SUSTAINABLE AVIATION

NET ZERO CARBON ROAD-MAP

TECHNICAL REPORT

Enabling delivery of a UK-led zero carbon aviation revolution

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ABOUT SUSTAINABLE AVIATION

Sustainable Aviation (SA) is a unique and growing alliance of the UK's airlines, airports, aerospace manufacturers, air navigation service providers and innovation companies in Sustainable Aviation Fuel (SAF) and carbon removals. Established in 2005 it is the first alliance of its kind in the world and has 46 members at the date of publication.

MEMBERS

DISCLAIMER

Sustainable Aviation (SA) believes the data forecasts and analysis in this report to be correct as at the date of publication. The opinions contained in this report, except where specifically attributed to, are those of SA, and based upon the information that was available to us at the time of publication. We are always pleased to receive updated information and opinions about any of the contents.

All statements in this report (other than statements of historical facts) that address future market developments, government actions and events, may be deemed 'forward-looking statements'. Although SA believes that the outcomes expressed in such forward-looking statements are based on reasonable assumptions, such statements are not guarantees of future performance: actual results or developments may differ materially, e.g. due to the emergence of new technologies and applications, changes to regulations, and unforeseen general economic, market or business conditions.

EXECUTIVE SUMMARY

Purpose of this report

In April 2023 Sustainable Aviation launched its updated Net Zero Carbon Road-Map which illustrates Sustainable Aviation's view of a pathway to achieving Net Zero Carbon emissions from UK aviation activity by the year 2050. A Summary Report was published in April 2023. This Technical Report provides further rationale, assumptions and data utilised to compile the Road-Map. Therefore the Summary Report and this document, the Technical Report, should be read in conjunction with each other.

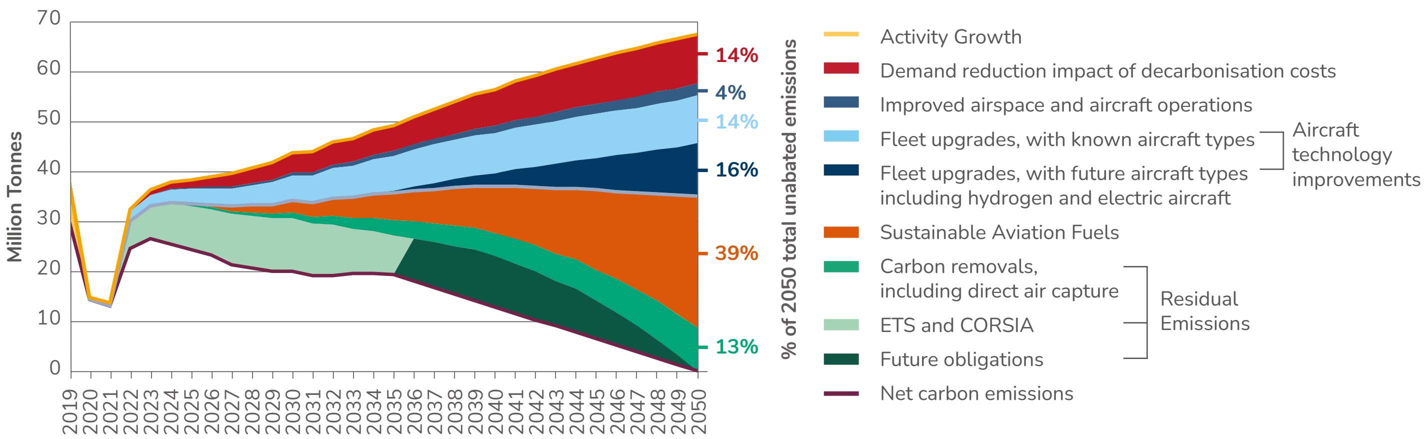
Sustainable Aviation Net Zero Carbon Road-Map

Climate change is a clear and pressing issue for people, businesses, and governments across the world. Measures to mitigate the threat of climate change include the achievement of societal net zero carbon emissions by 2050, which is now a committed goal for the entire global aviation industry[1] and the UK Government[2].

Following positive technological developments, Sustainable Aviation has updated its detailed plan on how we will reach net zero carbon aviation by 2050. The Road-Map draws on expertise from all corners of the UK aviation industry, including airlines, airports, aerospace manufacturers, air navigation service providers, fuel suppliers and innovation organisations. By supporting new innovations and growing these over the next 25 years, the UK aviation industry can deliver net zero carbon emissions in 2050 through the following initiatives:

- 9.6 Million Tonnes of carbon dioxide ($MtCO_2$) saving due to decarbonisation cost impact on activity growth;
- 2.5 $MtCO_2$ saving from more efficient air traffic management and operating procedures;
- 9.5 $MtCO_2$ saving from introduction of known types of more efficient aircraft and engines;
- 10.6 $MtCO_2$ saving from introduction of future aircraft and engines, including electric and hydrogen concepts;
- 26.4 $MtCO_2$ saving from sustainable aviation fuels;
- 8.8 $MtCO_2$ saving from durable carbon removals.

To enable this transition, considerable additional low carbon energy will be required. Sustainable Aviation forecasts that UK aviation will require approximately 147 TWh in additional low carbon electrical energy by 2050 in order to implement the above initiatives and achieve net zero carbon operations. To put this figure into context, in March 2023 the Climate Change Committee (CCC) published a report on 'Delivering a reliable decarbonised power system[3]' in which the economy wide demand for electricity in 2050 in their Balanced Pathway was estimated to be approximately 600 TWh. The ~147 TWh requirement for aviation as derived in this report is expected to be additional to this estimate from the CCC.



1 https://www.icao.int/environmental-protection/Pages/LTAG.aspx
2 https://www.gov.uk/government/publications/net-zero-strategy
3 https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/

EXECUTIVE SUMMARY

Industry commitment

- We remain committed to cutting carbon emissions from UK aviation to net zero by 2050
- We are supporting many initiatives today across operations, technology, sustainable fuels and carbon removal, to make our commitment a reality
- We will continually review this Road-Map to ensure it remains in line with the latest scientific advice on meeting the UK and International Civil Aviation Organization (ICAO) aviation climate goals
- Whilst non-CO_2 impacts are not addressed in this Road-Map, we are carrying out further work to determine the best way to manage these issues, in collaboration with the Jet Zero Council and UK Government

Key asks of the UK Government

Achieving net zero carbon for aviation will be harder than for most sectors, but it is achievable. It can only be delivered through an international approach, with substantial investment from industry, especially the aviation, energy, carbon removal and waste industries, and development of effective low carbon policies by the UK Government, working in partnership with the sector.

We ask the UK Government to support this Road-Map in the following ways:

- **Maximising short-term operational efficiencies** by accelerating the UK airspace modernisation programme to completion by the end of this decade
- **Delivering commercial UK SAF production at scale this decade** by providing a price stability mechanism, alongside a SAF mandate and by prioritising access to UK sustainable feedstocks
- **Investing in next generation flight technology** by uplifting matched funding levels to the Aerospace Technology Institute (ATI) programme through to 2031 – to drive efficiency improvements and the development of zero carbon emission technologies, alongside investing in the UK hydrogen supply and airport infrastructure
- **Supporting the means to address residual aviation emissions** by accelerating the rollout of carbon removals and including them in the UK Emissions Trading Scheme (ETS)

Additionally, alignment is required on strategic plans within Government to ensure sufficient low carbon electrical and hydrogen generation is in place to meet society wide demands, with UK aviation receiving its fair share alongside other industries.

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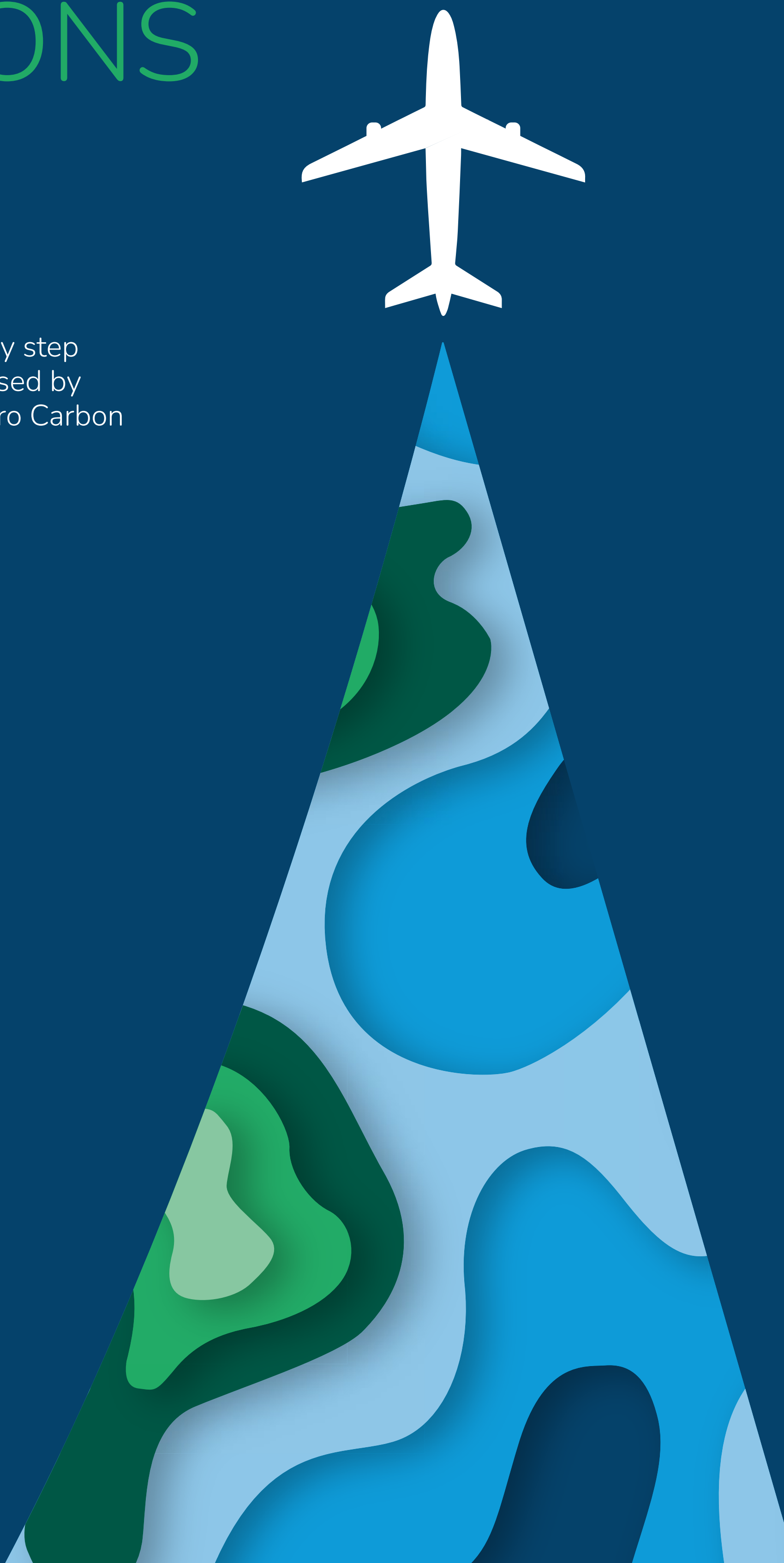
1. MODELLING METHODOLOGY AND ASSUMPTIONS



Introduction

This section of the report will detail the step by step method, assumptions made and data inputs used by Sustainable Aviation in developing the Net Zero Carbon Road-Map published in April 2023.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.1 Road-Map top level architecture

Overview

The Road-Map sets out Sustainable Aviation's view of how UK aviation activity can achieve net zero carbon emissions by 2050. In this analysis "UK aviation" includes all civil commercial flights which depart from UK airports, and carbon dioxide (CO_2) is the only emission modelled. The analysis includes operational tailpipe emissions from aircraft only. Upstream emissions from manufacturing operations and the wider supply chain including airport and surface access emissions are not included.

The Road-Map quantifies the contribution of a series of decarbonisation measures which have the combined result of achieving net zero carbon emissions by 2050. These decarbonisation measures as illustrated in the chart 'wedges' are:

- Improvements in aircraft operations and air traffic management
- Fleet upgrades to higher efficiency known aircraft & engines
- Fleet upgrades to higher efficiency future aircraft & engines, and those which utilise non-carbon fuels
- Use of SAF which has lower lifecycle carbon emissions than Jet A-1
- Purchasing of greenhouse gas removals
- Purchasing of UK Emissions Trading Scheme (ETS) allowances and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) offsets

In addition, the Road-Map illustrates that as a consequence of the above decarbonisation measures, increased costs to passengers are estimated to have some impact to reduce the theoretical growth of the aviation activity. For this reason there is a final wedge illustrated:

- Reduced aviation activity growth as a result of decarbonisation costs

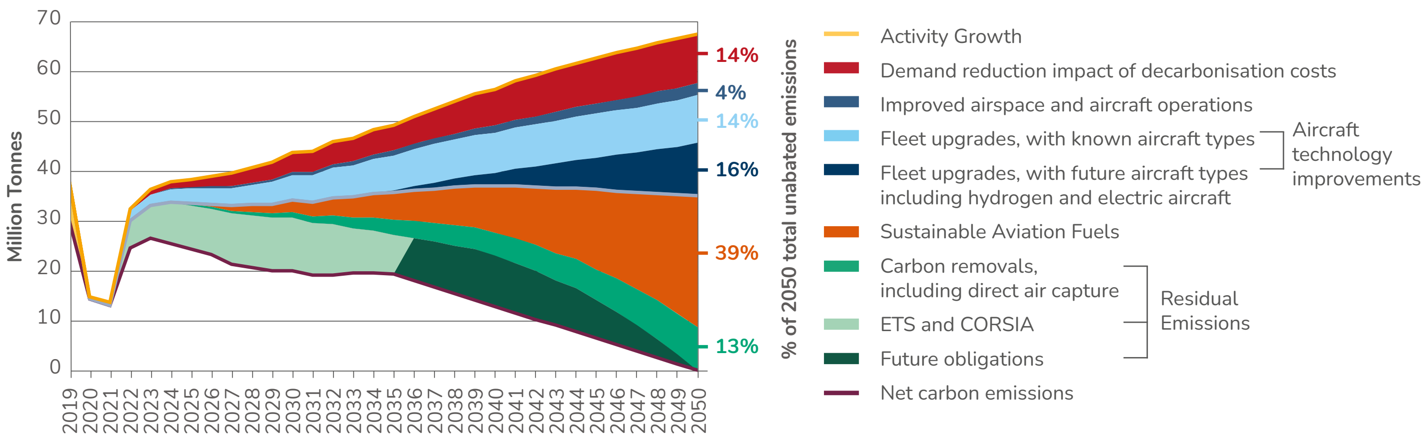


Figure 1: Sustainable Aviation Net Zero Carbon Road-Map

The Road-Map chart is built using a modelling tool. A functional diagram of this model is included in Appendix 7.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Hypothetical no-improvements scenario

The top line of the chart shows CO_2 emissions in a hypothetical "no-improvements" scenario in which emissions simply follow the estimated growth in aviation activity with none of the decarbonisation measures adopted, and in which growth in aviation activity is not affected by any decarbonisation costs. The estimated growth in aviation activity is based on the UK government's forecast of growth in aviation demand. The Road-Map estimates that by 2050, UK aviation activity would emit **67.5 MtCO_2**.

Activity reduction due to decarbonisation costs

The first illustrated wedge shows the estimated reduction in aviation activity over time as costs to decarbonise are absorbed by the industry and ticket prices change. Costs of carbon allowances, offsets, SAF and greenhouse gas removals are all included, therefore the size of this wedge is identified in the final calculation stage of the model. The subsequent chapters will detail the calculation methodology in the order undertaken by the model, with activity growth reduction last. An iterative approach is required to produce the published Road-Map illustrated in Figure 1 because activity reduction reduces the quantity of decarbonisation measures which must be purchased which then reduces costs and this affects the activity growth estimate. The Road-Map estimates that by 2050, this effect of decarbonisation costs impacting activity growth will reduce emissions in 2050 by **9.6 MtCO_2**.

Efficiencies in airspace management, operations and fleet replacement to latest technology

The next two illustrated wedges represent efficiency gains and therefore a reduction in the amount of fuel used and CO_2 emitted. These efficiencies are delivered by:

i) Improvements in airspace management and aircraft operations

ii) Fleet replacement to latest generation known products for higher efficiency aircraft and engines

The Road-Map estimates that the introduction of these efficiency improvements will reduce emissions in 2050 by **12 MtCO_2**.

Future technology introduction

The next wedge introduces a reduction in emitted CO_2 as a result of introducing the next generation of aircraft and engines which incorporate future technologies that are not currently commercially available. These technologies include two distinct but different concepts: firstly, the next generation of aircraft with higher efficiencies than the current best available products, that will use carbon-based fuels including SAF; and secondly, new aircraft types which will use electric or hydrogen power. These fleet renewals are estimated by the Road-Map to achieve a saving of **10.6 MtCO_2** emissions in 2050.

Residual emissions

The quantity of CO_2 which is still emitted from aircraft in operation is reflected at the bottom of the fleet technology upgrade wedges. It is this quantity of emissions which is assumed in scope of the obligations placed on the sector to achieve a residual emission level as defined by the rules of the UK ETS, CORSIA and their successor scheme. These obligation schemes define the position of the lowest line in the Road-Map chart which indicates the net residual emissions from UK aviation throughout the timeline.

The final three wedges illustrate the strategies available to abate the emissions on a net basis to achieve this targeted residual level, ultimately reaching zero in 2050:

- Utilising SAF
- Purchasing Greenhouse Gas Removals (GGRs)
- Purchasing CORSIA offsets and UK ETS allowances

SAF

The use of SAF results in a lower quantity of CO_2 emissions per tonne of fuel used, since SAF has a lower carbon intensity on a lifecycle basis. The size of the SAF wedge in the chart represents the quantity of CO_2 emissions abated through its use, and is derived from the quantity of SAF used and the lifecycle CO_2 saving associated with the SAF. The Road-Map estimates that a saving of **26.4 MtCO_2** will be achieved in 2050 through the use of SAF.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Greenhouse gas removals

The Greenhouse Gas Removals (GGRs) wedge represents purchases of GGRs by the aviation sector which act to offset unavoidable emissions. Although purchasing of GGRs may occur as part of compliance with carbon offsetting schemes, SA has specifically illustrated their ramp up since they are viewed as a distinct form of carbon credit and, in particular high durability carbon removals, will be influential to achieving a feasible energy transition for the sector. In 2050 the Road-Map estimates that **8.8 MtCO_2** will be abated by permanent carbon removals.

Market based measures

The reasonable assumption has been taken that engagement with SAF and GGRs will be recognised by the obligation schemes of the UK ETS, CORSIA and their successor scheme. Therefore the CO_2 emissions abated by the SAF and GGR wedges reduce the remaining obligation to purchase allowances and credits in the schemes. However the net residual emissions which must be achieved by the sector remains defined by the scheme rules when applied to the gross jet pipe emissions. The currently anticipated framework of the UK ETS and CORSIA schemes have been used to define the size of the final wedges (and associated costs), with an assumed successor scheme referred to as the 'future obligation scheme' coming into effect in 2035 which mandates a linear trajectory of the sector net residual emissions to zero in 2050.

Calculation method

All CO_2 values contained in the Road-Map chart are listed in Appendix 5. Some of the wedges are defined by absolute magnitudes of CO_2 abated: SAF, GGR, ETS, CORSIA and future obligations. The other wedge sizes (activity reduction due to cost, operational and Air Traffic Management (ATM) efficiency, and technology efficiency) are defined by a percentage reduction, and so the calculation is made using a "factor" and a "basis":

- The "factor" converts an efficiency gain into the proportional reduction in CO_2 emitted, i.e. a 10% efficiency gain would produce a factor of 0.9 to be applied to the CO_2 emissions
- The "basis" is the amount of CO_2 emitted prior to the efficiency gain being accounted for, and therefore the value from which that proportional CO_2 reduction should be calculated

For each of the percentage based wedges, the 'basis' used is the bottom of the previous wedge in the stack, from top to bottom. For example, the 'basis' for the technology wedges are the CO_2 values after reductions have already been applied for activity growth reduction due to cost and operational efficiencies. This prevents double counting of CO_2 abatement by avoiding the assumption that for example a 20% technology efficiency gain and a 5% operational efficiency gain both apply to the full 'no improvement scenario' CO_2 emissions.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.2 No improvement scenario demand forecast

The top line in the Road-Map chart illustrates the theoretical growth of CO_2 emissions from UK aviation if Government forecast demand for aviation is met with no actions taken to decarbonise. This is constructed as shown in Table 1:

2019-2021	2022-2024	2025-2050
Actual CO_2 emissions data	Estimated COVID recovery	% growth based on DfT aviation forecast

Table 1: 'no improvement' CO_2 emissions derivation method

For the years 2019-2021, actual CO_2 emissions data from the UK Government 'final UK greenhouse gas emissions national statistics'[4] and the 'digest of UK energy statistics'[5] were used. For the years 2022-2024, Sustainable Aviation made an estimate of the pace at which UK aviation activity would recover from the COVID pandemic, based on guidance developed from IATA data[6]. The assumed recovery rate is shown in Table 2.

2022	2023	2024
86% of 2019 activity	**96%** of 2019 activity	**100%** of 2019 activity

Table 2: Aviation activity recovery from the COVID pandemic

These estimated proportions of the pre-pandemic 2019 aviation activity are directly translated to quantities of CO_2 emissions for the years 2022-2024 based on the relevant proportion of the actual 2019 CO_2 emissions. For example, 2023 aviation activity was estimated to be 96% of 2019 aviation activity, therefore the 2023 CO_2 emissions are estimated to be 96% of 2019 emissions: 36.3 Mt. All CO_2 values contained in the Road-Map chart are listed in Appendix 5.

