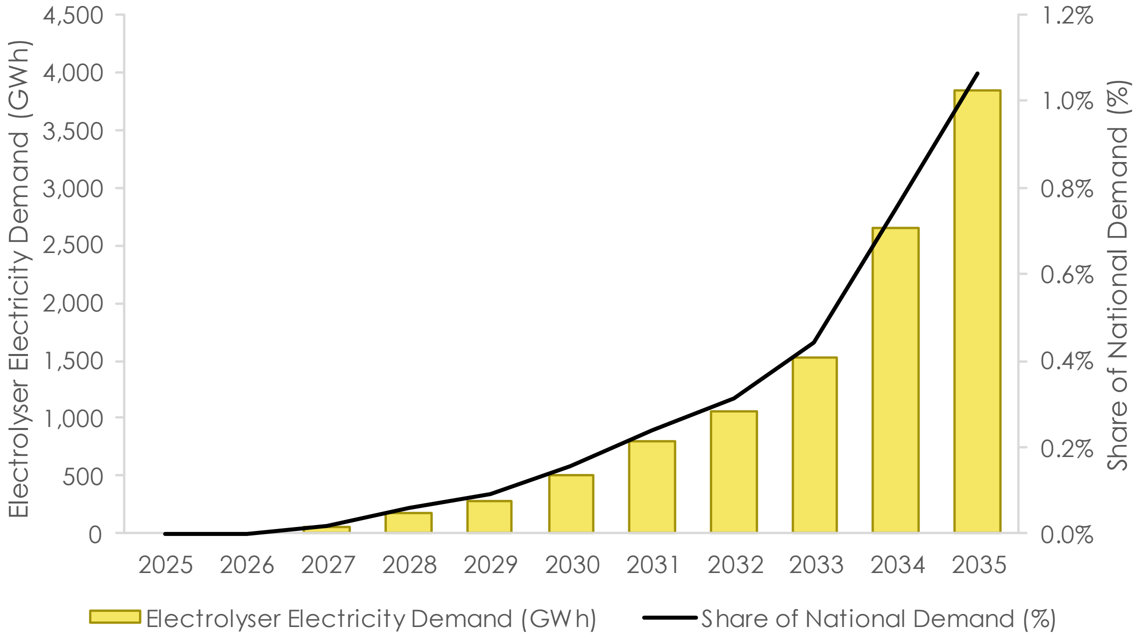


Figure 26 **PtL electrolyser electricity consumption, compared with national demand, for the BtL Mix scenario (jet fraction only)**

4.1.5. Emissions

Figure 27 shows the BtL Mix annual emissions between 2025 and 2035, split into a number of contributions. Total modelled emissions are represented by the short-dashed black line; the contributions to this total from burning fossil and alternative aviation fuels are represented by the dark and light grey columns respectively. The model shows substantial savings compared with the counterfactual 'fossil-only' scenario (represented by the upper long-dashed black line); these savings are split by fuel in the coloured stack. The difference between the two black lines is the total emissions savings, and in all, 2035 has an estimated 10.6% reduction compared to the counterfactual.

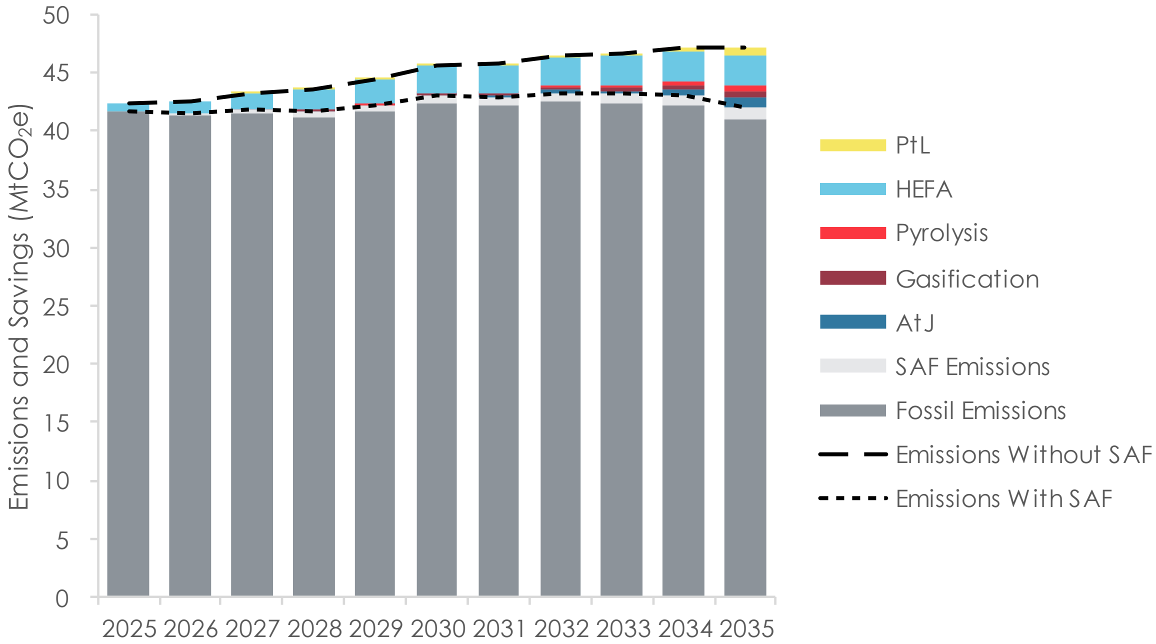


Figure 27 **Emissions from fossil and alternative jet fuels (shades of grey), and emissions savings (colours) versus the counterfactual scenario where all demand is met by fossil kerosene**

Dividing the emissions savings by the extra fuel cost (see Figure 23) allows us to estimate the cost of carbon abatement implied by the modelled scenario[59]. This is shown as the line in Figure 28, in comparison with the total annual emissions savings as columns. A value approaching 350 £/tCO_2e (approximately 420 $/t$CO_2$e or 390 €/t$CO_2$e) is significantly higher than carbon prices in existing carbon markets – for example CA-LCFS credits have in the past traded for around 200 $/t$CO_2$e before declining, while EU ETS credits (which mostly cover non-transport emissions) surpassed 100 €/tCO_2e in 2023 but have fallen to 70-80 €/tCO_2e since then. The implication of our model findings is that quantities of alternative fuel sufficient to fulfil the SAF Mandate will only be supplied at carbon prices much higher than these.

[59] This calculation excludes the buy-out expenditure from the denominator, as in early years of the programme buy-out represents a high proportion of costs without directly delivering greenhouse gas abatement.

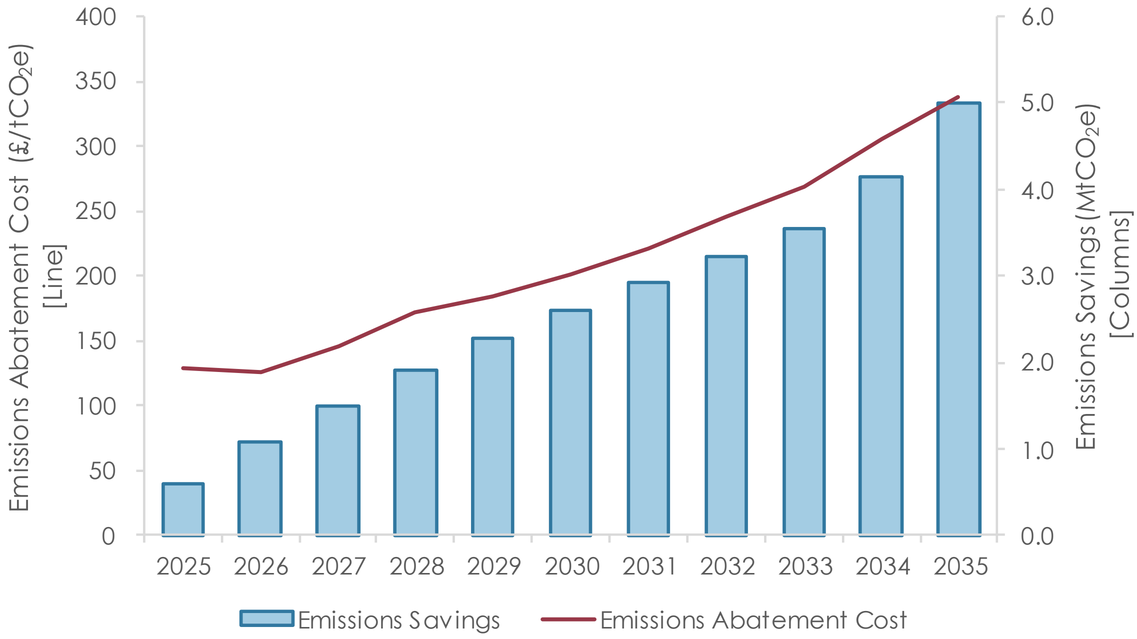


Figure 28 **Cost of carbon implied by the modelling (left axis, line), compared with the annual emissions savings (right axis, columns), for the BtL Mix scenario**

4.2. Scenario 2: AtJ Breakthrough

The next three scenarios are identical to the BtL Mix scenario in terms of the production and consumption of HEFA and PtL, but their relative emphasis on the three BtL technologies differs. For this and the following sections, we outline the scenario results with a few key plots, saving a comparative analysis for Section 4.6.

In the AtJ Breakthrough scenario, we assume that only the AtJ pathway produces meaningful quantities of fuel, while gasification and pyrolysis do not reach the level of technological or economic maturity to progress past first-generation plants. Figure 29, Figure 30, and Figure 31 show versions of plots familiar from the previous section. Figure 29 shows the dominance of AtJ fuel in this scenario. The PtL and HEFA contributions are unchanged from the BtL Mix scenario (cf. Figure 19).

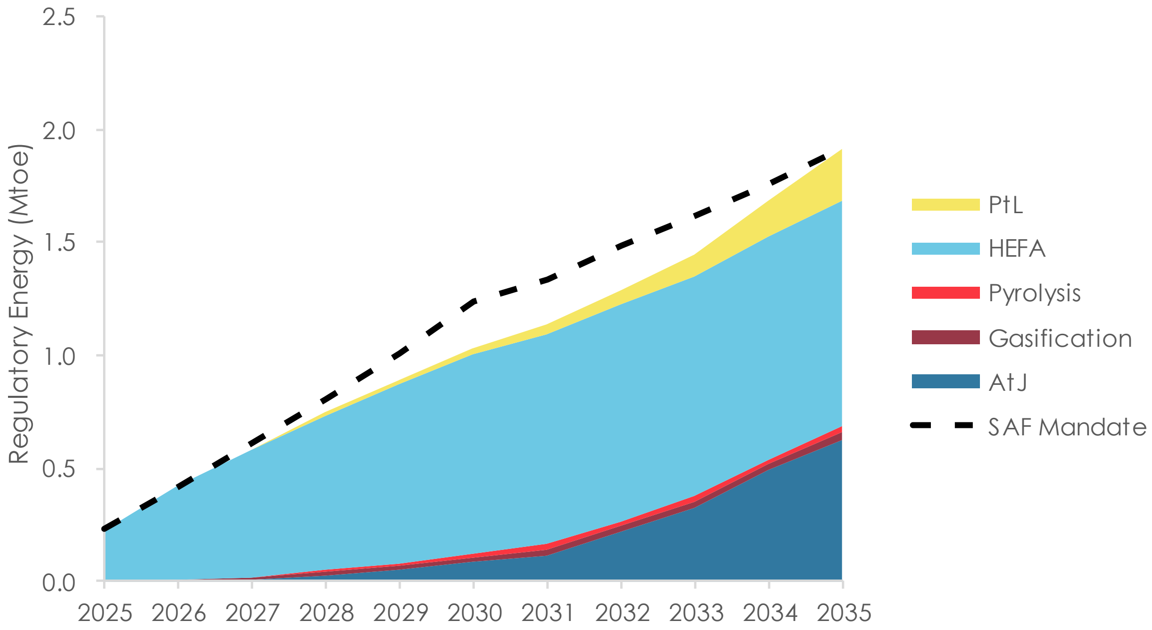


Figure 29 **Delivered fuel (with weighting factors) by type for the AtJ Breakthrough scenario**

Figure 30 shows the growth in plant building, which reaches a smaller total number of plants than in the BtL Mix scenario because AtJ plants are relatively large (almost twice as large as a gasification plant of the corresponding generation – see Table 7). In the 2030s, one to two AtJ plants are built per year.

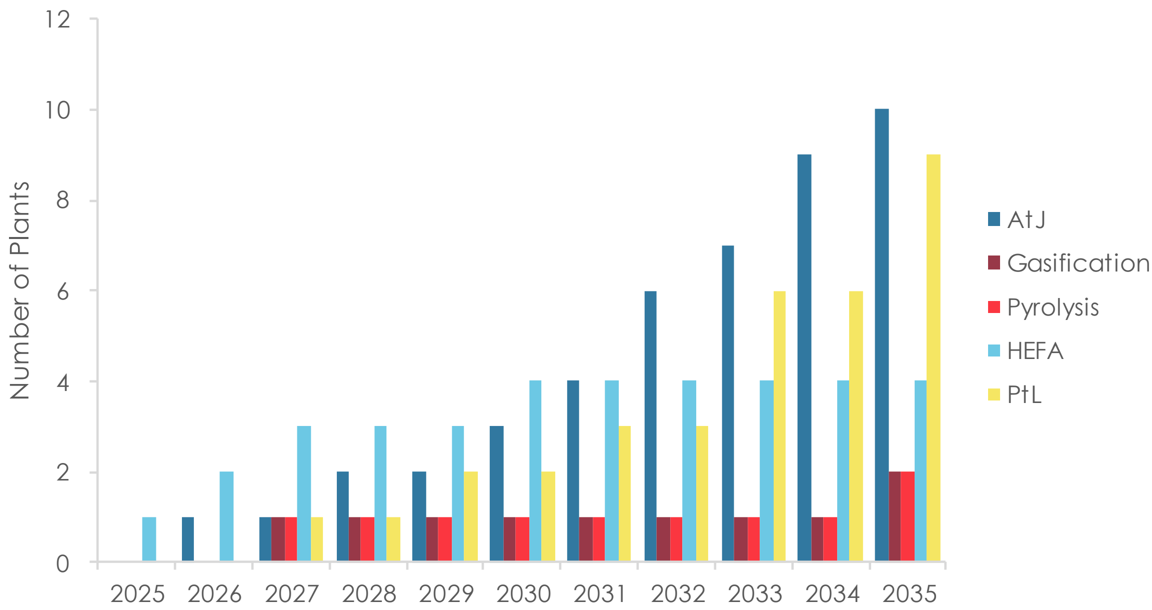


Figure 30 **Number of plants in operation, split by technology, for the AtJ Breakthrough scenario**

Figure 31 shows the unit cost impact on aviation fuel, again showing significant buy-out expenditures after the main SAF Mandate target exceeds the HEFA cap. The fuel cost increment is a little higher than in the BtL Mix scenario, as AtJ has higher operational costs than the other BtL technologies.

