Staying Aloft

Support Mechanisms for 'Sustainable Aviation Fuels' in the United Kingdom and European Union

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Summary

In pursuit of aviation decarbonisation, both the European Union (EU) and the United Kingdom (UK) have adopted mandates on the use of so-called 'sustainable aviation fuels' (SAF): under 'ReFuelEU Aviation' and the 'UK SAF Mandate' respectively. These regulations set ambitious targets to be fulfilled by aviation fuel suppliers; but given the expected high cost of SAF and the immature state of the industry, it is far from certain that sufficient fuel production capacity will be developed in time to hit near-term targets. It is anyway likely that there will be political pressure to reduce long-term targets.

Complementary policies have been developed to provide financial support to SAF on a 'per litre' basis, with the aim of facilitating uptake and/or production. The EU's reimbursement scheme mitigates the cost to airlines for each unit of alternative fuel they consume by reimbursing some fraction of the cost difference compared to fossil kerosene. The UK's guaranteed strike price (GSP), on the other hand, offers a Government-backed mechanism to shield SAF producers from variability in market prices, thereby establishing certainty over revenues and de-risking investment. The GSP seeks to provide reassurance to investors in early-stage commercial projects, facilitating finance availability in a way that is hoped to be effective in jump-starting production and reducing the cost of capital.

This report examines the SAF policy frameworks in the two regions and reviews their strengths and weaknesses. While the mandates share many characteristics in terms of fuel eligibility criteria, the UK system has the distinction of capping the contribution of lipid-based HEFA (and hence guaranteeing space for advanced biofuels and other next-generation fuels), while in the EU it can be expected that aviation biofuels will be heavily dominated by HEFA. The UK SAF Mandate's annually-increasing targets, moreover, provide a defined signal for production capacity to come online gradually, but ReFuelEU Aviation's targets are set in five-year 'steps' that may cause the SAF industry to vacillate between periods of relative high and low capacity.

The SAF space is beset by uncertainty over which next-generation production pathways will succeed, what the hierarchy of prices will be, and whether ambitious regulations will be upheld. All of this hinders investment prospects for novel technologies. Both the UK and EU systems seek to bring certainty to the market by defining the cost to fuel suppliers of non-achievement of mandated supply levels. The UK SAF Mandate addresses this via a 'buy-out' mechanism that establishes a fixed cost for each litre of shortfall compared to mandated supply levels. This helps to shape fuel suppliers' and fuel producers' expectations for off-take price negotiations. In the EU system, there is greater inherent uncertainty for stakeholders: ReFuelEU Aviation introduces a system of minimum fines that are not set in absolute terms but instead are dependent on reported SAF prices. While this approach is intended to guarantee that the cost of non-compliance will always be more than the cost of sourcing SAF, in practice it introduces the risk that in the event of supply shortfalls an unstable circularity will be created whereby the threat of fines increases the price of SAF, which in turn increases the minimum fines and so on. This dynamic relationship means that fuel suppliers may have little visibility on future compliance costs, and fuel producers will have little clarity on future SAF selling prices. Spiralling compliance costs could lead to a fundamental policy re-evaluation: an uncertainty that could undermine the effectiveness of dissuasive fines as an investment driver.

The policy frameworks of the EU and UK are currently the strongest incentives for SAF consumption in the world, but both face challenges, and this report argues that the structure and targeting of the complementary support mechanisms in the EU and the UK will deliver diverging outcomes. We anticipate that the EU's reimbursement scheme will primarily benefit airlines and reduce the costs to flyers; in contrast the UK's GSP targets support to fuel producers

and is more likely to stimulate investment in the SAF industry. Whereas its has been stated that the first batch of UK GSP contracts will not be available to HEFA producers, we expect that the available EU reimbursement scheme funds will be expended primarily on lipid-based HEFA – indeed there is a strong possibility that the funds will be exhausted before 2030 when production of other SAF types, in particular PtL fuels, may be starting to come on-line. HEFA is already the least-cost SAF option, and will be the first choice for fuel suppliers obligated under ReFuelEU Aviation; spending the available funds on HEFA may do very little to accelerate the deployment of SAF in general. And given that it is recognised that HEFA production cannot be scaled to fulfil long-term supply goals, and that increased HEFA production is also associated with sustainability concerns, the EU could benefit from targeting longer-term support towards next-generation fuel options.

The UK's GSP mechanism is both better targeted and longer-term in its outlook. By reducing offtake risk for SAF producers, there is a good chance that it can unlock lower-cost sources of financing, which will in turn reduce levelised fuel production costs. Design issues remain to be resolved though: we argue that the use of static strike prices (as currently proposed) may limit SAF producers' ability to remain viable in the face of variability in production costs; and that serious consideration must be given to how market prices can be properly identified. Disbursing funds based on self-declaration of sale prices by SAF producers could remove the incentive to negotiate higher prices, and increase the nominal cost of operating the scheme. Still, these issues appear tractable, and the GSP should be seen as a potential model for making the EU's mandates and industry support more effective.

Contents

1. Introduction

1.1. Decarbonising aviation

Aviation demand is projected to grow over the coming decades (ATAG, 2021); at the same time, the need to reduce its climate impact is growing in urgency. This contextualises efforts to increase aeronautical efficiency of new aircraft, optimise flight-paths to reduce contrail formation, increase the capacity utilisation of flights, develop novel battery- and hydrogen-powered engine systems for the longer term, slow and reverse demand growth, and substitute petroleum-based fuels with renewable alternatives.

These alternative fuels, often referred to as 'sustainable aviation fuels' (SAF)[1], can be produced using a number of technologies. They are promoted as being key to decarbonising aviation over the coming decades, as illustrated by UK's 'Jet Zero Strategy' in Figure 1[2].

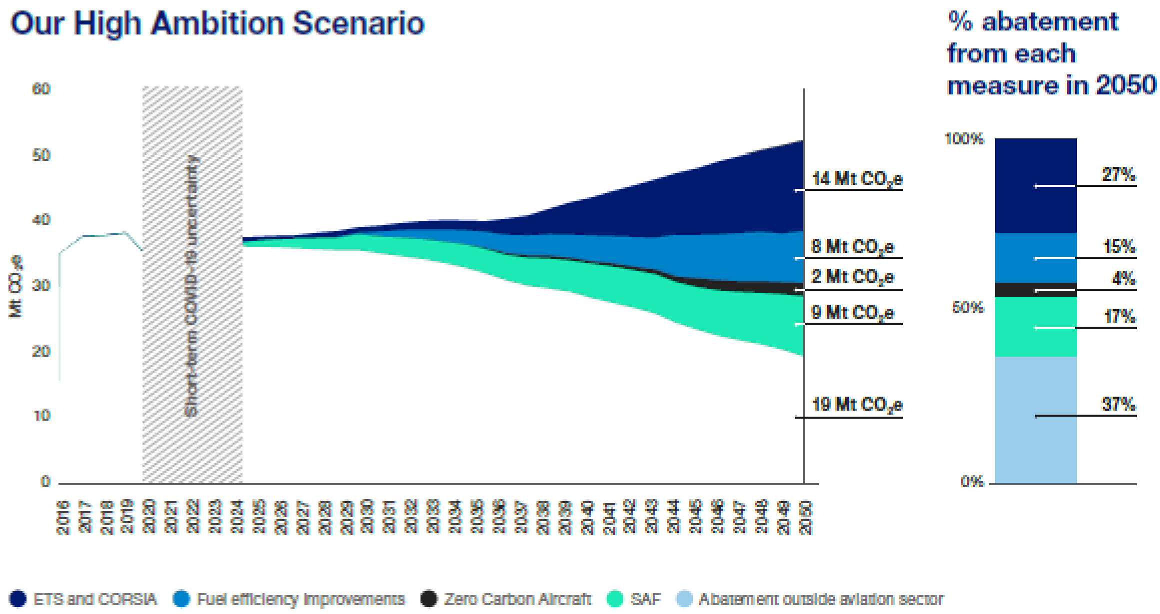

Figure 1 Illustrative scenario for aviation decarbonisation

Source: UK Department for Transport (2022b)

The appeal of SAF is two-fold. First, they are hydrocarbon fuels chemically similar to conventional jet fuel (fossil kerosene), and can be used with existing engines and fuelling infrastructure. This minimises disruption and costs to manufacturers of aeroplane engines and hulls, to airports and airlines, and to fuel handlers. Second, their potential to reduce net

[1] This term is favoured by many stakeholders, though it should be understood that SAF is not inherently more sustainable than conventional fossil fuel. We shall nonetheless use the term in this report for consistency. We emphasise that SAF is an umbrella term covering a range of technologies for producing aviation fuel; these are introduced in Section 1.3.

[2] Similar graphs exist for the global industry and other regions; see, e.g., the Air Transport Action Group's 'Waypoint 2050' report (ATAG, 2021).

greenhouse gas emissions is seen by industry as obviating the need to reduce air transport demand.

But while there is now broad support for SAF, the fanfare has so far failed to produce significant volumes of actual fuel. Uptake is limited by airlines' reluctance to pay the higher costs relative to fossil kerosene. An early EU target for 2 million tonnes per year to be consumed by 2020 was nowhere close to being met (ICAO, 2012). The International Air Transport Association (IATA) notes that 2024 saw production of only 1 million tonnes (0.3% of global jet fuel production)[3], complaining that "investors in new generation fuel producers seem to be waiting for guarantees of easy money before going full throttle" (IATA, 2024).

The landscape of government policies seeking to facilitate investment in alternative fuels has evolved considerably over recent years. The USA introduced tax rebates to SAF producers under its Inflation Reduction Act (IRA); the UK and EU have established legally-binding targets for the use of SAF, with dissuasive penalties for non-compliance (Section 2); and other countries around the world are beginning to enact mandates, targets, and incentive schemes to boost national consumption and production (Vogels et al., 2024). The extent to which these will actually galvanise production is yet to be seen. IATA analysis claimed that 3,000-6,500 new renewable fuel plants will be needed by 2050 to deliver net zero, which would entail an average CapEx spend of at least $128 billion per year (IATA, 2024). Graver et al. (2022) considered an ambitious global scenario where 100% of fossil kerosene is replaced in 2050 by 100 million tonnes of aviation biofuel and 215 million tonnes of aviation e-fuel.

1.2. This report

This report examines the policy frameworks and financial support mechanisms designed to reward the consumption of SAF litres in the EU and UK, highlighting their potential impact on consumption and production. It analyses the policies' potential effects on fuel prices and the degree to which support is targeted towards more sustainable fuel production technologies. This is accompanied by illustrative modelling of fuel uptake scenarios.

Unless otherwise noted, quantities of fuel will be specified in 'tonnes of oil equivalent', toe[4]. As all jet fuel must meet the same specifications on its physical and chemical properties, energy, mass and volume units are functionally interchangeable, and we refer to quantities of fuel generically as volumes even when not expressed in volume units. Financial values are expressed in euros, EUR, €[5].

1.3. SAF technologies

In the context of EU and UK policy, three broad categories of SAF can be distinguished: hydrotreated esters and fatty acids or HEFA, biomass-to-liquid fuel or BtL, and power-to-liquid

[3] The vast majority of which is lipid-based HEFA, see Section 1.3.1.

[4] 1 toe on a 'lower heating value' basis is equivalent to 1.02 tonnes or 1,200 litres of jet fuel.

[5] When converting from values quoted in pounds, GBP, £, or in dollars, USD, $, we use exchange rates 1.21 €/£ and 0.95 €/$.

fuel or PtL[6]. Here we outline the production processes for each in turn, their feedstocks and inputs, and ensuing sustainability considerations. More discussion is provided in Sandford & Malins (2024).

1.3.1. Hydrotreated esters and fatty acids (HEFA)

HEFA is a biofuel produced by chemically reacting lipid molecules with hydrogen to produce hydrocarbons. The same basic process can be used to produced hydrogenated vegetable oil[7] used as road fuel. The HEFA production technology is fully commercialised, with key elements borrowed from petroleum refining – indeed, HEFA can be made in conventional refineries after retrofitting, or even from lipids co-processed alongside petroleum.

Lipid feedstocks include crop-derived vegetable oil (e.g. soybean or rapeseed oil) and residual oils and fats like used cooking oil (UCO) or low-grade rendered animal fat. The use of crop-derived oils is expected to drive agricultural expansion, including in some cases deforestation[8], leading to indirect land use change (ILUC) emissions. For this reason, HEFA made with conventional crop-derived oils is excluded from support under recent EU and UK policy. Residual oils are considered more sustainable but have a limited supply. Growing demand threatens to displace these resources from their prior uses, leading to replacement with virgin vegetable oil or petroleum-based oil (O'Malley et al., 2021)[9]. The high value attributable to the policy incentives that promote residual oils above the price of virgin crop oils have also led to instances of mislabelling fraud (e.g. Suzan, 2025).

1.3.2. Biomass-to-liquid hydrocarbons (BtL)

In this report, BtL denotes hydrocarbon biofuel made from cellulosic feedstocks such as purpose-grown energy crops (e.g. miscanthus), or residues from agriculture (e.g. straw), forestry (e.g. branches and twigs), or industry (e.g. sawdust, black liquor). In EU terminology, these are classed as 'advanced' biofuels (Section 2.1).

BtL covers a number of technology pathways, including biomass gasification with Fischer-Tropsch synthesis, pyrolysis with catalytic upgrading, and cellulosic alcohol-to-jet fuel (AtJ). We briefly introduce these technologies in Annex A; but from the perspective of UK and EU regulation the feedstock is the critical factor rather than the conversion method (provided the latter has been certified for use in aircraft).

To our knowledge, no commercial-scale production of aviation fuel using these technologies has yet been successfully deployed[10]. There is also a question over how much feedstock can be sustainably supplied to the EU and UK markets (Carraro et al., 2021; O'Malley & Baldino,

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[6] There is also a category of non-renewable alternative aviation fuels referred to as recycled carbon fuels that could in principle contribute to EU and UK targets, but we do not consider them in this study.

[7] HVO, also known as renewable diesel.

[8] Oil palm and soybean expansion are both associated with tropical deforestation.