For the years 2025-2050, the CO_2 emissions are increased in each year by an annual growth rate indicated by the Department for Transport's (DfT) aviation forecast modelling data. Appendix 1 contains the data supplied by DfT to Sustainable Aviation in January 2023 to facilitate this. Passenger-kilometre (pax-km) figures are assumed to be a proxy for aviation activity and also therefore CO_2 emissions. An annual percentage change in activity is derived from the DfT pax-km data and applied to the previous year's CO_2 emissions.

For example:

2040 CO_2 emissions = 2039 CO_2 emissions + 1.73%

because forecast aviation activity in 2040 is 1.73% more than in 2039.

4 https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2020

5 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1135950/DUKES_2022.pdf

6 https://www.weforum.org/agenda/2022/12/when-will-air-travel-return-to-pre-pandemic-levels/

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.2 No improvement scenario demand forecast (continued)

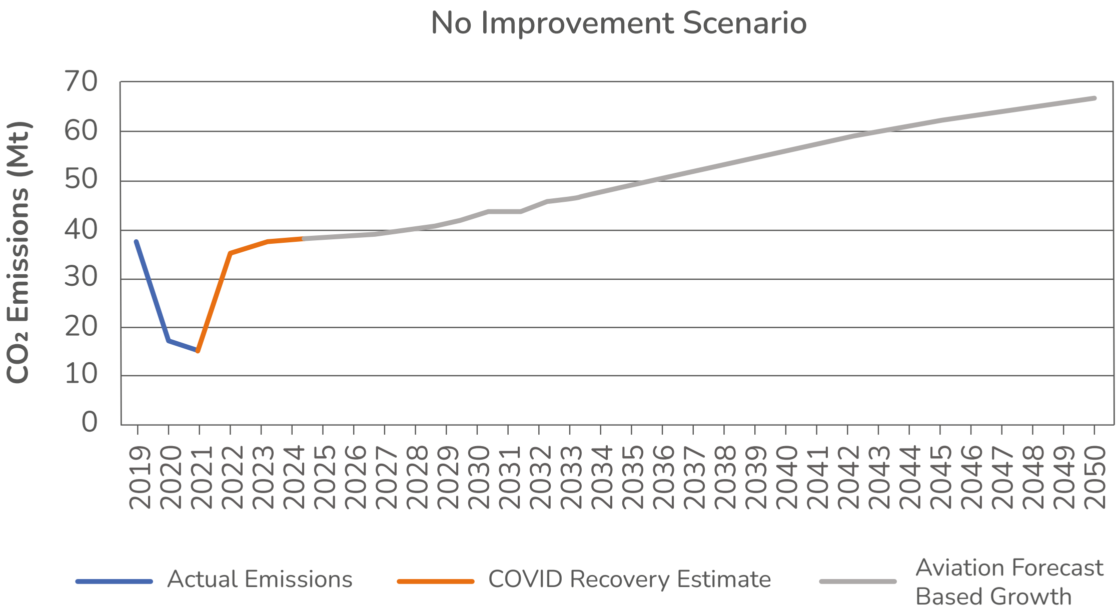


Figure 2: UK aviation CO_2 emissions growth in the absence of decarbonisation measures (top line of Road-Map chart)

1.3 Operational and air traffic management efficiency improvements

Three distinct efficiencies were considered to make contributions in the operations and air traffic management wedge, as listed in Table 3. These estimates were provided by subject matter experts from the SA membership.

Activity	Efficiency Gain	Start Year	End Year
ATM Modernisation (more efficient design and operation of airpace)	2.8%	2020	2050
Airport Ground Operations (more efficient aircraft movements on the ground)	0.3%	2023	2050
Airline Operations (more efficient airline procedures to operate the aircraft)	1.3%	2023	2050

Table 3: Ops & ATM efficiencies assumed in Road-Map

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.3 Operational and air traffic management efficiency improvements (continued)

The model simply assumes that these improvements are applied linearly between the start year and the end year. Before the start year, 0% of the efficiency gain has been achieved, and by the end year 100% of the eventual efficiency gain is realised. In the year 2050, all of these efficiencies are fully realised, such that a total efficiency gain of 4.4% is translated to a 'factor' of 0.956 which is applied to the 'basis' of the top of this wedge. In the interim years a lower factor is applied to establish the size of the wedge, according to the extent to which all three of the efficiency improving activities have been executed. Given all other assumptions in the published Road-Map, the resultant CO_2 abatement by the Operations & ATM wedge is illustrated in Figure 3.

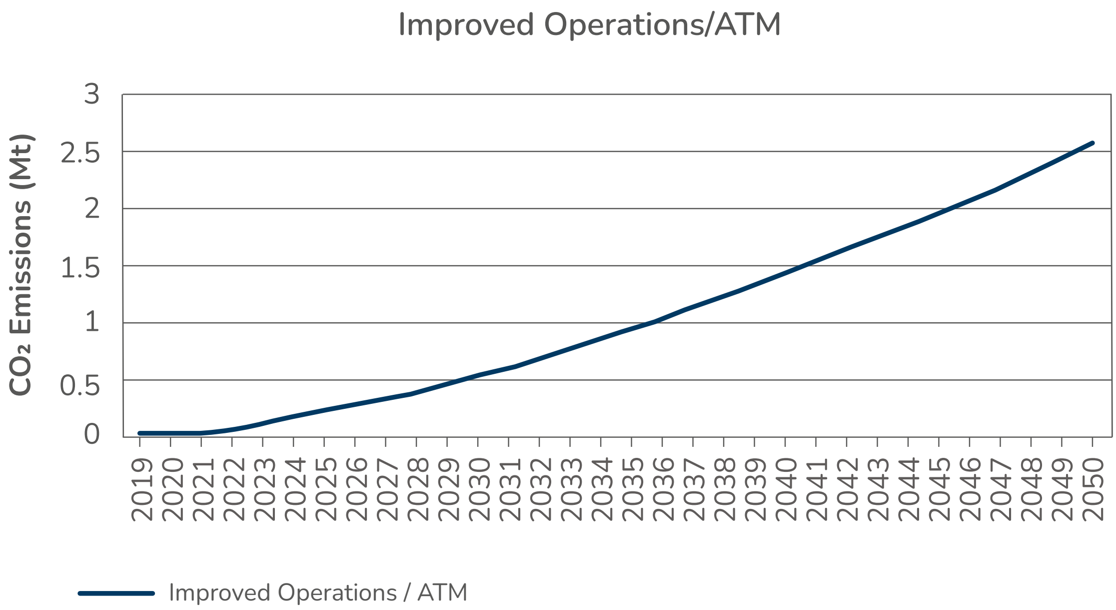


Figure 3: CO_2 abatement achieved with improved operations and air traffic management

The estimated efficiency gains reflect feasible improvements as a percentage of the total CO_2 emissions from flights departing UK airports where the vast majority of the emissions occur outside of UK airspace. With strong international collaboration on the development of ATM practices, larger improvements could be assumed. For specific subsets of flights within UK airspace or within European airspace, efficiency gains through improvement of airspace management of ~10% have been proposed. Aircraft operational improvements were forecast to deliver ~2% efficiency improvements for flights within the UK and Europe and just under 1% for flights beyond the UK and Europe. The net result weighted based on the 2019 baseline fleet activity produced the 1.3% figure assumed.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.4 Technology efficiency improvements: fleet replacement with new aircraft and engines

Baseline year characterisation

In order to model the CO_2 abatement achieved by introduction of new aircraft and engines into the fleet, it is necessary to characterise the 'baseline fleet'. This involved establishing the CO_2 emissions from all flights departing UK airports in the baseline year of 2019. The purpose of this exercise is to evaluate the proportion of the CO_2 emissions which are attributable to flights carried out by different categories of aircraft, over different distance ranges, to different global destinations and operated by different airlines. All of these generated data sets are required to define the technology wedge assumptions, as described in this chapter. The term "CO_2 materiality" is used to describe the results. As an example, if 96% of CO_2 emissions are produced on flights with an international destination, and the other 4% of CO_2 emissions are produced on domestic flights, the 'materiality' of international flights would be described as 96% of the fleet.

All 2019 departures were downloaded from the OAG database[7] including the following attributes:

- Departure airport
- Arrival airport
- Operating airline
- Specific aircraft type
- Available Seat Kilometres (ASKs) – a term used to quantify how many aircraft seats are provided by operators, multiplied by how far those seats fly

The flight distance was established using the Great Circle Distance and an averaged extra distance noted in Table 4 to account for inefficiencies in the route length. This could be caused by complying with specific departure routes from airports, airspace restrictions preventing direct routes between origin and destination and complying with specific arrival routings and timings into airports.

Great Circle Distance	Extra distance flown
<550km	50km
>550km, <5500km	100km
>5500km	125km

Table 4: Distance surplus assumed during baseline fleet characterisation

The ICAO fuel burn tables[8] provided fuel burn data for each specific aircraft type at discreet flight ranges. This data was interpolated to define a precise fuel burn over the flight distance specific to each departure in the 2019 baseline activity. Eight aircraft required to characterise the baseline fleet were either unavailable in the ICAO fuel burn tables or were proxied in the ICAO fuel burn tables by assuming they have identical fuel burn values to their preceding variant aircraft. These were:

- Airbus A220-100
- Airbus A220-300
- Embraer 190 E2
- Airbus A350-1000
- Boeing 787-10
- Airbus A320neo
- Airbus A321neo
- Boeing 737 MAX 8

To improve the accuracy of the analysis for these aircraft, a fuel burn dataset was calculated in relation to the closest variant available in the ICAO fuel burn tables, by comparison and interrogation of the publicly available payload range charts for these aircraft variants.

Finally, CO_2 emissions were assumed to be produced at a rate of 3.16kg per 1kg of jet fuel burned. This enabled the CO_2 emissions for every 2019 UK aircraft departure to be established and for the total UK aviation sector emissions to be presented in a series of materiality charts. One example is shown in Figure 5: the CO_2 emission materiality of different aircraft product families in the 2019 fleet.

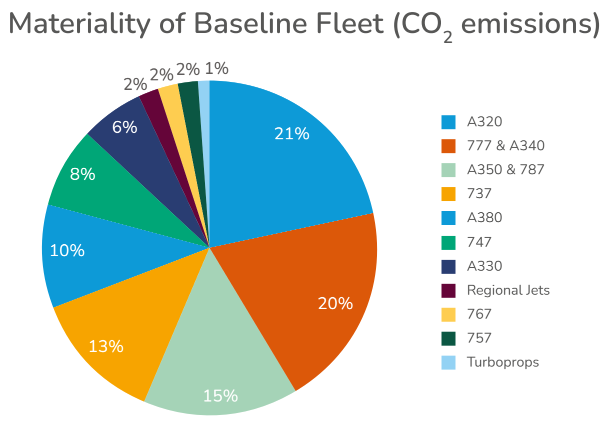


Figure 4: CO_2 emissions materiality of different aircraft product families in the 2019 fleet

7 https://www.oag.com/

8 Appendix C of ICAO Carbon Emissions Calculator Methodology Version 11: https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Aircraft categories

The aircraft in the baseline fleet are split into generically named categories and going forward each category can be thought of as a subset of the total ASKs provided by UK aviation activity, which in 2019 were achieved by a specific mix of aircraft. It is assumed that the overall nature of UK aviation activity grows evenly, such that if in 2019 21% of the CO_2 emissions were produced by Airbus A320 family aircraft, and 17% of the A320 family emissions were produced on flights destined for Spain, that these percentages will remain the same in 2050. In other words, SA do not take a position on how global flight patterns may evolve between 2019-2050, instead assuming this will be constant. This approach enables CO_2 abatement to be calculated as newer aircraft replace older aircraft in the same aircraft category. A factor for CO_2 reduction at the fleet level is derived by an efficiency improvement of a particular aircraft category, and applied proportionally to the whole fleet based on the materiality of that aircraft category.

The aircraft categories are intentionally named generically, since the efficiency gains and product upgrades used by SA to estimate the improvement in CO_2 emissions do not in most cases constitute an intended product strategy of airlines or manufacturers. The CO_2 emissions reductions are representative of likely product upgrades in each aircraft category, or in each portion of baseline fleet delivered ASKs.

For the purposes of characterising the baseline fleet, the following aircraft types in 2019 were used to define 11 aircraft categories:

Aircraft Category	2019 products included in characterisation
Turboprops	DHC8, DHC6 & DHC4, ATR 72 & 42-300 / 320, Saab 340 & 2000, Jetstream 41, Fairchild Dornier 228 & 328-100, BN-2a & -2b, Fokker 50
Regional Jets	Embraer 190, 175, 195, RJ145, 170, RJ135, 190E2, Canadair RJ 900 & 1000 & 700, Avro RJ85, Fairchild Dornier 328jet, A220-100, Bae 146-200, Fokker 100
Narrow Body A	A320, A319, A321, A320neo, A321neo, A318, A220-300
Narrow Body B	737-800, 737-300, 737MAX 8, 737-700, 737-900, 737-400, 737-500, 737-600
Large Narrow Body	757-200, 757-300
Small Wide Body	767-300, 767-400, A310-300, A300-600
Small Long Range Wide Body	A330-300, A330-200
Large Wide Body	777-300/300ER, 777-200/200ER, 777-200LR, A340-600, A340-300, A340-500
Jumbo	747-400, 747-8
Super Jumbo	A380-800
Latest Wide Body	A350-900, A350-1000, 787-8, 787-9, 787-10

Table 5: 2019 fleet products utilised to define the materiality of 11 aircraft categories.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Generation 1 upgrades

The first technology wedge illustrates the CO_2 savings estimated to be achieved by the replacement of the current fleet with new aircraft and engine products which are 'known'. These products are either commercially available or soon to enter service. Table 6 lists the efficiency gains achieved by these fleet renewals and the timescale assumed.

Aircraft Category	Efficiency Gain	Start Year	End Year
Turboprops	N/A	N/A	N/A
Regional Jets	25%	2019	2044
Narrow Body A	18%	2019	2036
Narrow Body B	17%	2019	2037
Large Narrow Body	30%	2019	2027
Small Wide Body	21%	2019	2027
Small Long Range Wide Body	14%	2019	2030
Large Wide Body	24%	2019	2035
Jumbo	25%	2019	2020
Super Jumbo	20%	2019	2035
Latest Wide Body	N/A	N/A	N/A

Table 6: Generation 1 technology upgrades to known products.

The model simply assumes that these improvements are applied linearly between the start year and the end year.

Turboprops

75% of the CO_2 emissions from this category were from the De Havilland Canada Dash 8 (DHC8). No known product to upgrade this aircraft was foreseen, therefore it was conservatively assumed that this aircraft category did not go through a generation 1 upgrade.

Regional Jets

90% of CO_2 emissions from this category were from Embraer aircraft. Upgrades to newer 'E2' variants of Embraer aircraft were therefore considered representative of the likely efficiency gains as this fleet is replaced. Embraer E2 variants were estimated to achieve a 25% better efficiency[9]. By judgement of the age of the current fleet and historic pace of replacement to the 190-E2 variant, a relatively long fleet refresh time of 25 years was chosen.

9 https://www.embraercommercialaviation.com/e2-a-force-with-nature/

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Narrow Body A

The Airbus A320 family of aircraft are currently being upgraded to neo variants. In terms of CO_2 materiality this category was:

- 5% neo variant with 0% associated efficiency gain (since already upgraded to Generation 1)
- 27% A319 with a 15%[10] efficiency gain when upgrading to neo
- 68% A320/A321 with a 20%[11] efficiency gain when upgrading to neo

The overall efficiency gain for this category is therefore 18%. Referring to the Cirium[12] fleet database to identify 'On Order' neo aircraft variants and planned delivery dates, the year 2036 was chosen for this portion of the fleet to have fully upgraded.

Narrow Body B

A representative upgrade in this category is the Boeing 737 family of aircraft upgrading to MAX variants. The baseline fleet includes Classic, Next Generation (NG) and MAX variants. Due to a series of improvements introduced to the NG variants since first entering service in 1998, later NG models are more efficient than earlier NG models. The MAX variants offer a 20% efficiency benefit relative to early NG aircraft, and 14% improvement relative to later NG aircraft[13]. Assuming the cut-off between early/late is effective from 2011 and interrogating aircraft delivery dates in the Cirium database, it was established that 50% of the NG models in this aircraft category were 'early' and would therefore achieve a 20% efficiency gain on upgrade to MAX, and 50% of the aircraft were 'late' therefore achieving a 14% improvement on upgrade. 1% of this category was already upgraded to MAX and 2% were Classics which would have a >20% efficiency improvement once upgraded to MAX. The effect of these latter two groups were assumed to cancel each other out. Therefore an overall efficiency gain of 17% was assigned to this category.

Referring to the Cirium fleet database to identify Delivered and On Order MAX aircraft and planned delivery dates, it was assumed that a 20 year fleet refresh timeline was likely from the Entry Into Service (EIS) date of 2017. Therefore the year 2037 was chosen for this portion of the fleet to have fully upgraded.

Large Narrow Body

A representative upgrade in this category is replacing a 757 aircraft with an A321LR or A321XLR which report a 30% efficiency benefit[14]. Examination of the fleet indicated that the number of 757 aircraft had roughly halved in the previous 3 years and the remaining aircraft had an average life of ~25 years. It was therefore assumed this category would be fully replaced by 2027.

Small Wide Body

The representative upgrade selected for this category was replacing Boeing 767s with Boeing 787 aircraft. The 787-10 variant was assumed to achieve a 25% efficiency improvement[15] while the 787-9 variant was assumed to achieve a 20% improvement[16]. By examination of the Cirium database it was established that 25% of 787s on order were the -10 variant achieving the higher efficiency improvement. The overall efficiency improvement was calculated by weighted average to be 21%. The most material operator of 767s in the baseline fleet was United Airlines whose 767 fleet had an average age >25 years. Therefore a relatively rapid upgrade pace was assumed, with the end year of 2027 selected.

Small Long Range Wide Body

The Airbus A330 aircraft are being upgraded with new more efficient engines, with these neo variants achieving a 14% efficiency improvement[17]. Examining orders of A330neo aircraft in the Cirium database, the A330 fleet is estimated to be ~80% neo variant by 2026 (~8 years after EIS in 2018). It was estimated conservatively that this fleet would be fully replaced by 2030.

10 https://aircraft.airbus.com/en/aircraft/a320-the-most-successful-aircraft-family-ever/a319neo
11 https://aircraft.airbus.com/en/aircraft/a320-the-most-successful-aircraft-family-ever/a320neo
https://aircraft.airbus.com/en/aircraft/a320-the-most-successful-aircraft-family-ever/a321neo
12 https://www.cirium.com/
13 https://www.boeing.com/commercial/737max/by-design/#/extending-the-advantage, viewed Dec 2022
14 https://aircraft.airbus.com/en/aircraft/a320/a321xlr
15 https://www.boeing.com/commercial/787/
16 https://boeing.mediaroom.com/2015-10-22-Boeing-Norwegian-Finalize-Order-for-19-787-9-Dreamliners/
17 https://www.airbus.com/en/new-efficient-engines-sustaining-the-a330neo-into-the-future

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Large Wide Body

In the large wide body category it is envisioned that Boeing 777s and Airbus A340s would be replaced by aircraft such as the Airbus A350 XWB and the Boeing 777X. The A350 XWB offers a 25% fuel efficiency improvement[18]. For the 777 aircraft, there is a 10% improvement when upgrading from a -200 variant to a -300 variant[19], and a further 20% improvement when upgrading from a -300 variant to a 777X[20]. Taking into account the specific composition of the baseline fleet in terms of individual aircraft variants, and assuming a 50% future market share between the A350 XWB and the 777X, the overall efficiency gain of 24% for this category was derived. It was assumed that this category would be fully replaced 20 years after the first A350 variant entry into service date, therefore 2035 was selected.

Jumbo

The baseline fleet Boeing 747s were operated by British Airways and Virgin Atlantic Airways. These airlines announced the expedited retirement of these aircraft following the COVID pandemic in 2020, and that they would be replaced by Airbus A350, Boeing 787 and Airbus A330neo aircraft with an estimated 25% fuel efficiency increase[21,22].

Super Jumbo

A representative product upgrade for this category was taken to be replacement of Airbus A380 aircraft with Airbus A350 XWB and Boeing 777X aircraft. As noted for previous categories, these aircraft deliver between 20-25% efficiency benefit relative to the aircraft they replace.

Conservatively, 20% improvement was chosen for this category. Bearing in mind that the A380 is no longer in production and judging the average age of the fleet, it was assumed that this category would be fully upgraded by 2035.

Generation 2 upgrades

The second technology wedge illustrates the CO_2 savings estimated to be achieved by the replacement of the fleet with future designs of aircraft and engines. Table 8 lists the efficiency gains achieved by these fleet renewals and the timescale assumed.

Aircraft Category	First Generation 2 Upgrade				
	Upgrade Type	Proportion of Fleet	Efficiency Gain	Start Year	End Year
Turboprops	Electric	9%	100%	2028	2043
Regional Jets	Electric	3%	100%	2028	2048
Narrow Body A	Narrow Body Hydrogen	62%	100%	2035	2060
Narrow Body B	Narrow Body Hydrogen	62%	100%	2035	2060
Large Narrow Body	Narrow Body Hydrogen	25%	100%	2035	2060
Wide Body Categories	Next Gen Conventional	100%	20%	2040	2060

18 https://aircraft.airbus.com/en/aircraft/a350-clean-sheet-clean-start/a350-less-weight-less-fuel-more-sustainable
19 https://www.boeing.com/commercial/777#/design-highlights/unmatched-capabilities/profitability/fuel-efficiency/
20 https://view.ceros.com/boeing/bca/p/3
21 https://mediacentre.britishairways.com/pressrelease/details/12456
22 https://flywith.virginatlantic.com/fr/en/stories/a-fond-farewell-to-the-boeing-747.html#:~:text=We%20planned%20to%20retire%20the,2020%20operated%20by%20G%2DVROS

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Generation 2 upgrades (continued)

Aircraft Category	Second Generation 2 Upgrade (if applicable)				
	Upgrade Type	Proportion of Fleet	Efficiency Gain	Start Year	End Year
Turboprops	Regional Hydrogen	80%	100%	2028	2043
Regional Jets	Regional Hydrogen	66%	100%	2028	2048
Narrow Body A	Next Gen Conventional	38%	20%	2035	2060
Narrow Body B	Next Gen Conventional	38%	20%	2035	2060
Large Narrow Body	Next Gen Conventional	75%	20%	2035	2060
Wide Body Categories	N/A				

Table 8: Generation 2 technology upgrades to future products.