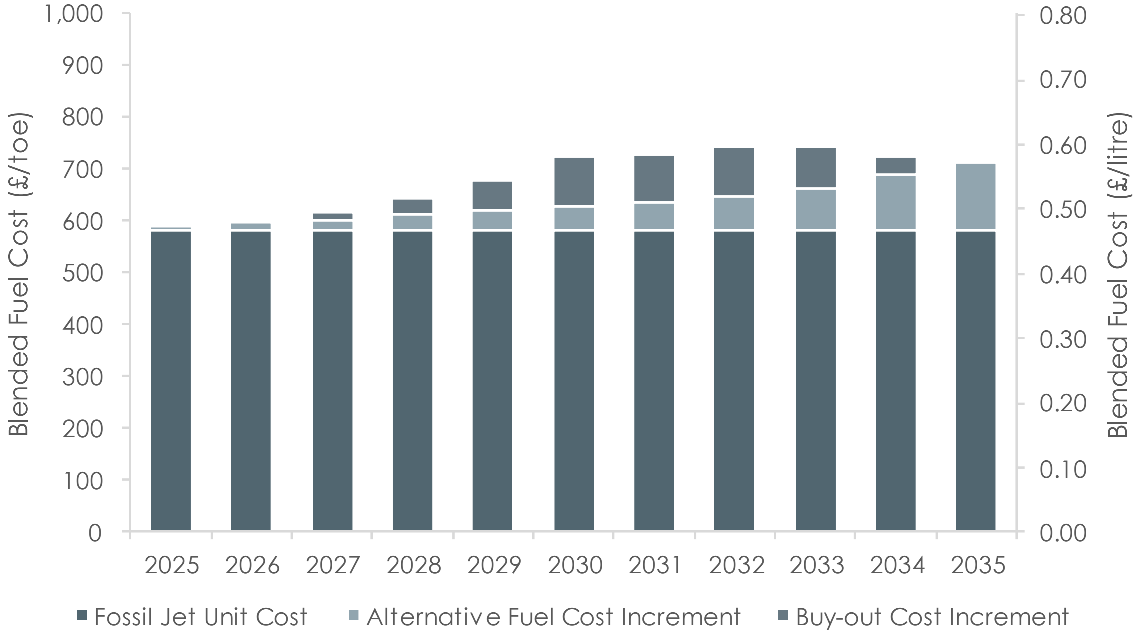


Figure 31 **Average cost of blended jet fuel for the AtJ Breakthrough scenario, showing increments to the baseline (fossil jet) which arise from purchase of alternative fuel and from buying out of SAF Mandate obligations**

4.3. Scenario 3: G+FT Breakthrough

The G+FT Breakthrough scenario is similar to the previous two scenarios, except that here gasification is the only BtL pathway that produces significant quantities of fuel. Figure 32 shows fuel production volumes from each technology. The PtL and HEFA contributions are unchanged from before, while gasification quickly establishes as the only BtL technology of consequence.

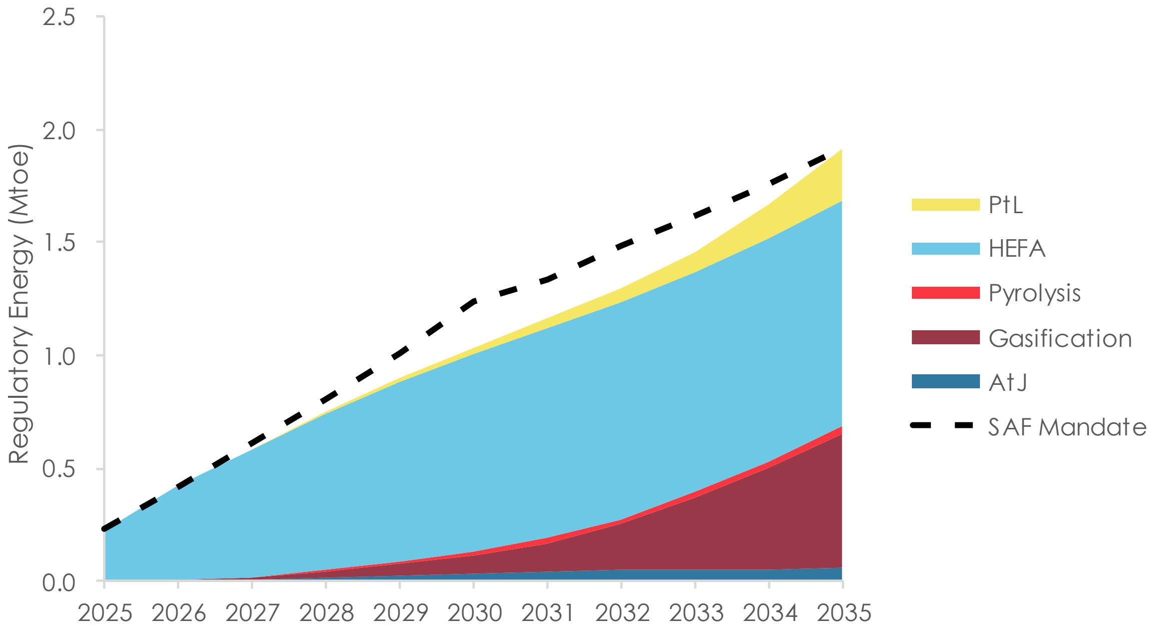


Figure 32 **Delivered fuel (with weighting factors) by type for the G+FT Breakthrough scenario**

This story is echoed in Figure 33, which shows that 17 gasification facilities would have to be built in order to satisfy the SAF Mandate. Gasification plants tend to be intermediate in size between AtJ and pyrolysis plants (Table 7), which explains the larger number needed compared to the previous scenario.

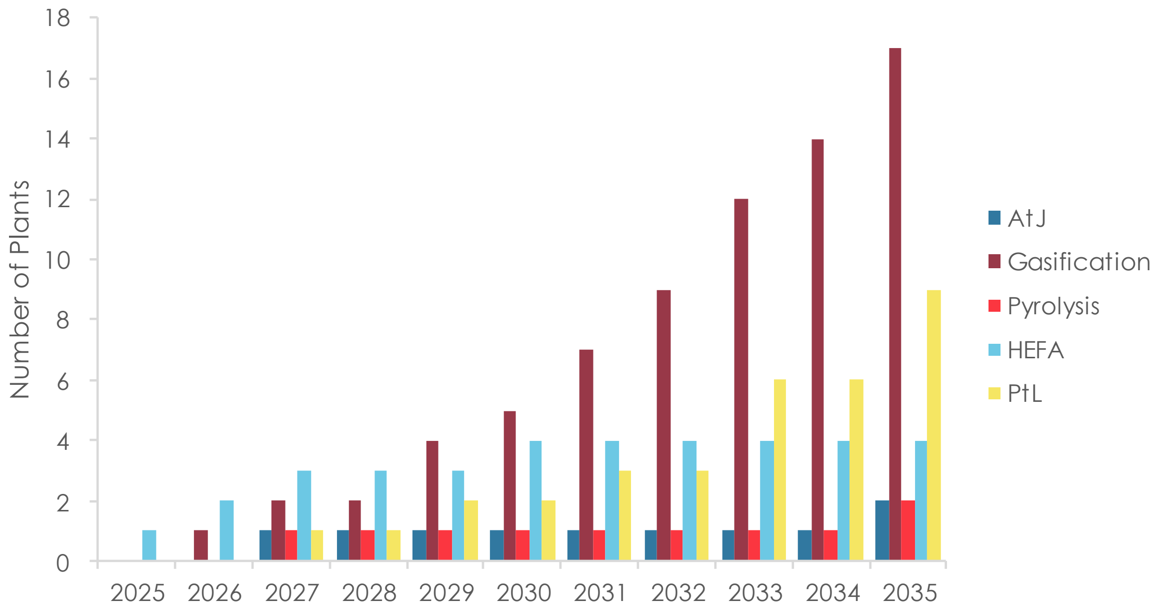


Figure 33 **Number of plants in operation, split by technology, for the G+FT Breakthrough scenario**

Figure 34 confirms that the early 2030s still witness significant buy-out expenditures. Gasification plants are projected to be expensive to build (especially given their slightly lower jet fraction yield), but lower running costs may bring down the price of the product slightly in this period.

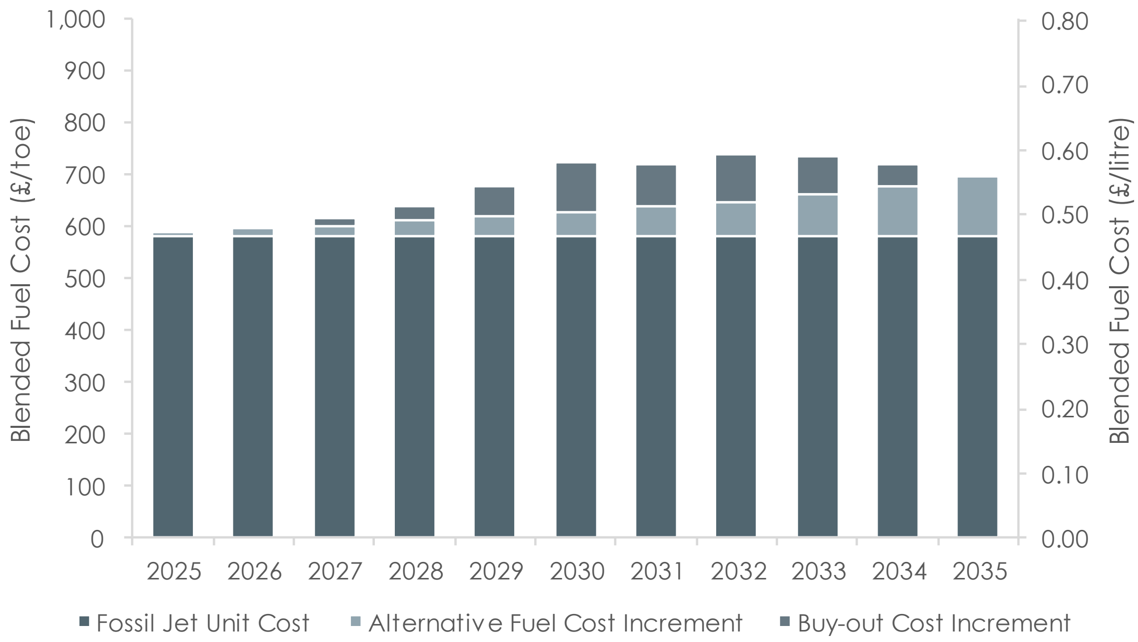


Figure 34 **Average cost of blended jet fuel for the G+FT Breakthrough scenario, showing increments to the baseline (fossil jet) which arise from purchase of alternative fuel and from buying out of SAF Mandate obligations**

4.4. Scenario 4: Pyrolysis Breakthrough

Pyrolysis Breakthrough is the last scenario which simply shuffles the dominance of the different BtL technologies. Figure 35, Figure 36, and Figure 37 respectively show the regulatory energy supplied by the five alternative fuel technologies; the growth in plant building (which reflects the smaller size of typical pyrolysis plants); and the unit cost impact on aviation fuel.

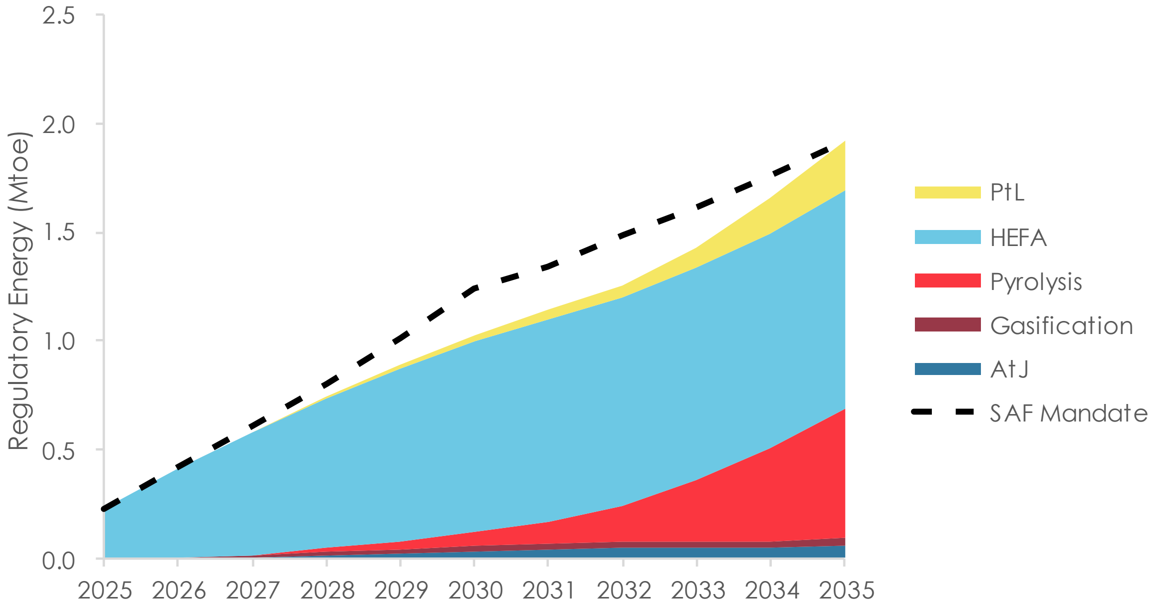


Figure 35 **Delivered fuel (with weighting factors) by type for the Pyrolysis Breakthrough scenario**