[9] Displacement emissions are not included in typical regulatory analyses but can be a factor in deciding whether to give extra incentives for the use of specific materials.

[10] Commercial-scale indicates production capacity of at least 40 kt.

2024; Searle & Malins, 2016). Should these challenges be overcome, however, BtL fuels will likely be able to report high emissions savings compared with fossil kerosene, in the 75-90% range.

1.3.3. Power-to-liquid hydrocarbons (PtL)

In this report, PtL refers to hydrocarbons produced from electrolytic 'green' hydrogen. In the aviation context this is sometimes called e-kerosene or electrojet; in EU terminology, it is a renewable fuel of non-biological origin (RFNBO)[11]. PtL is made by combining electrolytic hydrogen with carbon dioxide from either a point source (e.g. a thermal power station) or direct air capture (DAC)[12]. Hydrocarbons may then be produced using the Fischer-Tropsch synthesis process (Annex A) or via some other pathway with chemical intermediates. As with BtL technologies, commercial scale production has not yet been achieved, but as PtL is not subject to the limitations on feedstock availability that hinder the potential of HEFA and BtL it is considered an important sustainable aviation fuel option for the long-term.

The energy losses in the PtL production process means that 2 MJ (megajoules) of electricity produces only about 1 MJ of fuel (cf. Malins, 2017). The economic viability of this technology therefore depends on the availability of electricity at low cost and low carbon intensity. EU and UK regulations include requirements intended to ensure that PtL is produced with additional renewable electricity, i.e. renewable electricity that has not simply been diverted from other (potentially more efficient) applications (cf. European Commission, 2023a). For this report, we assume that these requirements are effective and PtL is produced from genuinely additional renewable power, in which case PtL has the potential to deliver considerable emissions reductions around 95% of fossil emissions (see Malins (2019) for further discussion).

1.4. Operators in the supply chain

SAF cost significantly more to produce than fossil aviation fuels (EASA, 2025; Sandford & Malins, 2024), and thus the market for SAF only exists because of policy (excepting demonstration projects funded by airlines or fuel suppliers, and a few niche initiatives to let flyers choose to pay more for greener fuels). Policy provisions apply to one or more of three stakeholders:

- SAF producers, who invest in and produce fuels.
- Fuel suppliers, who currently supply fossil fuels to airlines but may be mandated to supply a share of SAF.
- Airlines, who buy and consume the aviation fuel from fuel suppliers.

The distinction is important because, as will become clear in Section 2, different stakeholders are subject to different regulatory pressures[13]. Stakeholders buying fuels have a maximum

[11] RFNBO also includes other non-hydrocarbon like methanol (used e.g. in shipping) or hydrogen (used e.g. in road transport).

[12] Eligible CO_2 sources are restricted in the EU and UK, but not in other markets (such as the USA); this means that generic PtL will not necessarily be eligible (Wille et al., 2023).

[13] In reality, there may be some vertical integration where a fuel supplier owns SAF-producing facilities (or conversely a fuel producer sells directly to an airline). We may nevertheless treat the three stakeholders as separate entities from the point of view of regulatory compliance and incentives.

willingness to pay, but would always prefer to buy for less; stakeholders selling fuels have costs to cover, but would always prefer to sell for more.

More specifically, under the EU and UK frameworks (to be covered in Section 2) it is fuel suppliers that are subject to SAF supply mandates and who will be penalised if these mandates are not met. Their willingness to pay for SAF is driven by the scale of the penalties that will be imposed on them if they fail to comply with their obligations. Airlines, on the other hand, are in the EU offered incentives to use SAF but are not directly penalised if supply mandates are not met; they are under no obligation to use SAF and they will simply seek the lowest-cost fuel blends they can find[14]. Airlines' maximum willingness to pay for alternative fuels can be estimated as the cost of fossil kerosene plus the value of any additional incentives available to them: notably the value of the emissions allowances that no longer need to be surrendered under the EU and UK emission trading schemes when SAF are used instead of fossil fuels (Horton et al., 2024; Wille et al., 2022).

Airlines' willingness to pay is insensitive to either the balance of supply and demand or the production cost of alternative fuel – and therefore fuel suppliers may find themselves in a situation where they are forced to buy SAF at high cost and sell it to airlines for less. They will then have to then recoup this loss by increasing prices to airlines of fossil kerosene, thus placing some of the cost burden of alternative fuel policy onto conventional fuels. In practice, it may be that fuel suppliers sell a blend of fossil fuel and SAF to airlines at a combined price that takes all this into account. We shall return to this dynamic later in the report.

[14] While there are cases in which airlines have paid high prices for individual batches of SAF in order to demonstrate their technical viability and support the first producers, we assume that as volumes increase airlines will seek to minimise their costs to avoid becoming uncompetitive.

2. Policy landscape

2.1. European Union

The EU policy environment for SAF consists primarily of: the Renewable Energy Directive, RED III, which creates a mandate for renewable fuels in transport generally; ReFuelEU Aviation, which creates a mandate for renewable fuels in aviation specifically; the EU's Emissions Trading System, EU-ETS, which puts a cost on airline CO_2 emissions; and the EU-ETS reimbursement scheme, which subsidises airlines to buy SAF. We cover each of these in turn.

2.1.1. Renewable Energy Directive (RED)

The RED establishes the overall goals and sustainability criteria for biofuels and electrofuels used in EU transport, including the aviation segment. Its most recent iteration, RED III (European Union, 2023b)[15], requires that by 2030 Member States' transport energy should either: (a) be 29% renewable, or (b) have a greenhouse gas emissions intensity 14.5% lower than the fossil baseline of 94 gCO_2e/MJ (grams of CO_2 equivalent per megajoule of fuel energy). Beyond the main targets mentioned above, RED III establishes a minimum requirement for 0.5% of physical transport energy to come from RFNBOs by 2030, and 2.25% from advanced biofuels (though the legislative text frames these sub-targets slightly differently[16]). An ICCT policy update explains the RED III measures in more detail (Baldino, 2023).

The energy content of RFNBOs, including PtL hydrocarbons, is double-counted towards renewable energy targets provided they are made using renewable electricity and satisfy other sustainability conditions (additionality, temporal correlation, and geographic correlation) (European Commission, 2023a). PtL supplied to aviation or maritime transport modes gains a compounded energy multiplier of 1.5. Biofuels must satisfy the sustainability criteria in Article 29 of the Directive, including proscriptions on sourcing biofuel feedstock from forests, wetlands, and highly biodiverse areas, and maximum thresholds on fuels' lifecycle greenhouse gas emissions. The contribution of biofuels made from 'food and feed crops' is capped[17]. Biofuels produced in facilities which started operation from 2021 onwards must deliver at least 65% emissions saving compared to a standard fossil fuel baseline; the threshold is less stringent for older facilities.

Biofuels made from certain feedstocks identified as having desirable sustainability characteristics are listed in Annex IX of RED III and its amendments. These are also double-counted towards renewable energy targets, and if used for aviation and maritime segments, the energy content of these fuels receives a further energy multiplier of 1.2. Annex IX is divided into two parts: Part A lists feedstocks for producing 'advanced biofuels' for which the fuel

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[15] The deadline for EU Member States to adopt most RED III provisions into their national legislation is mid-2025. Until then, Member States may still be following RED II (European Union, 2018).

[16] RED III requires that 5.5% of double-counted transport energy (2.75% of physical energy), to consist of advanced biofuels and RFNBOs in 2030. Of this, at least 1% double-counted (0.5% physical) energy must be RFNBOs. Due to cost considerations, we assume that Member States will not go beyond the minimum RFNBO requirement, meaning that 4.5% of double-counted (2.25% of physical) transport energy will have to come from advanced biofuels.

[17] Food and feed crops are defined as, oil-, starch-, or sugar-rich main crops.

production technology is said to be less mature; Part B lists feedstocks that can be converted to biofuel using existing commercial technologies. Regarding the fuel production technologies discussed in Section 1.3, Annex IX Part A includes cellulosic feedstocks that could be used in BtL technology pathways, as well as oilseed crops that satisfy specified criteria and which are used to make aviation fuel (European Commission, 2024a); Part B includes among other things residual lipids that can be used to make HEFA. Part B biofuels are subject to a nominal cap of 1.7% in each year[18]: this serves to moderate diversion of feedstocks from existing uses, reduce mis-labelling fraud, and motivate the pursuit of more difficult but sustainable advanced fuel options (though since the insertion of HEFA feedstocks into Annex IX Part A, the policy value is shared between BtL and HEFA technologies).

2.1.2. ReFuelEU Aviation

The ReFuelEU Aviation Regulation (European Union, 2023a) is the primary instrument for decarbonising EU aviation. It primarily applies to fuel suppliers (i.e. not airlines), mandating minimum shares of alternative and PtL fuels that must be brought to market between 2025 and 2050: see Table 1. Renewable aviation fuels will count both towards ReFuelEU Aviation targets and towards RED targets.

Table 1 ReFuelEU Aviation targets, 2025-50

Fuel Target	Unit	2025	2030	2035	2040	2045	2050
SAF	%	2%	6%	20%	34%	42%	70%
	ktoe	914	2,755	9,193	15,752	19,641	31,936
PtL	%	0%	1.2%[19]	5%	10%	15%	35%
	ktoe	0	468	2,298	4,633	7,015	15,968

Note: Mandated fuel supply in energy units has been estimated following energy demand projections from the ReFuelEU Aviation impact assessment study (Giannelos et al., 2021).

The targets in Table 1 entail a step increase in SAF consumption every five years: a trajectory inconsistent with normal patterns of industrial development that would see plants continually coming into operation and each plant ramping up over time towards its nameplate capacity. As it stands, fuel producers seeking to sell into the EU market may find themselves subject to awkward vacillations between periods of low and high relative-demand. The European Commission has explicitly clarified that Member States are not permitted to set targets that deviate from ReFuelEU Aviation (European Commission, 2025b), and therefore no smoothing of the step increments in Table 1 is anticipated.

SAF must meet the sustainability criteria laid out in RED III to be allowed to contribute to ReFuelEU Aviation targets. There are also explicit proscriptions on the use of food and feed

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[18] Noting though that several Member States have been granted exemptions to raise their caps above 1.7% (Soquet-Boissy et al., 2024).

[19] ReFuelEU Aviation specifies that the average PtL share is not to be less than 1.2% in the period 2030-31, but the minimum in each year is 0.7%. Similarly, the average in the period 2032-34 is to be not less than 2.0%, with a minimum of 1.2% in 2032-33 and 2.0% in 2034.

crops as feedstocks, and on the use of palm- or soybean-derived materials[20]; and a limit of 3% (of total aviation fuel) on fuel derived from biofuel feedstocks not listed in Annex IX of RED.

As there is no sub-target for the use of BtL biofuels and the contribution of lipid feedstocks is not capped, the non-PtL part of the overall target could be met entirely with HEFA. This could include HEFA made from Annex IX Part B residual oils, from Annex IX Part A residual oils and intermediate oilseed crops, and/or from other lipids within the 3% category mentioned above. Supplying BtL aviation fuel to the EU market would be advantageous only if the stacked policy value of RED III's advanced biofuels mandate, the 2x advanced biofuel multiplier, and 1.2x aviation multiplier are able to bridge the cost gap between BtL and HEFA.

If an aviation fuel supplier fails to meet the targets in Table 1, Member States must impose a "proportionate and dissuasive" penalty fee, which must be at least twice the difference between the price of SAF and fossil kerosene (European Union, 2023a). In practice, the penalty for non-compliance with the main target will be based on the difference between HEFA and fossil kerosene (as HEFA will be the standard least-cost compliance option); the penalty for non-compliance with the PtL sub-target will be based on the difference between PtL and fossil kerosene, with official prices published annually. How these prices are to be determined is important; we return to the matter in Section 2.1.5. ReFuelEU Aviation directs Member States to "endeavour" to channel penalty revenues to the SAF industry: either to research and development, to SAF producers, or to SAF buyers.

Payment of the non-compliance penalty does not clear the fuel supplier's compliance deficit: any shortfall in one year must be compensated with extra SAF the following year. It will be interesting to see how this is handled by Member States, as if SAF supply is tight and/or prices high, authorities may come under pressure to delay enforcement or waive penalties.

ReFuelEU Aviation establishes provisions to prevent airlines from carrying excess fuel from other locations ('tankering') to avoid purchasing more expensive SAF-blended fuel from EU airports. Specifically, airlines operating commercial flights from EU airports must uplift at least 90% of their annual aviation fuel requirements, and report their fuel transactions for verification. By preventing leakage, this measure limits potential impacts on absolute aviation fuel demand in general, and hence on SAF demand in particular.

The European Commission is expected to review the success and the impacts of ReFuelEU Aviation every four years, giving regard to global policy and technology developments. The first report is due to be submitted to the European Parliament and the Council by 1st January 2027, and its findings may be used to justify revisions to the Regulation, including to fuels eligibility rules, measures for financially supporting uptake, and extension of the CBAM to cover aviation. The Commission's report may also cover implementation issues such as the enforcement of penalties.

2.1.3. Emissions Trading System (EU-ETS)

The EU-ETS is a cap-and-trade market covering greenhouse gas emissions from power generation, heavy industries (like cement, steel, and oil refining), airlines operating within the EU and EEA, and ships arriving at or departing from EU and EEA ports[21]. These sectors comprise over 40% of domestic EU emissions (European Commission, 2023c). To be clear, the EU-ETS

[20] Excepting any residues listed in Annex IX of RED.

[21] The EU-ETS does not cover the climate impact of aeroplane contrails or black carbon from ship exhausts.

contrasts with ReFuelEU Aviation in that it applies to airlines rather than fuel suppliers, and in that it only affects flights within the EU and EEA rather than all fuel supplied at EU airports.

Under the EU-ETS, a limited number of emissions allowances are released annually, with each allowance permitting the holder to emit one tonne of CO_2. Companies wishing to emit greenhouse gases can buy allowances from Member State governments; from other companies with a surplus of allowances (on the 'secondary market'); or they may be able to claim free allowances[22].