The model simply assumes that these improvements are applied linearly between the start year and the end year. Many of these future upgrades continue to be implemented beyond 2050. As such, only the proportion of the efficiency improvement expected to have been achieved by 2050 is included in the CO_2 abated in the Road-Map chart.

Eligibility for electric or hydrogen upgrade

It is recognised in the analysis that future envisioned electrical and hydrogen aircraft concepts have capability and logistical limitations which prevent the entire baseline fleet being upgraded to these types of aircraft. For this reason, multiple future upgrades are modelled where relevant for the smaller aircraft categories, and a set of eligibility criteria utilised to judge the proportion of each aircraft category which is upgraded to specific products.

The following broad definitions for future products were assumed to enter service prior to 2050:

- Electric aircraft
- Regional hydrogen aircraft
- Narrow body hydrogen aircraft
- Next generation narrow body aircraft utilising conventional (hydrocarbon based) fuels
- Next generation wide body aircraft utilising conventional (hydrocarbon based) fuels

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Eligibility for electric or hydrogen upgrade (continued)

A wide body hydrogen aircraft was not envisioned to enter service prior to 2050. Table 9 lists the key capability assumptions for each of the future products.

Future Product	Range	Number of Seats
Electric	1500km	19
Regional hydrogen	1500km	70
Narrow body hydrogen	4500km	180
Next gen narrow body (conventionally fuelled)	Not limited beyond current generation narrow bodies	Not limited beyond current generation narrow bodies
Next gen wide body (conventionally fuelled)	Not limited beyond current generation wide bodies	Not limited beyond current generation wide bodies

Table 9: Future technology products included in Road-Map modelling.

In the cases of future electrical and regional hydrogen aircraft, it is feasible that smaller aircraft could be used to deliver the ASKs currently delivered in the baseline year by the larger aircraft which compose the baseline fleet. This will have the effect of increasing the number of aircraft operating in the airspace and the number of landing and take-off Air Traffic Movements (ATMs) at airports. Given the associated logistical challenges with this, a limit is applied in the eligibility criteria to only allow up to 2 aircraft to replace one baseline year aircraft. This means for example for electric aircraft, only flights in the baseline fleet which had a range <1500km, and are currently delivered by aircraft with no more than 38 seats, were considered eligible to upgrade to an electric concept. The same method was applied to only allow up to 2 hydrogen regional aircraft to replace one baseline year aircraft.

An additional eligibility criteria for hydrogen aircraft was required to account for the fact that hydrogen fuel infrastructure will typically be required at the destination airport to facilitate refuelling, and this hydrogen infrastructure development may not occur globally. Bearing this in mind, Table 10 summarises the high level assumptions used to develop an illustrative proportion of activity which could be upgraded to hydrogen fuelled aircraft.

Region	Hydrogen Infrastructure	% of Flight Emissions Eligible
USA & Canada	Yes	80%
Nothern Europe	Yes	80%
Western Europe	Yes	80%
Southern Europe	Yes	80%
Rest of the World	No	0%

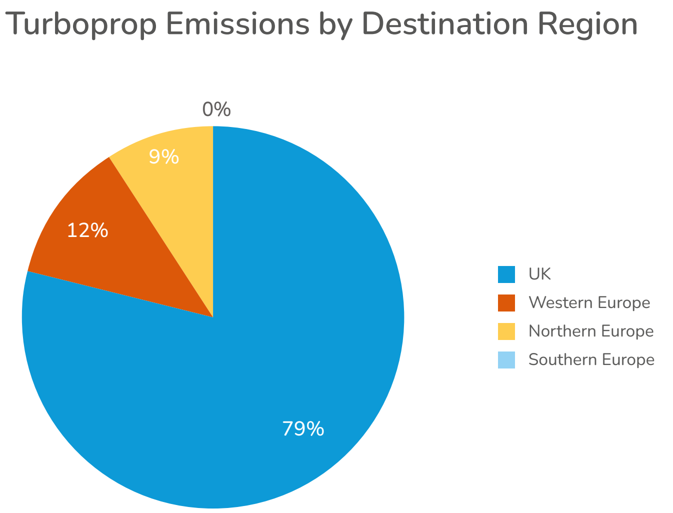
Table 10: Future technology products included in Road-Map modelling.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Eligibility for electric or hydrogen upgrade (continued)

Due to the existence of national and regional hydrogen strategies, it was assumed that a domestic hydrogen infrastructure will develop within the USA & Canada, Northern, Western and Southern Europe, and it was conservatively assumed that in the rest of the world no hydrogen infrastructure will develop. For departures to eligible destinations it was assumed that only 80% of the materiality of the activity to this region would be eligible to upgrade to a hydrogen aircraft. This was to account for the hydrogen infrastructure not necessarily being implemented in all airports.

The characterisation of the baseline fleet activity facilitated the above criteria to be applied, with two examples shown in Figure 5.



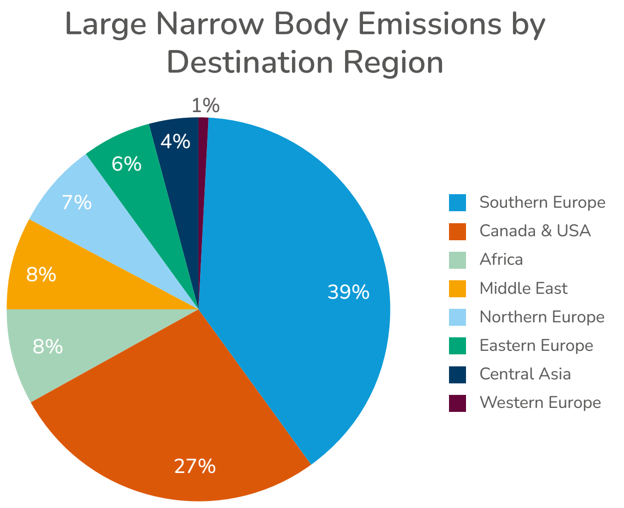


Figure 5: CO_2 emissions from Turboprop & Large Narrow Body aircraft categories, divided into destination regions.

To elaborate on these two examples; in the Turboprop category, all destinations are regions considered to develop hydrogen infrastructure, therefore 80% of the activity in this category which was otherwise eligible (i.e. also falling within range and seat number limitations) was considered eligible for hydrogen upgrade. In the Large Narrow Body category, only 74% of the activity flies to eligible destinations.

The overall result of the eligibility calculations for all aircraft categories is shown in Table 11. This shows an indicative proportion of activity from the baseline year, measured by CO_2 emissions, which is eligible to upgrade to the broadly defined future products, considering product capability limitations of range and seat number, and infrastructural limitations of destination region. In the final two columns, the resulting chosen upgrade types are noted and the proportions for each.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Eligibility for electric or hydrogen upgrade (continued)

Aircraft Category	Proportion activity eligible for Electric	Proportion activity eligible for Regional Hydrogen	Proportion activity eligible for Narrow Body Hydrogen	Future product type chosen	
				Upgrade 1	Upgrade 2
Turboprops	9%	80%	80%	**9%**: electric	**80%**: regional hydrogen
Regional Jets	3%	66%	77%	**3%**: electric	**66%**: regional hydrogen
Narrow Body A	0%	5%	62%	**62%**: narrow body hydrogen	**38%**: next gen narrow body (conventionally fuelled)
Narrow Body B	0%	0%	62%	**62%**: narrow body hydrogen	**38%**: next gen narrow body (conventionally fuelled)
Large Narrow Body	0%	0%	25%	**25%**: narrow body hydrogen	**75%**: next gen narrow body (conventionally fuelled)
Wide Body Categories	0%	0%	0%	**100%**: next gen wide body (conventionally fuelled)	N/A

Table 11: Eligibility calculation results.

It was not considered economically feasible that larger aircraft would be used in the future to deliver ASKs currently performed by smaller aircraft categories. Therefore despite for example the hydrogen narrow body aircraft having the technical and logistical capability to deliver activity in the Turboprop category, the Turboprops are instead assumed to upgrade to the fullest feasible extent to electric aircraft (9%), and to regional hydrogen aircraft (80%).

For both the Turboprop and Regional Jet categories, the eligibility criteria shows that some proportion of the category is not eligible to upgrade to either a future electric or hydrogen aircraft product. This portion of the categories is conservatively assumed to be ineligible for a Generation 2 upgrade, and instead remains at a 'Generation 1' technology standard.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Efficiency gain

A 100% saving in CO_2 emissions is assumed when aircraft are replaced with either an electric or hydrogen concept aircraft. Sufficient low carbon energy is therefore assumed to be available to produce hydrogen fuel and charge electric aircraft such that this CO_2 saving is achieved on a lifecycle basis.

The next generation of conventionally fuelled aircraft are assumed to deliver a 20% efficiency improvement, through contributions from both the engines and the airframe, in both the narrow body and wide body classes. This view was developed through observation of recent announcements of technology research programmes, including:

- Rolls-Royce UltraFan[23] engine design achieving a 10% fuel efficiency benefit over current state of the art engine technology, now demonstrated to maximum power
- Airbus folding wing[24] project targeting a 5-10% improvement in fuel consumption
- Transonic Truss-Braced Wing program[25] from Boeing and NASA, targeting emissions reductions of up to 30% in the narrow body class, with 10% contribution from the novel wing design[26]
- MTU, Collins Aerospace and GKN Aerospace partnership[27] on new engine concepts combining water enhanced turbofan and hybrid electric architectures, targeting a 25% reduction in CO_2 emissions

The selection of a 20% efficiency improvement for the next generation of conventionally fuelled aircraft also aligns well with the analysis carried out for the ICAO Long Term global Aspirational Goal (LTAG) report which was contributed to by SA members. It can be observed in the Technology Sub Group Report[28] that a 20% improvement aligns well with the Higher Progress scenario for narrow body technology entering service in 2035 and, introducing some conservatism with respect to the SA CO_2 abatement strategy, with the Medium Progress scenario for wide body technology entering service in 2040.

Assumed fleet refresh timelines

A small electric aircraft concept is assumed to enter service in 2028. This is based on announcements from multiple manufacturers of electric aircraft concepts including Eviation Alice[29] (targeting commercial service in 2027) and Heart Aerospace[30] (targeting entry into service in 2028). After consideration of the eligibility criteria, future electric aircraft are only relevant to the Turboprop category.

A regional hydrogen aircraft is assumed to enter service in 2028. This relatively near term date is based on the fact that the earliest available concepts in this class could have retrofitted hydrogen propulsion systems, as reflected in ZeroAvia's[31] strategy targeting aircraft from 2027. This assumption has a relatively small effect on the overall results of the Road-Map, since the Turboprops and Regional Jets categories to which this is relevant, only produce 3.5% of the total fleet emissions.

A hydrogen narrow body aircraft is assumed to enter service in 2035, based on announcements from Airbus on their Zero E programme[32].

The principles of a Boeing paper[33] which notes key findings on airplane economic life were used in part to establish a likely timeline for the future fleet replacements. This paper notes that airplane economic life has not materially evolved over time. Current fleets can be observed to be replaced by successive products in ~20 year timeframe. Assuming this timeline remains consistent is considered conservative since carbon taxation and increased pressure to improve environmental performance in the run up to 2050 may act to expedite fleet upgrades. According to the referenced paper, aircraft type survival rate of 50% has remained consistently at 20-25 years from entry into service. This was also considered with respect to the entry into service dates of the generation 1 aircraft (preceding products) in each category and therefore the dates at which it is considered likely that these aircraft would need to be upgraded to the future products.

23 https://www.rolls-royce.com/media/press-releases/2023/13-11-2023-rolls-royce-announces-successful-run-of-ultrafan-technology-demonstrator-to-maximum-power.aspx

24 https://aviationweek.com/air-transport/airbus-progresses-folding-wing-project

25 https://www.nasa.gov/news-release/nasa-issues-award-for-greener-more-fuel-efficient-airliner-of-future/

26 https://aviationweek.com/air-transport/aircraft-propulsion/nasa-picks-boeings-transonic-truss-based-wing-sustainable-x-plane

27 https://aviationweek.com/aerospace/emerging-technologies/airbus-support-pratt-whitney-future-engine-technology-effort

28 https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM3.pdf

29 https://airwaysmag.com/ceo-eviation-alices-trajectory/

30 https://heartaerospace.com/newsroom/crane-and-heart-aerospace-to-collaborate-on-electrical-power-distribution-system-for-es-30/

31 https://zeroavia.com/

32 https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

33 https://787updates.newairplane.com/Boeing787Updates/media/Boeing787Updates/aircraft_economic_life_whitepaper.pdf

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Assumed fleet refresh timelines (continued)

A shortened timeline of 15 years was chosen for the Turboprop category since a generation 1 upgrade was not accounted for in this category. A longer timeline of 25 years was assumed in the narrow body aircraft categories since a proportion of these upgrades were to hydrogen narrow body aircraft. The additional 5 years to achieve the complete fleet upgrade reflects the expected logistical challenges and an assumed 'learning curve' associated with implementing hydrogen fuelling and novel aircraft handling. For conservatism, this increased timeline was applied to the entire category's upgrade, rather than only the proportion of the category which upgrades to hydrogen.

Table 12 shows the fleet refresh rate assumed for all aircraft categories.

Aircraft Category	Fleet Refresh Rate
Turboprops	15 years
Regional Jets	20 years
Narrow Body A	25 years
Narrow Body B	25 years
Large Narrow Body	25 years
Wide Body Categories	20 years

Table 12: Fleet refresh periods for aircraft category upgrades to future products.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Implementation in the Road-Map

Assuming a linear implementation of the CO_2 emissions reduction between the start and end year for each aircraft category and for each upgrade, and taking into account the materiality of each category within the fleet as a whole, an improvement factor at the fleet level is derived and applied to the Road-Map CO_2 emissions by year. Figure 6 shows the CO_2 abatement in the Road-Map which is achieved by the technology wedges. In total, upgrading the fleet to known technology results in reducing CO_2 emissions by 9.5Mt in 2050. Upgrading the fleet to future technologies saves a further 10.6Mt CO_2 in 2050.

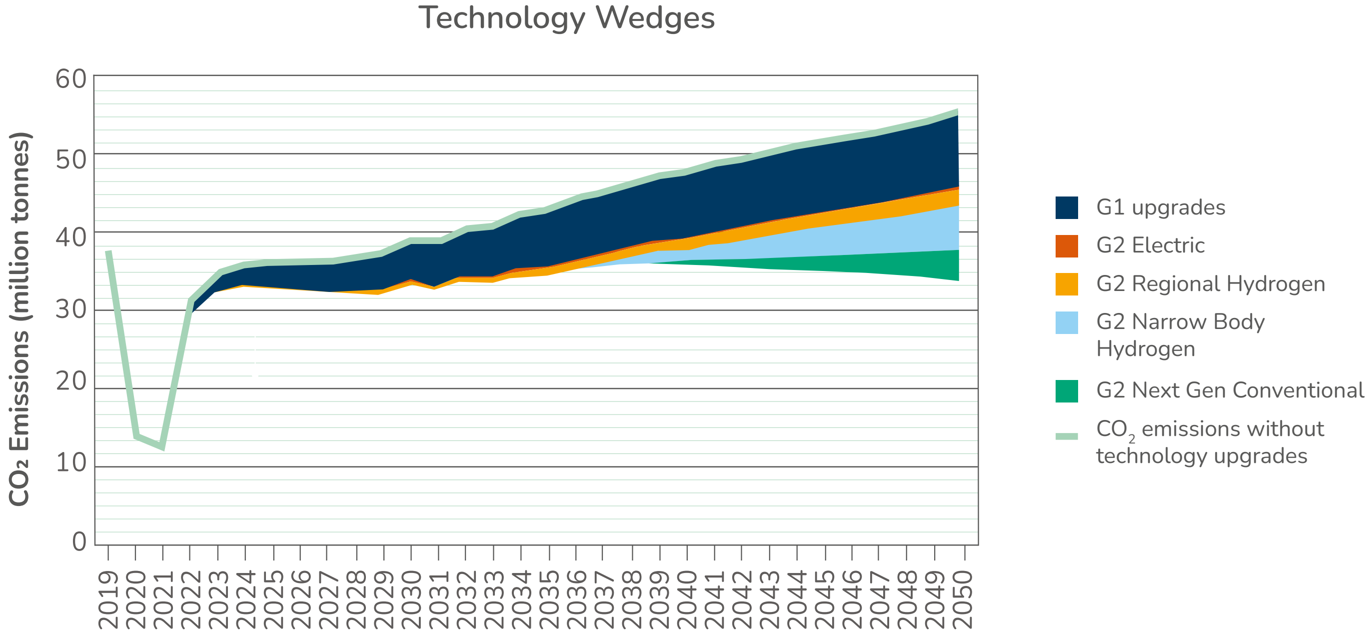


Figure 6: Results of the technology wedges in the Road-Map.

Improvements for Freight Modelling

In baseline year characterisation (see page 13) it was detailed how the baseline year fleet is characterised using departure data from the OAG database. This allows improvements offered by individual aircraft types to be accounted for at the fleet level in a proportionate manner. The OAG database does not include all dedicated freight flights, and therefore the current SA methodology does not permit explicit individual modelling of freight aircraft upgrades. Freight CO_2 emissions are still accounted for in the Road-Map since the CO_2 values are all built on actual total CO_2 emissions in the first 3 years of the timeline.

The simplification of not explicitly modelling the freight flights means that the modelling assumes that efficiency upgrades to these aircraft will occur on average in the same manner as the rest of the passenger fleet. This is considered a reasonable assumption with minimal impact on the overall Road-Map results since dedicated freight activity is expected to contribute a small and reducing percentage of the overall aviation emissions. In the future the fleet-wide improvements could be modelled with greater granularity if a data source could be identified which reliably included all departure data for dedicated freight flights.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.5 Sustainable Aviation Fuels

Sustainable Aviation commissioned ICF to complete an independent analysis[34] of the potential for the development of the UK SAF industry which took place during 2022 and prior to the recent UK government SAF mandate policy announcement. This exercise included a bottom-up assessment of the quantities of SAF which could be produced in the UK and what proportion could be made available to the aviation sector, based on biological and waste-based feedstock quantities, and feasible scaling rates of low carbon energy to produce Power to Liquid (PtL) type SAF. In this evaluation, only sustainable feedstocks were considered which had no negative impact on agricultural land. The following UK produced SAF types were evaluated:

- UK produced Hydroprocessed Esters and Fatty Acids (HEFA) / co-processed SAF – e.g. used cooking oil
- UK produced waste based SAF – e.g. produced from domestic or commercial landfill waste
- UK produced PtL SAF – e.g. combining captured atmospheric carbon with green hydrogen produced using renewable energy

The assumed quantities of UK produced SAF are presented in Figure 7 and Appendix 2 alongside cost estimates for these SAF types which were also generated by the ICF study. The cost (and hence sales price to buyers) of these UK produced SAF types are based on an estimate of the cost of production plus an assumed margin for the SAF producer, presented in Table 13.

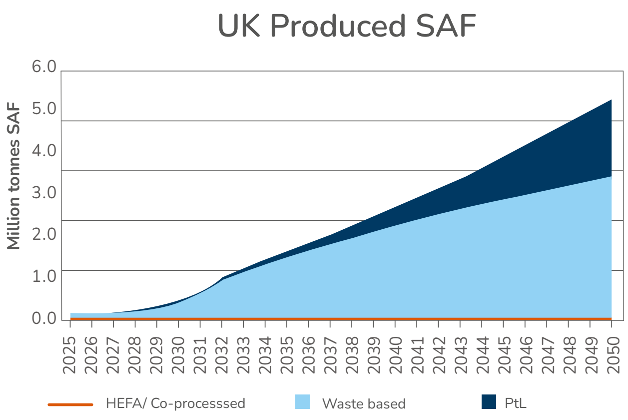


Figure 7: UK produced SAF assumed available to aviation sector.

	2020	2030	2040	2050
HEFA/co-processed	10%	8%	8%	8%
Waste-based	25%	20%	15%	10%
PtL	25%	20%	15%	10%

Table 13: Margin over cost of production for UK produced SAF.

The Road-Map model assumes a preference to use UK produced SAF over non-UK produced SAF where possible to meet demand. The model calculates the aviation fuel required for UK departures after cost-based activity reduction and efficiency savings are made from new aircraft technology and operations. It is assumed that a UK Government SAF mandate policy defines the percentage of the fuel mix used by the aviation sector for departures from UK airports which must be SAF, for each year out to 2050. The assumed mandate level is detailed in Appendix 2. If the UK produced SAF quantity is insufficient to meet the mandated level, it is assumed that SAF can be imported and the model calculates what quantity of imported SAF is required. The cost estimate for imported SAF was developed by the ICF study and is based on competitively purchasing US produced SAF.

34 https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/Sustainable-Aviation-SAF-Roadmap-Final.pdf

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.5 Sustainable Aviation Fuels (continued)

In reality purchased imported SAF could originate from many countries including in the EU, but it was assumed that likely price points could develop around SAF produced in the US which is currently supported by a stack of policy measures. For this analysis it was therefore assumed that US SAF is likely to dominate the international SAF market. Although this assumption is more likely to be true in the short term due to currently active policies, it is assumed to also remain the case in the medium to long term in the absence of alternative information at the time of developing the Road-Map. The costs are detailed in Appendix 2, with three types of SAF considered:

- US produced HEFA SAF
- US produced waste based SAF
- US produced PtL SAF

The cost per tonne of SAF in each year is calculated as a weighted average considering for each year the proportions of each type of SAF being used in the overall fuel mix. In most cases for the different SAF types, real data is unavailable and so the costs of different pathways can only be estimated. Since distinct costs were estimated for 3 types of imported SAF, the import mix was assumed to mirror the mix of UK produced SAF in each given year. This aspect of the calculation is only required for the purposes of generating an average cost of SAF used. The model does not otherwise consider distinct forms of imported fuels.