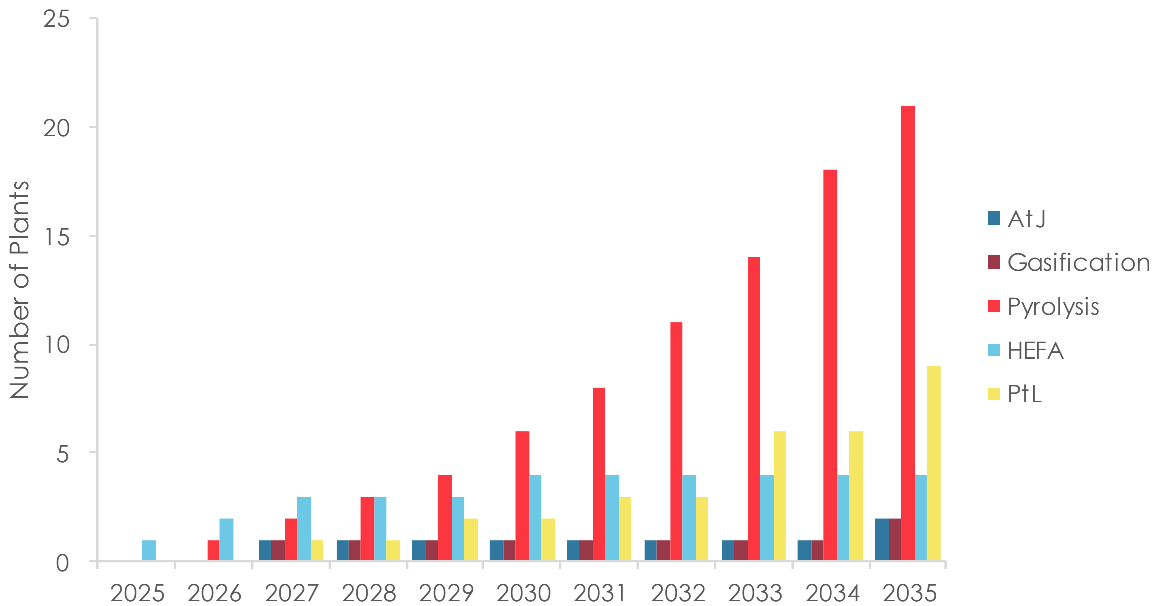


Figure 36 **Number of plants in operation, split by technology, for the Pyrolysis Breakthrough scenario**

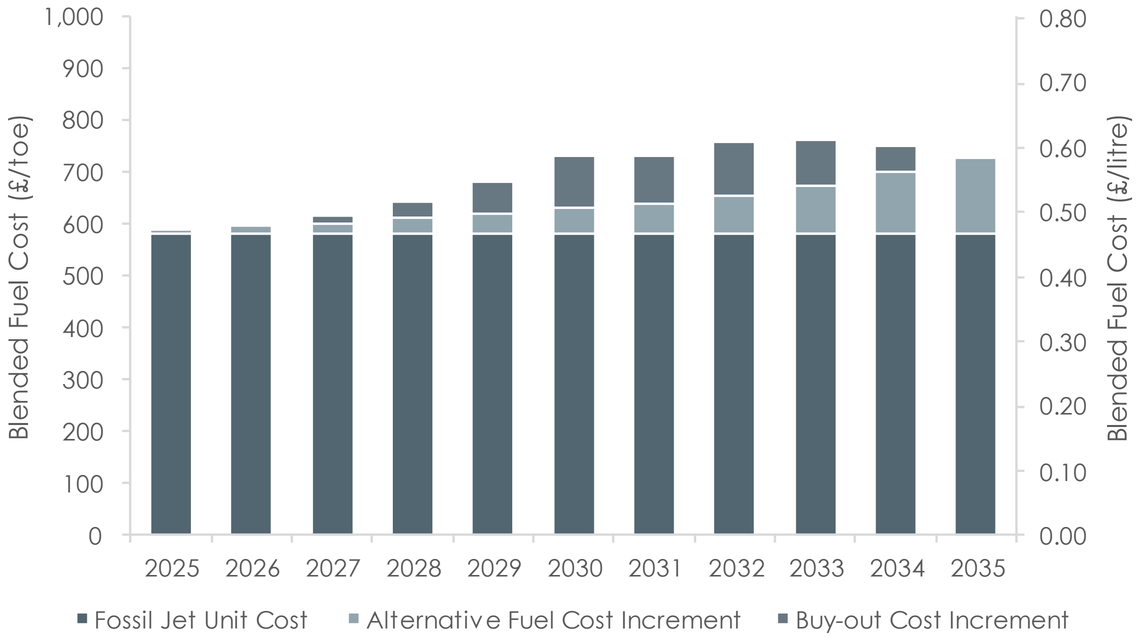


Figure 37 **Average cost of blended jet fuel for the Pyrolysis Breakthrough scenario, showing increments to the baseline (fossil jet) which arise from purchase of alternative fuel and from buying out of SAF Mandate obligations**

4.5. Scenario 5: PtL Breakthrough

For the PtL Breakthrough scenario, we use PtL growth parameter that is approximately 50% higher than in previous scenarios – i.e., 50% higher than what we found would be needed for meeting, on average, the Mandate's PtL target (see Figure 20). In addition, the time interval between plant generations is shortened by 20%. For this scenario we allow PtL plants to be built even if production of PtL jet fuel exceeds the PtL target. However, all technologies, including PtL, are still constrained by the overall target; when alternative fuel production surpasses the main target, plant construction ceases.

HEFA consumption is unchanged from previous scenarios, and we assume a token amount of BtL plant construction that leaves room for PtL to make up the – otherwise, the PtL Breakthrough scenario would end up delivering significantly more fuel than the other scenarios, leaving only a limited basis for the forthcoming comparison (discussed in Section 3.4).

Figure 38 shows the fuel delivered from each technology pathway. The dominance of PtL is evident: in this scenario, a cumulative total of 3.4 Mtoe of PtL fuel (regulatory value) is delivered in the period 2025-35, compared with 0.5 Mtoe in the other scenarios. See also the comparison in the next section, Section 4.6.

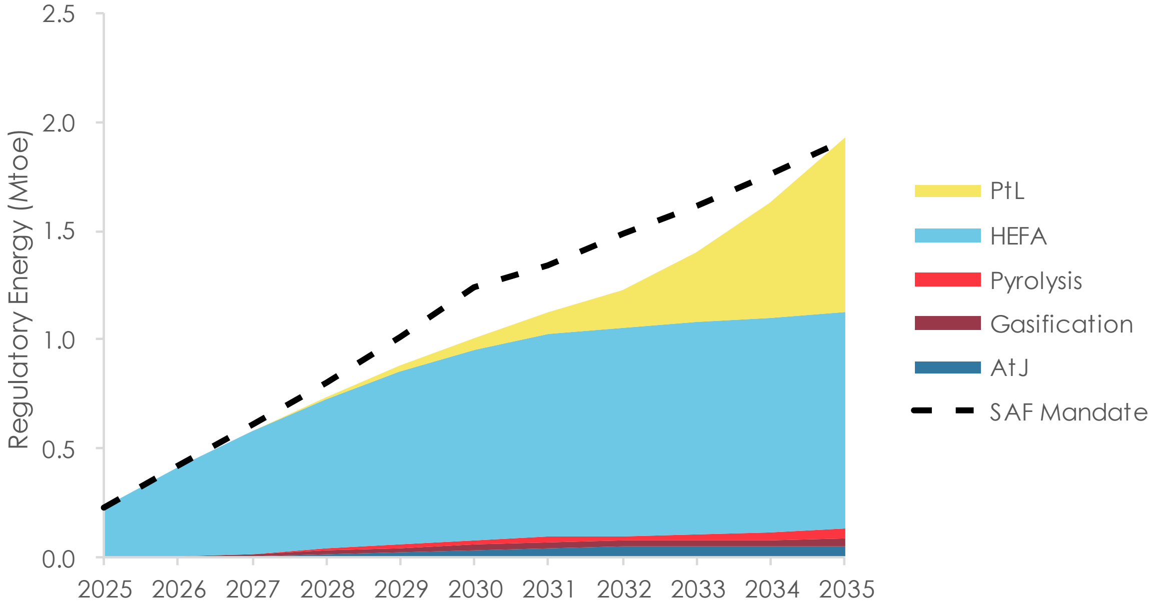


Figure 38 Delivered fuel (with weighting factors) by type for the PtL Breakthrough scenario

Rapid construction of PtL facilities is evident in Figure 39, reaching 24 plants in 2035 – compare with the standard building rate in e.g. Figure 36. Since only PtL scales to meet the target beyond the HEFA cap in this scenario, PtL construction will only cease once the main target is fulfilled.

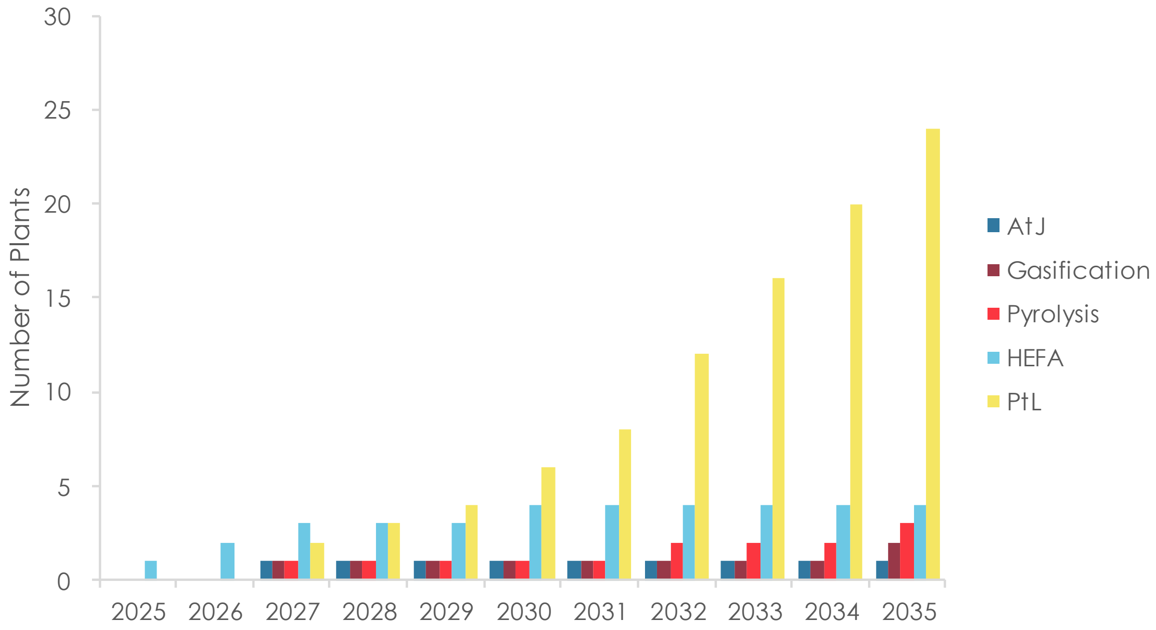


Figure 39 **Number of plants in operation, split by technology, for the PtL Breakthrough scenario**

The implied demand for PtL electricity is shown in Figure 40 – this easily eclipses what was found in the other scenarios (Figure 26), surpassing 3.5% of projected national demand throughout the whole economy in 2035.

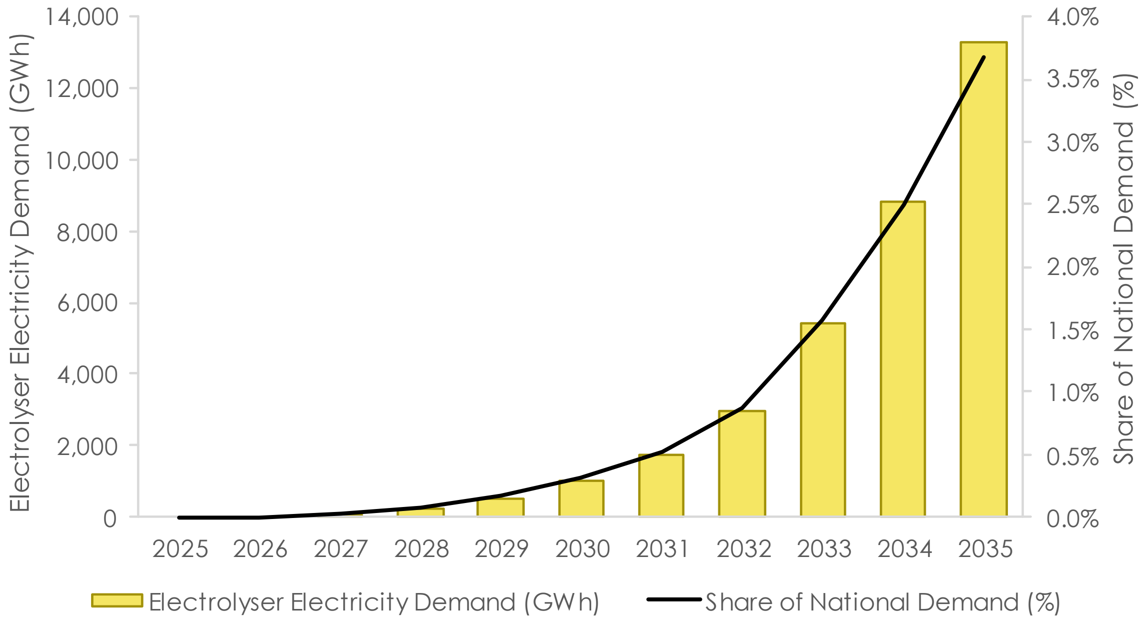


Figure 40 **PtL electrolyser electricity consumption, compared with national demand, for the PtL Breakthrough scenario**

Note: Resource use is for the jet fuel fraction only.

4.6. Scenario comparison

This section compares our scenarios side by side to more clearly discern the implications of the differing technology development paths.

4.6.1. Fuel supply

The introduction to the SAF Mandate drew a distinction between the physical volume of alternative fuel and the number of SAF certificates awarded – the difference being the weighting that accounts for the emissions intensity of the fuel being supplied. So, even though the scenarios have very similar compliance characteristics in 2035, the total volume of physical fuel supplied differs more significantly, as shown in Figure 41. For instance, the superior emissions performance which we assumed for PtL compared to AtJ and pyrolysis (see Figure 17) means that less fuel has to be supplied to meet the targets in the PtL Breakthrough scenario.

