UK NET ZERO DOMESTIC FLIGHTS STUDY

Final Report

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EXECUTIVE SUMMARY

This study analyses existing technological options, their potential barriers and policy interventions deemed necessary to support the achievement of net zero UK domestic aviation by 2040.

As defined in the Department for Transport's Jet Zero Strategy, net-zero is achieved when total greenhouse gas emissions are equal to or less than the emissions removed from the environment. This can be achieved by a combination of emission reduction and emission removal. **The technological intervention options reviewed within the report** therefore include **sustainable aviation fuels (SAF), zero emission flight (ZEF) technologies and greenhouse gas removals (GGR).**

1. Sustainable Aviation Fuels

At present, SAFs are expected to become the favoured solution for short-to-medium term decarbonisation of the aviation sector as a whole and will be fundamental to the decarbonisation of UK domestic aviation by 2040. While some SAF technologies, such as Hydroprocessed Esters and Fatty Acids (HEFA), are commercially available today, for the full benefit of SAFs to be realised the development of synthetic kerosene (manufactured from captured carbon and hydrogen produced from renewable electricity) to commercial scale will be critical.

Due to their drop-in nature and applicability across international markets, many of the barriers limiting SAF uptake globally are evident in a domestic context such as the lack of processing infrastructure, limited availability of feedstock, high price, and blend limits. However, there may be greater potential for UK policy to influence the uptake of SAF on domestic flights. Consequently, several policy interventions have been identified which can be considered by the UK government to support deployment of SAF in a domestic setting including:

1. Prioritisation to the production and use of synthetic kerosene.
2. Ensuring appropriate sustainability assurance and traceability to ensure the use of SAF leads to appropriate reductions in emissions.
3. Establishing a more stringent SAF mandate for domestic aviation.

2. Zero Emission Flights

Offering high levels of potential in the longer term, zero emission aircraft technologies are again an international endeavour. By 2040, **battery-electric aircraft with a maximum of 19 seats; hydrogen fuel cell aircraft with up to 80 seats and 1,000 km range and hydrogen combustion engine powered aircraft** will all potentially be available in the market. However, given the long lifespan of aircraft, the vast majority of aircraft flying then will still be conventionally powered (i.e., using conventional jet fuel or SAF) in 2040. Nonetheless, **shorter UK domestic routes with lower passenger numbers** could offer an early niche network for their commercial deployment.

The findings of this study suggest that policy could play a key role in supporting the earlier deployment of ZEF.

The UK could:

1. With international partners, work towards the development of appropriate standards and certification procedures.
2. Create financial incentives (e.g., via tax breaks of scrappage schemes) for airlines to purchase zero emission aircraft.
3. Ensure that UK airport infrastructure is capable of supporting ZEF technologies.
4. Consider the role of zero-emission aircraft in appropriate Public Service Obligations (PSOs).

3. Greenhouse Gas Removals

While technology is predicted to make substantial progress in meeting net zero, residual emissions will continue to require action; **GGRs or Negative Emissions Technologies (NETs) are therefore essential to achieving net zero in UK domestic aviation by 2040** and a key mechanism for compensating for the residual emissions associated with low carbon fuels.

Although there are no commercial scale GGR plants available in the UK, the deployment of GGRs is accelerating both in the UK and internationally. Policy and regulatory support are also building, and the UK Government is already providing a range of support through grant funding schemes for capital costs, as well as funding schemes to provide subsidies for operating expenses, and transport and storage costs. **While**

different GGR options have varying resource requirements, current policy support remains technology agnostic.

To support the deployment of GGR, and in turn enable its contribution in meeting the net-zero domestic UK aviation targets, a multi-pronged policy support is needed to alleviate the associated barriers, including:

1. Direct capital support shifting towards market-based mechanisms.
2. The creation of a capable regulatory framework addressing issues such as the sustainability of different GGR technologies and adequate carbon accounting.
3. For use in aviation offset schemes beyond UK domestic aviation, there is a need for alignment between policies to reduce implementation and regulatory costs for airlines.