The process of buying and trading allowances on the primary and secondary markets leads to the emergence of a carbon price, as shown in Figure 2. In February 2023 this reached a maximum of 105.73 €/tCO_2e (euros per tonne of CO_2 equivalent), and over the course of 2024 ranged between 55-80 €/tCO_2e (Trading Economics, 2024). Taking 80 €/tCO_2e as an indicative price for ETS allowances, each toe of jet kerosene burned on obligated flights would incur an EU-ETS charge of €258[23]. SAF do not incur this cost, giving an effective incentive for their use of 258 €/toe.

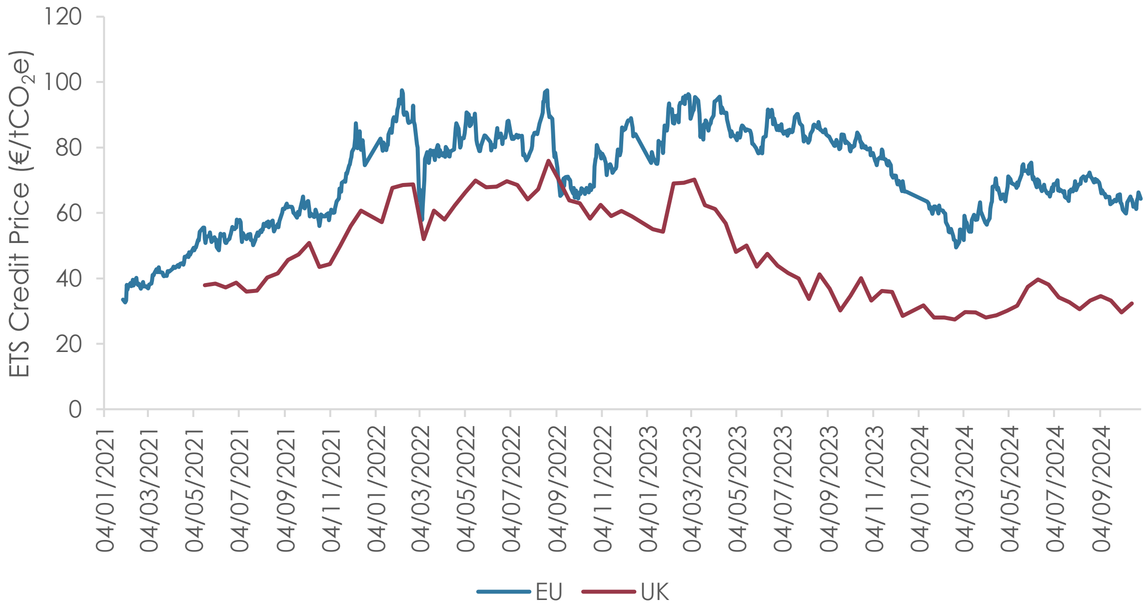

Figure 2 Allowance prices under the EU-ETS and the UK-ETS

Source: International Carbon Action Partnership (2024)

2.1.4. EU-ETS reimbursement scheme

In 2023, new language inserted into the ETS Directive established a system of incentives for airlines to purchase SAF. The amending directive states that the EU-ETS, "should contribute to

[22] The system of free allowances was originally instituted to maintain EU companies' international competitiveness and prevent 'leakage' to jurisdictions without a carbon price. Going forward, the EU's Carbon Border Adjustment Mechanism (CBAM) is intended to mitigate these issues, and free allowances for aviation will be phased out in 2026.

[23] Annex III of the ETS Directive stipulates that combustion of fossil jet kerosene shall be treated as emitting 3.15 tCO_2e per tonne of fuel (European Commission, 2024b).

incentivising the decarbonisation of commercial air transport. The transition from the use of fossil fuels would play a role in achieving such decarbonisation. However, considering the high level of competition between aircraft operators, the developing Union market for sustainable aviation fuels, and the significant price differential between fossil kerosene and sustainable aviation fuels, that transition should be supported by incentivising early movers" (European Union, 2023c). This support is to be delivered by using EU-ETS allowances to refund a fixed percentage of the price difference between alternative and fossil fuels is reimbursed (European Union, 2024).

More precisely, a Commission Delegated Regulation (European Commission, 2025a; hereafter simply the 'Delegated Regulation') specifies that the price difference for the purpose of reimbursement must be calculated as:

$$\text{Price difference} = \text{Price of SAF} - \text{Price of fossil kerosene} - \text{ETS value} - \text{Difference in taxation}$$

The percentage of this cost difference to be reimbursed varies for different types of SAF: 95% for PtL, 70% for BtL, and 50% for HEFA[24]. The assessment of these fuel prices is linked to the assessment for the ReFuelEU Aviation penalties, which we discuss in Section 2.1.5.

Reimbursements are to be paid to airlines in the form of EU-ETS allowances, with 20 million allowances set aside for the period 2024-30. Taking an indicative EU-ETS price of 80 €/tCO_2e as above, the total subsidy fund would come to €1.6 billion[25]. It is understood that allowances will be awarded annually and retroactively on a first-come-first-served basis until the fund runs out: so at the end of each reporting year allocations will be disbursed for all SAF supplied in the preceding year. If the volume of eligible fuel consumed in a given year exceeds the funds remaining in the bank, they are to be disbursed on a pro-rata basis.

Each unit of SAF used to meet ReFuelEU Aviation targets will be able to claim subsidy. The rate at which the bank is drawn down depends on the product of the consumption volume and the subsidy value for each fuel. The consumption volume is determined by ReFuelEU Aviation targets (with the split between HEFA and BtL informed by the policy value of the RED III advanced biofuel sub-target – this is less well determined than the broader split between biojet and PtL SAF). The subsidy value per unit of fuel depends on the calculated price difference; considerable uncertainty remains over what this is likely to be.

If the subsidy value is high, then available funds will be exhausted quickly[26]. Figure 3 shows a case where funding could be exhausted by 2028, before the PtL sub-target kicks in (in 2030). In this case, little if any of the fund would go to supporting PtL purchases. The assumptions underlying this figure – including the fuel prices – are discussed in Section 4 below along with three other scenarios for subsidy disbursal.

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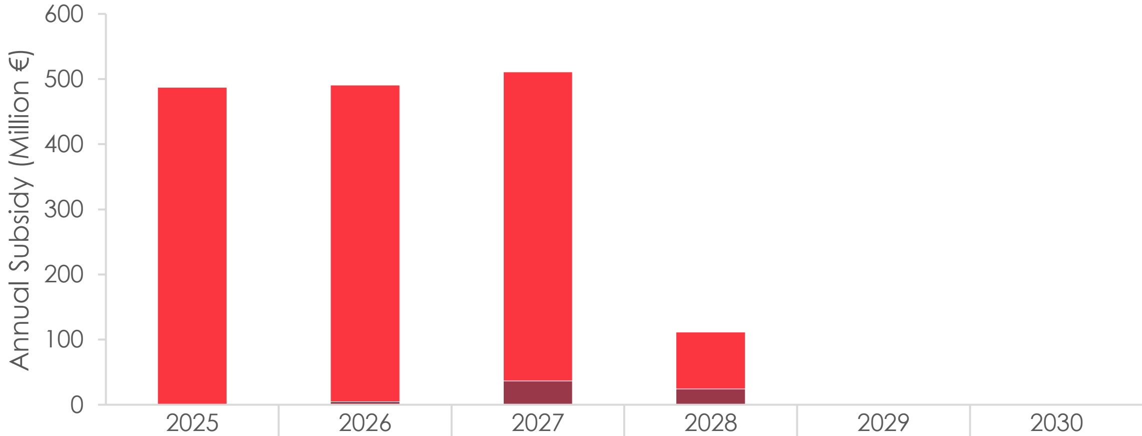
[24] For other fuels like nuclear-powered PtL, the compensated percentage is 50%. Airports in small islands and in the EU's outermost regions may claim reimbursement for 100% of the price difference irrespective of the type of fuel.

[25] If we imagine the subsidy spread over airlines' total fuel expenditures in the period 2025-30, the cost offset to airlines comes to 5.82 €/toe (about half a euro-cent per litre). If a round-trip flight between Brussels and New York consumes 83 toe of fuel, the subsidy would save the airline €480 in fuel costs on this route (around €1.50 per passenger).

[26] This is especially true in scenarios where more BtL and PtL are brought to market, as these attract higher subsidy value per unit of fuel.



	2025	2026	2027	2028	2029	2030
HEFA	487	486	474	87	0	0
BtL	0	5	37	24	0	0
PtL	0	0	0	0	0	0

PtL BtL HEFA

Figure 3 Subsidy disbursal under an illustrative EU fuel demand scenario

If, on the other hand, the subsidy value is low (i.e. the assessed gap between the market price for SAF and fossil fuel is smaller), then some funds may remain un-spent in 2030. If the fund lasts longer, then we would expect a higher share to be spent on BtL and PtL, but the main beneficiary of the reimbursement scheme would still be HEFA.

Making HEFA the main beneficiary limits the value of the scheme as an investment driver because HEFA is already the least-cost compliance option for ReFuelEU Aviation and would be supplied with or without the reimbursement scheme. Subsidising it reduces the financial burden on airlines, but does nothing to further reduce greenhouse gas emissions or support the development of more advanced fuel options[27]. This sub-optimal targeting of resources could be amended, for instance, by placing limits on annual disbursement of allowances (to ensure that some are available in or after 2030); by reducing the reimbursement percentage allocated to HEFA; or by excluding HEFA from the scheme altogether[28].

2.1.5. Price discovery for ReFuelEU Aviation and the reimbursement scheme

Both the penalties under ReFuelEU Aviation and the disbursement of free allowances under the EU-ETS reimbursement require an official assessment of the respective prices per unit of fossil kerosene and of SAF. The EU Delegated Regulation "laying down detailed rules for the yearly calculation of price differences between eligible aviation fuels and fossil kerosene and

[27] Indeed, the act of subsidising fossil-dominated aviation activity could marginally increase emissions.

[28] Responses to the public consultation for the Delegated Regulation (European Commission, 2024c), suggested that some defined portion of the allowances should be ring-fenced for PtL (Opportunity Green, 2025; Transport & Environment, 2025).

for the EU ETS allocation of allowances for the use of eligible aviation fuels" requires that prices should be identified for (European Commission, 2025a)[29]:

1. PtL (RFNBO) aviation fuel;
2. Advanced aviation biofuels from feedstocks listed in Part A of Annex IX of the RED III (including BtL aviation fuel);
3. Aviation biofuels from feedstocks listed in Part B of Annex IX of the RED III;
4. Aviation biofuels from other ReFuelEU-eligible feedstocks;
5. Synthetic aviation fuels produced from non-fossil hydrogen but not qualifying as RFNBOs[30].

The preferred basis for identifying these prices is an annual technical report that ReFuelEU Aviation directs the European Aviation Safety Agency (EASA) to publish annually including estimated prices (EASA, 2024, 2025). This EASA price report will inform both the calculation of ETS reimbursements and of ReFuelEU Aviation penalties. The EASA prices, if available, will directly determine the ETS reimbursement rates. The penalties under ReFuelEU Aviation are intermediated by Member State authorities, which are obliged to impose fines of at least the minimum required level and to "explain the methodology applied for determining the price of aviation fuel, of SAF and of synthetic aviation fuel", which must be based on "verifiable and objective criteria, including from the latest [EASA report]". For the purposes of this report, we assume that Member State authorities will defer to the prices in the EASA report where available, but we note that they have some leeway to adopt different values and therefore there could be variation in the calculated minimum penalty rates across the Union.

EASA (2024) describes the price assessment methodology to be used. The reference fossil fuel price is to include all costs incurred up to delivery at the airport and will be based on index prices published by 'price reporting agencies' (PRAs). Currently the relevant agencies are Argus Media, S&P Global Commodity Insights, and General Index). The 2024 value is equivalent to 750 €/toe (EASA, 2025)[31].

To the extent that index prices from PRAs are available for alternative fuels, EASA would also use those as the basis of its price reporting; but owing to the nascent nature of the market, the small volumes being traded, and the lack of price transparency for bilateral trades, relevant information is scarce. Currently only two agencies[32] report index prices for SAF. These reflect transactions for HEFA made from residual and waste oils. Importantly, we would expect these index prices to reflect the prices paid by fuel suppliers to SAF producers rather than the prices paid by airlines to fuel suppliers, which could be different (see Section 2.1.6). For 2024, this reference price was determined to be 2,131 €/toe.

EASA is not yet able to use price reporting by PRAs as the basis to report a market price for SAF other than HEFA, and will not be able to until there is a large enough number of transactions

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[29] The Delegated Regulation further calls for prices to be identified for both versions of these fuels produced in standalone facilities versus versions co-processed with fossil fuels at oil refineries, and for hydrogen.

[30] E.g. nuclear energy-derived fuels

[31] We have converted from tonnes to toe.

[32] Argus Media and S&P Global Commodity Insights.

with a sufficient degree of transparency[33] for one or more price reporting agencies to publish an index price. For PtL, the ReFuelEU Aviation target only begins in 2030, and we might expect traded volumes to be modest until then. It is unclear whether or when any significant volume of advanced aviation biofuel will be supplied in the EU, and therefore when index prices for these fuels could become available.

Member States are expected to refer to the EASA report to inform the minimum fines imposed whether or not EASA is able to directly report market prices, but (anticipating scanty public information) the Delegated Regulation sets out two backup options for establishing reference prices to determine the ETS reimbursements, if the EASA report does not include market price data for a given fuel category. The first of these is that aircraft operators are invited to disclose to the Commission each year the actual prices they have paid for SAF. Those that report this data would be given reimbursement based on the average reported prices.

Finally, if neither EASA-reported market prices nor airline-reported prices are available, the European Commission may calculate a 'minimum selling price' for each fuel as the EASA-estimated production cost plus 10%. EASA has started publishing such estimations: using the 2024 reported prices (EASA, 2025) as a basis to calculate a minimum fine under ReFuelEU Aviation, would put a non-compliance cost of 2,760 €/toe on the main part of the ReFuelEU Aviation mandate and of 14,230 €/toe on the PtL mandate – this latter being 19 times the price of a toe of fossil kerosene.