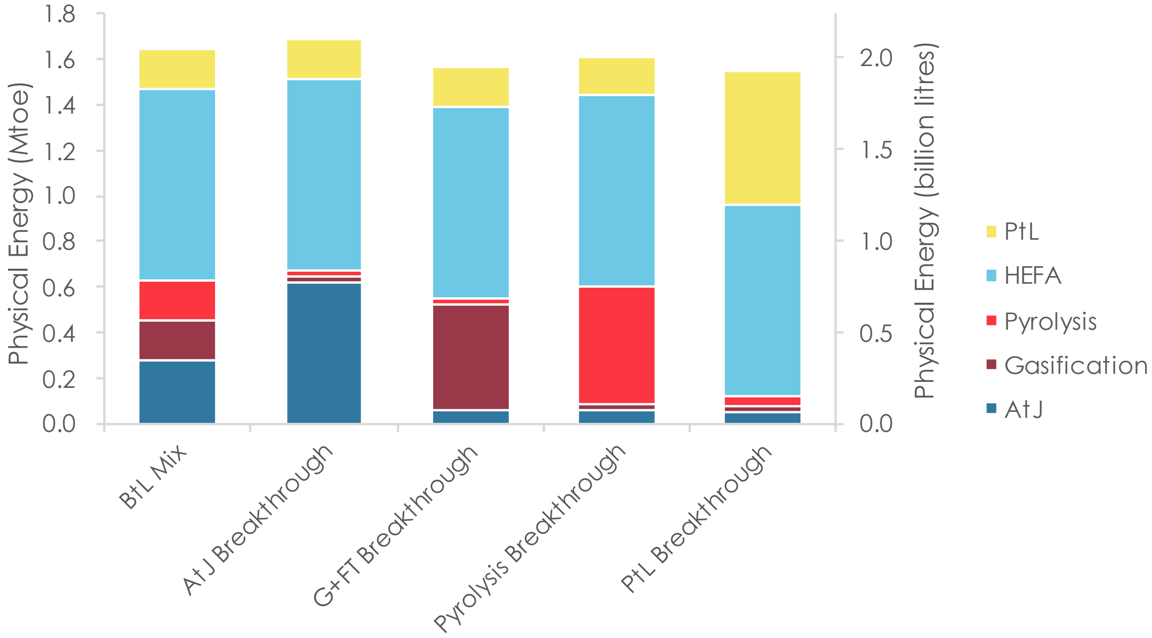


Figure 41 **Scenario comparison of physical energy supply from each fuel in 2035, in million toe and billion litres**

In 2022, just over 3.3 billion litres of renewable fuel was declared under the RTFO (UK Department for Transport, 2023f). The volume of renewable jet fuel required to fulfil the SAF Mandate in 2035 is therefore comparable to the present-day consumption of biofuels in the road sector. It is not impossible that the electrification of road transport will eventually free up volumes of biofuel which could be adapted for use in the aviation sector. However, the proposed SAF Mandate eligibility criteria (HEFA capped, waste and residue bio-feedstocks only, a major role for PtL) mean that there is in reality limited scope for this transfer from road to aviation. Moreover, short-term RTFO targets may well be adjusted to maintain the use of biofuels in the road sector. Either way, production and supply of alternative fuels would have to roughly double in the next ten years in order to meet the extra aviation demand.

4.6.2. Plant construction

The total number of plants built is another distinguishing factor between the scenarios – naturally, a technology like AtJ which tends to need larger plants to achieve technoeconomic feasibility will also require fewer plants. This is apparent in Figure 42.

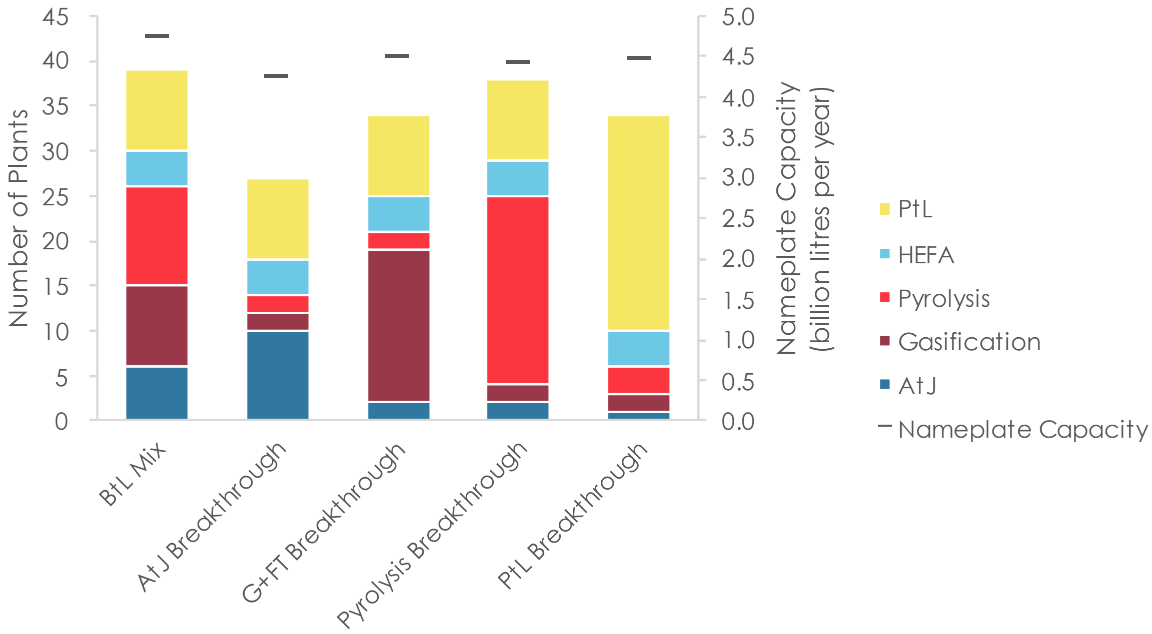


Figure 42 **Cumulative number of plants built up to 2035 for each scenario, split by plant type, indicating total production capacity**

In all, the modelling suggests that, depending on the technology mix, between 27-39 new alternative jet fuel production plants would have to be operational in 2035 in order to supply the UK's requirements. Many of these will be generation 1 and 2, which must be built first to develop the technology; but even so, there is no question that the pace of development required will be enormously challenging to deliver.

This modelled total is naturally sensitive to our capacity assumptions and the pace at which the technologies mature through the generations, and so we compare the result with the E4Tech study (Sustainable Aviation, 2020), which used a similar modelling framework and similar parameters for plant sizes and construction rates. This study, published before the SAF Mandate was announced, concluded that a 'fast growth' scenario could see 14 plants built in the UK by 2035, provided the first was completed in 2023. The introduction of the SAF Mandate may yet galvanise the sector to catch up with and even surpass this trajectory; but the required pace of building would have to be distributed beyond the UK, and there will be a major role for imports into the UK in years to come. A 2023 report by ICF (commissioned by the same industry group as the E4Tech study, Sustainable Aviation) estimated that the UK was on track to supply only 50% of the 2030 Jet Zero / SAF Mandate target of 10% alternative jet fuel from domestic sources – and that even if plans for new capacity were to be announced, getting facilities built and operational in time may be challenging (Blanshard & Gibson, 2023).

The idea that the UK will have to resort to imports is widely accepted; but this in itself merely off-shores the issue of insufficient capacity by assuming that alternative fuels will be available on the global market. As noted in prior work on EU aviation fuel policy (Malins, 2023, Section 2.2), the rate of alternative fuel capacity development that would have to be achieved to meet the EU's targets is unprecedented. There is, therefore, likely to be considerable competition between jurisdictions for the available fuel volumes. This will be elaborated in Section 5.

The total investment required to build all these plants by 2035 is shown in Figure 43. The gasification-heavy scenario is modelled as the most expensive in terms of up-front cost (our unit CapEx values were shown in Figure 15). But as we shall see in the next sub-section, this does not necessarily translate into a higher average cost of the fuel output. In Section 5, we will return to the implications of high capital costs for the development of the alternative aviation fuels industry – especially in light of existing and planned public finance initiatives.

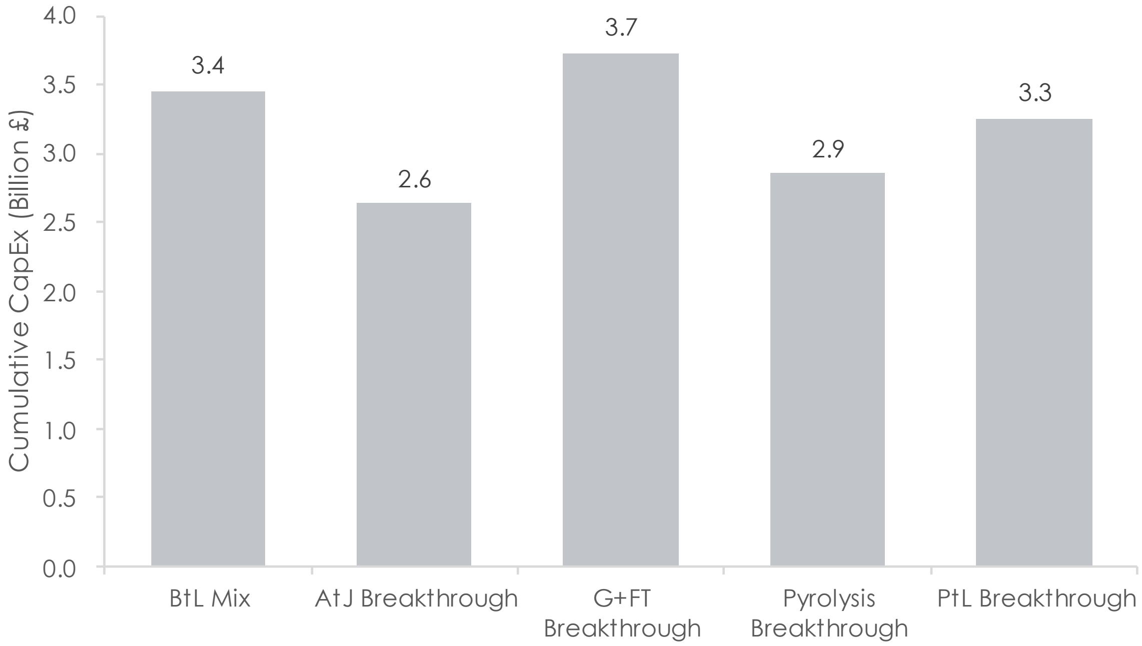


Figure 43 CapEx investment required by 2035, for each scenario

4.6.3. Fuel cost

All our scenarios fail to meet the SAF Mandate in the short term – we do not anticipate that industrial capacity could be built fast enough given the immature state of the technologies involved. This results in buy-out, making the buy-out price indicative of the value of SAF supply in the early years of the policy. The high buy-out level adopted by DfT will accelerate investment in alternative fuel production, while making the UK an attractive destination for alternative aviation fuel produced globally.

The evolving cost of a unit of average blended aviation fuel – including fossil and alternative components, as well as the bundled contribution from buying out – is shown in Figure 44. This is a combination of fuel cost results already presented for each scenario (see Figure 23, Figure 31, etc.). As a reminder, we assume that all SAF Mandate costs experienced by fuel suppliers are passed through to buyers (airports and airline companies). The lines are colour-coded according to the dominant fuel technology in the scenario, though all fuels contribute something to the overall cost of each scenario.

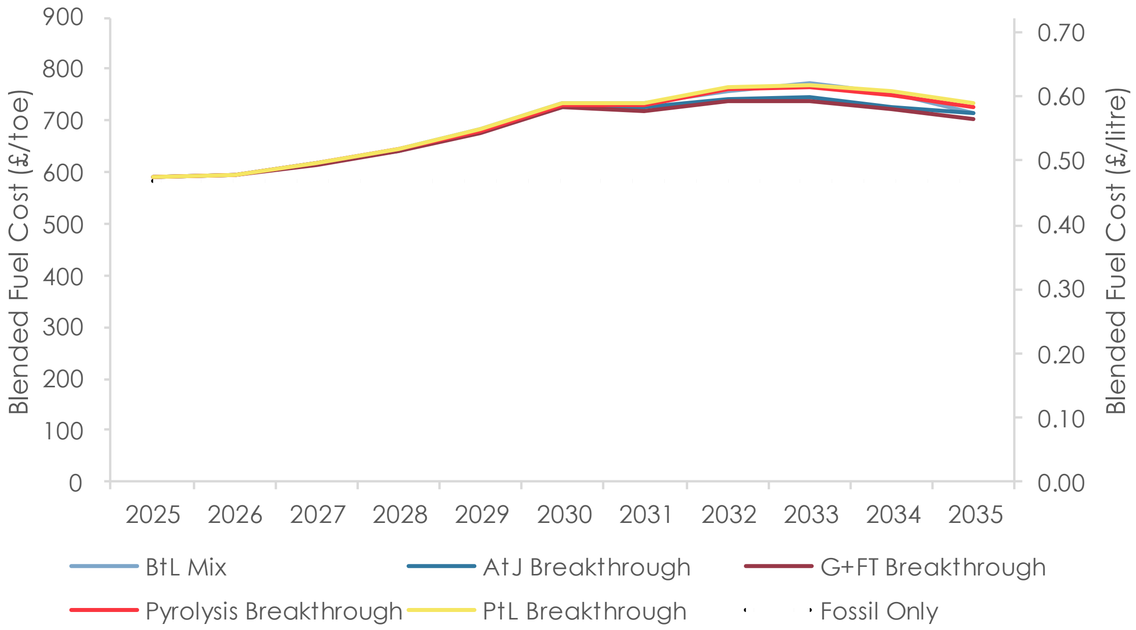


Figure 44 **Time-series of total fuel unit cost for each scenario, assuming full pass-through of compliance costs**

Note: Graphed lines are coloured according to the dominant fuel technology for each scenario (recall Table 5), though a mix of technologies contributes to each, as was shown in Figure 42.