4. Cost estimations

To understand, at a high level, the **potential cost implications of achieving net zero for domestic aviation in 2040**, estimates have been made of the costs associated with the different technologies under study. Overall, the **total cost estimate for 2040 was approximately £513 million**, with around **75% of those costs resulting from the higher user of SAF** (which is forecasted to still be more expensive that conventional jet fuel by that point). The remaining costs derive from the acquisition of battery electric and hydrogen fuel cell aircraft (around 15% total for both), and the use of GGR to offset residual emissions (around 10%).

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LIST OF ABBREVIATIONS

Abbreviation	Full term
AAM	Advanced Air Mobility
ATM	Air Traffic Management
ATJ-SPK	Alcohol to Jet Synthetic Paraffinic Kerosene
ASTM	American Society for Testing and Materials
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CDR	Carbon Dioxide Removals
CHJ	Catalytic Hydrothermolysis Jet Fuel
CIF	CCS Infrastructure Fund
CAA	Civil Aviation Authority
CS2	Clean Sky 2

Abbreviation	Full term
CCC	Committee on Climate Change
CfD	Contract for Difference
DAC	Direct Air Capture
DSHC	Direct Sugar to Hydrocarbon
eVTOL	Electric Vertical Take-Off and Landing
ETS	Emissions Trading Scheme
EfW	Energy from Waste
FOGs	Fats, Oils, and Greases
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
FOAK	First of a Kind
FCH	Fuel Cells and Hydrogen
GFGS	Green Fuel Green Skies Programme
GGR	Greenhouse Gas Removals
GHG	Greenhouse Gases
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HEFA	Hydroprocessed Esters and Fatty Acids
IPCC	Intergovernmental Panel on Climate Change
MCFC	Molten Carbonate Fuel Cell
MSW	Municipal Solid Waste
NETs	Negative Emissions Technologies
NO_X	Nitrogen Oxides
PM	Particulate Matter
PtL	Power-to-Liquid
PSO	Public Service Obligations
RED	Renewable Energy Directive
SRF	Solid Recovered Fuels
SO_X	Sulphur Oxides
SAF	Sustainable Aviation Fuels
ICC	Industrial Carbon Capture
RTFO	Transport Fuel Obligation
T&S	Transport and storage
UAM	Urban Air Mobility
UCO	Used Cooking Oil
VTOL	Vertical Take-Off and Landing
WTW	Well-to-Wake
ZEF	Zero Emission Flight Technologies

1. INTRODUCTION

Ricardo has been commissioned by the Department for Transport to conduct a study to analyse existing technological options and expected potential barriers to the deployment of technologies required to achieve net zero UK domestic aviation by 2040. Furthermore, the study also includes recommendations on potential policy interventions that could be enacted to achieve those goals.

Ricardo has conducted a review of the UK domestic aviation market, offering an overview of the key routes, distances, passenger, and aircraft sizes, which are key to identifying appropriate technological interventions.

This report provides a top-level analysis of three key approaches to decarbonising domestic aviation through technological intervention. These are defined as SAF, ZEF, and GGR. It is organised as follows:

- **Chapter 2 – Relevant decarbonisation technologies:** Top level overview of SAF, ZEF and GGR technologies that are available (or are expected to become available in the near future) to support the achievement of net zero for the UK aviation sector by 2040.
- **Chapter 3 – Characterisation of relevant technologies:** Analysis of a set of shortlisted technologies across the categories of SAF, ZEF and GGR appropriate for the UK domestic aviation sector. The section includes an overview of each technology, and a review of suitability based on technological readiness, investment trends, market and policy drivers, and sustainability constraints.
- **Chapter 4 – Potential barriers and challenges:** Identification of main barriers to implementation of technologies under discussion in this study (SAF, ZEF and GGR).
- **Chapter 5 – Recommendations on potential policy interventions required for net zero UK domestic aviation:** High-level non-technical policy recommendations in respect of technology, legislation and funding that could be actioned to enable net zero domestic aviation.
- **Chapter 6 – Conclusions:** Summary of the main messages of the study in respect to the three key approaches to decarbonisation.
- **Appendices:** Three appendices, the first covering different definitions of net zero, the second outlining additional issues beyond the three main issues under discussion in this study (SAF, ZEF, GGR) but which should also be considered when analysing approaches to net zero UK domestic aviation by 2040 and the third providing further details of the calculations of costs presented in Section 4.4.