2.1.6. Production cost, fuel-supplier price and airline price

The three price-finding options defined in the Delegated Regulation on the calculation of price differences provide an illustration of three related but distinct price points for the SAF market (refer to Section 1.4):

1. The market price reported by EASA based on the index prices from the PRAs is expected to reflect the price paid by aviation fuel suppliers to SAF producers (the 'fuel-supplier price'). This price is capped by the willingness to pay of the fuel suppliers, which will be driven by the penalties they face for failing to meet their obligations.

2. The price that airlines report paying fuel suppliers for SAF (the 'airline price'). This price is capped by the willingness to pay of the airlines, which is limited by the incentives that they are offered and may be quite different from the willingness to pay of fuel suppliers.

3. The estimated production cost of SAF. This is driven by the cost of feedstock, operations, and capital incurred by SAF producers.

In a market where supply and demand are balanced, we would expect that the EASA-reported market prices would tend towards the typical cost of fuel production – but if the supply of SAF is lower than the amount needed to comply with targets, fuel suppliers will compete with each other to buy that limited supply of fuel, pushing prices up. Given the potentially high penalties associated with non-compliance under ReFuelEU, especially for PtL fuel, prices could be pushed very high indeed. The fuel-supplier price (EASA's market price) could therefore potentially be much higher than the production cost, especially for PtL.

[33] Given corporate trading customs, there is nothing to suggest that long-term contracts agreed between fuel suppliers and fuel producers, and between airlines and fuel suppliers, would routinely be made public.

The second price in the list, the price paid by airlines per unit of SAF, could be independent of both these other prices. We can assume that the willingness of airlines to pay for SAF would be determined by the value to the airlines of the fuel energy (i.e. the fossil kerosene price), plus the avoided EU-ETS costs, plus any subsidy. The airlines' willingness to pay could therefore potentially be less than the production costs – and perhaps much less than the willingness to pay of the fuel suppliers, who are subject to the mandate and associated fines. Such a situation is possible for HEFA and likely for PtL. Fuel suppliers would then have to sell these fuels to airlines 'at a loss', and therefore need to 'cross-subsidise' SAF by increasing the price they charge for fossil fuels. In fact, as noted in Section 1.4, it is likely in practice that many airlines will not buy one batch of fossil kerosene and a second batch of SAF from a fuel supplier but instead simply buy a single batch of blended fuel. This would obscure the underlying prices of the two components, and may make it difficult for the SAF price to be established using the second option from the Delegated Regulation. We would still expect that the price of the blend would represent a weighted average of the underlying prices of the fossil and SAF parts, but it may be difficult for competent authorities or even for airlines to separate these two prices.

ReFuelEU Aviation treats the fuel-supplier price (as defined above) and production cost as being somewhat interchangeable, allowing either to be used as the basis of the assessed minimum fines. This conflation could lead to significant jumps year-on-year in the ReFuelEU Aviation fines and the EU-ETS reimbursements, adding uncertainty to the market. For example, in the event that PtL supply is inadequate to meet the obligation, there is the possibility that prices could spiral out of control. We noted above that based on 2024 price data, the minimum fine for failing to meet PtL obligations would be 14,230 €/toe. We also noted that it seems unlikely that PRAs will be able to publish index prices for PtL until after the targets start in 2030. One could easily imagine a situation in which ReFuelEU Aviation fines are around 14,000 €/toe for non-compliance with the PtL mandate in 2030 or 2031. Under those conditions the fuel-supplier price for PtL could reach 15,000 €/toe or higher.

At the point that a PRA is able to identify and report a market price and this became the basis for the price reported by EASA, the calculation of the minimum fines would move from being based on estimated production cost to reported market price. For example, if a PRA reported the price of 15,000 €/toe as an index price and it was included in EASA's report on 2032 prices, the 2032 minimum fine would double from around 14,000 €/toe to 2 x (15,000 – 750) = 28,500 €/toe. This would further push up the willingness to pay of fuel suppliers, which could further increase the fuel-supplier price used as the basis for index pricing by the PRA and then reported by EASA, which would further increase the calculated minimum fine, further increasing the willingness to pay, and so on, with this inflationary spiral potentially continuing for as long as the supply of PtL was less than the mandated demand. Using the production cost assessment as the only basis for setting the minimum fines would avoid this instability; but the fines would then be less dissuasive in the context of the actual market price of PtL fuel.

Spiralling prices could be argued to provide a strong incentive for investment in PtL production – but these elevated prices would likely provoke vigorous political opposition from fuel suppliers and other stakeholders, and in any case would collapse back towards the production cost as soon as supply overtook demand. This uncertainty, both political and economic, does not inspire confidence in the policy framework as a good driver of long-term investments. The penalties in ReFuelEU Aviation are designed to be high enough to drive investment in PtL; but there is a real risk that by making these penalties theoretically unlimited, the market and political outlook become so unpredictable that producers still do not have the confidence to make those investments.

2.2. United Kingdom

The major policies affecting demand for SAF in the UK are: the UK-ETS, which imposes a cost on airline CO_2 emissions; the SAF Mandate, which creates a quota for renewable fuel use in aviation; and the Revenue Certainty Mechanism / Guaranteed Strike Price, which seeks to build investor confidence in the industry. We cover each of these in turn.

2.2.1. UK Emissions Trading System (UK-ETS)

The UK-ETS (UK Government, 2020) commenced operation in 2021 to replace the UK's participation in the EU-ETS. Like the EU-ETS, the UK-ETS issues emission allowances up to a specified annual cap for sectors including energy-intensive industries, power generation, aviation, domestic maritime transport (from 2026), and waste incineration (from 2028). Companies may receive free allowances and/or bid for them at Government auctions[34] (UK DESNZ, 2021). Aircraft operators historically received free allowances, but these are to be phased out from 2026 (UK DESNZ, 2023). Use of fossil aviation fuel burned on flights between the UK and the EEA generates a UK-ETS obligation, but aviation biofuel does not. It is our understanding that (unlike the EU-ETS) the UK-ETS does not currently exempt PtL fuels, but that the UK Department for Transport expects this treatment to be revised in due course so that PtL and biofuels have equal treatment.

Average UK-ETS credit prices in 2021 reached a high of 75 £/tCO_2e, but fell in 2023 to 36 £/tCO_2e (International Carbon Action Partnership, 2024; World Bank Group, 2023); the trends are shown in Figure 2 above. A Cost Containment Mechanism (CCM) is implemented so that unusually high credit prices can be moderated through intervention by the UK Government (UK DESNZ, 2025).

2.2.2. SAF Mandate

The UK's SAF Mandate applies to all aviation fuel supplied in the UK, and hence has a broader scope than the UK-ETS. It began operation at the start of 2025 (UK Department for Transport, 2025a). Many elements are based on the UK Renewable Transport Fuel Obligation (RTFO) which was the original UK regulatory instrument for supporting uptake of alternative transport fuels[35]. The SAF Mandate obligates aviation fuel suppliers to supply a quota of alternative fuel according to a set schedule (Table 2). In the near term, the quota will rise from 2% in 2025 to 10% in 2030.

[34] In 2025, just under 56 million allowances will be auctioned, down from 69 million in 2024.

[35] The RTFO was introduced in 2008 and adjusted in 2009 to align with the RED while the UK was still a member of the EU. It is road-transport focussed, but prior to the introduction of the UK SAF Mandate also supported alternative aviation fuels.

Table 2 Regulatory fuel volumes required by the UK SAF Mandate, in % of total aviation fuel consumption and ktoe

SAF Mandate Target	Unit	2025	2030	2035	2040
Main obligation	%	2.0%	10.0%	15.0%	22.0%
	ktoe	230	1,238	1,918	2,918
PtL obligation	%	0.0%	0.5%	1.5%	3.5%
	ktoe	0	58	166	360

Note: The regulatory percentages in this table have been translated into estimated fuel volumes using DfT's jet fuel demand projection (UK Department for Transport, 2024b). The SAF Mandate includes a weighting factor which scales with fuels' lifecycle emissions intensity; as such, a physical litre of fuel may count as more or less than a litre for regulatory purposes. See the explanation in Sandford & Malins (2024).

To comply with the SAF Mandate, individual fuel suppliers may either surrender 'SAF certificates' (earned through supplying SAF or bought from another party that has surplus certificates), or 'buy out' of the obligation[36]. Buying out entails paying a pre-defined fee to the UK Department for Transport (DfT) in lieu of surrendering a SAF certificate – this effectively caps the value of SAF certificates and hence the cost of compliance.

To be eligible, a batch of SAF must satisfy a number of sustainability conditions. Its lifecycle greenhouse gas emissions intensity must be at least 40% below the baseline of 89 gCO_2e/MJ[37] (DfT may raise this percentage over time (UK Department for Transport, 2024b)). As it stands, the only biofuels eligible for the SAF Mandate will be those made from residue-and-waste feedstocks; these are the same as the double-counted biofuels under the RTFO (UK Department for Transport, 2024a). DfT has stated that it "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, 2024b).

A novel feature of the SAF Mandate is that each litre of fuel generates a number of certificates proportional to its reportable lifecycle emission saving (specifically, equal to its percentage lifecycle emissions savings divided by 70%). Hence, a batch of fuel that reported a 100% emissions saving would be able to generate 1.43 certificates per litre. The lifecycle emissions of fuels is calculated according to the RTFO methodology and may in principle be negative (UK Department for Transport, 2024b).

Aside from the main SAF Mandate quota there is also a sub-target to stimulate the supply of PtL, reaching 0.5% of aviation fuel in 2030 (Table 2). As PtL emissions savings typically exceed 70%, its greenhouse gas weighting factor will be greater than 1 and it will be possible to meet the target with less than 0.5% of physical fuel. Companies supplying PtL jet fuel will be issued with 'PtL certificates', which will trade in a different market to general SAF certificates and are expected to command a higher price.

In acknowledgement of the limited scope for sustainably increasing consumption of residual oils, and the likelihood that a significant volume of material would just be displaced from existing use in production of road biofuel, the SAF Mandate caps the contribution of HEFA. This

[36] Failure to comply through one of these pathways will result in a punitive penalty, which would cost more than the buy-out. We assume this will therefore not happen in practice.

[37] This is the value adopted by ICAO (ICAO, 2024a), but note that the EU's RED II/III and the UK's RTFO use a higher comparator of 94 gCO_2e/MJ (UK Department for Transport, 2021) so care must be taken when comparing percentage emissions reductions.

cap increases until 2035, after which it levels out at 7.8% of aviation fuel[38]. In 2030 it is set at 7.1%, out of an overall Mandate target of 10%. Assuming that fuel suppliers hit the HEFA cap, and that the PtL quota is met, this leaves 2.4% of aviation fuel in 2030 to be supplied as BtL (or as extra PtL, but we consider this unlikely due to price and availability issues). This, in combination with the high buy-out price discussed in the next paragraph, makes the SAF Mandate the strongest policy signal in the world for production of BtL aviation fuel.

When compliant fuels are in short supply (which is likely under stretching SAF Mandate targets (Sandford & Malins, 2024)), competition will raise the SAF Mandate certificate price towards the buy-out level; the buy-out price plus fossil fuel price then provides an indication of the price that fuel suppliers will be willing to pay. The adopted buy-out price is 4.75 £/l (6,850 €/toe) for the main mandate, and 5.00 £/l (7,210 €/toe) for the PtL mandate (UK Department for Transport, 2024a), with the slightly higher PtL price providing extra incentive to achieve the PtL target. These prices are high compared to the current RTFO buy-out of 0.50 £/l, and even the 'development fuel' (i.e. the equivalent of the RED's Annex IX) buy-out of 1.60 £/l, but they provide a stable and predictable basis for fuel suppliers to plan compliance strategies, while capping total imposed costs. This contrasts with the variable and retrospective minimum penalty and unlimited costs under ReFuelEU Aviation.

It is worth noting that the DfT has committed to intervening in the event of "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, 2024c). Modifications could include lowering the buy-out level, or "broadening the list of eligible fuel types and feedstocks, for example, to include sustainable crops and cover crops". It is understandable that the DfT should seek to provide reassurance against price rises it would see as excessive, but pre-emptively identifying broad contexts in which the policy would be revised may be seen as introducing extra investment uncertainty.

2.2.3. Guaranteed strike price (GSP)

In parallel with the SAF Mandate, a revenue certainty mechanism will support investment in SAF facilities. The DfT has chosen a 'guaranteed strike price' (GSP) model (UK Department for Transport, 2024d)[39]: similar to a contract for difference, under the GSP fuel producers may enter an agreement with a Government counterparty[40] on a target sale price per unit of fuel. This is called the 'strike price'. Should sale prices (assessed either by calculating a reference price based on market data or by self-reporting, see Section 5.3) dip below the strike price, the Government funds the difference, and vice-versa if sale prices exceed the strike price the Government would be paid the excess revenue[41]. The mechanism is illustrated in Figure 4.

[38] Recall again that compliance may be achieved with a higher or lower percentage of physical fuel, depending on the emissions intensity score of contributing fuel.

[39] Other options were considered in a Government consultation (UK Department for Transport, 2024e).

[40] The Low Carbon Contracts Company (LCCC).

[41] It has been suggested in the past that uptake could be encouraged if producers were allowed to keep some or all of revenues above the strike price rather than paying them back to the Government (Calderbank & Malins, 2021). This would relieve the pressure on operators to bid for a high strike price to give them a buffer against increased costs, such that the strike price could more closely reflect the actual expected production cost.