Notwithstanding its higher assumed capital costs seen in Section 4.6.2, the gasification-dominated scenario delivers the lowest ongoing cost due to lower assumed operating expenses. Following DfT's Central fuel cost scenario (UK Department for Transport, 2024b), The increase on the average cost of aviation fuel in 2035 is in the range 120-150 £/toe (+20-26%). Considering just the buy-out costs during the whole 2025-35 period, about 8% of total cumulative fuel costs come from buy-out.

It is worth noting that both the additional fuel costs and additional buy-out costs experienced by fuel suppliers are sensitive to the HEFA cap and to the amount of HEFA actually gets supplied. The cap ultimately adopted by DfT was considerably higher than the maximum considered in the second SAF Mandate consultation (UK Department for Transport, 2021a), reflecting the expectation that other compliance options are limited in the near term. For this study we have assumed that the cap will be completely filled, but competition with other markets for compliant fuel volumes will certainly push up prices, and could lead to shortfalls in the UK and hence a need to buy-out.

4.6.4. Feedstock consumption

All scenarios considered in this study have the same level of HEFA consumption, and hence the same demand for lipid feedstock (shown in Figure 24). Demand for cellulosic biomass feedstock, on the other hand, depends on the volume of BtL fuel produced in each scenario (Figure 41), as well as the conversion efficiency of each BtL technology. These factors determine the demand levels shown in Figure 45. In PtL Breakthrough scenario there is naturally a reduced biomass demand.

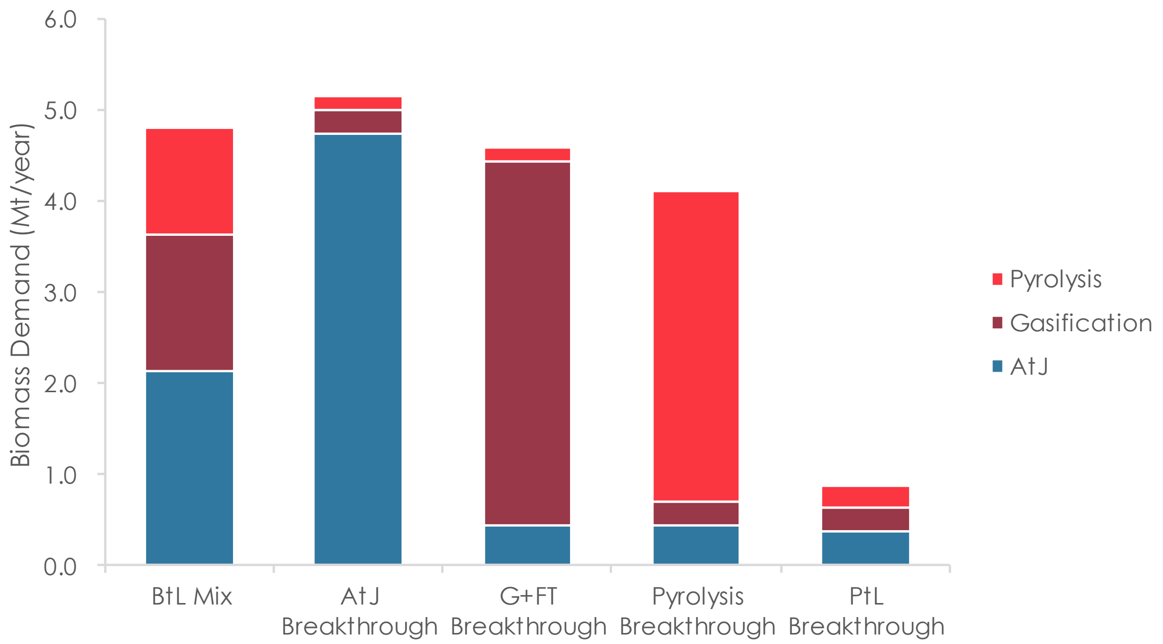


Figure 45 **Biomass feedstock consumption by conversion pathway in 2035 for each scenario**

Note: Resource use is for the jet fuel fraction only.

For context, we may look to the UK's Biomass Strategy, published in 2023 by the UK Department for Energy Security and Net Zero (DESNZ). This found that 370 PJ (about 25 Mt) of 'sustainable biomass' could be available domestically in 2035, or up to 500 PJ (about 32 Mt) with imports in the 'Restricted' scenario (UK Department for Energy Security and Net Zero, 2023a, Figure 4.3). Focussing in on feedstocks that could be used for SAF Mandate-compliant BtL fuels, we find that roughly 85% of the domestically-available resource (315 PJ, or 20 Mt) would fall into the category of wastes and residues (UK Department for Energy Security and Net Zero, 2023a, Figure 4.4). Further eliminating feedstocks that would be more appropriate for the production of biogas / biomethane (i.e. sewage, landfill gas, and animal manure), the figure falls to 226 PJ, or 14.5 Mt. This is consistent with research by the ICCT, which found about 16.3 Mt of relevant feedstocks could be sustainably produced in 2030 (Carraro et al., 2021). Neither of these figures are expected to grow significantly after 2035. Finally, the DfT estimates that between 3.7 and 7.4 Mt of appropriate biomass feedstocks will be available in 2035 (UK Department for Transport, 2024b, Figure 14).

The modelled results in Figure 45 show that around 5 Mt per year of dry biomass would be required by 2035 for the BtL-dominated scenarios. This figure covers the jet fuel fraction only – the actual feedstock demand which covers all fractions would be higher. While some fraction of BtL fuel is likely to be imported into the UK (cf. the DfT's domestic fuel production scenarios discussed in Section 1.4.2), domestic production would, under the BtL-dominated scenarios, have to claim a significant portion of the biomass that could be sustainably supplied. This would bring it into competition with other uses of biomass: in manufacturing, materials, and power generation[60]. Barring the rapid scale-up of PtL deployment, the SAF Mandate will require BtL production to continue ramping up past 2035, but a similar rate of growth is not expected for total feedstock availability. (Panoutsou & Maniatis, 2021) projects Annex IX biomass resources growing by only 2-5% in the UK between 2030-50, while the UK Department for Energy Security and Net Zero (DESNZ) shows practically net zero change in the availability of waste biomass in the same period (UK Department for Energy Security and Net Zero, 2023a, Figure 4.4). Biofuels' relatively low position in the waste management hierarchy (UK Department for Energy Security and Net Zero, 2023a, Figure 5.2) means securing enough feedstock to fulfil the SAF Mandate will be challenging if there is much demand in other sectors.

Figure 46 shows hydrogen demand for SAF production in each scenario. As mentioned in Section 4.1.4, fossil jet fuel production already consumes significant volumes of hydrogen (made from fossil natural gas), but the expectation is that the alternative fuels under consideration will require new sources of renewable hydrogen.

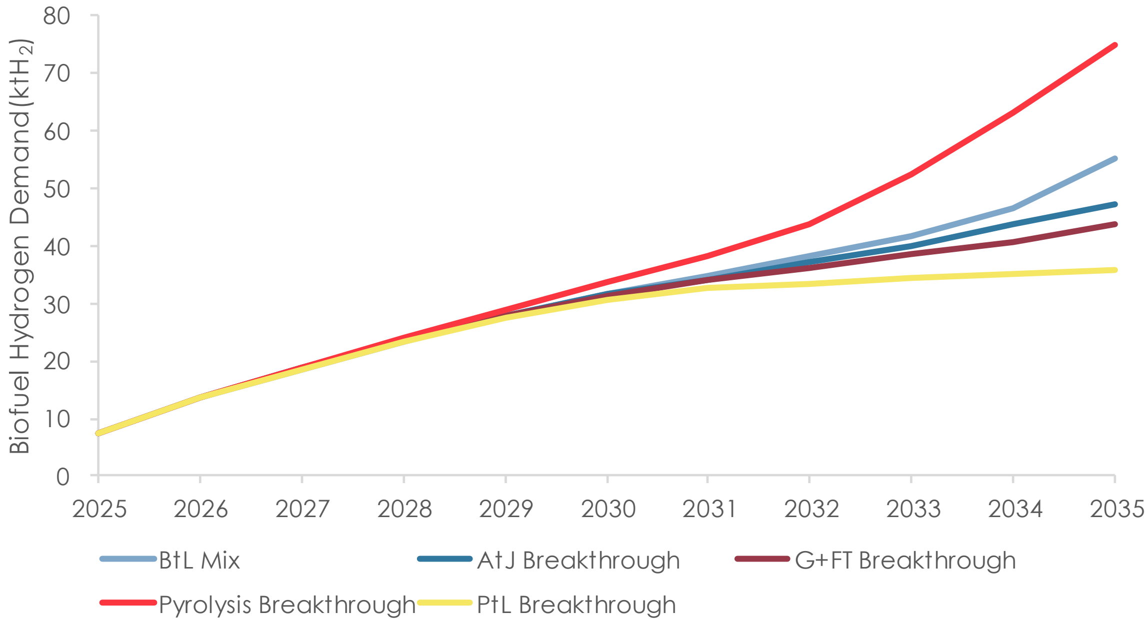


Figure 46 Biofuel hydrogen consumption over time for each scenario

Note: Resource use is for the jet fuel fraction only. Graphed lines are coloured according to the dominant fuel technology for each scenario (recall Table 5), though a mix of technologies contributes to each.

Figure 47 shows PtL electricity demand for the PtL Breakthrough scenario versus the other scenarios. The implied electricity consumption for running PtL electrolysers was compared to projected national electricity demand in Section 4.1.4 and Section 4.5. The modelling showed that a non-trivial share of the economy's resources would have to be devoted to the aviation sector: to achieve the SAF Mandate's PtL sub-target, the equivalent of 1.1% of the UK's total

[60] Another common use of biomass is for heating, but in the UK this comprises only 6% of national heat, or 0.2% of overall fuel and heat consumption in industry, buildings, and other sectors excluding transport (IEA Bioenergy, 2021).

national electricity demand (both renewable and non-renewable sources) would be needed to run electrolysers in 2035; this rises to 3.7% when we consider the PtL Breakthrough scenario[61].

It is worth remembering that, due to feedstock availability, land use impacts, and indirect effects, PtL based on additional renewable electricity is considered to be the most scalable avenue for the sustainable production of liquid fuels. But wherever the PtL industry begins to expand, it should stimulate some debate about the efficient allocation of low-carbon resources. For example, in the model scenarios where there was no breakthrough in PtL technology, 2035 sees 0.17 Mtoe of physical PtL jet fuel produced, requiring more than 3.8 TWh of electricity. This is enough to fly roughly 7 billion passenger-kilometres[62] (about 660,000 round-trips between LHR and JFK airports). If this power were supplied to battery electric vehicles it could deliver 21 billion kilometres of driving, based on today's average energy efficiency[63]. Assuming a single person per car, this would be equal to a year's worth of daily driving for 3 million people[64], and the number would rise with multiple occupancy. For the PtL Breakthrough scenario, these numbers are multiplied by a factor of 3.5.

In a future where there is competition for available renewable electricity supply, it is debatable whether PtL would represent the most efficient use in the short and medium term. This being said, the technologies that PtL depends on – electrolytic hydrogen and carbon dioxide capture – are positioned to be critical for applications beyond aviation, and PtL jet fuel may be an early use-case capable of funding the early stages of their development. Due to the potentially long incubation times for new, relatively expensive technologies to become capable of displacing incumbent systems, it is plausible that an inefficient investment of resources now may yet become a future boon. The case can be made for or against the PtL 'opportunity cost'; it will be interesting to see which side turns out to be more convincing to policy- and decision-makers.

[61] These values consider only the jet fuel fraction of the PtL output. The full electricity demand to produce all the hydrocarbon co-products will be higher still.

[62] Derived from data on UK emissions and flight distances (Graver et al., 2020). For reference, flights departing UK airports in 2019 racked up 365 billion passenger-kilometres.

[63] https://ev-database.org/uk/cheatsheet/energy-consumption-electric-car

[64] https://evbox.com/uk-en/how-much-electricity-does-an-electric-car-use

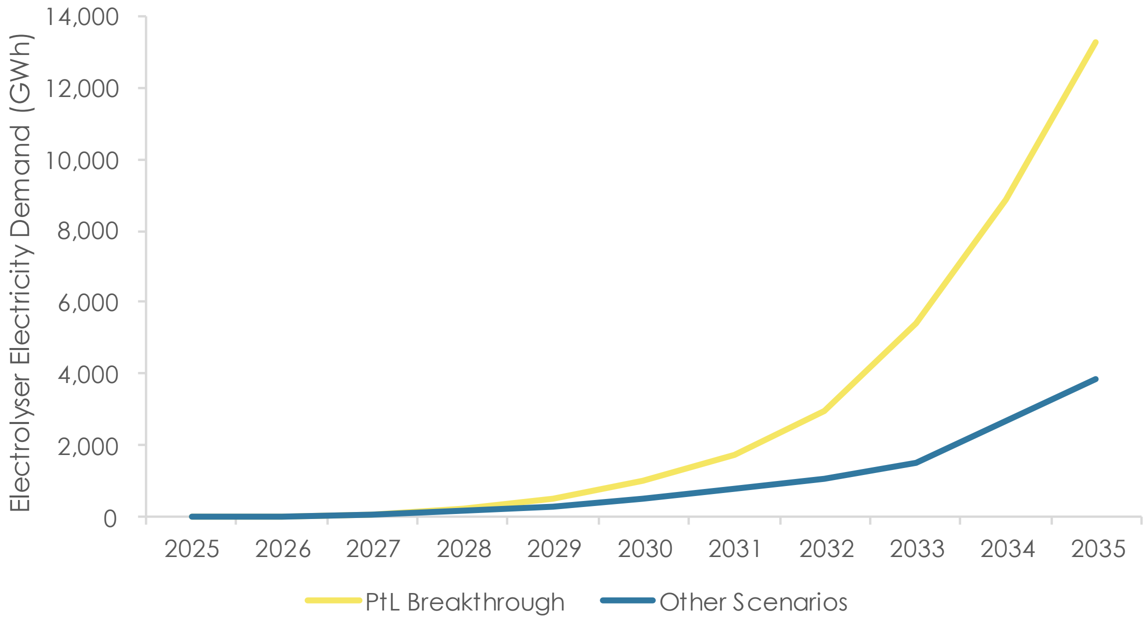


Figure 47 **PtL electricity consumption over time for the PtL Breakthrough scenario and for the other scenarios**

Note: Resource use is for the jet fuel fraction only.