1.1 CONTEXT

The UK domestic aviation market provides a key role in the UK economy in terms of jobs, investment, connectivity, and trade. As well as serving business and leisure customers, domestic aviation connects rural communities and delivers vital supplies. **Although emissions from domestic aviation account for a small share of the UK's total aviation emissions (4% in 2019)** (DfT, 2022a)**, domestic aviation offers a key stepping-stone to enabling net zero aviation by 2050.** However, as with the industry as a whole, UK domestic aviation is hard-to-decarbonise, and the sector faces some key barriers (like its traditionally low profit margins in a very capital-intensive industry) that will bring specific challenges if it is to achieve net zero by 2040.

Aviation decarbonisation technologies are in development across the sector, with manufacturers such as Airbus targeting deployment of next generation commercial aircraft by 2035. It is expected that these aircraft will serve routes between 1,700 and 3,200+ km with up to 200 passengers (Airbus, 2020). UK domestic routes cover much shorter distances with 65% falling between 200 to 750 km. **There is therefore agreement within industry that aircraft technologies required to decarbonise international aviation will be available earlier for shorter domestic aviation routes.** Furthermore, domestic aviation potentially offers more levers for government intervention (when compared to international aviation), which make it well-suited to the deployment of new aircraft technologies, and a key stepping stone to enabling the decarbonisation of UK aviation. Action on domestic aviation by 2040 also ensures that aviation is not left behind as other transport modes (notably road transport) progress quickly towards decarbonisation.

The Department for Transport's Jet Zero Strategy targets net zero domestic aviation in the UK by 2040. This ambition for domestic aviation could act as an early adopter of low and zero emission fuels and technology, as well as signalling early demand for GGRs (DfT, 2022b). While technology is predicted to make substantial progress in meeting net zero, residual emissions will continue to require action. **This report therefore**

considers three key approaches to decarbonising domestic aviation through technological intervention *(the report does not review demand measures or taxation)*:

- **Sustainable aviation fuels.**
- **Zero emission flight technologies.**
- **Greenhouse gas removals.**

Wide scale deployment of these technologies by 2040 will require substantial intervention across policy, incentives, and investment. The report therefore concludes with several non-technical policy recommendations in respect of technology and legislation that could be actioned by the UK Government to enable net zero domestic aviation by 2040.

The impacts of aviation on the climate go beyond those from CO_2 emissions, in particular altitude emissions of oxides of nitrogen (NOx), particulate matter (PM) and water vapour (forming condensation trails, or “contrails" when emitted at particular altitudes) have been implicated in climate change. This report, however, focuses on the primary issue, which is that of CO_2 emissions.

1.2 SCOPE OF STUDY

1.2.1 Definition of UK domestic aviation

Before considering the technologies available to help deliver the objective of a net zero UK domestic aviation sector by 2040, it is important to determine the scope of the domestic aviation sector and, hence, the capabilities required for its continued operation (sizes of aircraft, range capabilities, etc.).