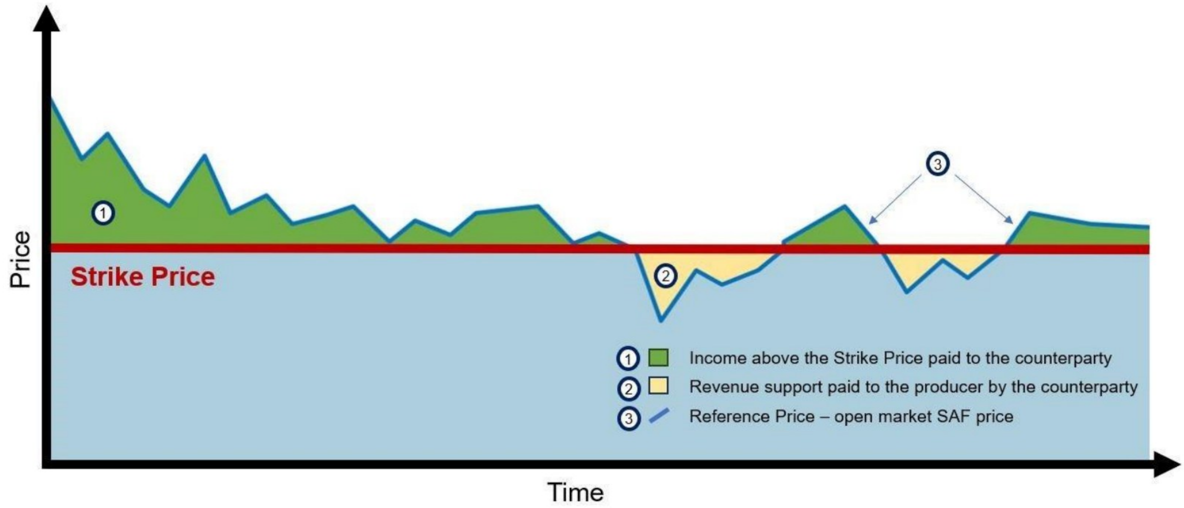

Figure 4 Illustration of the guaranteed strike price mechanism proposed by DfT

Source: UK Department for Transport (2024e)

The GSP is intended to allow fuel producers to plan for a predictable revenue in a potentially volatile market. It is expected that the GSP will be available to UK-based fuel producers only, and the first round of GSP contracts will focus on BtL and PtL projects, with HEFA excluded (UK Department for Transport, 2024e). Accounting for the need for primary and secondary legislation, DfT anticipates that the GSP will come into force no earlier than the end of 2026 (UK Department for Transport, 2024e).

While the implementation details are still under development, we can consider the case that each fuel producer seeking to enter a GSP contract proposes their own strike price[42]; this would need to cover all project costs including loan interest and payments to shareholders, and account for revenues from co-products (e.g. road fuel or chemical industry feedstocks like naphtha). It's incumbent on producers to propose a strike price that they are reasonably confident will deliver project viability under evolving market conditions, while remaining competitive for securing award of a GSP contract.

In a recent consultation, the DfT confirmed its intention to raise GSP funds from aviation fuel suppliers (UK Department for Transport, 2025c), such that any Government pay-out to fuel producers would ultimately come from the industry rather than the Exchequer. However, at the time of writing this hasn't been finalised. The DfT proposed a levy on fuel suppliers that will cover the expected costs of the GSP, with the total distributed among fuel suppliers in proportion to their share of the aviation fuel market. Should the levied funds exceed what is needed to honour GSP contracts, the excess will be re-distributed; conversely, if levied funds are insufficient, excess costs will be added onto the levy for the next period. If the agreed strike prices turn out to give a reasonable reflection of producers' achieved sale prices, then the cost of levy may be small; but this is not guaranteed, and would depend on market conditions, and also on how the reference and sale prices are to be calculated. We return to this matter in Section 5.3.

[42] There have been suggestions that uniform strike prices might be proposed to cover entire technology classes, but we are not aware of any official statement or consultation.

2.3. International policy

2.3.1. UN ICAO

The International Civil Aviation Organisation (ICAO) established the Carbon Offsetting and Reduction for Sustainable International Aviation scheme (CORSIA) in 2016 to manage the greenhouse gas emissions from a growing aviation industry. CORSIA obligates airlines to cancel out increases in CO_2 emissions above their 2019 baselines, either by surrendering offset certificates or by supplying SAF. Participation is currently voluntary but will become mandatory in 2027 (IATA, 2024), at which point CORSIA will be the first global legally-binding policy regulating emissions from international aviation.

Domestic flights within the EU and EEA are already obligated to pay for EU-ETS allowances, and are exempted from CORSIA. In 2026 the European Commission will examine the performance of CORSIA, with a view to potentially extending the EU-ETS to cover international flights departing from the EU if the value signal from CORSIA is deemed to be weak[43] (European Commission, 2023b). The UK is currently conducting a public consultation on the overlap between CORSIA and the UK-ETS, exploring whether to exempt flights within the scope of the UK-ETS from CORSIA or allow both schemes to overlap with a mechanism to compensate the double-counting of emissions (UK Department for Transport, 2025b).

It is expected that compliant SAF will be expensive compared to offsets, and therefore that offsets will generally be the preferred compliance option. CORSIA's reliance on offsets over reductions in fuel lifecycle emissions means that the integrity of compliant offsets is paramount, though this has been questioned (Schneider & Wissner, 2022).CORSIA is therefore not placed to be a driver of SAF uptake – a fact that is freely acknowledged by the industry[44] – but it may incrementally reduce the price gap in jurisdictions where uptake is already mandated. Fuel supplied under ReFuelEU Aviation and the SAF Mandate is very likely to be CORSIA-compliant, and hence eligible for earning credits when used on international flights.

2.3.2. United States

The USA's SAF Grand Challenge (U.S. Department of Energy et al., 2022) is a collaboration between the U.S. Departments of Energy, Transportation, and Agriculture, and implements a strictly voluntary target of 3 billion gallons (9.6 Mtoe) of domestic production in 2030 and to meet 100% of the USA's aviation fuel demand by 2050. At the time of writing, it is unclear what the fate of the programme will be under the new Government. Near-term progress towards the goals as they stand is to be stimulated through the award of grant funding (U.S. Department of Transportation, 2024) and through tax credits issued under the Inflation Reduction Act (IRA) (U.S. Government, 2022). The USA framework can be thought of as based on giving incentives and support rather than imposing regulatory obligations. This could mean that the USA will start producing alternative fuels that would then be supplied to regulated foreign markets, such as the EU and UK.

[43] At present, the cost of CORSIA compliance is low compared with EU-ETS allowances (L, 2024); but some industry analyses have forecast that high demand for CORSIA-eligible credits will drive up credit costs (AlliedOffsets, 2024; L, 2024; Limón Portillo, 2024).

[44] "CORSIA is an offsetting scheme. It allows an airline to use SAF to meet its offsetting obligations, but the scheme does not promote SAF." (Gill, 2019).

Of relevance to PtL fuels, the IRA's Section 45V establishes a tax credit of up to 3 $/kg of 'clean' hydrogen, and Section 45Q establishes a credit of up to 0.13 $/kg of CO_2 captured. For the hydrogen credit, a range of technologies including nuclear electricity and fossil methane reforming are eligible provided they meet the threshold emissions intensity. Renewable electricity used for green hydrogen production must satisfy some of the same criteria as in the EU and UK, signifying reduced barriers to fuel trade between these markets.

Section 45Z more specifically targets SAF, with a credit of up to 1.75 $/gallon (480 €/toe) depending on the fuel's reported emissions intensity, throughout the period 2025-27. Guidance published in 2025 on the Clean Fuels Production Credit ('Section 45Z') clarified that this support will be available to a broad base of first-generation biofuel producers (U.S. Department of the Treasury, 2025): a move which caused consternation among civil society groups in the USA (Lashof & Denvir, 2025). It also has a double-edged implication for SAF supply in these markets: on one hand, the USA's acceptance of first-generation HEFA and AtJ will mean less international competition for next-generation feedstocks and fuels (i.e. BtL and PtL); on the other hand, a smaller global market may reduce the pace of investment and progress in next-generation production technology. There may still be some spillover learnings for processes such as alcohol-to-jet that can use both food-based and cellulosic ethanol.

3. Production and investment

3.1. Current capacity

At the beginning of 2024, EASA reported that production of aviation biofuels through co-processing HEFA at oil refineries and at biofuel-only plants (EASA, 2024), with total production capacity of around 1 Mtoe/year. Virtually all of this is HEFA, with only experimental volumes of PtL and BtL being produced (Mutrelle, 2024).

Looking ahead, EASA (2024) estimated annual EU production capacity in 2030 under two growth scenarios: 'Realistic' and 'Optimistic'[45]. The Realistic scenario was based on plants that were already operational, under construction, or had been green-lit for investment; the Optimistic scenario incorporated in addition announced projects that were deemed likely to be delivered by 2030. The aggregated production capacities in these two scenarios were 3.2 Mtoe/year and 5.5 Mtoe/year respectively, with the 'Realistic' figure comprised entirely of HEFA and 'Optimistic' being split into 4.4 Mtoe/year of biojet (presumed to be HEFA) and 1.1 Mtoe/year of PtL[46].

Project SkyPower (2024) identifies 0.3 Mtoe/year of capacity as having strong potential to start production in the EU by 2030[47]. Given that it will take at least 3-4 years to get each plant built, commissioned, and operating at anything close to nameplate capacity, delivering production in significant volumes by 2030 would require these projects to be approved in the very near term.

In the UK, the DfT estimated that HEFA production capacity could reach 0.32 Mtoe/year in 2030, PtL would be in the range 0-60 ktoe/year, and BtL 150-310 ktoe/year (UK Department for Transport, 2024c). Even at the upper end, the UK would be unable to fulfil the UK SAF Mandate with domestic supply alone, and so imports from the EU and beyond would be needed.

3.2. Production cost

3.2.1. Cost components

SAF production costs can be broken down into operational costs and capital costs. Operational costs can be further divided into variable and fixed. Variable operational costs include feedstocks, electricity, and other inputs: these are proportional to the amount of fuel produced in a given period. Fixed operational costs include rents and permanent staff salaries, which are independent of the amount of fuel produced in each period. Capital costs can be split into the upfront cost of planning and installing a facility, and the cost of paying interest on

[45] While the modelling accounted for the slate of co-products coming from the refineries, here we quote just the aviation fraction.

[46] Companies in Norway, Denmark, Iceland, Sweden, Germany, Spain, and France have been identified as pursuing deployment of this technology (EASA, 2024; Mutrelle, 2024).

[47] Note that this is significantly less than the EASA (2024) 'Optimistic' scenario.

the debt incurred and paying returns to equity investors (returns to equity investors can either be framed as part of capital cost, or considered separately as the required profit margin)[48].

The capital costs can be amortised over the lifetime of an investment and added to the operational costs to give the overall 'levelised cost of production' (LCOP). For HEFA, feedstock is the dominant cost. For BtL, capital costs are a larger fraction (Soubly & Riefer, 2020; Wille et al., 2023). For PtL, the largest cost is likely to be the electricity, but capital costs are also high (Malins, 2017).

Naturally, a fuel producer will hope that revenues will cover all of these costs, and ideally provide additional profit. If, however, revenues cannot even cover variable cost, a facility will stop producing fuel, at least temporarily. If revenues cover variable cost but cannot cover debt repayment and fixed operational costs, the business will produce fuel in the short term, but persistent shortfalls will eventually result in business failure. If revenues cover costs but don't support the promised/expected return to equity, the business should remain operational but may find it difficult to secure new investment and grow. Producers with a higher share of variable costs have more scope to react to low fuel prices by temporarily stopping production, which can make them more resilient to unpredictable fuel market conditions (though they are also more exposed to variation in feedstock price).

3.2.2. Production cost

A detailed review of production cost estimates is beyond the scope of this study, but we quote a few examples in Table 3 (ranges indicate uncertainty and/or the assumed price range on feedstocks for a given fuel). For reference, the market price of fossil jet kerosene is given as 750 €/toe by EASA (2025).

[48] The cost of capital is further discussed in Section 5.3.1

Table 3 SAF production cost estimates from selected studies (€/toe)

Reference	Year	Production Cost (€/toe)			
		HEFA	BtL	AtJ	PtL
Royal Netherlands Aerospace Centre & SEO Amsterdam Economics (2021)	2021	971-1,393	1,365-2,499	2,045-3,522	1,169-3,195
Navarrete et al. (2024)	2022	903-1,972	786-3,399	903-2,270	1,892-3,694
EASA (2024)	2023	--	1,661-2,735	--	6,747-8,894
EASA (2025)	2024	1,494[49]	1,958-2,775	--	6,820-9,405
Soubly & Riefer (2020)	2030	420[50]	842	1,136	1,513-2,408
Blanshard et al. (2021)	2030	1,259-1,383	1,056-1,278	1,077-1,194	2,712
Zhou et al. (2022)	2030	--	--	--	1,856-3,834
UK Department for Transport (2024c)	2030	809-1,779	2,786-5,763	2,190-5,855	1,425-8,252

Note: BtL cost is based on gasification and Fischer-Tropsch synthesis. 2030 costs quoted where available. Values have been converted to standard €/toe units, but are otherwise presented as stated in the original sources without adjusting for inflation.

3.2.3. Investment risk

Deploying unproven technologies in uncertain markets brings a risk of project failure and lost investments (Miller et al., 2013). Investors must not only consider the prospects of their own technology, but take a view on likely competition from other technologies – for example early investors in gasification BtL might be concerned that pyrolysis BtL may break through first and leave them with uncompetitive stranded assets. On top of this is the risk that policy-makers will move the goalposts (or dismantle them altogether): changing political priorities and lobbying by legacy industries could weaken targets or water down the eligibility criteria, shrinking the market for the more advanced novel technologies. Even apparently-generous policy support has in the past failed to mobilise successful advanced fuel projects – e.g. cellulosic biofuels in the USA, which have consistently failed to match the ambitious production targets set under the Renewable Fuel Standard (Miller et al., 2013).

This deterrent to potential investors is exacerbated when up-front costs are high, as is the case with CapEx-heavy BtL and PtL production, because large sums of money have to be spent on a novel and complex industrial facility before any money can be earned back. 'First-of-a-kind' (FOAK) plants are particularly expensive because there has not yet been an opportunity to identify potential cost savings through practical experience. For example, Giannelos et al. (2021) anticipate considerable potential to bring CapEx for BtL/PtL plants down over time, as plant designs are presumed to become more standardised and as industry practices more established and refined.

Financing (debt and equity investment) can therefore be difficult for FOAK projects; and those projects that secure funds will typically attract a higher cost of capital because investors

[49] The market price for HEFA is given alongside this production cost, and is equivalent to 2,131 €/toe.