4.6.5. Emissions

The main goal of the SAF Mandate is to reduce emissions from aviation. Mathematically, the emissions saving in a given year is proportional to the number of SAF credits issued; since the scenarios are designed to deliver more or less the same number of certificates in 2035, we would expect the emissions saving in 2035 to be similar for all scenarios, and this is indeed the case, as can be seen in Figure 48. The lines are not perfectly co-incident as each scenario follows a slightly different emissions path to the common end point (owing to the different rates of decarbonisation of the dominant fuels and the scenario-specific sequence of plant construction that leads to different levels of fuel supply in each year).

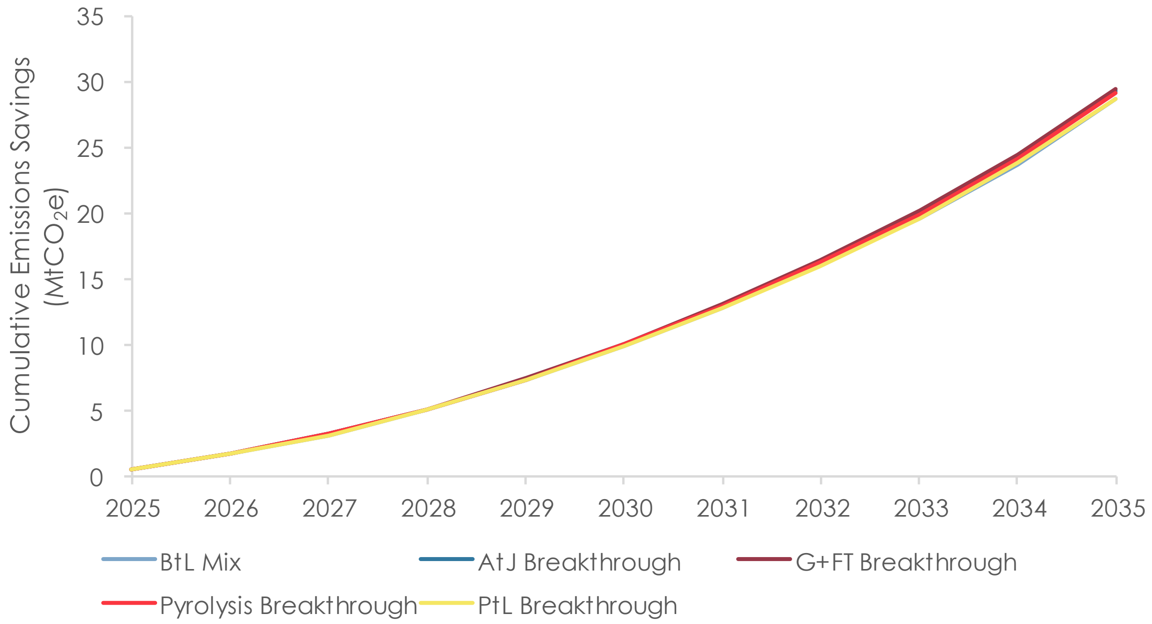


Figure 48 **Cumulative emissions savings from the use of alternative jet fuel for each scenario between 2025-2035**

Note: Emissions savings from the use of the jet fuel fraction only. Graphed lines are coloured according to the dominant fuel technology for each scenario (recall Table 5), though a mix of technologies contributes to each.

In a fossil-only scenario where there were no SAF Mandate and no alternative fuels are supplied in the UK, we would expect to see cumulative emissions of around 495 $MtCO_2e$ between 2025 and 2035. Hence, the modelled savings of roughly 29 $MtCO_2e$ as seen in Figure 48 would represent a 5.8% reduction in cumulative greenhouse gas emissions compared to the fossil-only counterfactual.

Combining the emission savings presented in this section with the cost impacts of Section 4.6.3, we calculate the implied cost of greenhouse gas abatement under the SAF Mandate, for each of our scenarios. The result is shown in Figure 49. On the same graph, the black dashed line represents the 2035 carbon value required to achieve net zero by 2050[65]. This carbon value is modelled by the DESNZ, based on the UK's Net Zero Strategy (UK Department for Energy Security and Net Zero, 2023b); the graphs shows the central estimate.

[65] Substitution of high-emissions technologies and processes, e.g. those using fossil fuels, with lower-emissions alternatives often comes at a cost in the short term: the carbon value is the difference in cost or the subsidy that would have to be paid by society to shift towards lower-emissions technologies in pursuit of the net-zero goal.

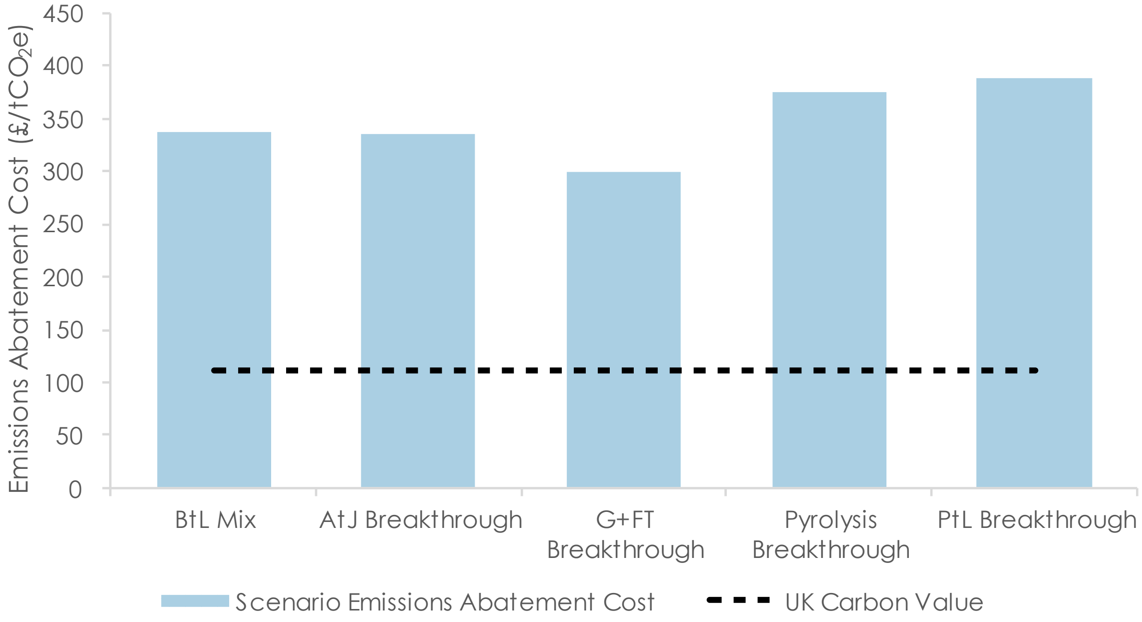


Figure 49 **Cost of greenhouse gas emissions abatement ('cost of carbon') in 2035 under the five scenarios, compared with the UK Government's predicted carbon value**

These abatement costs are predicated on DfT's central modelling results which are lower than other estimates in the literature (e.g. Pavlenko et al., 2019, Figure 6 shows significantly higher costs for PtL and AtJ pathways). In any case, as was already mentioned in Section 4.1, existing carbon markets have to date witnessed credit values in the region 100-200 $/tCO_2e$. Aviation is a rapidly growing emitter of greenhouse gas, but is characterised as a hard-to-decarbonise sector compared with power generation and even road transport. Thus it should come as no surprise that the value of emissions avoidance will have to reach a higher level in order to deliver decarbonisation.

Figure 49 shows that according to the DfT's cost modelling (discussed in Sections 2.3 and 3.2), the cheapest route to reducing emissions is given by the G+FT scenario. Major hurdles remain, however, as building facilities for gasification and Fischer-Tropsch synthesis is expensive compared to other technologies (see Figure 43). The larger average size of these plants compared to, say pyrolysis plants makes them a little less modular, and increases the catchment radius for feedstock collection. As discussed in Section 4.6.5, the availability of suitable feedstock is not necessarily guaranteed.

There is some agreement and some disagreement between the hierarchy of emissions abatement costs shown in Figure 49 and the DfT's assessment (UK Department for Transport, 2023e, Figure 10). DfT compared the price paid for alternative aviation fuel per tonne of CO_2 avoided (£/tCO_2 in the figure) with three 'carbon appraisal values' from DESNZ: when the price is high, then it could be considered a cost-ineffective way to reduce emissions, and vice-versa. For DESNZ's central estimate, DfT found that (waste-and-residue-based) HEFA and gasification are already cost-effective; pyrolysis and AtJ become cost-effective around 2035; and PtL between 2045 and 2050. The ordering of PtL and AtJ is therefore switched compared to the model assumptions, owing in part to the lower greenhouse gas savings we have ascribed to AtJ.

It bears mentioning again that only the greenhouse gas emissions are considered in the DfT's carbon cost analysis; radiative forcing from contrail formation is not taken into account. This is a common omission in such analyses, even though non-CO_2 effects are just as significant on average, and ignoring them risks over-playing the benefits of alternative fuels over other measures like demand reduction and mandating lower particulate emissions from engine exhausts.

5. Discussion

5.1. SAF Mandate scenarios

The UK's SAF Mandate aims to reduce the environmental impact of flights leaving the UK by obligating fuel suppliers to procure a minimum share of alternative aviation fuels. The minimum is set to increase over time, and fuels are to be credited in proportion to their (direct) lifecycle greenhouse gas emissions. The scheme therefore creates an incentive for investment in low-carbon fuel production technology, as well as incremental improvements to related industrial processes.

The UK Department for Transport (DfT) has laid out some of the foundational rules that will govern the working of the SAF Mandate (UK Department for Transport, 2024a); though at the time of writing these have not yet been legislated. In this report we have explored five pathways for meeting the SAF Mandate targets between 2025 and 2035, and assessed their implications for fuel supply, cost, greenhouse gas emissions and resource consumption. The five scenarios place different weights on fuel production technologies: alcohol-to-jet, gasification with Fischer-Tropsch synthesis, pyrolysis with catalytic upgrading, and power-to-liquid jet fuel.

A major conclusion of the study is that it will be very difficult to meet SAF Mandate's ambitious targets in the near term[66]. This is notwithstanding the concession to allow high volumes of first-generation biofuel (i.e. HEFA) to contribute; the increase of the targets over time is likely to outpace the development and deployment of alternative jet fuel production facilities (notwithstanding government support schemes, discussed momentarily). This is not necessarily a bad thing: an ambitious, stretching target can send an unambiguous signal to the alternative fuels industry that consumption of fuels with low direct lifecycle emissions will be strongly incentivised in UK aviation. If the SAF Mandate is successful, the UK will be able to report world-leading reductions in aviation sector emissions. However, these may come to some extent at the expense of emissions increases in other industries due to resource diversion – a fact that is already acknowledged by the DfT.

Until alternative fuel production catches up with the SAF Mandate target, we expect to see a reliance on the 'buy-out' pathway, where fuel suppliers pay a fee in lieu of satisfying their obligations to supply alternative fuel. While this does not deliver any emissions reductions, it may nevertheless be seen as an effective way to galvanise investment in alternative fuels, as obligated parties know they will save money if they can source SAF that has a lower marginal cost than the buyout price. It will also have a secondary effect of reducing fuel demand (cf. UK Department for Transport, 2024a, Paragraph 4.49).

[66] Cf. Section 4.6.3 which shows the modelled buy-out cost.

5.2. Costs and investment

The scenarios considered in this report suggest fuel cost increases of 20-26% in 2035 compared to prevailing rates for fossil jet fuel, based on the fuel cost projections by DfT[67]. This corresponds to 0.10-0.12 £/litre. To get to the point of using alternative fuel volumes, significant up-front investment in building production capacity would be needed: over the SAF Mandate's initial 2025-35 period, model results indicated an investment requirement of £2.6 to £3.7 billion (around $3.3-4.6 billion), depending on the scenario[68]. Many of these plants will be smaller-scale generation 1 and 2 plants; however, achieving decarbonisation goals beyond 2035 will require continued building of larger and more capital-heavy 'generation N' and 'generation N+1' plants.

Given this scale of investment, it is worth considering whether the SAF Mandate alone will be sufficient to propel the nascent industry to meet its ambitious targets. The UK Government has established the Advanced Fuels Fund (AFF) to allocate grants to UK-based fuel producers and prospective producers[69]. The fund amounts to £135 million – a fraction of what would be needed to build the first five UK plants promised by the government by 2030, and about 4% of what is needed by 2035 according to our model results. Moreover, some of the AFF is directed towards R&D and pilot studies rather than the building of commercial fuel-producing plants.

A recent report to the UK Government (New, 2023) reported an 'industry consensus' that interventions beyond the AFF would be necessary to assure a sufficient pace of capacity expansion. This is in part because capital-intensive projects must rely heavily on debt financing, which typically comes with a low risk appetite. Unfortunately for project developers seeking loans with commercially viable interest rates, the industry is still a long way from being able to demonstrate predictable business models based on well-established technologies.

The U.S. Government's 'SAF Grand Challenge' targets 3 billion gallons (11.4 billion litres) of alternative aviation fuel by 2030 (U.S. Department of Energy et al., 2022). It is estimated that building this much production capacity and transport infrastructure will cost approximately $30 billion (U.S. Bioenergy Technologies Office, 2022)[70]. The SAF Grand Challenge's 2050 target of 35 billion gallons, to replace 100% of jet fuel, will require hundreds of billions of dollars of capital investments. The U.S. has initiated a number of relevant grant programmes (called Funding Opportunity Announcements, FOAs) under the Inflation Reduction Act and the Infrastructure Investment and Jobs Act. FOAs in 2021[71], 2022[72], and 2023[73] between them allocated $231 million to projects in the pre-commercialisation phases of development. Many of these

[67] See Section 4.6.3.

[68] See Section 4.6.2.

[69] See Section 1.1.4.

[70] The U.S. SAF Grand Challenge places a lesser emphasis on advanced technologies, and so the cost is lower than for an equivalent production capacity in the UK.