The ICF analysis additionally estimated the lifecycle CO_2 saving achieved through the use of SAF, detailed in Appendix 2, which increases as SAF production methods and technology matures. The lifecycle CO_2 saving is an assumed average over all tonnes of SAF used, and therefore the achievement of 100% CO_2 abatement per tonne of SAF in 2050 requires a proportion of produced SAF to be carbon negative (e.g. through the use of carbon capture and storage during production) to counteract any produced SAF which has an embedded quantity of lifecycle CO_2 emissions above zero. Although the SA model assumes a single average value of lifecycle CO_2 emissions savings achieved by using a tonne of SAF, in reality distinct SAF types from different suppliers will have a range of carbon intensities, which will also impact the cost per tonne of the fuel, intrinsically linking the carbon intensity and cost assumptions.

Combining the lifecycle CO_2 abatement associated with SAF with the quantity of SAF used provides the quantity of residual CO_2 emissions which are abated in the Road-Map chart, as shown in Figure 8.

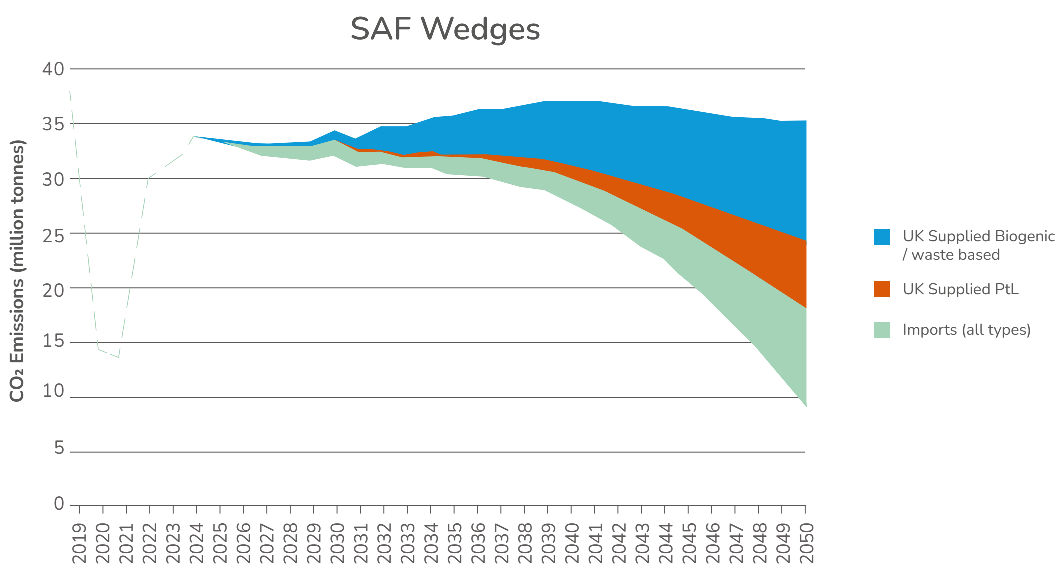


Figure 8: Abated CO_2 through use of SAF in the Road-Map.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.6 Greenhouse gas removals

Supply and cost model summary

To inform how UK aviation might address its residual emissions to achieve net zero carbon, a model was developed to understand the potential supply and related costs of UK Greenhouse Gas Removals (GGRs) throughout the timeline to 2050. The view was taken that by 2050, 100% of UK aviation residual emissions should be abated to zero through highly durable GGRs, in line with best practice offsetting principles[35], for a credible net zero carbon claim. Therefore UK aviation's demand for GGRs in 2050 is the total residual emissions remaining after taking account of all other mitigation measures outlined in the other sections.

To determine the supply and cost per tonne of GGRs, a review of trusted publicly available sources was undertaken, supplemented by subject matter expert interviews. The scope of this review was for UK produced GGRs as a whole, which must be shared by all relevant sectors requiring GGRs to manage residual emissions in order to achieve a national net zero carbon economy. The concept of a 'fair share' of GGR supply for UK aviation was introduced, derived by assessing the expected proportion of total UK GHG emissions attributable to aviation and applying this to the total anticipated UK GGR supplied in the market.

The model initially made an assessment of three future GGR supply scenarios: 'foresight' (low cost-high availability); 'central' (mid cost-mid availability), and 'scramble' (high cost-low availability). Since the central case is used in the Road-Map, only the results of this scenario are presented here.

The model generates the total annual cost of purchasing GGRs, for use in modelling of activity growth reduction (see Decarbonisation costs and reduction in activity growth), and the quantity of GGRs accessed by the aviation sector, comparing this to the 'fair share' of the total available GGR supply that was established.

UK GGR supply and cost forecasts

A desktop study was undertaken to identify GGR supply (tCO_2) and cost (£/t) forecasts for nine key GGR types listed in Table 14. Only publicly available reports from sources considered robust were used and which covered both nature-based and engineered removals. Wherever possible, sources with a UK context were selected, including the UK Government commissioned reports listed in Table 15. Most sources provide a high, medium and low supply and/or cost forecast. Where some reports provided periodic forecasts, for example every 10 years, annual figures were derived using linear interpolation.

Engineered	Nature-Based Solutions
Direct Air Carbon Capture and Storage (DACCS)	Afforestation
Bioenergy with Carbon Capture and Storage (BECCS)	Habitat Restoration
Wood in Construction	Soil Carbon Sequestration
Enhanced Weathering	Wood Based Biomass
Biochar	

Table 14: GGR technologies for which supply and cost data has been collected.

35 Oxford Principles

1. MODELLING METHODOLOGY AND ASSUMPTIONS

UK GGR supply and cost forecasts (continued)

GGR Supply and Cost Forecasts
BEIS Phase 2 Projects[36]
IEA (2022) DAC Tracking[37]
BEIS Element UKCEH Potential GGR Deployment Study (2022)[38]
BEIS Ricardo Potential BECCS (2020)[39]
Vivid Economics GGR Report 2019[40]
Royal Society and Royal Academy of Engineering (2018) GGR Report[41]
CCC VCM and Offsetting (2022)[42]
CNE Report 2021[43]
GGR Cost Forecasts only
IPCC AR6 WGIII Report (2022)[44]
Global CCS Institute 2022[45]

Table 15: Data sources used for GGR supply and cost forecasts.

Interviews with GGR subject matter experts were also undertaken to validate and expand on the data collected. Interviewees were asked to provide their view on likely supply and costs and views on the future UK and global GGR market. For a fair representation of the market, a range of companies were targeted, including both producers and vendors, and nature-based solutions and engineered removals companies:

- 1pointfive
- Aker Carbon Capture
- Biomass UK / REA
- Carbon Engineering
- Climeworks
- Drax
- Forest Carbon / Woodland Carbon Code
- Ocean Based Climate Solutions
- Verra

The data from the desktop review and expert interviews was used to calculate an average high, medium and low forecast for both supply and cost, for each of the nine key GGR types. The full dataset used in the GGR model is available in Appendix 3.

36 BEIS, DESNZ (2022) Projects selected for Phase 2 of the Direct air capture and greenhouse gas removal programme
37 IEA (2022) DAC technology deep dive
38 BEIS, Element Energy, UK CEH (2022) Greenhouse gas removal methods and their potential UK deployment
39 BEIS, Ricardo (2020) Analysing the potential of bioenergy with carbon capture in the UK to 2050 Summary for policymakers
40 BEIS, Vivid Economics (2019) Greenhouse Gas Removal (GGR) policy option – Final Report
41 Royal Society, Royal Academy of Engineering (2018) Greenhouse gas removal
42 Climate Change Committee (2022) Voluntary Carbon Markets and Offsetting
43 Coalition for Negative Emissions (2021) The case for Negative Emissions. A call for immediate action
44 IPCC (2022) Climate Change 2022: Mitigation of Climate Change
45 Global CCS Institute (2022) The economics of direct air carbon capture and storage

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Market Scenarios

The findings of the SA research on GGRs supported a view that cost and supply were fundamentally interlinked in market and policy futures. Early investment and scaling of the GGR sector is assumed to deliver lower cost profiles throughout the timeline, and late investment accompanied by an assumed last minute 'dash' for carbon to achieve 2050 goals, is expected to result in the higher cost profiles. Therefore Table 16 shows the averaged supply and cost datasets which were used to establish the three market scenarios.

Scenario	Supply Data	Cost Data
Upside: 'Foresight'	High Supply	Low Cost
Central (Road-Map)	Mid Supply	Mid Cost
Downside: 'Scramble'	Low Supply	High Cost

Table 16: Forecast data used per scenario.

Establishing a 'fair share'

The proportion of total UK GHG emissions attributable to aviation is forecast to increase as other 'easier to decarbonise' sectors reduce emissions at a faster pace. Modelling undertaken for the CCC's Balanced Net Zero (BNZ) scenario in the Sixth Carbon Budget[46] shows aviation emissions reaching approximately a quarter of all residual emissions by 2050. Aviation's proportion of emissions per year was calculated from the BNZ pathway dataset thus:

Proportion aviation emissions = aviation's forecast emissions / ((sum of traded and non-traded emissions) – (traded engineered removals + LULUCF* Sinks + non-traded removals))

*LULUCF = Land Use, Land-Use Change and Forestry

The resulting proportion (%) of emissions per year for aviation is shown in Figure 9 and Table 16. This is taken as a proxy for the proportion of GGR supply that UK aviation could fairly access without jeopardising access for other sectors.

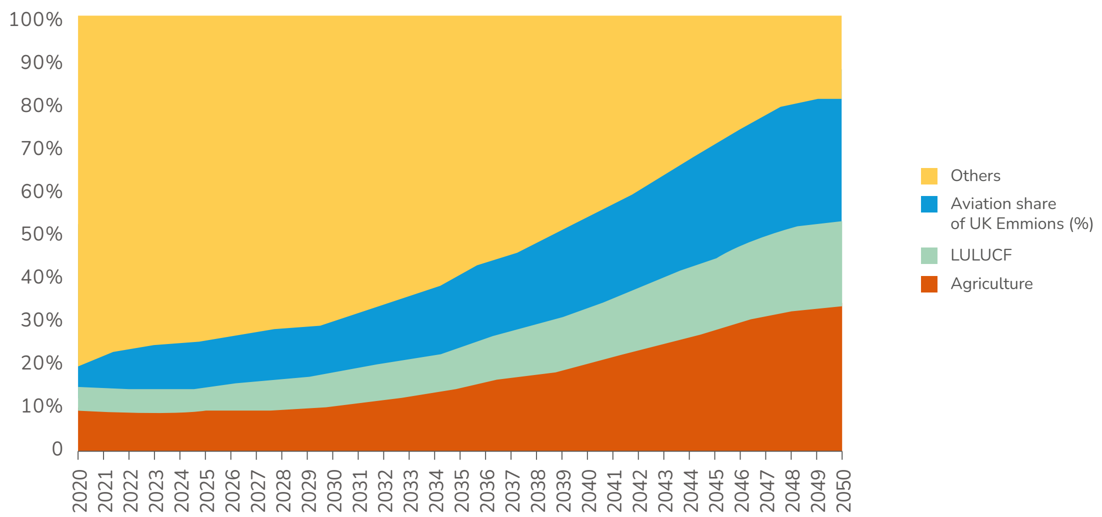


Figure 9: Proportion of UK emissions by key sector (derived from CCC's Balanced Net Zero Pathway).

46 CCC 6CB Dataset Tab 'Traded and non-traded emissions in the Balanced Net Zero pathway'.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Establishing a 'fair share' (continued)

Share of total UK emissions (%)	2025	2030	2035	2040	2045	2050
Aviation	**8%**	**10%**	**13%**	**17%**	**22%**	**24%**
Agriculture	11%	12%	17%	23%	31%	37%
LULUCF	6%	8%	10%	13%	18%	21%
All Others	75%	70%	60%	47%	29%	18%

Table 17: Proportion of UK emissions by key sectors (derived from CCC's Balanced Net Zero dataset).

The model assumes UK aviation accesses a 'fair share' of the supply per year until 2035. After 2035, an incremental increase toward meeting 100% of residual emissions by 2050 occurs, regardless of the 'fair share' limit.

Implementation in the Road-Map

An additional input is required from the SAF wedge to account for the additional carbon removal required to generate the carbon feedstock for the estimated UK produced PtL SAF used in the Road-Map. The quantity of GGRs available to aviation are first discounted to supply PtL production prior to addressing aviation residual emissions. An indicative carbon requirement for the PtL SAF was simply derived by multiplying the tonnage of fuel required by 3.18 which reflects the typical carbon content of jet fuel (tank-to-wake, DEFRA emission factors[47]).

Prior to 2045, aviation demand is met by using all GGR types in the proportions that they are available nationally in each year (a portfolio approach). After 2045, a transition towards covering demand solely through engineered removals occurs, unless available supply does not allow demand to be met. The calculation is altered to prioritise use of engineered GGR types: DACSS then BECCS. If demand cannot be met by engineered removals, nature-based removals continue to be accessed.

The cost of GGRs in each year is calculated as a weighted average based on the proportions of each type of GGR being accessed in any one year.

47 DEFRA GHG Conversion Factors 2022

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Implementation in the Road-Map (continued)

The key outputs of the Central scenario are illustrated in Figure 10 with a brief explanation:

- Total UK GGR supply reaches 83Mt in 2050
- In 2050, aviation requires access to 19% of estimated UK GGR supply, including carbon feedstock requirement for production of PtL, which is below the calculated 'fair share' of 24%

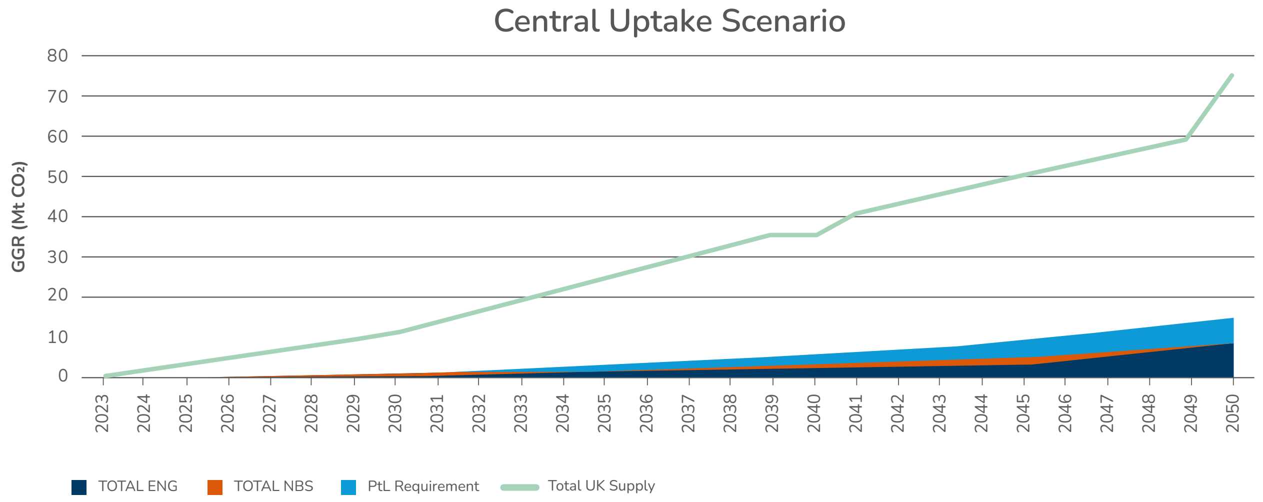


Figure 10: Results of the Central scenario of GGRs for the Road-Map.

Figure 11 shows the results of the model's calculations which provide the quantity of each type of GGR purchased by the aviation sector.

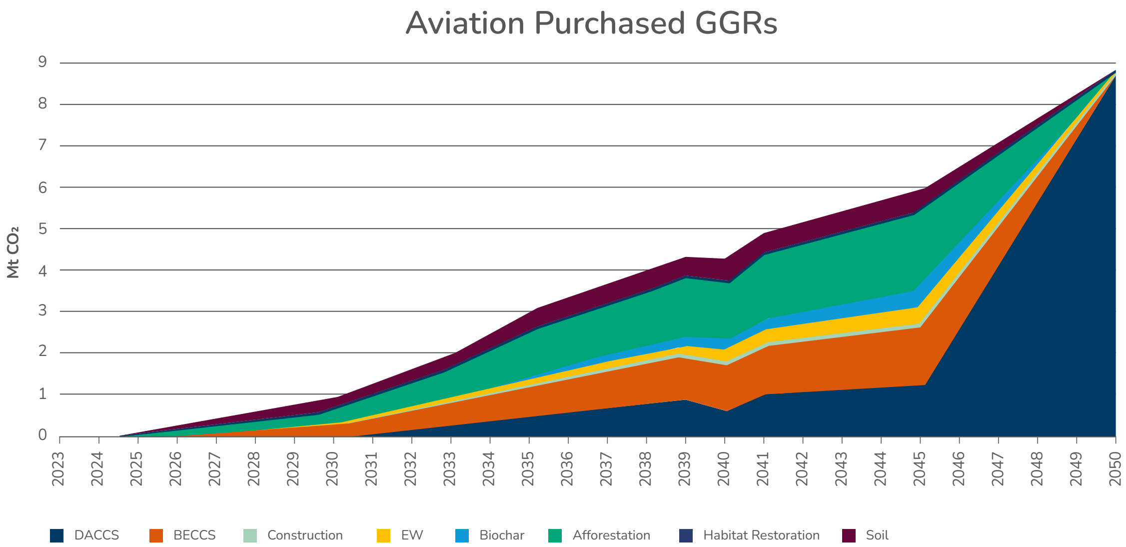


Figure 11: Aviation purchased GGR types assumed in model.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.7 UK ETS and CORSIA

The assumption was taken that the UK Emissions Trading Scheme (ETS) & the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) applied to all gross emissions, i.e. from the top of the SAF wedge. Using the rules of both schemes it could be established what proportion of the total emissions were subject to each scheme. Following this, it could be established what quantity of ETS credits and CORSIA offsets the sector was obligated to purchase. These purchases result in the CO_2 emissions being reduced on a net basis, which is illustrated in the Road-Map chart as the lowest line: the net residual emissions. This is considered to be the level of net residual emissions which the sector is obligated to achieve, as defined by the current ETS & CORSIA rules to 2035, shown in Figure 12.

A policy assumption is made that SAF and GGRs will be recognised within the ETS and CORSIA rules, such that the utilisation of SAF and/or purchasing of GGR reduces the number of allowances/credits which must be purchased. The net residual emissions level is fixed by the terms of the obligation schemes, but the quantity of purchased credits can be offset by utilising SAF and purchasing GGRs. This aspect is relevant when calculating the total costs to the sector.

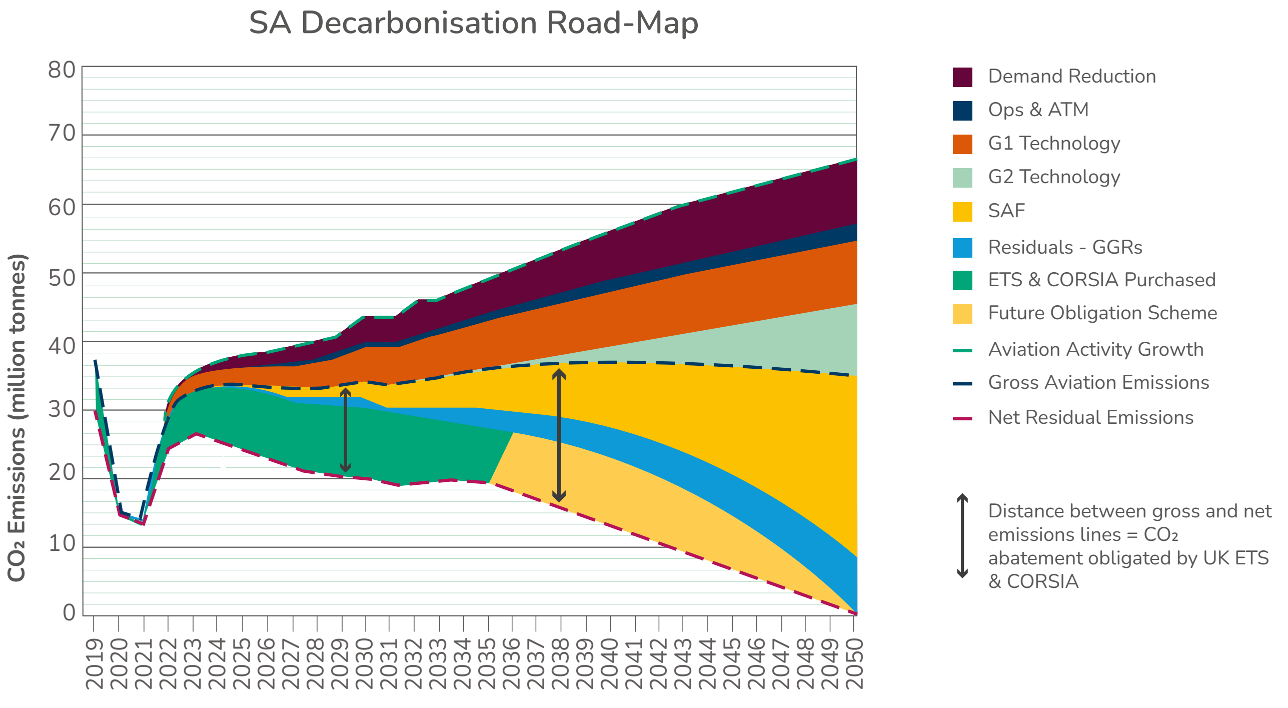


Figure 12: Residual emission level obligated to be achieved by compliance with UK ETS and CORSIA.