[50] The Soubly & Riefer (2020) estimate for HEFA cost is on the low side, perhaps reflecting an optimistic outlook and lower vegetable oil prices at the time of the study. At present, the cost of feedstock would be above this level even before any fuel conversion costs are added.

expect a risk premium to compensate for the inherent uncertainty. This can create a vicious cycle where a high cost of capital increases the levelised cost of fuel production, making investment less likely, meaning that there is no opportunity to bring costs down by learning, meaning that cost of capital remains high.

3.3. Grant programmes

Section 3.2.3 outlined some of the challenges faced in getting new plants financed. Direct investment from governments (as grants, equity, and below-market loans) can act as a catalyst for getting demonstration and FOAK plants built and operational.

3.3.1. EU Innovation Fund

The European Union's Innovation Fund is dedicated to the demonstration and deployment of low-carbon technologies in renewable energy, transport, carbon capture, and industrial production. It is financed through EU-ETS revenues.

At the time of writing, the Innovation Fund website lists two alternative aviation fuel projects that had received grants (European Commission, 2025c):

- HySkies, a partnership between Shell, Vattenfall, and LanzaTech, is based in Sweden and aims to produce 82 kt/year of AtJ (and 9 kt/year of alcohol-to-diesel) from gas-fermentation ethanol, biogenic CO_2, and electrolytic hydrogen. The Innovation Fund has provided €80 million out of an €780 million CapEx, and the plant is scheduled to begin operation in 2027 (HySkies, 2022).
- Biorefinery Östrand, also in Sweden, will use a BtL technology capable of processing a range of feedstocks (primarily forest residues), and has a target production capacity of 185 kt/year of aviation fuel and 50 kt/year of naphtha. The Innovation Fund grant was €170 million, and the plant is expected to begin operating in 2029.

Beyond these directly relevant projects, 30% of Innovation Fund funding in 2024 (about €1.4 billion) went towards hydrogen production (European Hydrogen Observatory, 2024); some of this hydrogen may ultimately be used in aviation fuel, and more generally any innovations that reduce the cost of hydrogen production could improve the economics of PtL.

Some industry stakeholders have urged expansion of the Innovation Fund to support more aviation-related projects. Project SkyPower (2024) states that support of €400-600 million per PtL project would be necessary to match support granted in the USA (assuming a production capacity of 50-70 kt/year). Whatever the precise figure, the availability of grant funding will bring an early-stage project's finances closer to the go-ahead threshold.

3.3.2. UK Advanced Fuels Fund

In 2022, the DfT established the Advanced Fuels Fund (AFF), which allocates grants to UK-based SAF projects at the FOAK and demonstration stage. The AFF builds on past initiatives: the Advanced Biofuels Demonstration Competition with total funding £25 million (€30 million) (UK Department for Transport, 2015); and the more aviation-focussed Future Fuels for Flight and Freight and the Green Fuels, Green Skies competitions with total available funding of £37 million (€44 million) (Ricardo, 2022; UK Department for Transport, 2018).

The AFF programme allocated £135 million under its first two application windows, and aims to allocate a further £63 million in 2025 (together amounting to £198 million, or €237 million) (Ricardo, 2024). In parallel with this, the SAF Clearing House has been established with facilities for testing and certifying aviation fuels (UK Department for Transport, 2022a; UK SAF Clearing House, 2025). This will support the UK Government's commitment that five UK-based SAF plants will begin construction by the end of 2025 (Harper, 2023); though at present this ambition looks difficult to fulfil (Climate Catalyst, 2024).

4. Deployment in the EU

4.1. SAF demand

To explore some of the implications of the EU policy framework, a simple model of demand for different aviation fuels covering the period 2025-30 was developed, based on ReFuelEU Aviation's quinquennial targets. Four scenarios representing different fuel mixes and regulatory choices were adopted; these are outlined in Table 4.

Table 4 EU fuel demand scenarios

EU Scenario	Description
Maximum HEFA	The PtL sub-mandate is fulfilled, and the remainder of the quota is met with HEFA.
BtL Support	The PtL sub-mandate is fulfilled, and a certain volume of BtL aviation fuel enters the mix. The remainder is met with HEFA.
Cut HEFA	Fuel demand is identical to the 'BtL Support' scenario, but we assume that a change in regulation means that the reimbursement scheme is available only to BtL and PtL.
Delayed	SAF supply is sufficient to meet only 50% of the ReFuelEU Aviation targets.

The first three scenarios deliver compliance with ReFuelEU Aviation targets, while the last one falls short. As noted in Section 2.1.4, we expect HEFA to be the least-cost (and hence the default) compliance option in the absence of additional policy support. For PtL, this additional support is provided by the sub-target, which we assume is fulfilled in the first three scenarios and 50% fulfilled in the fourth. For BtL, we invoke complementary RED III incentives to motivate supply in Scenarios 2, 3, and 4, assuming that some amount of cellulosic hydrocarbon fuel capacity comes online driven by RED III targets, and that the 1.2x multiplier incentivises some of it to be supplied as aviation fuel[51]. Comparing the estimated production costs of HEFA and BtL (EASA, 2025) suggests that the RED III compliance value would have to be around 2,200 €/toe to close the gap with HEFA – assuming fuel is sold at cost – otherwise it would not be rational to supply BtL. Our Scenarios 2 and 3 represent an optimistic indication of the BtL SAF volumes that could reach the market in the period 2025-30.

SAF demand under the four scenarios is shown in Figure 5[52]. The abrupt jumps between 2029 and 2030 are a feature of ReFuelEU Aviation quotas, as introduced in Section 2.1.2; some implications of this will be discussed below. Figure 5 does not show the 94% of aviation fuel that will still be fossil kerosene in 2030 even under the first three scenarios which are fully compliant.

[51] The RED III advanced biofuels sub-target reaches a presumed 2.25% of physical transport energy in 2030. For Scenarios 2 and 3, we assume that this target is met and that a fifth of it is supplied as BtL fuel (as opposed to cellulosic ethanol, biomethane, and 'advanced' lipid-based fuel). Of this, we assume that 30% is suitable for use in aviation. This implies a BtL share of 0.9% of aviation fuel in 2030, and we assume that deployment ramps up over time.

[52] We assume that total aviation fuel demand follows the ReFuelEU Aviation Impact Assessment 'Policy Option A2' scenario (Giannelos et al., 2021). Other sources have projected somewhat stronger industry growth (EUROCONTROL, 2024).

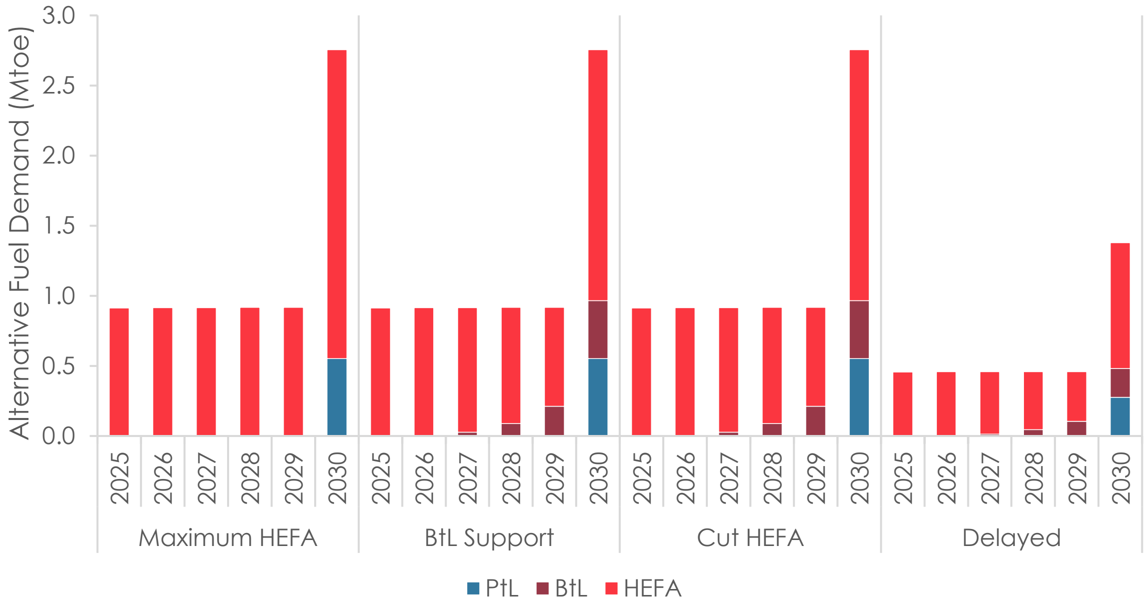

Figure 5 EU SAF demand, modelled according to ReFuelEU Aviation targets for the four EU scenarios

For compliance with ReFuelEU Aviation, biojet demand reaches 2.2 Mtoe/year and PtL demand reaches 0.55 Mtoe/year in 2030. The EASA (2024) analysis presented in Section 3.1 suggests that the EU would be self-sufficient for biojet under its 'Realistic' scenario. The EU could meet its own needs for PtL (considering the 1.2% average target for 2030, Table 1) under EASA's 'Optimistic' scenario, but not under the production rate considered likely by Project SkyPower (2024).

4.2. ETS reimbursement payment

We have made illustrative calculations of the potential rate of disbursement of the EU-ETS reimbursement fund based on the SAF and fossil fuel prices identified by EASA in the latest price report (EASA, 2025). Treating those prices as fixed to 2030, the subsidy value available would be 7,622 €/toe for PtL, 1,391 €/toe for BtL and 533 €/toe for HEFA[53].

In our model, these subsidies are applied until the bank of EU-ETS credits is exhausted[54]. The annual subsidy disbursal for the 'BtL Support' scenario was shown in Figure 3 above, where it was evident that the fund would run out in 2028 before any PtL supply was mandated. Figure 6 presents results for all four scenarios, showing the share of the total fund that is used for subsidising each fuel type. The scenarios are differentiated by their fuel consumption trajectories, and by the zero subsidy for HEFA in the 'Cut HEFA' scenario.

[53] The HEFA subsidy value is based on the published market price and the fossil kerosene price of 750 €/toe (EASA, 2025). For BtL and PtL we assume a minimum selling price equal to the production cost plus 10%, following the Delegated Regulation (European Commission, 2025a).

[54] Again assuming an EU-ETS price of 80 €/tCO_2e.

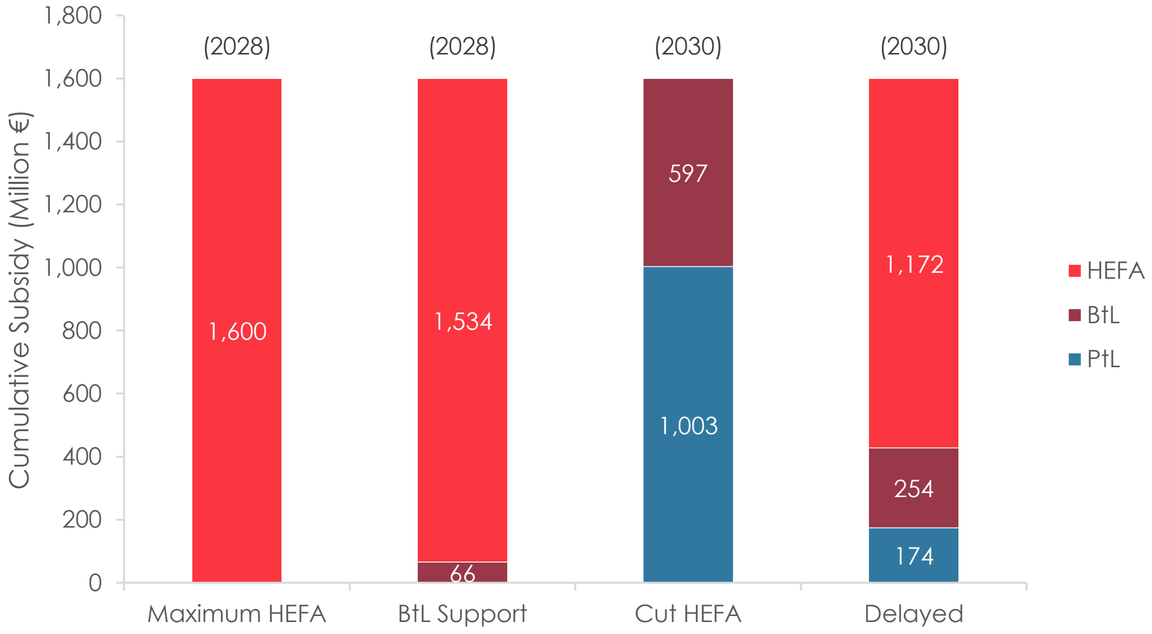

Figure 6 Cumulative subsidy disbursed by 2030 to each SAF under the four scenarios; years in parentheses indicate when the fund is exhausted

Under the 'Maximum HEFA' scenario, no BtL is supplied and the reimbursement fund is exhausted in 2028; thus the entirety of the fund is spent in subsidising airlines to buy HEFA. Under 'BtL Support', small amounts of BtL are supplied and subsidised, but the vast majority of the fund still goes to HEFA. Again, the fund runs out in 2028. In the 'Cut HEFA' scenario, only BtL and PtL are eligible for reimbursement; this slows the overall annual disbursal and preserves some funding for 2030 so that PtL derives some benefit. Excluding HEFA from the subsidy system would therefore be a viable way to target available funds towards more advanced and sustainable options. Finally, slower disbursal in the 'Delayed' scenario also weights payments towards BtL and PtL, which are consumed more by the end of the period, though the bulk of the funding still goes to HEFA.

It is important to re-emphasise that the subsidies do not in themselves provide a systematic incentive for airlines to consume larger volumes of alternative fuel: the volumes are determined by fuel suppliers' need to meet ReFuelEU Aviation obligations. Depending on market conditions, the EU subsidy could either reduce the net fuel costs borne by the airlines[55] or could be at least partly passed through to fuel producers.