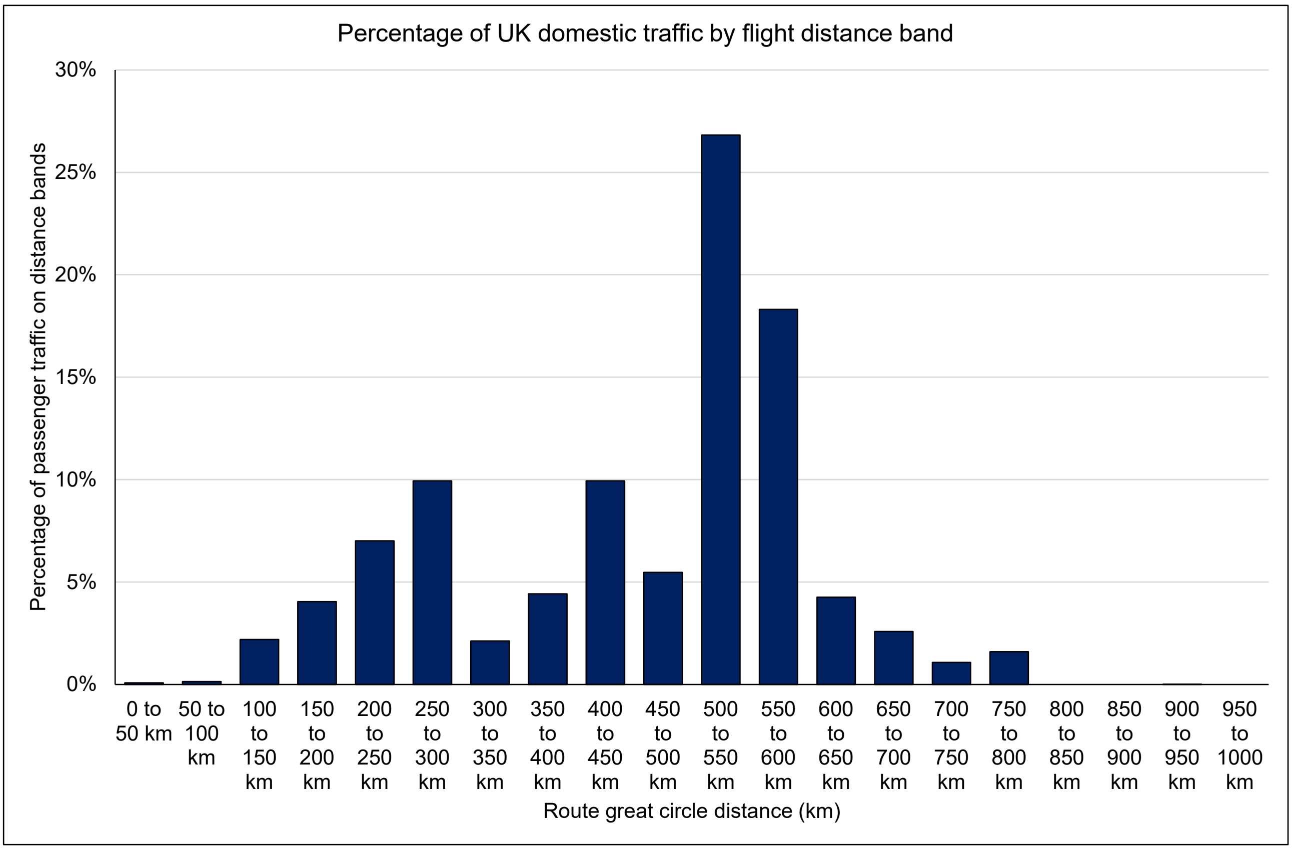
1.2.1.1 Review of UK domestic market and routes

At a high level, an initial definition of UK domestic aviation could be “Commercial flights (passenger and freight) between two UK domestic airports, including passengers whose destination is in the UK and those travelling to a hub airport for connection to an overseas flight”. For the purposes of this study, we have included routes between airports in Great Britain and Northern Ireland. Consideration was given to whether to include flights to the Crown Dependencies (Alderney, Guernsey, Jersey and the Isle of Man) and Overseas Territories such as Gibraltar (the UK Civil Aviation Authority (CAA) traffic data (CAA, 2022) includes flights to and from the Crown Dependencies in the Domestic flight data, but those to Gibraltar are considered to be international flights, for example), but it was decided to focus the assessments on those routes over which the UK Government can implement policy levers.