The second phase of CORSIA is defined until 2035. An assumption was made that a successor scheme will come into effect with terms which mandate a linear trajectory of net residual emissions from the level achieved at the end of CORSIA in 2035 to zero by 2050. This was termed the Future Obligation Scheme.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

UK ETS

The UK ETS covers domestic flights and flights to Gibraltar and the European Economic Area[48]. The baseline fleet characterisation determined the CO_2 emissions resulting from all relevant flights. 35% of the total emissions were covered by the UK ETS. This proportion was assumed to remain constant as aviation activity grew throughout the timeline to 2050. It was assumed that double counting between the UK ETS and CORSIA would not occur, so this 35% of activity was not additionally eligible for obligations under CORSIA.

It is assumed the sector must pay for every tonne of in scope emissions once the free allocations to airlines are retired from 2026, i.e. 35% of the total emissions from UK departures. A notional emissions cap for UK aviation was defined within the ETS. This is the business as usual 'fair share' to aviation of the issued allowances within the total UK ETS cap. If all participants were decarbonising at the same pace, aviation should only use allowances up to the notional aviation cap to remain proportionally relative to the other participants. The notional cap was calculated assuming the EU ETS rules for phase 4 apply (whereby 82% of the aviation cap is free of charge aviation allowances and referring to the UK free allocations to airlines[49]). It was assumed that in the near term, available free allocations to airlines are calculated based on historical activity for these airlines and are relative to other participants in the UK ETS. This results in a cap for aviation of ~5.3 $MtCO_2$ or ~3.4% of the total UK ETS cap in 2021. It is also assumed that the aviation cap declines by 2.2% per annum from 2024-2026 and thereafter by 4.2% per annum.

The SA derived 'in scope' emissions (35% of the total) will exceed the notional aviation cap, meaning that the aviation sector will need to fund more than the current business as usual 'fair share' number of allowances. In other words, other participants (and sectors) in the ETS will receive additional funding from the aviation sector to decarbonise faster and release these allowances to be traded with airlines. This proportion of the allowances purchased by airlines which is above the aviation cap is modelled to achieve CO_2 emissions abatement. The rationale behind this is that within the UK ETS cap, emission allowances cannot be used twice, so emission savings created elsewhere in the economy, are purchased by the airline sector at whatever price the market requires. The ETS is a mechanism to transfer funds from aviation to decarbonisation in other sectors resulting in economy wide carbon savings in the most affordable way. Aviation funded CO_2 emissions reductions are shown in the SA model as 'net' CO_2 emissions reduction.

Payments made by aviation for emissions up to the level of the aviation cap also add cost to providing aviation activity, so have been included in the 'demand reduction impact of decarbonisation costs' model, but these emissions are not considered to be abated in the Road-Map wedge. Up to the cap, these are pre-agreed upon emissions by the aviation sector and in the absence of a mechanism in which these funds support the decarbonisation of the aviation sector, these emission allowance purchases do not result in any CO_2 abatement.

CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has a pilot phase (2021-2023), a first phase (2024-2026) and a second phase (2027-2035). The materiality of CO_2 emissions produced on flights in scope of CORSIA was slightly different between the voluntary pilot/first phase[50] and the mandatory second phase due to additional countries expected to join the scheme after 2026[51]. Until 2026, 49% of the total UK aviation emissions were produced on flights to destinations covered by CORSIA, and after 2026, 58% of emissions were CORSIA eligible.

CORSIA rules[52] stipulate that from 2024-2035 net aviation emissions should not exceed 85% of the level of 2019 emissions, and that carbon offsets must be purchased to reduce emissions on a net basis to achieve this. It has been assumed that accredited offsets within CORSIA are legitimate and additional, such that the aviation sector funding them, results in abatement of CO_2 emissions from aviation activities. Therefore all CORSIA purchases in the model cause CO_2 abatement.

The rules further define that obligations will be based on growth of the whole aviation sector until 2032. From 2033 the obligations will be based 85% on whole sector growth and 15% on individual growth. This has been represented in the analysis by use of:

- Sectoral: IATA data on sector mid growth forecast factors (listed in Appendix 6) and methodology[53]
- Individual: UK aviation growth derived in SA Road-Map

These rules are used to calculate the annual in scope emissions of the CORSIA scheme, which are based on:

1. Total emissions estimated from UK aviation, multiplied by 49% before 2026 and 58% thereafter
2. No growth baseline CO_2 emissions (85% of 2019 emissions), differentiated between pre and post 2026 due to the different destination countries signed up to the scheme
3. Sector growth factor
4. Ratio between sector vs individual basis for CORSIA obligations

48 https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets
49 https://www.gov.uk/government/publications/uk-ets-aviation-allocation-table
50 https://www.icao.int/environmental-protection/CORSIA/Pages/state-pairs.aspx
51 https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---corsia/
52 https://www.icao.int/environmental-protection/CORSIA/Documents/Resolution_A41-22_CORSIA.pdf
53 https://www.iata.org/contentassets/fb745460050c48089597a3ef1b9fe7a8/corsia-handbook.pdf

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Carbon price

Carbon price estimates were taken from the National Grid's Future Energy Scenarios 2022 data workbook[54]. Specifically, the High case for UK carbon price in €/tonne was selected and converted to £/tonne using an exchange rate of 0.89. The dataset is included in Appendix 4.

It was assumed that there will be a convergence between the price of a UK ETS allowance to emit 1 tonne of CO_2, and for a CORSIA offset of 1 tonne of CO_2. This follows the principle of the development of a rational international marketplace for carbon as the quantity of CORSIA offset purchases become significant over time. Therefore the same price (in a given year through the timeline to 2050) was used for the UK ETS, CORSIA, and Future Obligation schemes.

Since the same carbon prices are used, the Road-Map chart joins the ETS and CORSIA abatements in one wedge. Alternatively the modelling could keep them separate which would allow more granularity to apply distinct carbon prices and to visualise the emissions abated by either scheme including an option in the Road-Map not to illustrate the ETS resulting in CO_2 abatement.

Implementation in the Road-Map

Collectively, the UK ETS rules, CORSIA rules and the future obligation scheme presumed to chart a linear trajectory from 2035 to zero in 2050 define the position of the net residual emissions line. The total purchased credits from obligation schemes are calculated as shown in Figure 13. All CO_2 values contained in the Road-Map chart are listed in Appendix 5.

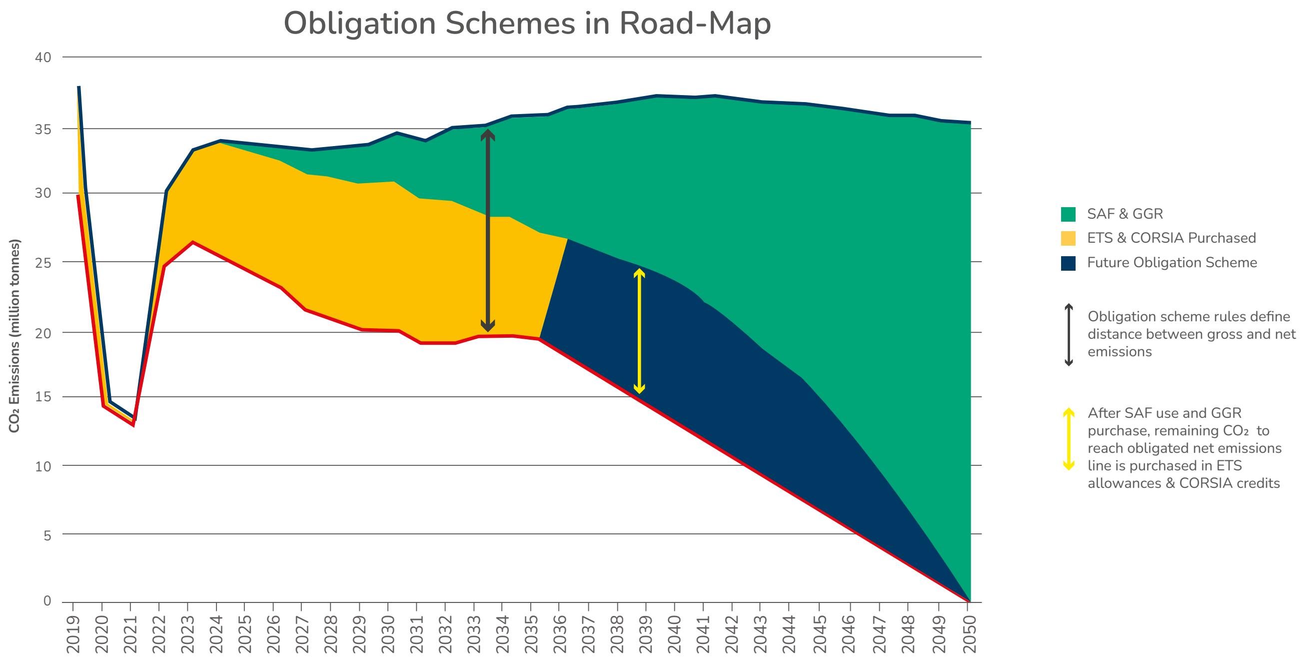


Figure 13: Definition of the net emissions line by the obligation schemes and quantity of CO_2 abated by obligation scheme purchases

54 https://www.nationalgrideso.com/future-energy/future-energy-scenarios/documents

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.8 Decarbonisation costs and reduction in activity growth

In the near and mid-term, delivering UK aviation activity with net zero emissions of carbon will incur additional and ongoing costs relative to 'business as usual' without taking any actions to decarbonise. The following so-called "decarbonisation costs" are included in this analysis:

- Additional cost of SAF (portion which is higher than conventional Jet A-1 fuel)
- Purchasing GGRs
- Purchasing UK ETS allowances & CORSIA credits

It is assumed that these costs are transferred to the ticket prices for flights departing UK airports, and that the resulting increase in ticket prices for passengers has an impact on demand. One-off costs for any necessary investments in infrastructure upgrades are not included in the analysis. Similarly the one off costs of investment in new aircraft are not included, since the cost to operators of periodically upgrading their aircraft are already built into existing ticket pricing decisions today, and therefore this represents no change from the 'business as usual' assumptions.

SAF

The SAF prices are listed in Appendix 2. An overall cost per tonne of SAF used in each year is calculated as a weighted average of the quantities of the different types of SAF, which have a built in assumption that the costs of production reduce over time as efficiencies are discovered and implemented. The overall result is shown in Figure 14.

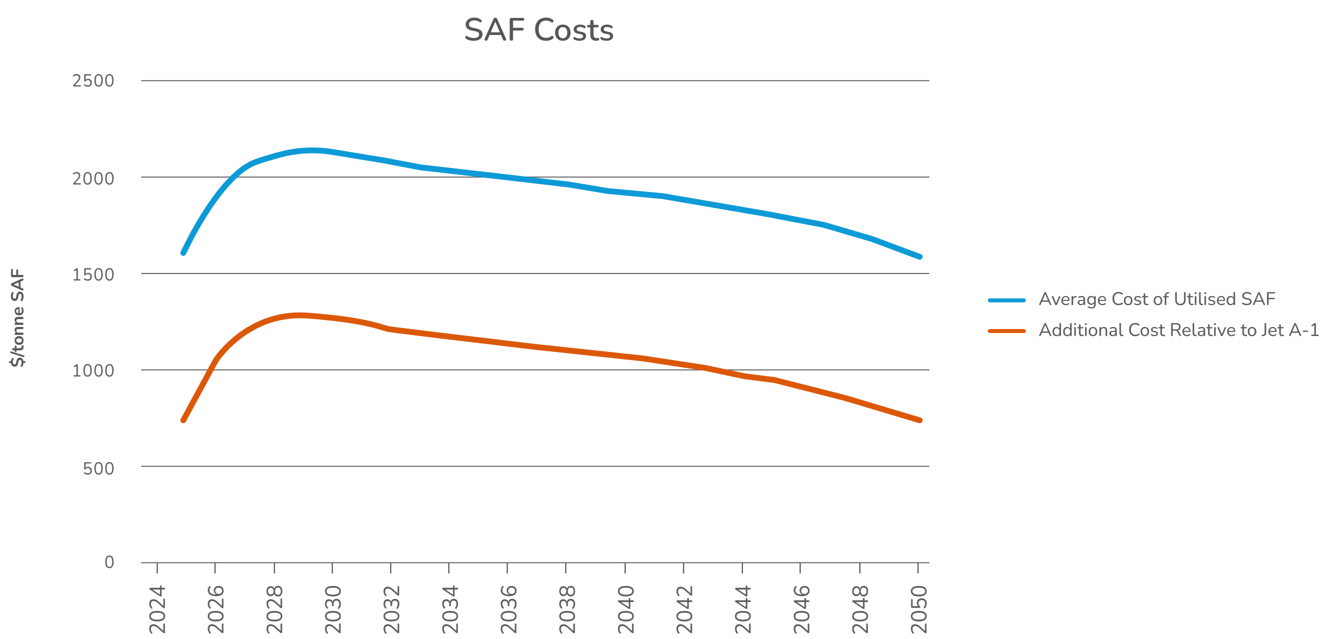


Figure 14: Average cost per tonne of all SAF utilised in the Road-Map.

A constant price of \$860/tonne is assumed for Jet A-1 throughout the timeline[55].

55 https://www.iata.org/en/publications/economics/fuel-monitor/ - read on 13/03/23

1. MODELLING METHODOLOGY AND ASSUMPTIONS

GGRs

The GGR prices are listed in Appendix 3. A weighted average cost per tonne of GGR each year is calculated accounting for the specific proportion of each type of GGR purchased in each year. The overall result is shown in Figure 15.

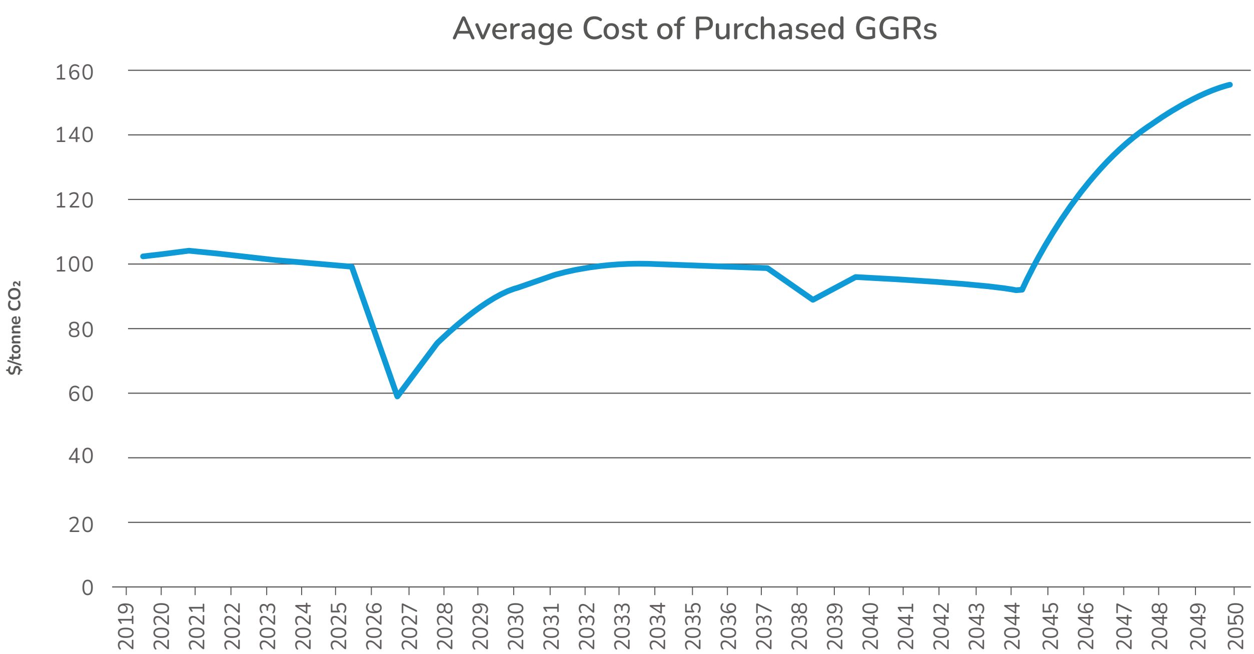


Figure 15: Average cost per tonne of all GGRs purchased in the Road-Map.

ETS, CORSIA and Future Obligation Scheme

Section 1.7 detailed the calculation to establish the quantity of credits which must be purchased to achieve the obligated net residual emissions after SAF utilisation and GGR purchases have been taken into account. The 'carbon prices' assumed for 1 tonne CO_2 in each of the obligation schemes are listed in Appendix 4.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Activity Reduction

The total decarbonisation costs per year are calculated:

Total decarbonisation cost = (tonnes SAF x additional cost SAF) + (tonnes GGRs x average cost GGRs) + (tonnes obligated UK ETS/CORSIA credit purchases x carbon price)

This total cost is divided into an average price impact to an individual ticket by dividing it between the predicted number of seats. The number of available seats in the baseline year was extracted from the baseline fleet characterisation, and this number is multiplied by the factor of activity growth established in the Road-Map – see Section 1.2, no improvement scenario demand forecast. An average ticket price of £150 was assumed for all UK departures in 2019. This permitted the increase in individual ticket price to be expressed on a percentage basis.

DfT utilise econometric model data to produce the national aviation forecasts. This DfT data on price elasticity of demand[56] for tickets to different global destinations was used:

	Price Elasticity of Demand
Domestic	-0.6
Southern Europe	-1.0
Rest of Europe	-0.9
OECD	-0.9
Rest of World	-0.9

Table 18: DfT data for price elasticity of demand.

Taking into account the materiality of CO_2 emissions to different global regions, a price elasticity of demand of -0.9 was used. For a 1% increase in average ticket price, a reduction in activity of 0.9% was assumed. Figures 16 and 17 show the overall results of the decarbonisation costs impact on activity growth.

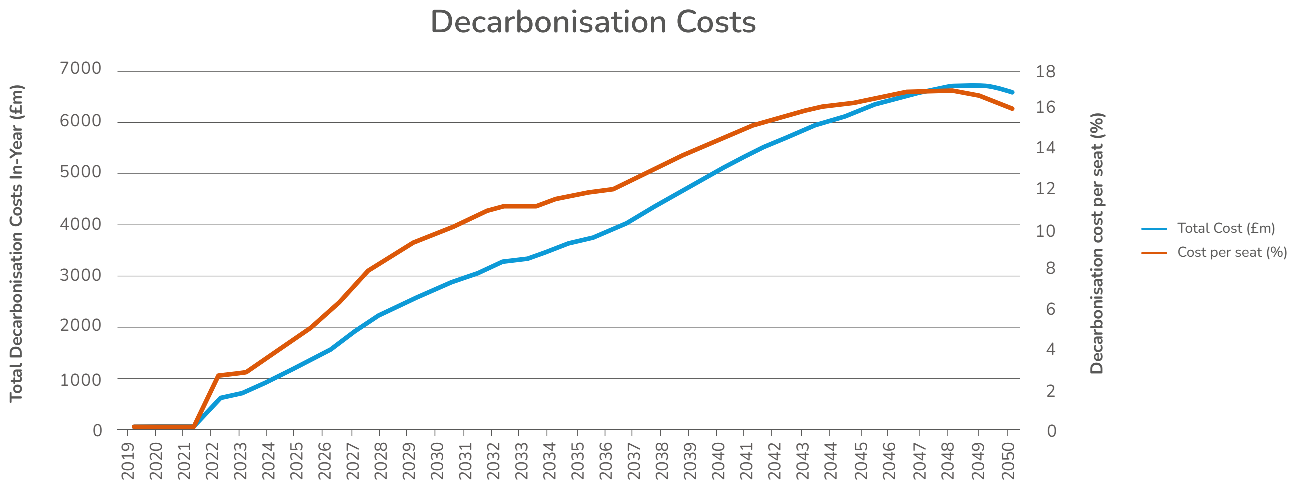


Figure 16: Decarbonisation costs total per year and the impact on a % increase in individual ticket price

56 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1061918/econometric-models-to-estimate-demand-elasticities-for-the-national-air-passenger-demand-model.pdf

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Activity Reduction (continued)

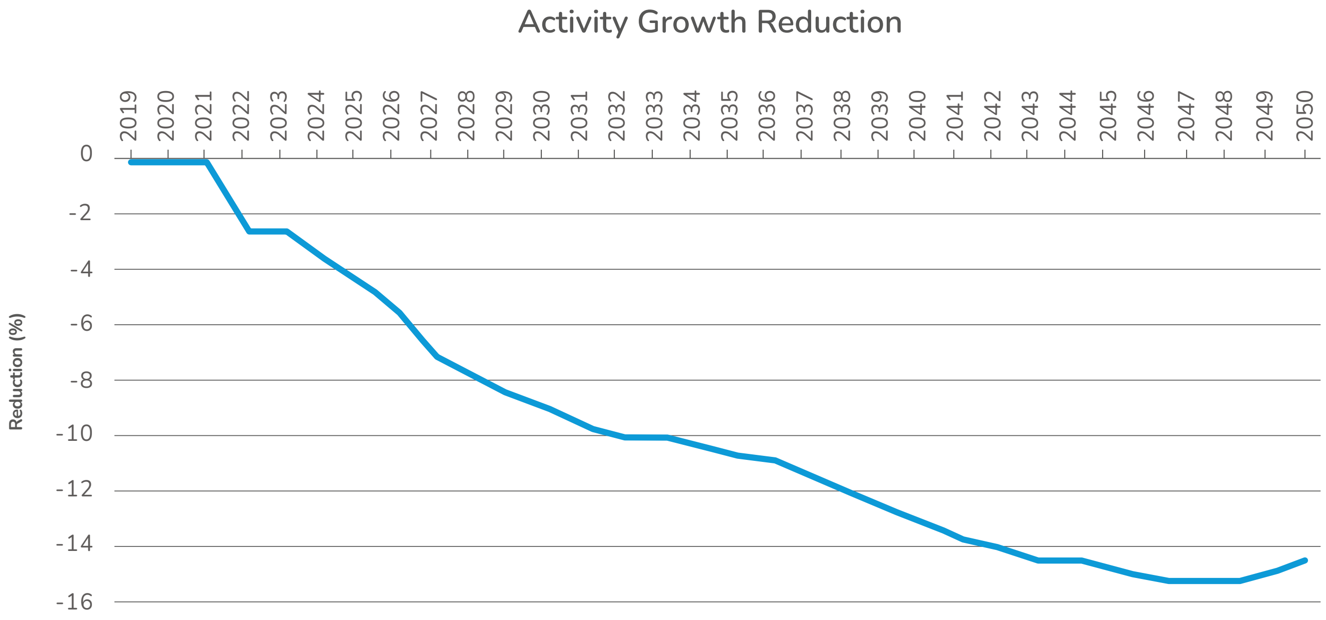


Figure 17: Reduction in unconstrained UK aviation activity growth per annum due to decarbonisation costs

Implementation in the Road-Map

The percentage reduction in activity growth is translated directly to a percentage reduction in the CO_2 emissions which would occur as aviation activity grows in the absence of actions to decarbonise. In other words, the “basis” for the reduction is the top line of the Road-Map chart, the so-called “no improvement scenario”. It is necessary for the model to be iterated in order to converge on the solution in Figure 1. This is due to the fact that reducing overall aviation activity results in fewer CO_2 emissions and therefore fewer decarbonisation costs, which acts to increase activity again, and so on. All CO_2 values contained in the Road-Map chart are listed in Appendix 5.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Annual % reduction in UK aviation activity growth due to decarbonisation costs

Another useful result is to compare the various decarbonisation strategies in terms of their cost per tonne of resultant CO_2 abatement as shown in Figure 18. This can be simply derived by dividing the total cost of each strategy by the number of tonnes of CO_2 abatement which is achieved by each, as derived in Sections 1.5 to 1.7. The analysis indicates that by 2050, the decarbonisation strategies included in the SA Road-Map will converge and be approximately equally effective in abating CO_2 emissions for a certain cost.