Even if fuel producers could accrue some of the benefit of the reimbursement scheme, however, it is such a short term value signal that it would be useless to investors considering twenty or thirty year projects. An early PtL project entering production in 2029 might, or might not, get a couple of years of slightly improved revenue, and then the scheme ends – the investors cannot know whether it will be renewed after that point (though extended support is being considered under the EU's Clean Industrial Deal (Pavlenko & Baldino, 2025)). As it stands, we see it as providing no relevant value signal or tangible improvement in market uncertainty that would motivate development and investment of the industry. This ought to raise concerns

[55] Perhaps counter-intuitively, this cost reduction could end up being delivered through cheaper fossil fuel. If the subsidy enables airlines to pay more to fuel suppliers for alternative fuel, the airlines might lose the 'direct' benefit of the subsidy by paying higher prices, but recoup the value when fuel suppliers are able to marginally reduce fossil fuel prices.

about whether sufficient stimulus exists for the ambitious capacity-building programme, especially beyond HEFA production, needed to fulfil EU targets in the longer-term.

4.3. Capacity development

Table 5 shows estimates of the total plant capacity required to supply SAF in the EU under the 'BtL Support' / 'Cut HEFA' scenarios (as well as for the UK fuel demand trajectory, to be discussed in Section 5). These numbers are only illustrative, as the required capacity will depend on the utilisation factor of the plants and the extent to which plants are optimised to produce jet-compatible fuel molecules versus road fuels/chemicals[56], and the number of plants required to provide this capacity will depend on their size as they progress through generations of technology development[57].

Table 5 Estimated number of fuel plants needed in 2030 to satisfy SAF demand (includes all fuel fractions)

Quantity	Region	PtL	BtL	HEFA	Total
Plant Capacity (Mtoe/year)	EU	1.4	0.9	3.2	**5.4**
	UK	0.1	0.5	1.4	**2.0**
	Total	**1.5**	**1.4**	**4.6**	**7.5**
Number of Plants	EU	20	12	10	**41**
	UK	3	9	5	**15**
	Total	**23**	**21**	**15**	**56**

Note: The underlying calculations assume plants are optimised for production of jet fuel, with the slate of other fuels and chemicals depending on the technology. The number of plants has been rounded up.

The implied scale of investment depends on the how the CapEx per unit of capacity evolves over time, but we can be sure that billions of euros of investment would be needed between 2025 and 2027 to preserve a chance of meeting targets in 2030. For example, Sandford & Malins (2024) conservatively estimated that a cumulative investment up to €4.4 billion would be needed by 2035 to fulfil the UK SAF Mandate; Wille et al. (2023) concluded that globally 100-200 plants would have to be built by 2030, requiring investment on the order of €100 billion (and by 2050 the total figure would be €500-900 billion); and Project SkyPower (2024) estimated that investment of €15-25 billion would be needed to meet the EU+UK mandates for PtL in 2030.

[56] Producing co-products for other markets does also mean that the cost can be shared with those other markets. Cf. (ATAG, 2021; Sustainable Aviation, 2020; van Dyk & Saddler, 2021).

[57] For these assumptions we follow Sandford & Malins (2024).

5. Deployment in the UK

5.1. Fuel supply and cost

The UK's SAF Mandate establishes two buy-out prices: one for PtL and for other alternative fuels. When supply is expected to be tight (i.e. for BtL and PtL), competition between fuel suppliers for the available volumes will put fuel producers in a favourable negotiating position, driving the producer-price up towards the maximum fuel-supplier willingness to pay. Given that the targets are stretching and therefore that compliance is likely to be difficult, we would expect that fuel suppliers will be willing to pay roughly the fossil kerosene price plus the respective buy-out price for BtL and PtL fuels. Fuel producers and their investors can use this to determine which technologies and business models may be viable for selling to the UK market.

HEFA is capped under the UK SAF Mandate, and the buy-out price for the main mandate is set safely above the expected production cost of HEFA; we would therefore expect that there will be enough HEFA capacity to supply HEFA up to the capped level.

Capping HEFA means that there is a clear market space for BtL fuel to contribute to the SAF Mandate; they would compete in this space with PtL, which we expect to be significantly more expensive than BtL, and with recycled carbon fuels, which could potentially be more competitive. Coupling this market space with the high price ceiling established by the buy-out makes the SAF Mandate the strongest policy signal in the world for consumption of BtL aviation fuel. In the EU, by contrast, the entirety of the non-PtL quota can be met with HEFA and the non-compliance penalty is tied to the HEFA price.

The relative attractiveness of the UK as a market for aviation PtL is harder to discern, as it depends on the value signal from the neighbouring EU, which will be dictated by the penalty levels that emerge under ReFuelEU Aviation. We showed above that these penalties could be very high for PtL, in which case if the globally available supply of PtL is limited compared to mandated levels it would go preferentially to the EU, leaving UK-based fuel suppliers to resort to the buy-out mechanism and use fossil kerosene in place of the missing PtL. On the other hand, it seems at least plausible that Member States or the Commission may baulk at imposing very high fines on airlines if PtL supply is significantly below the mandated level – and if those ReFuelEU penalties are reduced or waived, the UK could yet come out as the more attractive market.

The willingness to pay of airlines in the UK will be fossil kerosene price plus the UK-ETS allowance value (Horton et al., 2024; Wille et al., 2022), which, precluding an unforeseen dramatic rise in UK-ETS prices, will be quite a bit lower than the production cost of even the cheapest types of SAF. Fuel suppliers will therefore be forced to raise the price of fossil kerosene to cross-subsidise SAF.

5.2. SAF demand

Figure 7 shows a fuel supply scenario to meet the UK's 2030 policy targets. PtL is supplied to fulfil the PtL mandate, HEFA is supplied up to the cap, and the remainder is represented as BtL – this follows the assumptions in Sandford & Malins (2024). In order to estimate the physical fuel demand corresponding to the SAF Mandate's emissions-intensity-weighted targets, we assume average emissions intensities for PtL, BtL, and HEFA of 95%, 85%, and 75% below the fossil fuel comparator.

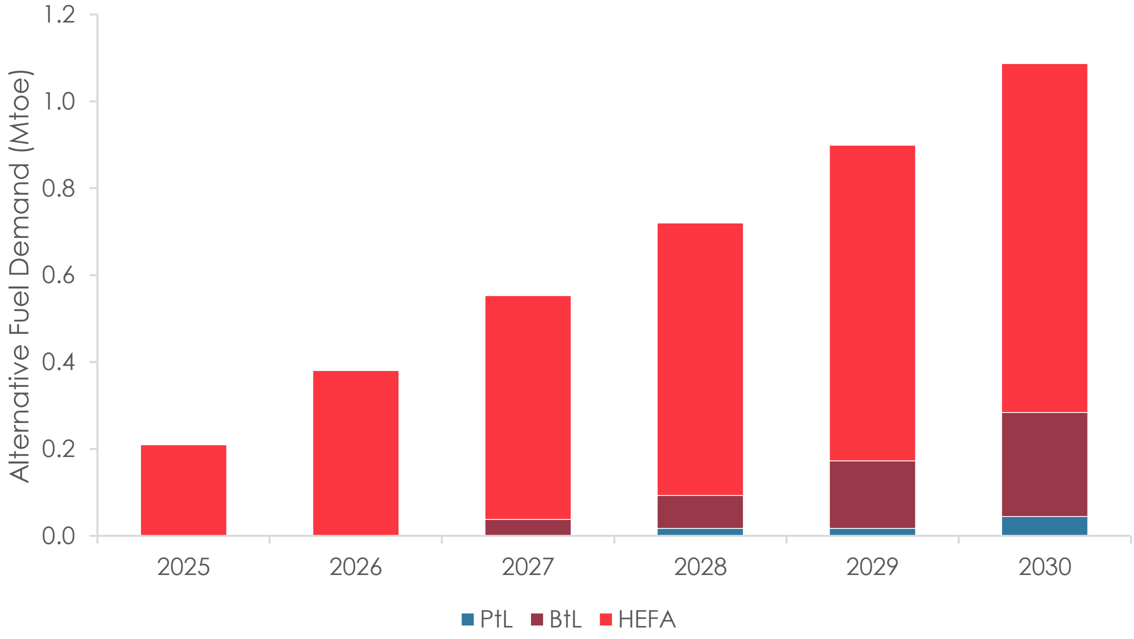

Figure 7 Modelled UK demand for SAF, 2025-30

The estimated number of plants that would have to be built in the UK and beyond to supply this SAF was already shown in Table 5 above. Our calculation assumes that compliance with regulatory targets is delivered through SAF supply, though it is likely that some fraction of the SAF Mandate obligation will instead be bought out (Sandford & Malins, 2024) – this implies that the required capacity may be quite a bit lower than the values presented in Table 5.

5.3. Guaranteed Strike Price

5.3.1. Impact on investment

The number of FOAK plants that must be successfully operationalised before a new fuel production technology can be considered mature (and the need for external support to sustain industrial growth is obviated) is a matter of long-standing discussion (Peters et al., 2016). There is no precise answer to a question like this, but anecdotal evidence from industry players suggests that 6-10 successful commercial-scale plants for a given technology would be enough to move to a second, less challenging, phase of deployment. If the UK's policy framework were to enable deployment of just two or three operational plants using a BtL or PtL technology, that would already be a major contribution to the development of a global industry.

Under the SAF Mandate, about 15 operational plants, across all technologies, would be needed to fulfil the UK's 2030 targets (Table 5). The GSP mechanism (Section 2.2.3) will offer investment certainty for UK producers of next-generation fuels[58], which ought to make investment more likely. It may also have a role to play in reducing capital costs, so that in the best case, the GSP mechanism results in more projects being delivered and lower levelised production costs on the fuel produced.

New fuel production projects can be funded by a combination of debt funding and equity funding (and, where available, government grants, cf. Section 3.3). Debt is provided by banks at a defined interest rate and must be repaid over an agreed timeframe. Equity investment, in contrast, means investing in exchange for a share of the ownership of the asset. Equity investors do not receive scheduled repayment in the same way as lenders, but take a share in the value of the asset and may receive dividends when the asset generates profits. Lenders hope to get their money back plus interest, but could still lose their money of a project fails. The outcomes for equity investors can be more variable – they could lose their money due to project failure, or could achieve returns below, at or above the targeted level. While mature HEFA technology may be able to recruit investors with a predicted internal rate of return (IRR) as low as 10% (Howe et al., 2024; ICAO, 2024b), more speculative projects would need to have rather higher expected returns to get funded.

Using the GSP to increase revenue certainty for SAF projects could enable financing in two ways – firstly by making partial debt-financing available, and secondly by reducing the rate of return required by equity investors. FOAK projects with very uncertain returns such as advanced biofuel or PtL plants will generally struggle to raise debt from banks (Elobio, 2010) due to the high uncertainty of repayment, but the use of contracts for difference and similar mechanisms can allow a more leveraged financing structure with a mixture of debt and equity that, "allows lenders to offer lower interest rate premiums and longer debt tenures, thereby reducing the cost of capital for projects and creating a virtuous circle that reduces the cost of energy over time as more projects are developed" (Ason & Dal Poz, 2024). In the best case, the reduction of risk and availability of debt finance will make projects interesting to 'infrastructure investors' (e.g. pension funds or sovereign wealth funds) that have a lower risk appetite but lower expected rates of returns than the private equity investors who would be needed to fund projects without access to a revenue certainty mechanism. A long-term offtake agreement for produced fuel could also reduce revenue risk and make a project more appealing to investors with a lower risk appetite.

To illustrate the benefits of enabling funding by infrastructure investors we can consider a simple example comparing the 'weighted average cost of capital' (often abbreviated to WACC) and consequent levelised cost of production for an example PtL project[59] under two sets of financing assumptions (Table 6). In the first case, we assume that the project has no GSP contract and has to be 100% equity financed by private equity investors with an expected rate of return of 20%. In the second case, we assume that the project has a GSP contract and that this allows it to be financed with 30% debt at a 10% interest rate, and 70% infrastructure equity with an expected rate of return of 15%.

The version without the GSP has a weighted average cost of capital of 20% (just the expected return on equity) while the version with the GSP reduces the weighted average cost of capital

[58] Mitigating revenue uncertainty with this type of mechanism has been successful at catalysing investment in other parts of the green economy (cf. Wille et al., 2023).

[59] We have assumed a round unit CapEx of 10,000 €/(toe/year) and a unit OpEx of 2,000 €/toe (cf. Soubly & Riefer, 2020). The plant is assumed to have an 80% utilisation factor.

to only 13%[60]. The levelised cost of fuel production[61] is reduced from 4,570 €/toe to 3,750 €/toe – so if we are correct to believe that the GSP may make this more favourable financing model possible, it could reduce the cost of our example PtL fuel by as much as 18%. That could significantly reduce the overall cost of compliance with the PtL part of the SAF mandate if reflected in reduced costs to fuel suppliers.

Table 6 Illustration of the effect of the GSP on the required fuel sale price

Quantity	Unit	Without GSP	With GSP
Debt share	%	0%	30%
Debt interest	%	10%	10%
Equity IRR	%	20%	15%
Levelised cost of production	€/toe	4,570	3,750

5.3.2. Design issues

A GSP contract requires a fuel producer and the UK Government to agree on a fixed strike price that will be compared to the reference sales price achieved by the project in each reporting period. It is yet to be determined how the agreed strike prices will compare to the theoretical willingness to pay of the fuel suppliers, i.e. whether the strike prices will generally be more or less than the sum of the fossil kerosene price and the buy-out price. If agreed strike prices are below the value level that can be supported by the SAF Mandate then in a tight market we would expect that Government pay-outs would be minimal – the GSP contracts might even turn a net profit. In this price regime, the GSP can be understood as a form of insurance on the SAF Mandate credit market (cf. Calderbank & Malins, 2021), only paying out if SAF Mandate credit prices fall significantly below the level of the buy-out price. If, however, the strike price is set above the maximum fuel-supplier willingness to pay, then we would expect the Government entity to pay out on the contract more or less continuously to cover the price difference. The level agreed for strike prices therefore has significant implications for the cost of the programme.