[71] https://www.energy.gov/eere/bioenergy/articles/us-department-energy-announces-more-64-million-biofuels-research-reduce

[72] https://www.energy.gov/eere/bioenergy/articles/us-department-energy-announces-59-million-expand-biofuels-production-and

[73] https://www.energy.gov/eere/bioenergy/articles/us-department-energy-awards-118-million-accelerate-domestic-biofuel

focussed on aviation fuels or closely related industries. Award values ranged from $0.5 to $5 million[74] – comparable to or lower than those made through the UK's AFF (see Table 1). In theory, the U.S. Government is prepared to cover up to 80% of project costs for pre-pilot projects, and up to 50% of costs for pilot-stage and demonstration-stage projects (Messner, 2022).

Beyond grants, both the U.S. Department of Agriculture (USDA)[75] and the U.S. Department of Energy (DoE)[76] have mechanisms to guarantee loans for advanced fuels projects. These cover up to 80% of project costs. Such schemes offer an alternative form of support for projects which were unsuccessful in securing direct funding – indeed, the SAF Grand Challenge Roadmap (U.S. Department of Energy et al., 2022) acknowledges that securing debt financing can be especially difficult for first-of-a-kind commercial deployments of novel SAF feedstocks. Long-term policy signals could be instrumental in securing such finance.

The UK is in the process of developing proposals for Government-backed revenue certainty mechanisms[77], in order to catalyse investment in UK fuel production and provide certainty to lenders (UK Department for Transport, 2023a). The two options on the table are[78]: (i) a price floor, whereby a Government entity commits to buying SAF Mandate credits at a set price; and (ii) a price stability guarantee like a 'contract for difference', whereby a fuel producer would agree a target price for their produced fuel with a Government entity, and the latter would step in to make up the difference when the market price falls below this level (and receive the surplus when the market price rises above it). These schemes could be seen as a form of insurance on SAF mandate credit prices for fuel suppliers: insurance which would in turn support investment by providing investors with a government-backed assurance of risk reduction. The timeline for introduction of a revenue certainty mechanism has been set for the end of 2026; until then, the AFF and the SAF Mandate will remain the UK's primary policy drivers.

5.3. Competition for fuel

While the UK Government and UK-based industry are keen to position themselves as leaders in alternative aviation fuels[79], the DfT acknowledges that some portion of the fuel required for meeting SAF Mandate targets will have to be imported. But the existence of other alternative aviation fuel markets introduces competition for the limited volumes that are expected to be produced.

---

[74] Barring one project which received $80 million to support construction of a 1.2 million gallon (4.6 million litre) demonstration plant, producing BtL aviation and road fuels, https://www.energy.gov/sites/default/files/2023-01/2638-1618_AVAPCO_LLC_Subtopic_Area_3_SummaryAbstract.pdf.

[75] https://www.rd.usda.gov/programs-services/energy-programs/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance-program

[76] https://www.energy.gov/lpo/loan-programs-office

[77] Long-term subsidies for fuel producers are not under consideration.

[78] As discussed in Section 1.1.4.

[79] https://www.sustainableaviation.co.uk/

The EU's ReFuelEU Aviation Regulation will soon set ambitious and binding targets for the use of alternative fuels, including PtL, in the EU (Baldino, 2023; European Union, 2023). The Regulation's compliance criteria match up well with the UK's developing system, meaning that a given batch of fuel could likely be used in either market. Some EU Member States like Germany and Sweden, and non-EU countries like Norway, already established national aviation blending mandates during the RED II era, with associated support measures for their alternative fuels industries. The SAF Grand Challenge also represents a significant level of demand – though its fuel eligibility criteria have less overlap with the developing UK and EU systems, and hence direct competition will be limited[80]. Also relevant is the possibility that China will introduce aviation blending mandate (Aizhu, 2024): referring back to Figure 4, we see that China was the top originator of UCO for UK aviation fuel; it also supplied 25.6% of feedstock for HVO (UK Department for Transport, 2023c). Measures that would increase Chinese domestic demand for HEFA feedstock and cut exports may make it harder for the UK to hit SAF Mandate targets.

The fact that the UK will be one of a number of possible destinations for alternative fuel is a double-edged sword. On one hand, it provides layers of assurance to the industry that there will be a ready and diversified pool of demand, stimulating greater investor confidence than could have been achieved with a single market (no matter how generous the incentives). On the other hand, competition for limited supplies of alternative fuel, which is likely in the near term, may drive up prices, with fuel ultimately flowing to the market that is willing to pay the most.

Due to the high buy-out price set by DfT, there will be a high ceiling on what UK fuel suppliers are prepared pay to stay compliant. It is not trivial to compare this with ReFuelEU Aviation's non-compliance penalty, which is dynamically set to be at least double the difference between conventional and alternative fuel cost in each given year (European Union, 2023, Article 12.4)[81]. If we take HEFA as the benchmark alternative fuel for the overall alternative fuel target[82], then the DfT's fuel price scenarios (optimistic, central, pessimistic) imply ReFuelEU penalties which are easily lower than DfT's adopted buy-out price of about 5,900 £/toe – see the left of Figure 50. In the context of PtL sub-mandates, the ReFuelEU penalty calculated on the difference between PtL cost and fossil jet fuel cost may exceed those of the UK buy-out by a considerable margin – see the right of Figure 50.

[80] According to government predictions, 90% of this fuel will be HEFA in 2030, and in the years that follow there will be far more emphasis on starch- and sugar-based production pathways (U.S. Department of Energy et al., 2022).

[81] Moreover, as noted in Section 1.2.5, the ReFuelEU Aviation penalty doesn't discharge the fuel supplier's obligation as they still have to make up their deficit in the following year. This strengthens the EU's deterrence to non-compliance, making it a more attractive market. However, for the present comparison, we put this issue to one side and compare the systems based on penalty / buy-out value alone.

[82] This will be at the discretion of the Member State implementation. It isn't impossible that Member States will be lenient in imposing penalties in early years, which could add uncertainty to the EU market while prolonging the advantage enjoyed by the UK market.

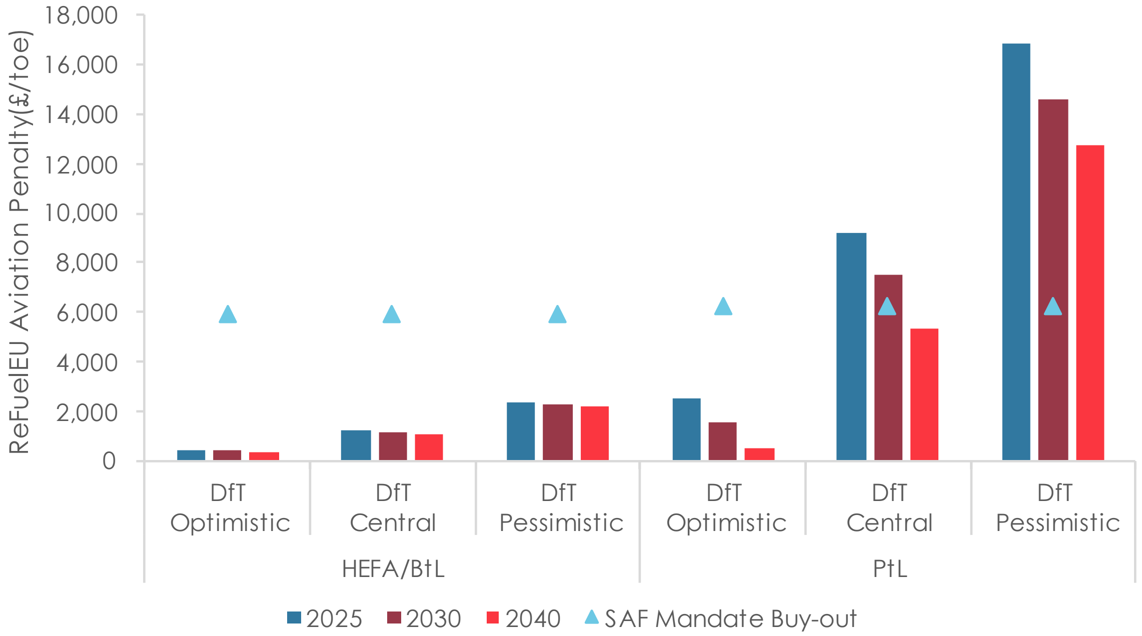


Figure 50 **Estimated ReFuelEU Aviation non-compliance penalties compared with the SAF Mandate buy-out price, considering HEFA and PtL jet as benchmark fuels, and invoking DfT's three fuel price projections**

If the UK maintains a higher effective ceiling on the price paid for BtL fuels (i.e. a relatively high buy-out price), it would be able to pull in extra volumes of BtL fuel that would otherwise have gone to the EU market. The ReFuelEU Aviation Impact Assessment estimates that EU AtJ production could reach 1 Mtoe in 2030, and that AtJ and gasification could together exceed 8 Mtoe in 2040 (Giannelos et al., 2021, Figure 42). Comparing with, e.g., Figure 19 above, we see this would be more than enough to plug the shortfall in the UK's targets (though in practice, we might expect EU Member States to strengthen the value signal if such export flows were undermining delivery of their targets). By the same token, UK policy-makers should note that unless low renewable electricity prices allow for relatively low-cost production of PtL, the EU may present a more attractive market.

5.4. In pursuit of a sustainable policy signal

Competition for a limited supply of eligible finished fuels may well spur investment and help the nascent industry to grow, but prices will inevitably rise in periods where fuel suppliers struggle to comply with their obligations. It would be a useful exercise to anticipate the possible 'failure modes' of the SAF Mandate, i.e. how a transient short-fall in fuel supply might play out. There is a risk that such a situation would be exploited by operators in the aviation industry wishing to undermine the SAF Mandate – for instance through reductions in targets, lowering of buy-out prices, or weakening of sustainability safeguards in order to allow a wider range of fuels and feedstocks to contribute (Malins & Sandford, 2022). Indeed, the DfT has already committed to intervening to control high prices, and has explicitly kept the door open to crop-based fuels (UK Department for Transport, 2024a).

It is critical that the SAF Mandate is established as a stringent but stable long-term strategy for decarbonisation of a sector with few existing alternatives. Only this will stimulate the development and production of 'SAF' that is sustainable in more than name.

References

Anuar, A., Undavalli, V. K., Khandelwal, B., & Blakey, S. (2021). Effect of fuels, aromatics and preparation methods on seal swell. *The Aeronautical Journal*, *125*(1291). https://www.cambridge.org/core/journals/aeronautical-journal/article/effect-of-fuels-aromatics-and-preparation-methods-on-seal-swell/CF929FF16F530C8ECBB1D454872E9EA4#

Atsonios, K., Kougioumtzis, M. A., Panopoulos, K. D., & Kakaras, E. (2015). Alternative thermochemical routes for aviation biofuels via alcohols synthesis: Process modeling, techno-economic assessment and comparison. *Applied Energy*, *138*, 346–366. https://doi.org/10.1016/j.apenergy.2014.10.056

Baldino, C. (2023). *Provisions for transport fuels in the European Union's finalized "Fit for 55" package*. https://theicct.org/wp-content/uploads/2023/07/fuels-fit-for-55-red-iii-jul23.pdf

Blanshard, A., & Gibson, I. (2023). Roadmap for the development of the UK SAF industry. In *ICF International; UK Sustainable Aviation*. https://iuk.ktn-uk.org/wp-content/uploads/2022/07/Sustainable-Aviation-SAF-Roadmap-Final.pdf

Cantarella, H., Mendes Souza, G., Nogueira, H., Filho, R. M., Costa De Paiva, G., Canabarro, N. I., Ortiz, P. S., Ekbom, T., Felipe, J., & Silva, L. (2023). Assessment of successes and lessons learned for biofuels deployment Assessment of successes and lessons learned for biofuels deployment Report Work package 2 | Meta-analysis of existing studies Published by IEA Bioenergy. *IEA Bioenergy*. https://www.ieabioenergy.com/wp-content/uploads/2023/08/IEA-Bioenergy-ITP-Assessment-of-successes-and-lessons-learned-for-biofuels-deployment.pdf

Carraro, C., Searle, S., & Baldino, C. (2021). *Waste and residue availability for advanced biofuel production in the European Union and the United Kingdom*. *2050*(July). https://theicct.org/wp-content/uploads/2021/12/eu-uk-biofuel-production-waste-nov21.pdf

Crawford, J. T., Shan, C. W., Budsberg, E., Morgan, H., Bura, R., & Gustafson, R. (2016). Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: Techno-economic assessment. *Biotechnology for Biofuels*, *9*(1), 1–16. https://doi.org/10.1186/s13068-016-0545-7

Elgowainy, A., Han, J., Wang, M., Carter, N., Stratton, R., Hileman, J., Malwitz, A., & Balasubramanian, S. (2012). *Life-Cycle Analysis of Alternative Aviation Fuels in GREET*. https://www.anl.gov/argonne-scientific-publications/pub/127787

Elgowainy, A., Mintz, M., Lee, U., Stephens, T., Sun, P., Krishna, R., Zhou, Y., Zang, G., Ruth, M., Jadun, P., Connelly, E., & Boardman, R. (2020). *Assessment of Potential Future Demands for Hydrogen in the United States*. https://doi.org/https://doi.org/10.2172/1710201

Erbach, G., & Jensen, L. (2021). EU hydrogen policy: Hydrogen as an energy carrier for a climate-neutral economy. *European Parliamentary Research Service*, *April*, 8. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI(2021)689332_EN.pdf

European Commission. (2020a). Assessment of ICAO's global market-based measure (CORSIA) pursuant to Article 28b and for studying cost passthrough pursuant to Article 3d of the EU ETS Directive. In *2020*. https://doi.org/10.2834/714858

European Commission. (2020b). Communication COM/2020/301: A hydrogen strategy for a climate-neutral Europe. *Communication From the Commission To the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*, *53*(9). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

European Court of Auditors. (2023). *The EU's support for sustainable biofuels in transport: An unclear route ahead*. https://www.eca.europa.eu/ECAPublications/SR-2023-29/SR-2023-29_EN.pdf

European Union. (2016). *Directive 2009/30/EC of the European Parliament and of the Council*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02009L0030-20160610

European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *L 328*, 82–209. https://eur-lex.europa.eu/eli/dir/2018/2001/2018-12-21

Fantuzzi, A., Saenz Cavazos, P. A., Moustafa, N., High, M., Bui, M., Rutherford, A. W., & von Holstein, I. (2023). Low-carbon fuels for aviation. *Imperial College London*, *Briefing P*, 1–32. https://spiral.imperial.ac.uk/bitstream/10044/1/101834/11/IMSE_Low_carbon_aviation_fuels_briefing_paper_2023.pdf

Favennec, J.-P. (2022). Economics of Oil Refining. In *The Palgrave Handbook of International Energy Economics*. https://doi.org/10.1007/978-3-030-86884-0_22

Giannelos, G., Humphris-Bach, A., Davies, A., Baxter, B., Cames, M., Kasten, P., Siskos, P., Tsiropoulos, I., Kalokyris, T., & Statharas, S. (2021). *Study supporting the impact assessment of the ReFuelEU Aviation initiative*.