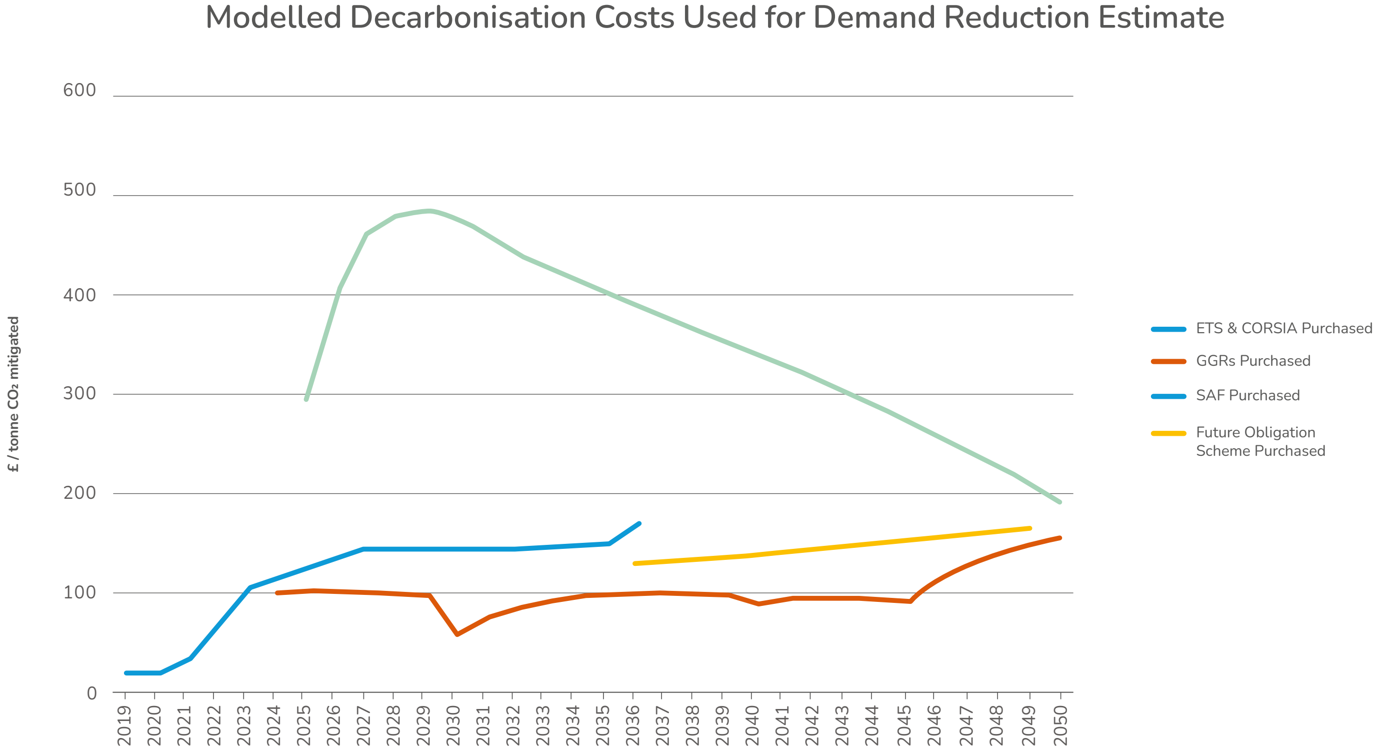


Figure 18: % reduction in activity growth due to increase in ticket prices

1. MODELLING METHODOLOGY AND ASSUMPTIONS

1.9 Energy Requirements to Achieve Net Zero Carbon

Some high-level calculations have been used to provide an indicative value of the low carbon energy requirements for aviation, in order to achieve net zero carbon operations by following the strategy defined in the Road-Map. Because the Road-Map purely focuses on tailpipe emissions in service, no estimates have been made for additional energy which may be required to produce and dispose of aircraft or develop new infrastructure. Arguably these aspects are represented in current energy demand from the sector as new aircraft are delivered and infrastructure like fuel pipelines and airports are maintained. A more detailed analysis would be required to estimate whether the energy intensity would be greater for the upfront development of future aircraft types and supporting infrastructure.

Figure 19 illustrates the sections of the Road-Map which are reliant on some level of access to low carbon energy. These sections span 32% of the total CO_2 abatement in 2050.

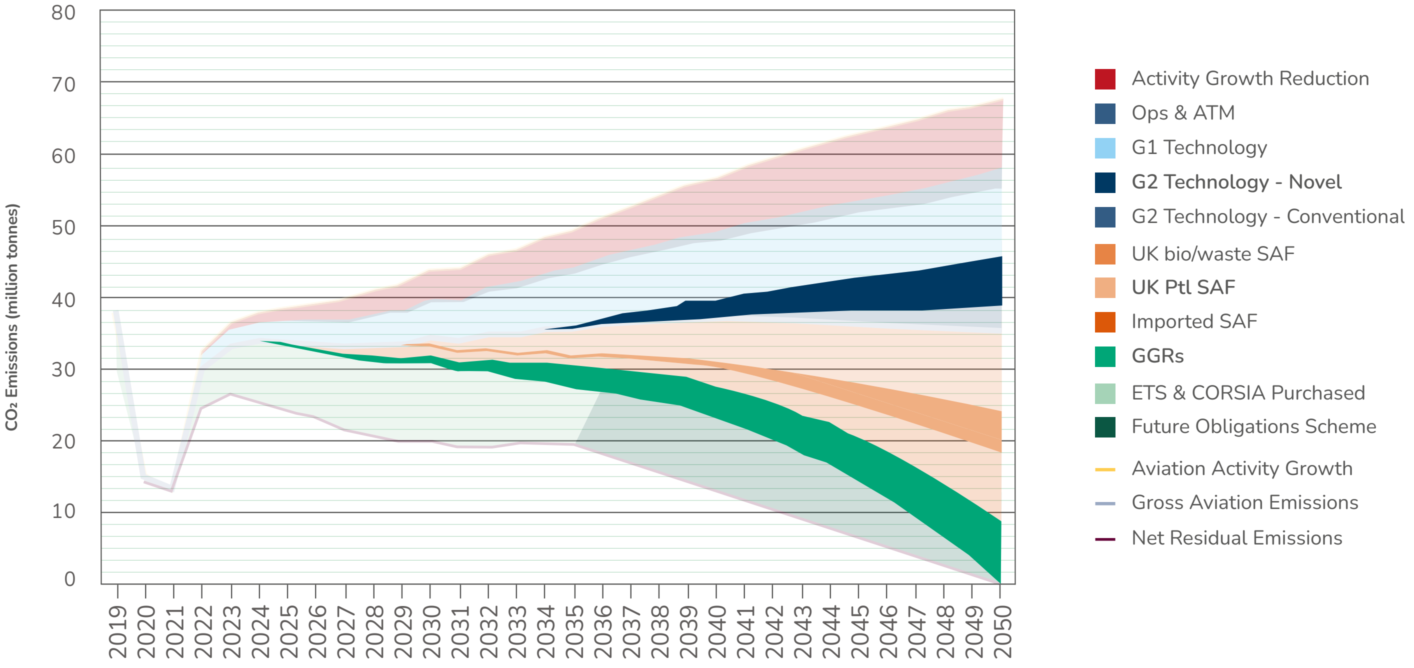


Figure 19: Energy dependencies of the SA Net Zero Carbon Road-Map. Sections with a requirement for access to low carbon energy are emphasised.

The following requirements for low carbon energy were considered:

- Production of hydrogen fuel for future aircraft
- Production of PtL SAF in the UK
- Direct Air Capture of CO_2

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Energy Requirements to Achieve Net Zero Carbon (continued)

In Section 1.4, eligibility calculations were described which established for the future technology wedge what proportion of different aircraft categories from the baseline year could be upgraded to hydrogen aircraft. These calculations were used to establish the quantity of Jet A-1 fuel used on relevant flight activity in the baseline year. The results are listed in Table 19.

Aircraft Category	Jet A-1 Used on Hydrogen Regional Eligible Flights in 2019 (tonnes)	Jet A-1 Used on Hydrogen Narrow Body Eligible Flights in 2019 (tonnes)
Turboprops	134,600	N/A
Regional Jets	175,300	N/A
Narrow Body A	N/A	1,575,000
Narrow Body B	N/A	948,700
Large Narrow Body	N/A	44,800
Small Wide Body	N/A	N/A
Small Long Range Wide Body	N/A	N/A
Large Wide Body	N/A	N/A
Jumbo	N/A	N/A
Super Jumbo	N/A	N/A
Latest Wide Body	N/A	N/A

Table 19: Fuel used in the baseline year on aircraft activity eligible for upgrade to a hydrogen product.

These fuel estimates were increased annually in accordance with the aviation activity growth predicted in the Road-Map. Additionally, the fleet upgrade model described in Section 1.4, Generation 2 upgrades, provides the proportion of the activity upgraded to a hydrogen aircraft in each year, depending on the fleet refresh time assumed. Assuming an energy density for Jet A-1 of 43MJ/kg, the quantity of fuel energy used by aviation activity upgraded to hydrogen aircraft could be calculated. For simplicity, a broad generalisation is made by assuming that future hydrogen aircraft will utilise fuel energy with the same efficiency as conventional aircraft which they are upgraded from. Therefore the quantity of required hydrogen fuel is simply generated by assuming an energy density for hydrogen of 120MJ/kg.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Energy Requirements to Achieve Net Zero Carbon (continued)

The results are illustrated in Figure 20. This high level assessment indicates that UK aviation will require ~0.97Mt hydrogen fuel by 2050.

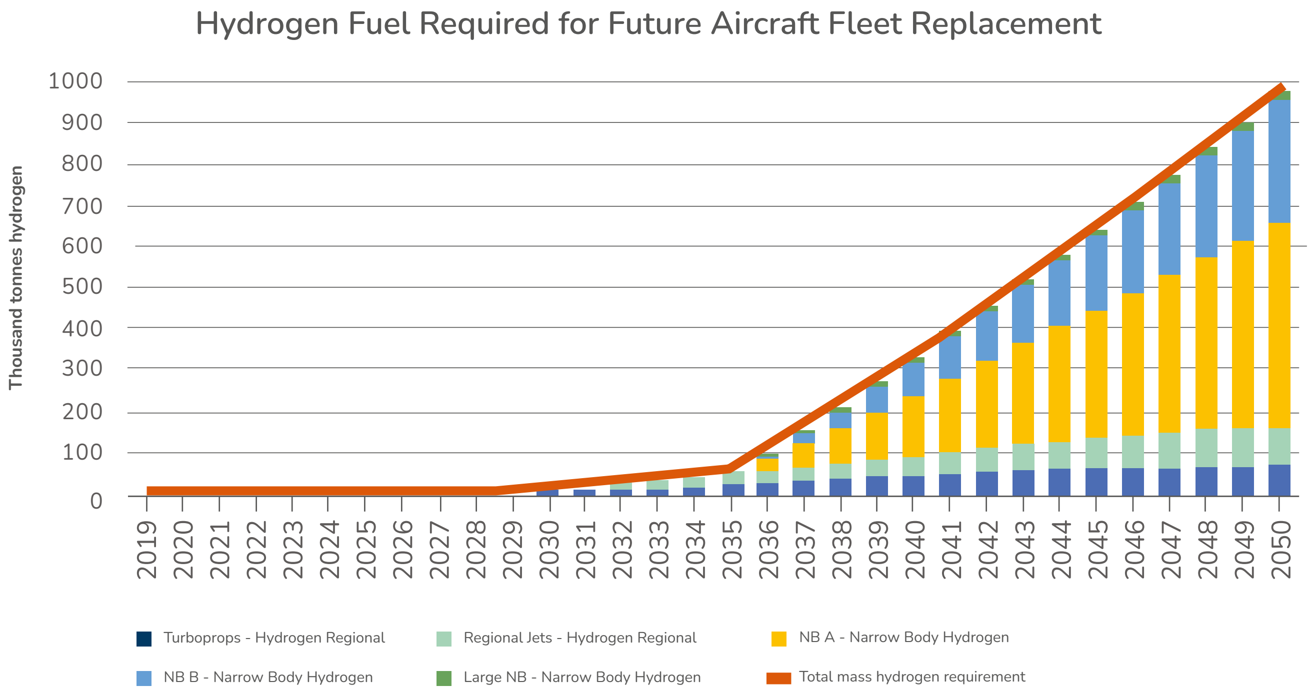


Figure 20: Hydrogen fuel required per year by different aircraft categories.

1. MODELLING METHODOLOGY AND ASSUMPTIONS

Energy Requirements to Achieve Net Zero Carbon (continued)

For simplicity, all of this aircraft activity is assumed to require liquid hydrogen, which is assumed to require 65MWh of energy to produce including the electrolysis and liquefaction. In 2050 ~63TWh of low carbon energy would be required to produce this fuel.

The independent ICF study advising SA on the SAF aspects of the Road-Map estimated ~50TWh of low carbon energy would be required in 2050 to deliver 1.9Mt of UK produced PtL SAF.

Since the purchased GGRs are assumed to be 100% delivered by DAC technology in 2050 and this is expected to be the most energy intensive method to achieve GGR, only the energy requirements to operate DAC plants are considered for this wedge. The Royal Society estimated 148TWh energy is required to remove 38Mt CO_2 with DAC technology[57]. Using this conversion rate it is estimated that in 2050 the aviation sector will require 34TWh of low carbon energy to utilise for operating DAC technology.

Figure 21 shows the total low carbon energy demands over the timeline.

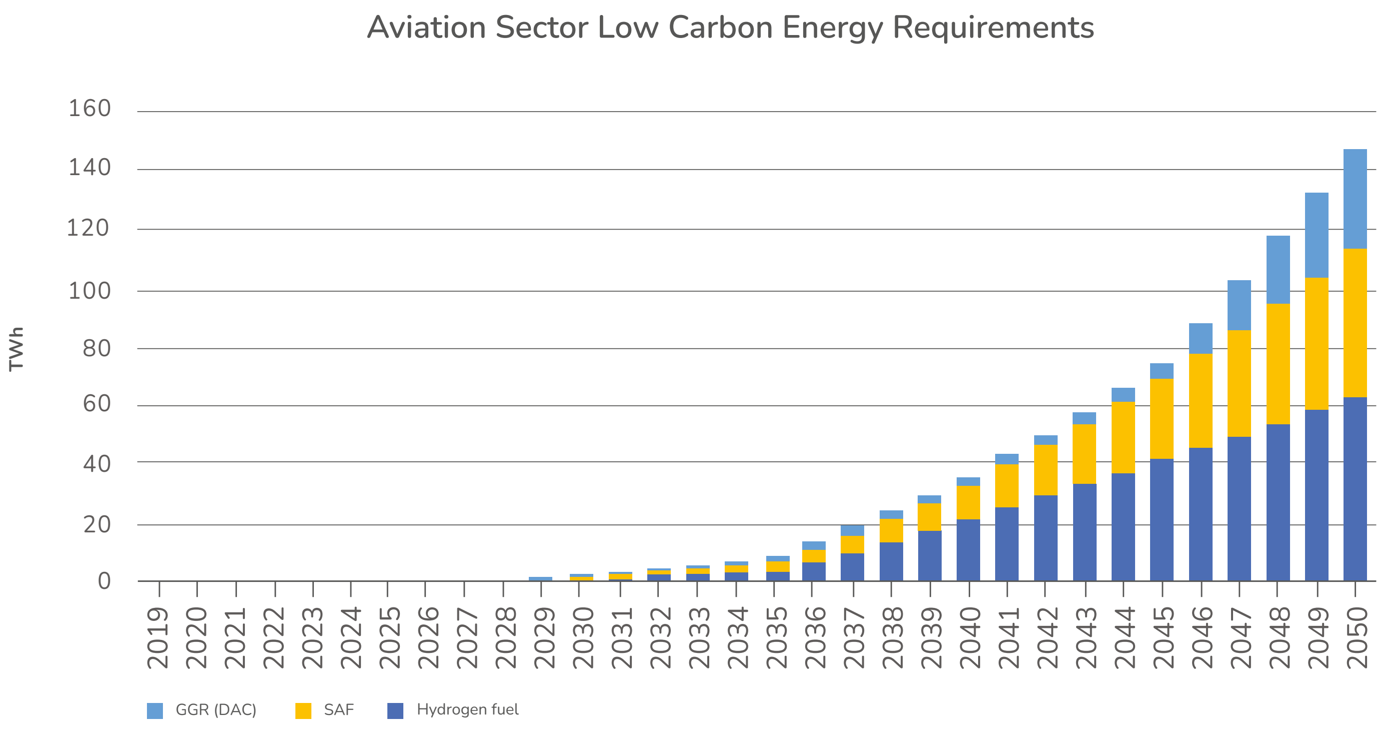
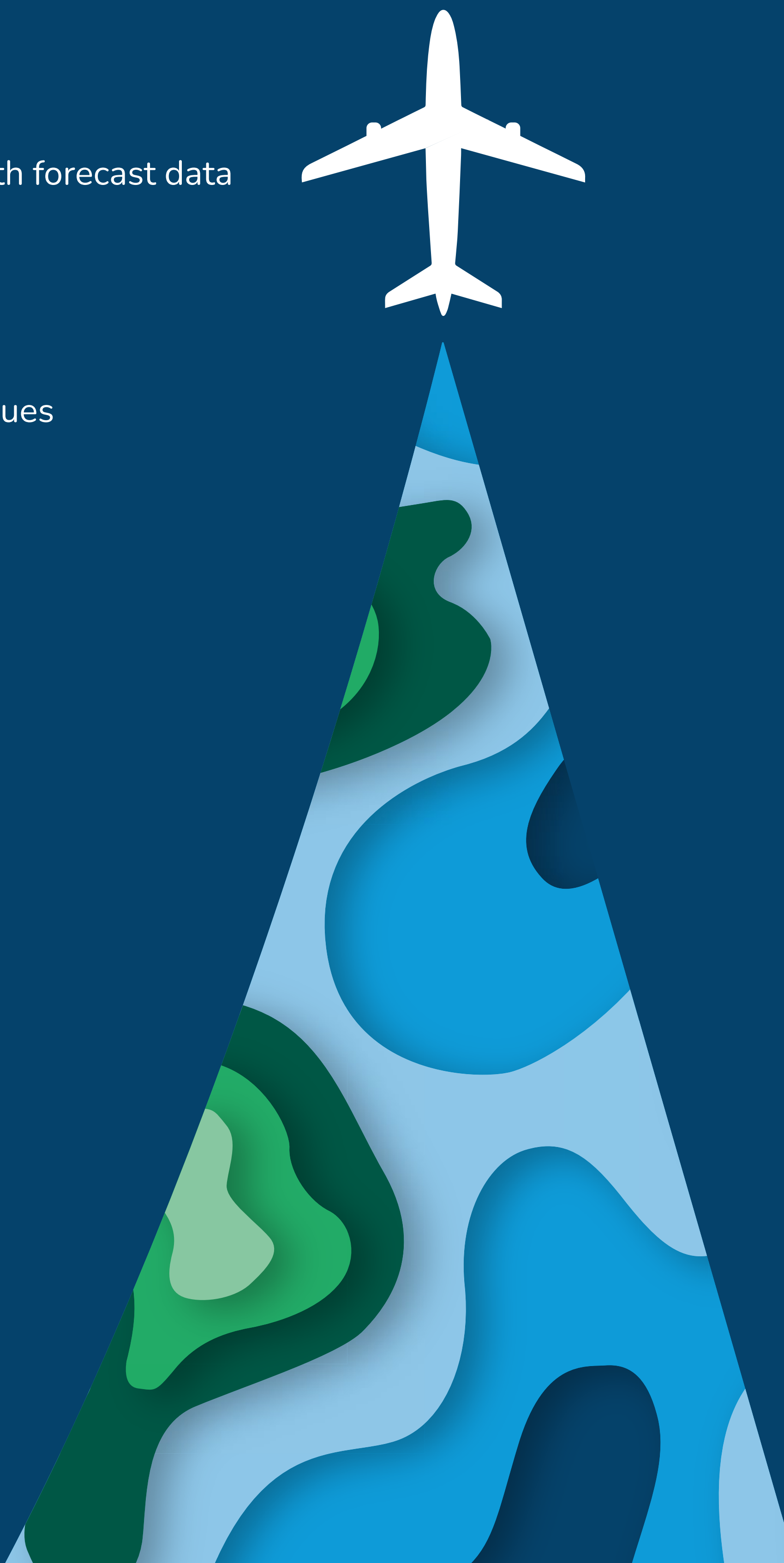


Figure 21: UK aviation demand for low carbon energy to deliver the net zero carbon strategy.