A second issue arises because fuel production costs will change over time in response to technological breakthroughs, industrial and operational efficiencies, and the changing costs of inputs like feedstock and electricity. Responses to the DfT's GSP consultation (UK Department for Transport, 2024d) highlighted that market fluctuations may cause real-world production costs to rise unexpectedly so that production costs actually rise above agreed strike prices. In that situation, the GSP mechanism's static strike price could make it impossible for SAF producers to cover their costs – even if the producer increased their sales price the extra revenue would have to be paid back to the Government. In the worst case, this could mean that a producer that would be financially viable *without* a GSP contract would go bust *with* a GSP contract. In the GSP contract tendering process, fuel producers would need to balance the need to include safety margins in their strike price proposals with the need to compete for contracts. If the GSP is completely inflexible in this regard, the Government risks either

[60] We follow the standard WACC formula (Hargrave, 2024), with an indicative tax rate of 25%.

[61] The levelised cost of fuel production is simply the total costs divided by the total fuel energy output. Total costs are the sum of OpEx (which we assume for the sake of argument is 2,000 €/toe) and the cost of capital. This latter term is calculated using a standard formula for amortised loan repayments (Allred, 2025), with a unit CapEx of 10,000 €/(toe/year), a cost of capital as calculated above, and a debt amortisation time of 20 years.

overpaying for fuel or accidentally forcing companies out of business! One solution would be to allow fuel producers to index their proposed strike price to key input costs or other relevant market indicators. Strike prices would then be able to remain reflective of production costs, which could enable a more efficient targeting of funds.

An even more important question is how the reference sales prices are to be determined. A reference price methodology that is perceived to yield systematically high values compared to a given strike price would undermine the incentive signal to fuel producers, as they would be wary of excessive repayment obligations. A methodology that conversely yields systematically low reference prices compared to the strike price would entail continuous government-mediated pay-out, which would in turn inflate the levy it imposes on fuel suppliers (Section 2.2.3).

DfT has suggested that the reference price could be determined for each GSP contract by self-reporting of actual sale prices by the producer (UK Department for Transport, 2024e). An obvious problem with this is that under the proposed GSP system a producer would have no incentive to negotiate the sales price higher – as the sale price increases towards the strike price, the cost to government reduces but the producer gets no benefit; as the sale price increases above the strike price the government receives repayments and again the producer gets no benefit. With no incentive to negotiate, producers could sell to fuel suppliers well below the market rate in order to secure offtake agreements, knowing that the Government entity will make up the difference. Even if these Government payouts are then funded by a levy on fuel suppliers, it would be poor policy design to effectively reward fuel producers and suppliers who artificially suppress the nominal price of fuel, imposing the costs of that undercharging on their competitors.

A version of these concerns has been acknowledged by the DfT[62], which suggested that a floor could be put on the reference price. The utility of a floor price would depend on how it was set – DfT has mooted the use of the fossil kerosene price, but this would be an extremely low floor compared to the expected production costs of GSP projects, and therefore would only marginally improve the situation. An alternative to asking fuel producers to set their own reference prices would be to introduce independent sources of price information. The UK could potentially echo the EU approach by using price reporting agencies to calculate a 'standard reference price' for GSP contracts – but this wouldn't work if no index prices were available. Discussing options for a GSP-like mechanism to be used to support the RTFO development fuel mandate, Calderbank & Malins (2021) proposed to base price discovery on the sum of the fossil kerosene price and the price of the development fuel certificates (called RTFCs). This itself would require that development fuel certificate prices should be transparent, and therefore Calderbank & Malins (2021) also proposed the introduction of a blind auction system to allow price identification. Another possibility would be to obligate producers to sell a portion of their fuel on the spot market and use the resulting spot prices as an indicator for the reference price. A DfT consultation on these options would be welcome.

[62] UK Department for Transport (2024e) writes in an appendix that their proposal introduces "Risk of limiting incentives for Producers to maximise sales price".

6. Discussion and recommendations

The EU and UK have set out ambitious goals for the use of alternative fuels in their aviation sectors. Given the early stage of some of the technologies involved, and based on past experience, it is still far from guaranteed that sufficient production capacity will materialise to meet these targets in the near term. There is then a risk that underperformance and/or high costs will undermine political support for renewable energy targets. Challenges notwithstanding, the EU and UK currently offer the strongest policy frameworks in the world for catalysing development of the SAF industry.

6.1. European Union

6.1.1. ReFuelEU Aviation trajectory

ReFuelEU Aviation obligates fuel suppliers to meet SAF quotas which increase step-wise every five years. These steps create a disconnect between demand for SAF and the likely reality of industrial development. SAF producers are effectively encouraged to either time their plants to come online in groups once every five years, or else to open plants gradually and either run them at a lower and lower capacity factor as they approach the next step change, or stockpile fuel in anticipation on the next demand jump. Any of these realities would introduce unnecessary risk and inefficiency to the market.

The steps may be somewhat ameliorated by the availability of other EU markets (road and maritime) and international markets to which excess fuel could be supplied. The UK's aviation fuel market will be an attractive option: the UK SAF Mandate's fuel eligibility criteria are similar to the EU's, and it imposes annually increasing quotas on fuel suppliers. Even so, having a sudden displacement of fuel out of road use and the UK market every five years will tend to destabilise these markets, potentially undermining the predictable business environment that would be most conducive to investment. The EU and/or Member States are recommended to consider whether options are available (through legislative revisions or otherwise) to adopt a more gradual supply-growth requirement.

6.1.2. Penalty setting

ReFuelEU Aviation differs from the RED III because it includes a framework for defining minimum non-compliance penalties for fuel suppliers. These minimum fines, determined in relation to market prices to be published annually by EASA, provide a clear value signal across the EU to fuel suppliers, incentivising them to meet their targets. While these minimum fines are an important part of the system, and using a clearly defined formula to assess the minimum fines gives a degree of predictability to the market, the system is undermined as an investment driver by challenges in price identification and because the possibility of unlimited costs could undermine political support.

If supply does not keep up with mandated demand, for PtL fuels in particular, there is a possibility that the dissuasive penalties will drive their market price upwards, which in turn causes the penalties to increase – creating a spiral of increasing costs to airlines until supply catches up. At the same time, ReFuelEU Aviation includes with a review clause requiring the Commission to assess "the cost-effectiveness of lifecycle emissions reductions" and to "evaluate the possible need to revise the scope of this Regulation, the SAF definition, the eligible fuels and the minimum shares". Taken together with the possibility of spiralling costs, this introduce an element of policy uncertainty to the framework that could undermine the investment climate that defined penalties are intended to foster. We recommend that the Commission consider whether a fine structure that limits the maximum costs to the aviation industry, such as the UK's buy-out mechanism approach, might be more effective at driving investment.

6.1.3. *Subsidy targeting*

The EU's reimbursement scheme has been allocated 20 million EU-ETS allowances to disburse to airlines for each unit of SAF they consume. As fuel suppliers are already compelled to supply defined volumes of alternative fuels by ReFuelEU Aviation, and airlines will consume them even without any subsidy, the main effect of the reimbursement scheme could be to reduce airlines' fuel costs. Perhaps surprisingly, this may manifest as a reduction in fossil kerosene prices: the subsidy will increase the willingness of airlines to pay for SAF, passing value back to the fuel suppliers; the fuel suppliers, experiencing less pressure to cross-subsidise SAF prices from fossil fuel revenues, will be expected to pass that value back to the airlines as lower fossil kerosene prices. In any case, given that airlines will not be the ones deciding how much SAF is supplied in Europe in this period, the attempt to 'incentivise early movers' through this scheme may be misdirected.

Most SAF supplied to the EU market in this period will be HEFA, and funds for the reimbursement scheme are likely to run out in or before 2030. Only a minimal share of the reimbursement fund will go towards PtL and BtL. Our analysis suggests that in a 'business-as-usual' scenario, the entire bank of EU-ETS allowances will be disbursed to airlines for consumption of HEFA that would have been supplied anyway: this is because BtL is expected to have higher costs and hence little deployed capacity, and because the bank is exhausted in 2028 before the PtL mandate kicks in. Stronger-than-expected policy value from the RED for aviation BtL could shift the picture slightly – our 'BtL Support' scenario sees 4% of the allocated fund (around €66 million) going towards BtL and the remainder to HEFA; but this doesn't change the situation for PtL. Excluding HEFA from the EU-ETS reimbursement scheme on the other hand would extend the life of the bank to 2030, allowing PtL purchases to garner support of around €1 billion and BtL €600 million. Our illustrative 'Delayed' scenario where the industry fails to achieve its ReFuelEU Aviation quotas also preserves the bank until 2030; and while three-quarters of the bank still goes towards HEFA, later disbursal means that BtL and PtL purchases have more opportunity to claim support.

The potential of the EU's reimbursement scheme to support investment in long-term SAF technologies is doubly limited – the funding is targeted towards HEFA fuels that do not need the investment support, and much of the benefit of the scheme may be expressed through reducing the cost of aviation rather than by supporting producers. We recommend that the EU review eligibility for this funding to exclude HEFA fuels, but also more fundamentally review the structure of this scheme, and consider whether there are more effective ways to disburse the not-inconsiderable value in EU-ETS allowances that has been committed to it.

The UK's GSP provides a better model for how support could be targeted to novel fuel producers by creating a favourable investment environment, potentially at low cost. Funding an EU-GSP using EU-ETS allowances has been proposed as a way fund such a mechanism (Horton et al., 2024).

6.2. United Kingdom

6.2.1. Interaction with the EU market

The UK SAF mandate is in some respects similar to ReFuelEU Aviation, but has important differences that will affect the way that the EU and UK SAF markets develop and interact. Compared to the EU system the UK SAF Mandate offers more clarity on expected price regimes. The buy-out price establishes a bounded window of compliance costs for fuel suppliers, which can serve as a starting point for offtake negotiations with SAF producers.

For the non-PtL part of the UK SAF Mandate, we expect that the cost of the UK buy-out price will be higher than the minimum fines for the non-PtL part of ReFuelEU Aviation (assuming cost spirals are controlled), and therefore that the UK should be able to out-compete the EU for waste-and-residue-based HEFA. Further, the cap on the contribution of HEFA means that there is guaranteed space for next-generation fuels; this makes the UK the most attractive market in the world for BtL aviation fuel. As was discussed in Section 6.1.1, the five-yearly steps in ReFuelEU targets may also make the UK an attractive market for excess EU production towards the end of each period. This should tend to reduce compliance costs to the UK, but may simultaneously complicate the investment picture for UK SAF producers having to deal with cycles of excess and inadequate supply in the EU.

The PtL market may be different. Because the penalties in ReFuelEU Aviation are not bounded, PtL prices in the EU are likely to exceed the maximum level supported under the UK buy-out, in which case the EU would out-compete the UK for PtL fuel. Given that supply of PtL is likely to be limited, and may well be insufficient to meet EU demand, it seems likely that a large part of the UK PtL mandate will need to be bought out in 2030 when EU targets kick-in, and perhaps for some years after. This dynamic could be countered if UK producers in receipt of GSP contracts are obliged to supply some or all of the produced fuel to the UK market. Persistent expensive buy-out is likely to be challenged by airlines and may be politically unpopular; nevertheless, given that there is some uncertainty around the stability of the EU system, the UK SAF Mandate should be recognised as an important market signal driving development of PtL supply, even if much of that supply ends up being consumed on European flights.

6.2.2. Supporting producers

The GSP mechanism shields fuel producers from variability in the prices paid by fuel off-takers, providing a degree of assurance that could be instrumental in widening the pool of prospective investors and getting plants built. Investor confidence may also reduce production costs by attracting lower target IRRs and opening the door to debt financing. While the exact value of this benefit is difficult to anticipate, we have presented an example in which improved financing terms reduced the levelised cost of production of PtL fuels by nearly a fifth. Successfully supporting the deployment of three or more cellulosic/PtL production facilities would make a major contribution to accelerating the broader commercialisation of the industry.

While the GSP mechanism has strong potential, careful design is crucial. One issue is that unpredictable shifts in input costs may render agreed strike prices unviable for SAF producers. Compelling SAF producers to counter this with inflated safety margins would systematically obscure actual SAF costs and have a distorting effect on the market; it may therefore be appropriate to consider dynamic strike prices with the flexibility to respond to external economic conditions.

Another major challenge for the GSP mechanism is the need to characterise the reference market price for different types of SAF in a way that allows producers with GSP contracts to be fairly compensated without distorting price-setting. The Government has signalled an intention to allow each fuel producer to self-report their reference price; this could create a perverse incentive for these producers to sell fuel below the going market price, saddling the Government counterparty with higher apparent GSP costs, and saddling fuel suppliers with higher levies to cover these costs. This may introduce an unnecessary and obscure dynamic into the support framework, and we recommend that the DfT should consider options to use market information to set the reference price.

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Annex A BtL technologies

Section 1.3.2 in the main text alluded to three key BtL production technologies. These are briefly introduced here.

Gasification of biomass entails subjecting it to high temperatures (typically 800-1,200°C) under oxygen-controlled conditions. This produces a synthesis gas (syngas) composed primarily of hydrogen and carbon monoxide, which can be cleaned and fed into a Fischer-Tropsch reactor. The Fischer-Tropsch process catalyses the formation of hydrocarbons; depending on the setup these can be the basis to produce aviation fuel.

Pyrolysis is another thermochemical method for producing hydrocarbons from lignocellulosic biomass. Heating biomass at an intermediate temperature (typically in the range 350-800°C) in a low-oxygen environment produces volatile gases, a solid biochar, and 'bio-oil'. Bio-oil is a liquid mixture of organic compounds which can be deoxygenated, cracked, and hydroprocessed using specialised catalysts and hydrogen to produce aviation fuel.

Cellulosic AtJ is a biochemical process. The first step involves the use of enzymes and microbes to break down cellulose into simpler sugars, which are then fermented into alcohols (such as ethanol or butanol) by specialised yeasts. These alcohols are catalytically oligomerised and de-oxygenated (again using hydrogen) to form hydrocarbons. In the USA and elsewhere, alcohol to jet (AtJ) pathways based on food-crop ethanol (e.g. corn or sugarcane) may also be relevant. Design and operation of these plants may help to grow industry expertise, but the fuels would not be eligible for use in the EU and UK.

Other technologies under development include industrial gas fermentation, biomethane upgrading, and hydrothermal liquefaction.