Graver, B., Rutherford, D., & Sola, Z. (2020). CO2 emissions from commercial aviation: 2013, 2018, and 2019. *International Council on Clean Transportation*, *October*, 36. https://theicct.org/publications/co2-emissions-commercial-aviation-2020

Hamelinck, C., Defillet, M., Smeets, B., & Heuvel, E. van den. (2021). *Conversion efficiencies of fuel pathways for Used Cooking Oil*. https://www.studiogearup.com/wp-content/uploads/2021/03/2021_sGU_EWABA-and-MVaK_Options-for-the-deployment-of-UCO.pdf

Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy*, *104*, 199–212. https://doi.org/10.1016/j.energy.2016.03.119

Herzog, H. (2022). Chapter 6: Direct Air Capture. In M. Bui & N. Mac Dowell (Eds.), *Greenhouse Gas Removal Technologies*. https://doi.org/10.1039/9781839165245

Holladay, J., Abdullah, Z., & Heyne, J. (2020). *Sustainable Aviation Fuel: Review of technical pathways*. 1–4. https://www.energy.gov/eere/bioenergy/downloads/sustainable-aviation-fuel-review-technical-pathways-report

ICAO. (2021). *CORSIA Eligible Fuels – Life Cycle Assessment Methodology*. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA Supporting Document_CORSIA Eligible Fuels_LCA Methodology.pdf

IEA Bioenergy. (2021). *Implementation of bioenergy in the United Kingdom*. 1–15. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1028157

International Energy Agency. (2022). Direct Air Capture: A key technology for net zero. *International Encyclopedia of Geography*, 1–76. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf

Kelesidis, G. A., Nagarkar, A., Trivanovic, U., & Pratsinis, S. E. (2023). Toward Elimination of Soot Emissions from Jet Fuel Combustion. *Environmental Science and Technology*, *57*(28), 10276–10283. https://doi.org/10.1021/acs.est.3c01048

Landälv, I., Waldheim, L., & Maniatis, K. (2018). *Technology status and reliability of the value chains: 2018 Update*. https://artfuelsforum.eu/news-articles/updated-sgab-report-technology-status-and-reliability-of-the-value-chains/

Malins, C. (2017a). Waste not want not: Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production. *Contract Journal*, *439*(6630), 28.

Malins, C. (2017b). *What role is there for electrofuel technologies in European transport's low carbon future?* Cerulogy. https://www.cerulogy.com/wp-content/uploads/2022/10/Cerulogy_What-role-electrofuels_November2017_v1_3.pdf

Malins, C. (2021). *SAFty in numbers*. Cerulogy. https://www.cerulogy.com/safty-in-numbers/

Malins, C. (2023). *Scrutinising the future role of alternative fuels in delivering aviation decarbonisation | Part 3 – the pathway to decarbonised aviation*. *October*. https://www.aef.org.uk/uploads/2023/11/Cerulogy_Alternative-fuels-in-aviation_Part-3-decarbonisation_Oct2023-1.pdf

Malins, C., & Sandford, C. (2021). *Aviation biofuels in Spain*. https://www.ecologistasenaccion.org/wp-content/uploads/2022/01/report-aviation-biofuels-spain.pdf

Malins, C., & Sandford, C. (2022). *Animal, vegetable or mineral (oil)? Exploring the potential impacts of new renewable diesel capacity on oil and fat markets in the United States Animal, vegetable or mineral (oil)?* https://theicct.org/wp-content/uploads/2022/01/impact-renewable-diesel-us-jan22.pdf

Maniatis, K., Heuvel, E. van den, & Kalligero, S. (2017). Building up the Future: Cost of Biofuel. *Sustainable Transport Forum Sub Group on Advanced Biofuels*, 1–71. https://platformduurzamebiobrandstoffen.nl/wp-content/uploads/2020/04/2017_SGAB_Cost-of-Biofuels.pdf

MathPro. (2011). An Introduction To Petroleum Refining and the Production of Ultra Low Sulfur Gasoline. *The International Council on Clean Transportation*, 1–38.

Messner, J. (2022). *DE-FOA-0002638: Scale-Up of Integrated Biorefineries and Greenhouse Gas Reduction in First Generation Ethanol Production: webinar slides*. https://eere-exchange.energy.gov/FileContent.aspx?FileID=65ec382f-b087-42e2-8fac-eef375ccd0c2

Miller, N., Christensen, A., Park, J. E., Baral, A., Malins, C., & Searle, S. (2013). *Measuring and Addressing Investment Risk in the Second- Generation Biofuels Industry*. 50. http://www.theicct.org/sites/default/files/publications/ICCT_AdvancedBiofuelsInve%5CnstmentRisk_Dec2013.pdf

Moore, R. H., Thornhill, K. L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A. J., Barrick, J., Bulzan, D., Corr, C. A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., … Anderson, B. E. (2017). Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. *Nature*, *543*(7645), 411–415. https://doi.org/10.1038/nature21420

Mutrelle, C. (2024). *The challenges of scaling up e-kerosene production in Europe*. https://www.transportenvironment.org/wp-content/uploads/2024/01/2024_01_E-kerosene_Tracker_TE.pdf

Neiva, R., Horton, G., Pons, A., Lokesh, K., Casullo, L., Kauffmann, A., Giannelos, G., Ballesteros, M., Kemp, M., & Kusnierkiewicz, N. (2022). *Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050 Final Study*. *September*. https://www.europarl.europa.eu/RegData/etudes/STUD/2022/699651/IPOL_STU(2022)699651_EN.pdf

New, P. (2023). *Developing a UK Sustainable Aviation Fuel Industry*. https://assets.publishing.service.gov.uk/media/64afb9edc033c1000d80621c/developing-uk-sustainable-aviation-fuel-industry-independent.pdf

O'Malley, J., Pavlenko, N., & Searle, S. (2021). Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand - International Council on Clean Transporation. *The International Council on Clean Transportation*, *March*, 1–19. https://theicct.org/publication/estimating-sustainable-aviation-fuel-feedstock-availability-to-meet-growing-european-union-demand/

Owens Thomsen, M., Mistry, H., & Block, A. (2023). Media Briefing: Update on Sustainable Aviation Fuels (SAF). *IATA Annual General Meeting*. https://www.iata.org/en/iata-repository/pressroom/presentations/sustainable-aviation-fuel-agm-2023/

Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. *IScience*, *25*(4), 103990. https://doi.org/10.1016/j.isci.2022.103990

Padella, M., O'Connell, A., & Prussi, M. (2019). What is still limiting the deployment of cellulosic ethanol? Analysis of the current status of the sector. *Applied Sciences (Switzerland)*, *9*(21). https://doi.org/10.3390/app9214523

Park, H., Chae, H.-J., Suh, Y.-W., Chung, Y.-M., & Park, M.-J. (2022). Techno-Economic Analysis and CO2 Emissions of the Bioethanol-to-Jet Fuel Process. *ACS Sustainable Chem. Eng.*, *10*(36). https://pubs.acs.org/doi/10.1021/acssuschemeng.2c03853

Pavlenko, N. (2018). *FAILURE TO LAUNCH: WHY ADVANCED BIOREFINERIES ARE SO SLOW TO RAMP UP PRODUCTION*. International Council on Clean Transportation. https://theicct.org/failure-to-launch-why-advanced-biorefineries-are-so-slow-to-ramp-up-production/

Pavlenko, N., & Searle, S. (2020). *A comparison of methodologies for estimating displacement emissions from waste, residue, and by-product biofuel feedstocks*. *October*, 30. https://theicct.org/sites/default/files/publications/Biofuels-displacement-emissions-oct2020.pdf

Pavlenko, N., & Searle, S. (2021). Assessing the sustainability implications of alternative aviation fuels. *International Council on Clean Transportation*, *11*. https://theicct.org/sites/default/files/publications/Alt-aviation-fuel-sustainability-mar2021.pdf

Pavlenko, N., Searle, S., & Christensen, A. (2019). *The cost of supporting alternative jet fuels in the European Union*. https://theicct.org/publications/cost-supporting-alternative-jet-fuels-european-union

Pavlenko, N., & Zheng, S. (2024). *Evaluating the potential role of a National Low-Carbon Fuel Standard to support sustainable aviation fuels*. *January*, 1–24. https://theicct.org/wp-content/uploads/2024/01/ID-30-–-Aviation-LCFS-working-paper-letter-20225-fv.pdf

Rojas-Michaga, M. F., Michailos, S., Cardozo, E., Akram, M., Hughes, K. J., Ingham, D., & Pourkashanian, M. (2023). Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. *Energy Conversion and Management*, *292*(July), 117427. https://doi.org/10.1016/j.enconman.2023.117427

Shahriar, M. F., & Khanal, A. (2022). The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). *Fuel*, *325*. https://doi.org/10.1016/j.fuel.2022.124905

Soubly, K., & Riefer, D. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. *World Economic Forum*, 43. https://www.mckinsey.com/~/media/mckinsey/industries/travel transport and logistics/our insights/scaling sustainable aviation fuel today for clean skies tomorrow/clean-skies-for-tomorrow.pdf

Spath, P. L., & Dayton, D. C. (2003). Preliminary Screening—Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas. *National Renewable Energy Laboratory*, *December*, 1–160. https://doi.org/10.2172/15006100

Sustainable Aviation. (2020). *Sustainable Aviation Fuels Road-Map*. https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf

Suzan, S. (2023). *Biofuels: From unsustainable crops to dubious waste?* https://www.transportenvironment.org/wp-content/uploads/2023/12/202312_TE_biofuels_update_report.pdf

U.S. Bioenergy Technologies Office. (2022). *Sustainable Aviation Fuel Grand Challenge*. https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

U.S. Department of Energy, U.S. Department of Transport, U.S. Department of Agrigculture, & U.S. Environmental Protection Agency. (2022). *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel*. 1–128. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf

U.S. Internal Revenue Service. (2023). *Sustainable Aviation Fuel Credit*. https://www.irs.gov/credits-deductions/businesses/sustainable-aviation-fuel-credit

UK Department for Energy Security and Net Zero. (2023). *Biomass Strategy*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1178897/biomass-strategy-2023.pdf

UK Department for Transport. (2021a). *Sustainable aviation fuels mandate: A consultation on reducing the greenhouse gas emissions of aviation fuels in the UK*. *July*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005382/sustainable-aviation-fuels-mandate-consultation-on-reducing-the-greenhouse-gas-emissions-of-aviation-fuels-in-the-uk.pdf

UK Department for Transport. (2021b). *Targeting net zero - Next steps for the Renewable Transport Fuels Obligation. Government response.* (Issue March). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1109226/government_response_to_the_consultation_targeting_net_zero_next_steps_RTFO.pdf

UK Department for Transport. (2022a). *Jet Zero: Illustrative scenarios and sensitivities*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096929/jet-zero-strategy-analytical-annex.pdf

UK Department for Transport. (2022b). *Jet Zero Investment Flightpath*. *July*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1097747/jet-zero-investment-flightpath.pdf

UK Department for Transport. (2022c). *Jet Zero Strategy: Delivering net zero aviation by 2050*. *July*, 83. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1095952/jet-zero-strategy.pdf

UK Department for Transport. (2022d). *The Renewable Transport Fuel Obligation—An Essential Guide*. https://assets.publishing.service.gov.uk/media/6582d97ded3c34000d3bfc69/rtfo-essential-guide-2024.pdf

UK Department for Transport. (2023a). *Government Response to Developing a UK Sustainable Aviation Fuel Industry Report*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1169992/government-response-developing-uk-sustainable-aviation-fuel-industry.pdf

UK Department for Transport. (2023b). *Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate - A second consultation on reducing the greenhouse gas emissions of aviation fuel in the UK*. 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

UK Department for Transport. (2023c). *Sustainable Aviation Fuels Mandate Consultation-stage Cost Benefit Analysis*. https://assets.publishing.service.gov.uk/media/642478402fa8480013ec0f49/uk-sustainable-aviation-fuel-mandate-consultation-stage-cost-benefit-analysis.pdf

UK Department for Transport. (2023d). *Renewable fuel statistics*. https://www.gov.uk/government/collections/renewable-fuel-statistics

van Dyk, S., & Saddler, J. (2021). *Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF): Technologies, potential and challenges*. IEA Task 39. https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf

Voigt, C., Kleine, J., Sauer, D., Moore, R. H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M., Bauder, U., Boose, Y., Borrmann, S., Crosbie, E., Diskin, G. S., DiGangi, J., Hahn, V., Heckl, C., Huber, F., … Anderson, B. E. (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. *Communications Earth and Environment*, *2*(1), 2–11. https://doi.org/10.1038/s43247-021-00174-y

World Economic Forum. (2021a). *Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition*. https://www3.weforum.org/docs/WEF_Clean_Skies_for_Tomorrow_Power_to_Liquid_Deep_Dive_2022.pdf

World Economic Forum. (2021b). *Clean Skies for Tomorrow: Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe*. https://www3.weforum.org/docs/WEF_CST_EU_Policy_2021.pdf

Yang, Z., Qian, K., Zhang, X., Lei, H., Xin, C., Zhang, Y., Qian, M., & Villota, E. (2018). Process design and economics for the conversion of lignocellulosic biomass into jet fuel range cycloalkanes. In *Energy* (Vol. 154). https://doi.org/10.1016/j.energy.2018.04.126

Yugo, M., & Soler, A. (2019). A look into the role of e-fuels in the transport system in Europe (2030-2050). *Concawe Review*, *28*(1), 4–22. https://www.concawe.eu/wp-content/uploads/E-fuels-article.pdf