57 https://royalsociety.org/-/media/policy/projects/net-zero-aviation/net-zero-aviation-fuels-policy-briefing.pdf

2. APPENDICES



Appendix 1: DfT aviation activity growth forecast data

Appendix 2: SAF supply and costs

Appendix 3: GHG scaling and costs

Appendix 4: Carbon prices

Appendix 5: Road-map wedge CO_2 values

Appendix 6: Sector growth factors

Appendix 7: Model functional diagram

2. APPENDICES

Appendix 1: DfT Aviation Activity Growth Forecast Data

DfT aviation forecast data supplied to Sustainable Aviation.

Year	Pax km	Annual change in pax km (%)
2019	744,623,747,539	2.91
2020	701,067,179,779	-5.85
2021	730,332,384,811	4.17
2022	796,126,539,760	9.01
2023	803,301,139,652	0.90
2024	815,305,245,585	1.49
2025	828,221,244,543	1.58
2026	842,177,284,745	1.69
2027	856,658,838,451	1.72
2028	880,259,462,884	2.75
2029	902,329,218,994	2.51
2030	942,621,645,827	4.47
2031	948,099,960,593	0.58
2032	989,150,280,924	4.33
2033	1,004,878,891,368	1.59
2034	1,041,972,951,604	3.69
2035	1,063,778,895,448	2.09
2036	1,099,912,673,264	3.40
2037	1,131,717,892,619	2.89
2038	1,164,475,682,329	2.89
2039	1,197,653,353,466	2.85
2040	1,218,333,294,123	1.73
2041	1,254,554,804,332	2.97
2042	1,277,713,332,969	1.85

2. APPENDICES

Appendix 1: DfT Aviation Activity Growth Forecast Data (continued)

Year	Pax km	Annual change in pax km (%)
2043	1,304,637,410,020	2.11
2044	1,331,019,991,340	2.02
2045	1,353,386,578,055	1.68
2046	1,375,593,483,399	1.64
2047	1,394,410,146,683	1.37
2048	1,419,857,679,049	1.82
2049	1,435,238,072,458	1.08
2050	1,454,287,190,402	1.33

2. APPENDICES

Appendix 2: SAF Supply and Costs

Forecast supply of UK produced SAF, derived by an ICF independent study on the development of the UK SAF industry[58].

Year	HEFA/Co-processing		Waste Based		Power-to-liquid	
	Production (Mt)	Price ($/tonne)	Production (Mt)	Price ($/tonne)	Production (Mt)	Price ($/tonne)
2025	0.100	1,342	0.040	2,202	0.002	3,404
2026	0.100	1,337	0.040	2,171	0.004	3,282
2027	0.100	1,332	0.040	2,141	0.008	3,159
2028	0.100	1,327	0.100	2,110	0.013	3,037
2029	0.100	1,322	0.140	2,080	0.019	2,915
2030	0.100	1,317	0.296	2,050	0.028	2,792
2031	0.100	1,314	0.521	2,024	0.040	2,727
2032	0.100	1,310	0.828	1,998	0.055	2,661
2033	0.100	1,306	1.072	1,973	0.075	2,596
2034	0.100	1,302	1.240	1,947	0.099	2,530
2035	0.100	1,298	1.414	1,921	0.131	2,465
2036	0.100	1,294	1.585	1,896	0.170	2,399
2037	0.100	1,290	1.751	1,870	0.218	2,334
2038	0.100	1,268	1.909	1,845	0.276	2,268
2039	0.100	1,282	2.058	1,819	0.347	2,203
2040	0.100	1,278	2.198	1,793	0.430	2,137
2041	0.100	1,276	2.330	1,772	0.526	2,088
2042	0.100	1,274	2.452	1,750	0.637	2,039
2043	0.100	1,272	2.590	1,728	0.762	1,990
2044	0.100	1,270	2.710	1,706	0.899	1,941

58 https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/Sustainable-Aviation-SAF-Roadmap-Final.pdf

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Appendix 2: SAF Supply and Costs (continued)

Year	HEFA/Co-processing		Waste Based		Power-to-liquid	
	Production (Mt)	Price ($/tonne)	Production (Mt)	Price ($/tonne)	Production (Mt)	Price ($/tonne)
2045	0.100	1,267	2.830	1,685	1.049	1,892
2046	0.100	1,265	2.950	1,663	1.209	1,843
2047	0.100	1,263	3.070	1,641	1.376	1,794
2048	0.100	1,261	3.180	1,619	1.549	1,745
2049	0.100	1,259	3.280	1,598	1.724	1,696
2050	0.100	1,257	3.400	1,576	1.900	1,647

Assumed SAF mandate policy implementation and lifecycle CO_2 saving achieved.

Year	Mandated SAF Fuel Use (%)	Lifecycle CO_2 Saving (%)
2025	0.5	66
2026	2.5	67
2027	4.5	68
2028	6.5	68
2029	8	69
2030	10	70
2031	12	71
2032	14	72
2033	16	73
2034	18	74
2035	20	75
2036	22	76
2037	24	78
2038	26	79

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Appendix 2: SAF Supply and Costs (continued)

Year	Mandated SAF Fuel Use (%)	Lifecycle CO_2 Saving (%)
2039	28	80
2040	31	82
2041	34	83
2042	37	85
2043	41	87
2044	44	88
2045	49	90
2046	53	92
2047	58	94
2048	63	96
2049	69	98
2050	75	100

Estimated costs of imported SAF.

Year	US HEFA Cost ($/tonne)	US Waste Based ($/tonne)	US PtL ($/tonne)
2025	2,157	2,297	3,404
2026	2,149	2,289	3,282
2027	2,141	2,281	3,159
2028	2,133	2,273	3,037
2029	2,125	2,265	2,915
2030	2,117	2,257	2,792
2031	2,109	2,248	2,272
2032	2,101	2,240	2,661
2033	2,092	2,232	2,596

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Appendix 2: SAF Supply and Costs (continued)

Year	US HEFA Cost ($/tonne)	US Waste Based ($/tonne)	US PtL ($/tonne)
2034	2,084	2,224	2,530
2035	2,076	2,216	2,465
2036	2,068	2,208	2,399
2037	2,060	2,200	2,340
2038	2,052	2,192	2,332
2039	2,044	2,184	2,324
2040	2,036	2,176	2,315
2041	2,036	2,176	2,315
2042	2,036	2,176	2,315
2043	2,036	2,176	2,315
2044	2,036	2,176	2,315
2045	2,036	2,176	2,315
2046	2,036	2,176	2,315
2047	2,036	2,176	2,315
2048	2,036	2,176	2,315
2049	2,036	2,176	2,315
2050	2,036	2,176	2,315

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Appendix 3: GHG Scaling and Costs

Forecast supply of UK delivered GHG removals, derived by averaging estimates (where available) sourced as detailed in Section 1.6 UK GGR supply and cost forecasts.

Year	GHG Removal Type								
	DACCS Supply (tonnes CO_2)			BECCS Supply (tonnes CO_2)			Construction Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2024	0	71,429	185,714	132,943	342,857	467,229	28,571	57,143	85,714
2025	0	142,857	371,429	265,886	685,714	934,457	57,143	114,286	171,429
2026	0	214,286	557,143	398,829	1,028,571	1,401,686	85,714	171,429	257,143
2027	0	285,714	742,857	531,771	1,371,429	2,224,095	114,286	228,571	342,857
2028	0	357,143	928,571	664,714	1,714,286	2,336,143	142,857	285,714	428,571
2029	0	428,571	1,114,286	797,657	2,057,143	2,803,371	171,429	342,857	514,286
2030	0	500,000	1,300,000	930,600	2,400,000	4,725,500	200,000	400,000	600,000
2031	0	1,375,000	2,735,000	1,369,580	2,992,500	4,260,640	235,000	455,000	710,000
2032	0	2,250,000	4,170,000	1,808,560	3,585,000	5,250,680	270,000	510,000	820,000
2033	0	3,125,000	5,605,000	2,247,540	4,177,500	6,240,720	305,000	565,000	930,000
2034	0	4,000,000	7,040,000	2,686,520	4,770,000	7,230,760	340,000	620,000	1,040,000
2035	0	4,875,000	8,475,000	3,125,500	5,362,500	8,220,800	375,000	675,000	1,150,000
2036	0	5,750,000	9,910,000	3,564,480	5,955,000	9,210,840	410,000	730,000	1,260,000
2037	0	6,625,000	11,345,000	4,003,460	6,547,500	10,200,880	445,000	785,000	1,370,000
2038	0	7,500,000	12,780,000	4,442,440	7,140,000	11,190,920	480,000	840,000	1,480,000
2039	0	8,375,000	14,215,000	4,881,420	7,732,500	12,180,960	515,000	895,000	1,590,000
2040	0	6,875,000	12,825,000	5,320,400	8,325,000	13,171,000	550,000	950,000	1,700,000
2041	0	10,125,000	17,085,000	6,392,520	8,917,500	15,095,740	585,000	1,005,000	1,810,000
2042	0	11,000,000	18,520,000	7,464,640	9,510,000	17,020,480	620,000	1,060,000	1,920,000
2043	0	11,875,000	19,955,000	8,536,760	10,102,500	18,945,220	655,000	1,115,000	2,030,000
2044	0	12,750,000	21,390,000	9,608,880	10,695,000	20,869,960	690,000	1,170,000	2,140,000

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type								
	DACCS Supply (tonnes CO_2)			BECCS Supply (tonnes CO_2)			Construction Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2045	0	13,625,000	22,825,000	10,681,000	11,287,500	22,794,700	725,000	1,225,000	2,250,000
2046	0	14,500,000	24,260,000	11,753,120	11,880,000	24,719,440	760,000	1,280,000	2,360,000
2047	0	15,375,000	25,695,000	12,825,240	12,472,500	26,644,180	795,000	1,335,000	2,470,000
2048	0	16,250,000	27,130,000	13,897,360	13,065,000	28,568,920	830,000	1,390,000	2,580,000
2049	0	17,125,000	28,565,000	14,969,480	13,657,500	30,493,660	865,000	1,445,000	2,690,000
2050	0	16,000,000	30,000,000	16,041,600	26,416,667	32,418,400	900,000	1,300,000	2,800,000

Year	GHG Removal Type								
	Afforestation Supply (tonnes CO_2)			Habitat Restoration Supply (tonnes CO_2)			Soil Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2024	428,571	532,857	714,286	0	32,143	128,571	0	437,143	1,714,286
2025	857,143	1,065,714	1,428,571	0	64,286	257,143	0	874,286	3,428,571
2026	1,285,714	1,598,571	2,142,857	0	96,429	385,714	0	1,311,429	5,142,857
2027	1,714,286	2,131,429	2,857,143	0	128,571	514,286	0	1,748,571	6,857,143
2028	2,142,857	2,664,286	3,571,429	0	160,714	642,857	0	2,185,714	8,571,429
2029	2,571,429	3,197,143	4,285,714	0	192,857	771,429	0	2,622,857	10,285,714
2030	3,000,000	3,730,000	5,000,000	0	225,000	900,000	0	3,060,000	12,000,000
2031	3,650,000	4,473,500	5,950,000	0	248,500	995,000	0	3,097,000	12,150,000
2032	4,300,000	5,217,000	6,900,000	0	272,000	1,090,000	0	3,134,000	12,300,000
2033	4,950,000	5,960,500	7,850,000	0	295,500	1,185,000	0	3,171,000	12,450,000
2034	5,600,000	6,704,000	8,800,000	0	319,000	1,280,000	0	3,208,000	12,600,000

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type								
	Afforestation Supply (tonnes CO_2)			Habitat Restoration Supply (tonnes CO_2)			Soil Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2035	6,250,000	7,447,500	9,750,000	0	342,500	1,375,500	0	3,245,000	12,750,000
2036	6,900,000	8,191,000	10,700,000	0	366,000	1,470,000	0	3,282,000	12,900,000
2037	7,550,000	8,934,500	11,650,000	0	389,500	1,565,000	0	3,319,000	13,050,000
2038	8,200,000	9,678,000	12,600,000	0	413,000	1,660,000	0	3,356,000	13,200,000
2039	8,850,000	10,421,500	13,550,000	0	436,500	1,755,000	0	3,393,000	13,350,000
2040	9,500,000	11,165,000	14,500,000	0	460,000	1,850,000	0	3,430,000	13,500,000
2041	10,150,000	11,908,500	15,450,000	0	483,500	1,945,000	0	3,467,000	13,650,000
2042	10,800,000	12,652,000	16,400,000	0	507,000	2,040,000	0	3,504,000	13,800,000
2043	11,450,000	13,395,500	17,350,000	0	530,500	2,135,000	0	3,541,000	13,950,000
2044	12,100,000	14,139,000	18,300,000	0	554,000	2,230,000	0	3,578,000	14,100,000
2045	12,750,000	14,882,500	19,250,000	0	577,500	2,325,000	0	3,615,000	14,250,000
2046	13,400,000	15,626,000	20,200,000	0	601,000	2,420,000	0	3,652,000	14,400,000
2047	14,050,000	16,369,500	21,150,000	0	624,500	2,515,000	0	3,689,000	14,550,000
2048	14,700,000	17,113,000	22,100,000	0	648,000	2,610,000	0	3,726,000	14,700,000
2049	15,350,000	17,856,500	23,050,000	0	671,500	2,705,000	0	3,763,000	14,850,000
2050	16,000,000	16,800,000	24,000,000	0	2,130,000	2,800,000	0	6,900,000	15,000,000

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type					
	Enhanced Weathering Supply (tonnes CO_2)			Biochar Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High
2024	0	42,857	171,429	0	48,571	157,143
2025	0	85,714	342,857	0	97,143	314,286
2026	0	128,571	514,286	0	145,714	471,429
2027	0	171,429	685,714	0	194,286	628,571
2028	0	214,286	857,143	0	242,857	785,714
2029	0	257,143	1,028,571	0	291,429	942,857
2030	0	300,000	1,200,000	0	340,000	1,100,000
2031	0	508,000	2,040,000	0	562,000	1,795,000
2032	0	716,000	2,880,000	0	784,000	2,490,000
2033	0	924,000	3,720,000	0	1,006,000	3,185,000
2034	0	1,132,000	4,560,000	0	1,228,000	3,880,000
2035	0	1,340,000	5,400,000	0	1,450,000	4,575,000
2036	0	1,548,000	6,240,000	0	1,672,000	5,270,000
2037	0	1,756,000	7,080,000	0	1,894,000	5,965,000
2038	0	1,964,000	7,920,000	0	2,116,000	6,660,000
2039	0	2,172,000	8,760,000	0	2,338,000	7,355,000
2040	0	2,380,000	9,600,000	0	2,560,000	8,050,000
2041	0	2,588,000	10,440,000	0	2,782,000	8,745,000
2042	0	2,796,000	11,280,000	0	3,004,000	9,440,000
2043	0	3,004,000	12,120,000	0	3,226,000	10,135,000
2044	0	3,212,000	12,960,000	0	3,448,000	10,830,000
2045	0	3,420,000	13,800,000	0	3,670,000	11,525,000

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type					
	Enhanced Weathering Supply (tonnes CO_2)			Biochar Supply (tonnes CO_2)		
	Low	Mid	High	Low	Mid	High
2046	0	3,628,000	14,640,000	0	3,892,000	12,220,000
2047	0	3,836,000	15,480,000	0	4,114,000	12,915,000
2048	0	4,044,000	16,320,000	0	4,336,000	13,610,000
2049	0	4,252,000	17,160,000	0	4,558,000	14,305,000
2050	0	4,460,000	18,000,000	0	4,890,000	15,000,000

Total UK produced GHG removals estimated in Low, Medium and High scenarios, alongside the derived "fair share" for the aviation sector, as detailed in UK GGR supply and core forecasts.

Year	Total UK Supplied GHG Removals			Aviation 'Fair Share'			
	Low Scenario (Mt CO_2)	Mid Scenario (Mt CO_2)	High Scenario (Mt CO_2)	(%)	Low Scenario (Mt CO_2)	Mid Scenario (Mt CO_2)	High Scenario (Mt CO_2)
2024	0.59	1.57	3.62	8	0.14	0.38	0.88
2025	1.18	3.13	7.25	8	0.29	0.76	1.77
2026	1.77	4.70	10.87	8	0.43	1.15	2.65
2027	2.36	6.26	14.85	9	0.58	1.53	3.62
2028	2.95	7.83	18.12	9	0.72	1.91	4.42
2029	3.54	9.39	21.75	9	0.86	2.29	5.30
2030	4.13	10.96	26.83	9.7	1.01	2.67	6.54
2031	5.25	13.71	30.64	10	1.28	3.34	7.47
2032	6.38	16.47	35.90	11	1.56	4.02	8.76
2033	7.50	19.22	41.17	11	1.83	4.69	10.04
2034	8.63	21.98	46.43	12	2.10	5.36	11.33
2035	9.75	24.74	51.70	13	2.38	6.03	12.61

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Appendix 3: GHG Scaling and Costs (continued)

Year	Total UK Supplied GHG Removals			Aviation 'Fair Share'			
	Low Scenario (Mt CO_2)	Mid Scenario (Mt CO_2)	High Scenario (Mt CO_2)	(%)	Low Scenario (Mt CO_2)	Mid Scenario (Mt CO_2)	High Scenario (Mt CO_2)
2036	10.87	27.49	56.96	14	2.65	6.71	13.89
2037	12.00	30.25	62.23	15	2.93	7.38	15.18
2038	13.12	33.01	67.49	15	3.20	8.05	16.46
2039	14.25	35.76	72.76	16	3.48	8.72	17.75
2040	15.37	36.15	75.20	17	3.75	8.82	18.34
2041	17.13	41.28	84.22	18	4.18	10.07	20.54
2042	18.88	44.03	90.42	19	4.61	10.74	22.06
2043	20.64	46.79	96.62	20	5.04	11.41	23.57
2044	22.40	49.55	102.82	21	5.46	12.09	25.08
2045	24.16	52.30	109.02	22	5.89	12.76	26.59
2046	25.91	55.06	115.22	23	6.32	13.43	28.11
2047	27.67	57.82	121.42	24	6.75	14.10	29.62
2048	29.43	60.57	127.62	24	7.18	14.78	31.13
2049	31.18	63.33	133.82	24	7.61	15.45	32.64
2050	32.94	78.90	140.02	24.4	8.04	19.25	34.16

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Appendix 3: GHG Scaling and Costs (continued)

Estimated cost of UK delivered GHG removals, derived by averaging estimates (where available) sourced as detailed in UK GGR supply and cost forecasts.

Year	GHG Removal Type								
	DACCS Cost (£/tonne CO_2)			BECCS Cost (£/tonne CO_2)			Construction Cost (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2024	210.35	-	463.49	60.11	-	260.68	-	-	-
2025	205.95	400.00	453.17	59.56	-	259.69	-	-	-
2026	201.56	387.33	442.86	59.00	-	258.70	-	-	-
2027	197.16	374.67	432.55	58.44	-	257.72	-	-	-
2028	192.76	362.00	422.23	57.89	-	256.73	-	-	-
2029	188.36	349.33	411.92	57.33	-	255.74	-	-	-
2030	177.17	318.33	451.34	57.19	87.50	206.32	-	-	-
2031	172.85	307.75	438.99	56.38	86.88	205.90	-	-	-
2032	168.53	297.17	426.65	55.57	86.25	205.48	-	-	-
2033	164.21	286.58	414.31	54.76	85.63	205.05	-	-	-
2034	159.90	276.00	401.96	53.95	85.00	204.63	-	-	-
2035	155.58	265.42	389.62	53.14	84.38	204.21	-	-	-
2036	151.26	254.83	377.27	52.33	83.75	203.78	-	-	-
2037	146.94	244.25	364.93	51.52	83.13	203.36	-	-	-
2038	142.62	233.67	352.58	50.71	82.50	202.94	-	-	-
2039	138.30	223.08	340.24	49.90	81.88	202.51	-	-	-
2040	133.99	212.50	327.90	49.10	81.25	202.09	-	-	-
2041	129.67	206.75	365.97	48.29	80.63	201.67	-	-	-
2042	125.35	201.00	355.06	47.48	80.00	201.24	-	-	-
2043	121.03	195.25	344.15	46.67	79.38	200.82	-	-	-
2044	116.71	189.50	333.24	45.86	78.75	200.40	-	-	-

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type								
	DACCS Cost (£/tonne CO_2)			BECCS Cost (£/tonne CO_2)			Construction Cost (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2045	112.39	183.75	322.34	45.05	78.13	199.97	-	-	-
2046	108.07	178.00	311.43	44.24	77.50	199.55	-	-	-
2047	103.76	172.25	300.52	43.43	76.88	199.13	-	-	-
2048	99.44	166.50	289.61	42.62	76.25	198.70	-	-	-
2049	95.12	160.75	278.71	41.81	75.63	198.28	-	-	-
2050	90.80	155.00	267.80	41.00	75.00	197.86	-	-	-

Year	GHG Removal Type								
	Afforestation Supply (£/tonne CO_2)			Habitat Restoration Supply (£/tonne CO_2)			Soil Supply (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2024	-	-	110.50	-	-	78.00	20.50	-	51.50
2025	-	-	110.50	-	-	78.00	20.50	-	51.50
2026	-	-	110.50	-	-	78.00	20.50	-	51.50
2027	-	-	110.50	-	-	78.00	20.50	-	51.50
2028	-	-	110.50	-	-	78.00	20.50	-	51.50
2029	-	-	110.50	-	-	78.00	20.50	-	51.50
2030	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2031	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2032	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2033	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2034	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00

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Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type								
	Afforestation Supply (£/tonne CO_2)			Habitat Restoration Supply (£/tonne CO_2)			Soil Supply (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
2035	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2036	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2037	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2038	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2039	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2040	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2041	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2042	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2043	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2044	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2045	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2046	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2047	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2048	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2049	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00
2050	-	12.50	81.33	-	28.75	53.67	15.00	12.00	41.00

2. APPENDICES

Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type					
	Enhanced Weathering Supply (£/tonne CO_2)			Biochar Supply (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High
2024	29.50	-	433.50	-	-	207.50
2025	29.50	-	433.50	-	-	207.50
2026	29.50	-	433.50	-	-	207.50
2027	29.50	-	433.50	-	-	207.50
2028	29.50	-	433.50	-	-	207.50
2029	29.50	-	433.50	-	-	207.50
2030	69.67	300.00	589.00	-	72.00	181.67
2031	69.57	299.40	588.42	-	72.00	181.67
2032	69.47	298.80	587.83	-	72.00	181.67
2033	69.37	298.20	587.25	-	72.00	181.67
2034	69.27	297.60	586.67	-	72.00	181.67
2035	69.17	297.00	586.08	-	72.00	181.67
2036	69.07	296.40	585.50	-	72.00	181.67
2037	68.97	295.80	584.92	-	72.00	181.67
2038	68.87	295.20	584.33	-	72.00	181.67
2039	68.77	294.60	583.75	-	72.00	181.67
2040	68.67	294.00	583.17	-	72.00	181.67
2041	68.57	293.40	582.58	-	72.00	181.67
2042	68.47	292.80	582.00	-	72.00	181.67
2043	68.37	292.20	581.42	-	72.00	181.67
2044	68.27	291.60	580.83	-	72.00	181.67
2045	68.17	291.00	580.25	-	72.00	181.67

2. APPENDICES

Appendix 3: GHG Scaling and Costs (continued)

Year	GHG Removal Type					
	Enhanced Weathering Supply (£/tonne CO_2)			Biochar Supply (£/tonne CO_2)		
	Low	Mid	High	Low	Mid	High
2046	68.07	290.40	579.67	-	72.00	181.67
2047	67.97	289.80	579.08	-	72.00	181.67
2048	67.87	289.20	578.50	-	72.00	181.67
2049	67.77	288.60	577.92	-	72.00	181.67
2050	67.67	288.00	577.33	-	72.00	181.67

59 https://www.nationalgrideso.com/future-energy/future-energy-scenarios/documents

2. APPENDICES

Appendix 4: Carbon Prices

UK carbon prices estimated in the National Grid's Future Energy Scenarios 2022 data workbook[59]. Data derived by SA for use in the Road-Map model is indicated in *italics*.

Year	Low case (€/tonne)	Base case (€/tonne)	High case (€/tonne)	*High case (£/tonne converted)*
2021	71.54	71.54	71.54	*63.67*
2022	76.34	88.91	101.49	*90.32*
2023	76.71	89.31	104.47	*92.98*
2024	77.09	89.72	107.47	*95.65*
2025	77.49	90.15	110.49	*98.33*
2026	77.91	90.61	113.53	*101.05*
2027	78.34	91.07	116.58	*103.76*
2028	78.77	91.53	119.63	*106.47*
2029	79.20	91.99	122.68	*109.18*
2030	79.63	92.44	125.73	*111.90*
2031	82.63	95.70	128.89	*114.72*
2032	85.63	98.95	132.06	*117.54*
2033	88.63	102.20	135.23	*120.35*
2034	91.63	105.46	138.40	*123.17*
2035	94.63	108.71	141.57	*125.99*
2036	97.63	111.96	144.73	*128.81*
2037	100.63	115.21	147.90	*131.63*
2038	103.63	118.47	151.07	*134.45*
2039	106.63	121.72	154.24	*137.27*
2040	109.63	124.97	157.41	*140.09*
2041	111.57	129.09	160.58	*142.91*
2042	113.50	133.22	163.74	*145.73*

59 https://www.nationalgrideso.com/future-energy/future-energy-scenarios/documents

2. APPENDICES

Appendix 4: Carbon Prices (continued)

Year	Low case (€/tonne)	Base case (€/tonne)	High case (€/tonne)	*High case (£/tonne converted)*
2043	115.44	137.34	166.91	*148.55*
2044	117.38	141.47	170.08	*151.37*
2045	119.31	145.59	173.25	*154.19*
2046	121.25	149.71	176.42	*157.01*
2047	123.19	153.84	179.59	*159.83*
2048	125.12	157.96	182.75	*162.65*
2049	127.06	162.09	185.92	*165.47*
2050	128.99	166.21	189.09	*168.29*

2. APPENDICES

Appendix 5: Road-Map Wedge CO_2 Values

The following table lists the values of CO_2 emissions corresponding with the major wedges of the Net Zero Carbon Road-Map Chart. All values are in units of Mt CO_2.

Year	Activity Growth	Activity Reduction due to Costs	Improved Operations/ ATM	Fleet Upgrades (known aircraft types)	Fleet Upgrades (known aircraft types)	SAF	GGR	ETS and CORSIA Purchased	Future Obligation Scheme	Net Residual Emissions
2019	37.82	37.82	37.82	37.82	37.82	37.82	37.82	30.09		30.09
2020	14.89	14.89	14.89	14.43	14.43	14.43	14.43	14.43		14.43
2021	13.64	13.64	13.63	13.08	13.08	13.08	13.08	13.08		13.08
2022	32.53	31.78	31.72	30.12	30.12	30.12	30.12	24.74		24.74
2023	36.31	35.40	35.30	33.18	33.18	33.18	33.18	26.60		26.60
2024	37.82	36.54	36.38	33.84	33.84	33.84	33.72	25.53		25.53
2025	38.42	36.77	36.56	33.64	33.64	33.34	33.10	24.33		24.33
2026	39.07	36.98	36.71	33.43	33.43	32.87	32.48	23.26		23.26
2027	39.74	37.03	36.70	33.05	33.05	32.05	31.51	21.47		21.47
2028	40.84	37.68	37.29	33.26	33.26	31.78	31.09	20.72		20.72
2029	41.86	38.35	37.89	33.47	33.42	31.57	30.71	20.08		20.08
2030	43.73	39.87	39.33	34.40	34.29	31.89	30.83	20.00		20.00
2031	43.98	39.83	39.24	34.00	33.84	30.96	29.58	19.13		19.13
2032	45.89	41.37	40.69	34.94	34.71	31.22	29.47	19.19		19.19
2033	46.62	42.00	41.25	35.09	34.81	30.75	28.60	19.65		19.65
2034	48.34	43.38	42.53	35.84	35.50	30.78	28.19	19.66		19.66
2035	49.35	44.16	43.22	36.08	35.69	30.32	27.19	19.42		19.42
2036	51.03	45.58	44.54	37.02	36.21	30.12	26.67	26.58	18.12	18.12
2037	52.50	46.57	45.44	37.71	36.46	29.66	25.89		16.83	16.83
2038	54.02	47.60	46.37	38.47	36.77	29.22	25.13		15.53	15.53
2039	55.56	48.65	47.33	39.25	37.08	28.73	24.35		14.24	14.24
2040	56.52	49.18	47.76	39.60	36.97	27.59	23.20		12.94	12.94

2. APPENDICES

Appendix 5: Road-Map Wedge CO_2 Values (continued)

Year	Activity Growth	Activity Reduction due to Costs	Improved Operations/ ATM	Fleet Upgrades (known aircraft types)	Fleet Upgrades (known aircraft types)	SAF	GGR	ETS and CORSIA Purchased	Future Obligation Scheme	Net Residual Emissions
2041	58.20	50.33	48.80	40.45	37.07	26.56	21.59		11.65	11.65
2042	59.27	51.07	49.44	40.97	36.84	25.25	20.00		10.36	10.36
2043	60.52	51.91	50.18	41.57	36.66	23.64	18.12		9.06	9.06
2044	61.75	52.89	51.04	42.27	36.58	22.36	16.58		7.77	7.77
2045	62.78	53.61	51.66	42.79	36.33	20.28	14.24		6.47	6.47
2046	63.81	54.31	52.25	43.28	36.03	18.47	11.87		5.18	5.18
2047	64.69	54.95	52.78	43.72	35.68	16.25	9.10		3.88	3.88
2048	65.87	55.98	53.69	44.46	35.56	14.08	6.39		2.59	2.59
2049	66.58	56.74	54.33	45.00	35.28	11.45	3.20		1.29	1.29
2050	67.46	57.84	55.30	45.80	35.19	8.80	0.00		0.00	0.00

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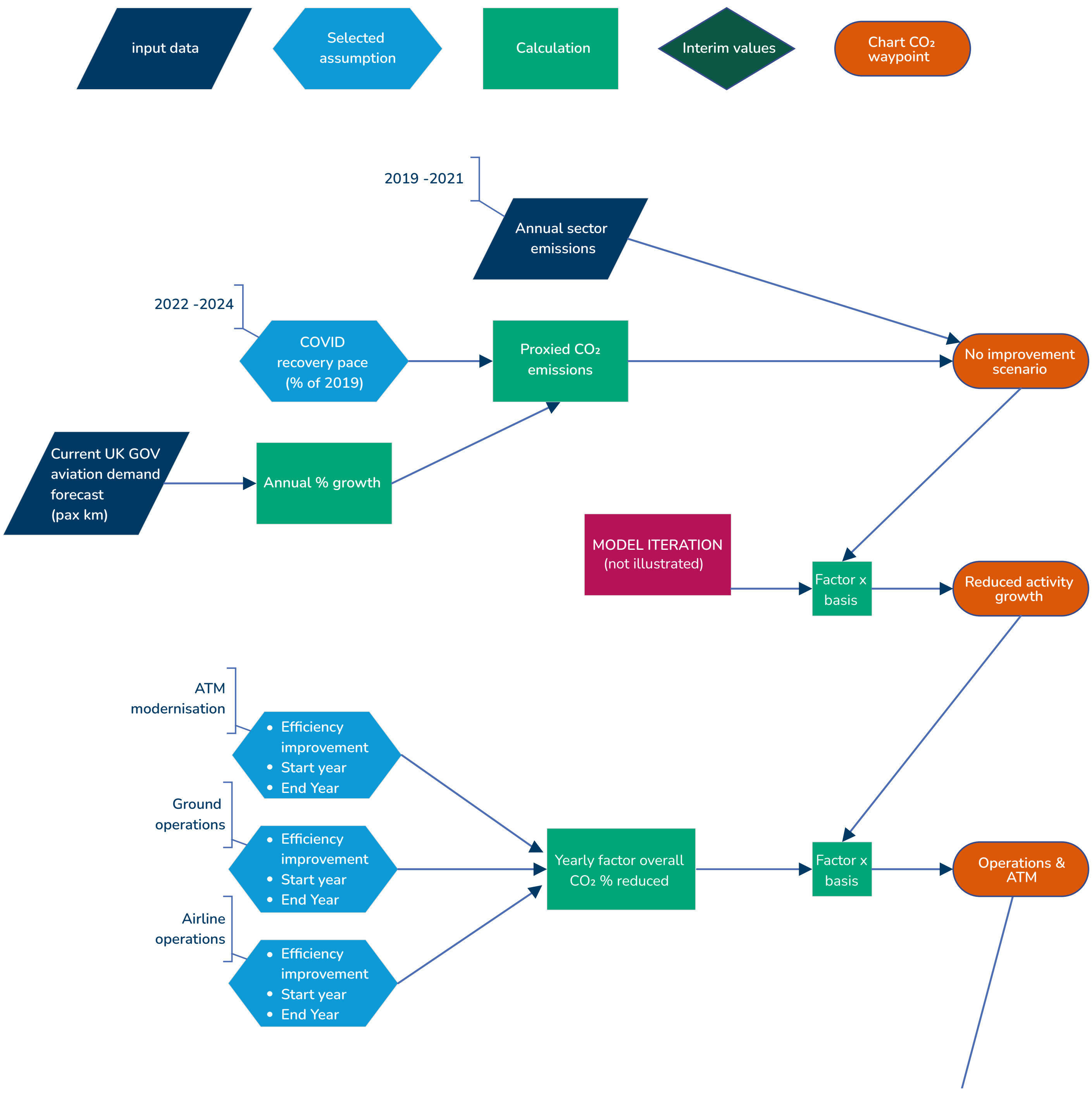
Appendix 6: Sector growth factors

CORSIA sector growth forecasts – September 2022.

Year	IATA Passenger Upside-growth Forecast	IATA Passenger Mid-growth Forecast
2021	0.00%	0.00%
2022	0.00%	0.00%
2023	0.00%	0.00%
2024	16.84%	7.49%
2025	21.02%	12.68%
2026	23.71%	17.13%
2027	26.76%	20.72%
2028	29.77%	23.88%
2029	32.37%	26.47%
2030	34.52%	28.59%
2031	36.45%	30.49%
2032	38.12%	32.10%
2033	39.59%	33.50%
2034	40.92%	34.75%
2035	42.14%	35.87%

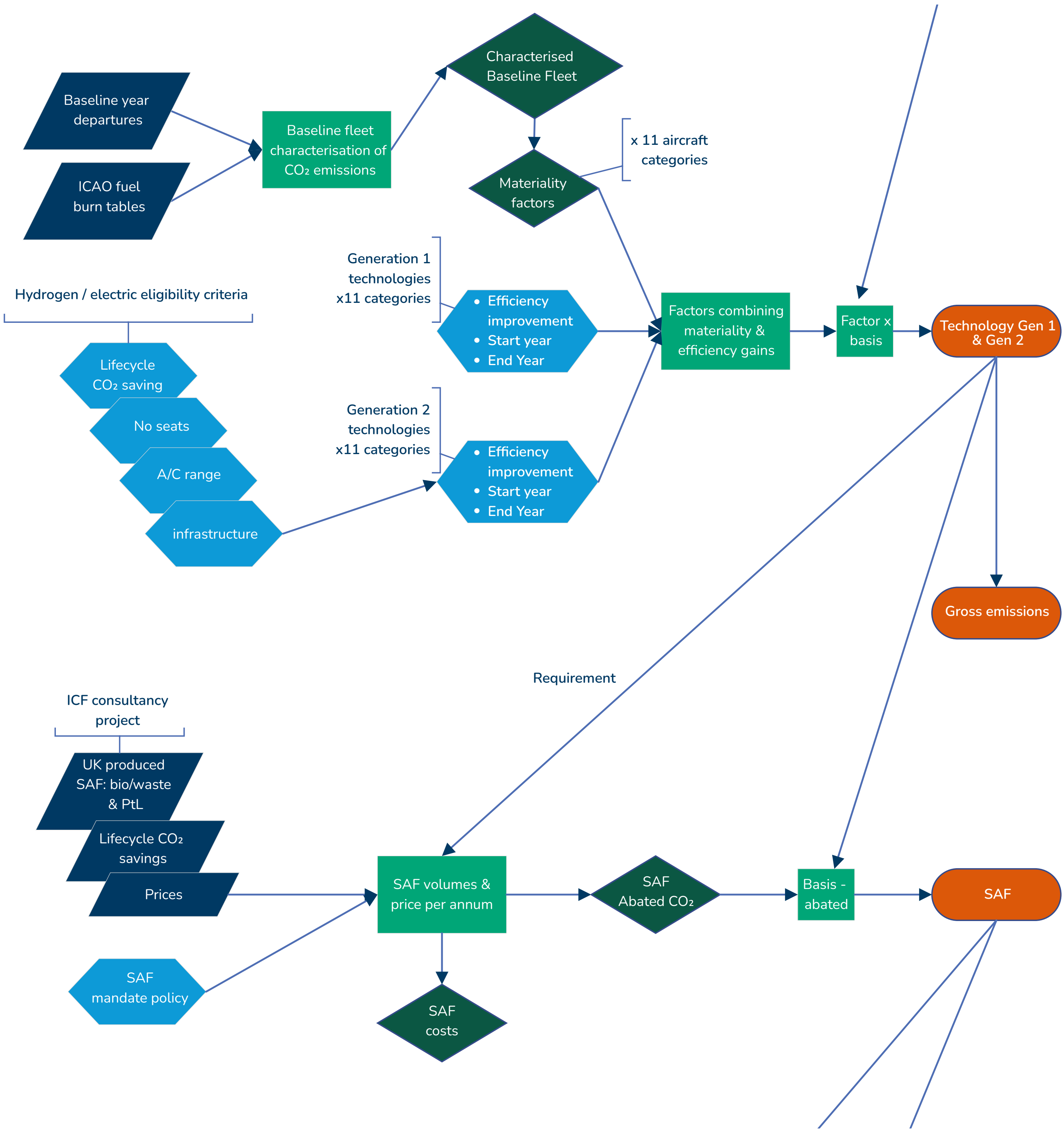
2. APPENDICES

Appendix 7: Model functional diagram



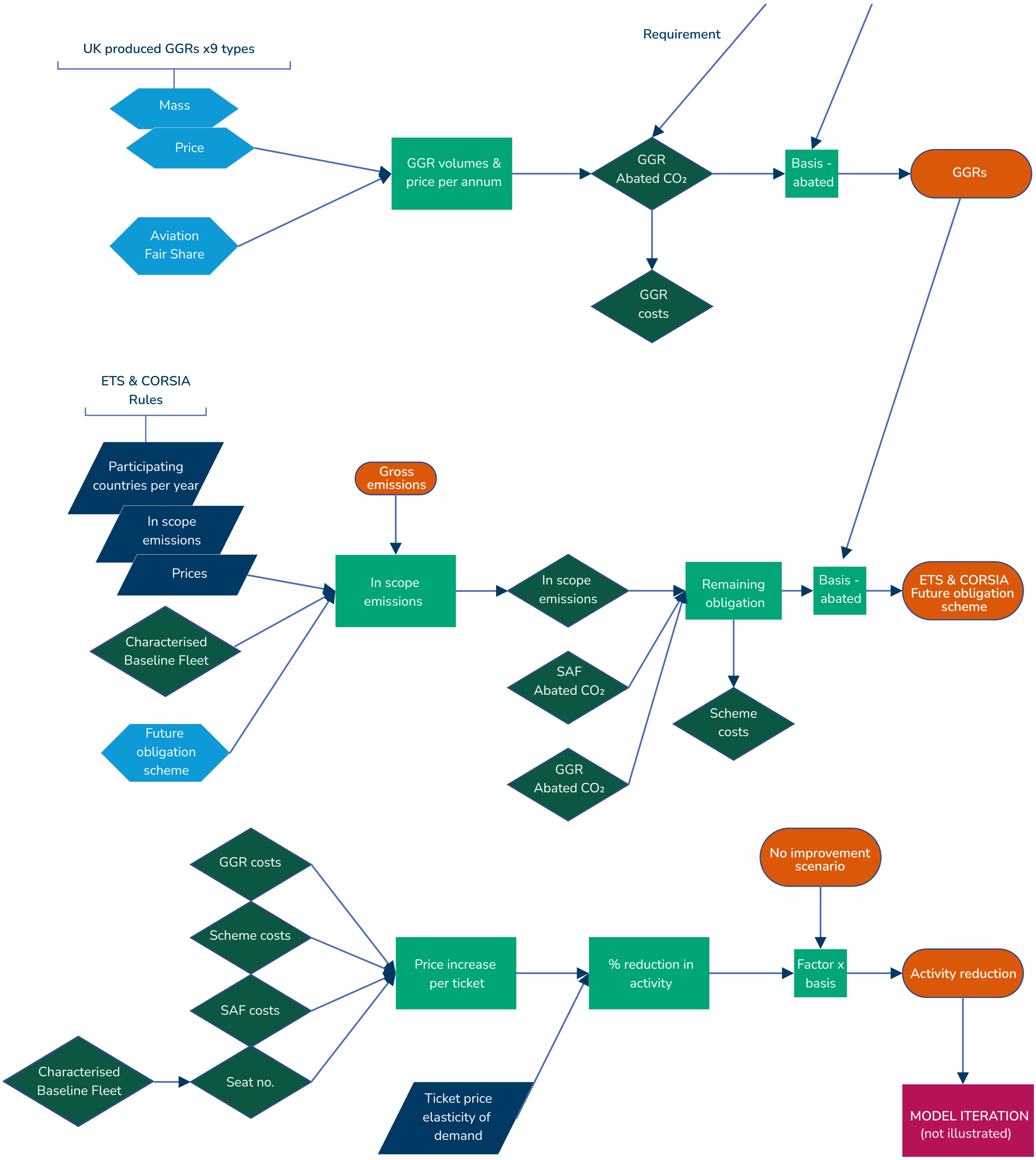
2. APPENDICES

Appendix 7: Model functional diagram (continued)



2. APPENDICES

Appendix 7: Model functional diagram (continued)



3. ABBREVIATIONS

A/C	Aircraft
ASKs	Available Seat Kilometres
ATI	Aerospace Technology Institute
ATM	Air Traffic Management
ATMs	Air Traffic Movements
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Climate Change Committee
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DESNZ	Department for Energy Security and Net Zero
DfT	Department for Transport
ETS	Emissions Trading Scheme
EIS	Entry Into Service
GGRs	Greenhouse Gas Removals
GHG	Greenhouse Gas
HEFA	Hydrotreated Esters and Fatty Acids
ICAO	International Civil Aviation Organization
IATA	International Air Transport Association
km	Kilometres
LTAG	Long Term Aspirational Goal
LULUCF	Land Use, Land-Use Change and Forestry
$MtCO_2$	Million tonnes carbon dioxide
NB	Narrow Body
Pax km	Passenger kilometres
PtL	Power to Liquid (SAF type)
SA	Sustainable Aviation
SAF	Sustainable Aviation Fuel
TWh	Terrawatt hours

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