The shortest distance between two airports falling under this definition is 8.8 km, between Sanday and Eday London, both in the Orkneys, while the longest is Newquay to Sumburgh at 940 km (these distances were calculated as great circle distances, actual flight distances would be longer due to air traffic control requirements, weather restrictions, etc.).

Data from the CAA (CAA, 2022) has been used to identify the levels of traffic (as numbers of passengers) on different UK domestic routes. The results are shown as percentages of total UK domestic aviation passengers in Figure 1-1.

Figure 1-1: Distribution of UK domestic passenger traffic by flight distance



Source: Ricardo analysis of passenger traffic data for October 2022 from the CAA (CAA, 2022) *(Table 12-2 (UK domestic flights))*

Figure 1-1 demonstrates that approximately 0.2% of UK domestic passenger traffic is on flights of less than 100 km, about 25% on routes of up to 300 km, while about 55% of traffic is on flights of over 500 km distance. Although flights of less than 100 km represent a small percentage of overall UK domestic demand, they remain key as they represent connectivity to smaller communities, for example.

1.2.1.2 Review of passenger demand and aircraft sizes

The traffic on the routes described above have been investigated to identify the types and sizes (numbers of passengers) of aircraft used on the routes and the percentage of total traffic they represent. Online resources such as online travel agents and metasearch sites were used to identify the relevant airlines and flight numbers, and then other resources to identify the types of aircraft flown on the routes. The level of traffic has been converted from the numbers of passengers to Revenue Passenger Kilometres (RPK) to align with common forms of presenting demand and to provide a high-level indication of the levels of emissions on the different routes[1]. The results, showing the percentage of traffic by ranges of seat numbers and flight distances are shown in Table 1-1.

[1] Although aircraft emissions depend on much more than just the number of passengers and the distance flown, using percentage of total RPK as an approximate proxy for percentage of emissions is reasonable for a high-level indication of the distribution of emissions across the different routes and aircraft sizes for the present study.

Table 1-1: Percentages of UK passenger traffic RPK flown by different aircraft sizes on different route lengths

								Flight distance (km)
	Min	**0**	**50**	**100**	**200**	**350**	**500**	**750**
	Max	**50**	**100**	**200**	**350**	**500**	**750**	**1000**
Seats (max)	9	0.01%	0.01%	0.00%				
	19		0.01%	0.03%	0.05%			
	50			0.21%	0.63%	0.65%	2.54%	
	100			0.60%	1.84%	2.06%	6.36%	
	150							
	200			1.38%	7.09%	15.60%	50.97%	2.75%
	250				0.56%		6.66%	

Source: Ricardo analyses of CAA passenger traffic data and estimates of aircraft sizes based on airlines flying each route

As shown in Table 1-1 the majority of passenger traffic is on aircraft of 150 to 200 seats and routes of 200 to 750 km distance (about 75% of the total). This seat range includes aircraft types from Airbus A319 to A321neo and Boeing 737-800.

Approximately 0.9% of the total passenger traffic is on routes of up to 200km. The majority of this traffic is on aircraft between 19 and 100 seats.

At this stage, it is important to recognise that, by 2040, only flights towards the top left-hand corner of the table (e.g., up to 200 km distance, with up to 50 seats) are likely to be able to be performed using zero-emission aircraft. More details of the capabilities of such aircraft, and hence the percentage of domestic traffic that can be addressed, are given in section 2.2.

1.2.2 Definition of net zero emissions

In addition to the identification of the scope of the study, in terms of the flights that fall under the UK domestic aviation heading, it is important to consider the definition of the term "net zero" in the context of UK domestic aviation.

To align with the UK Jet Zero policy, the definition that is used in this study is:

> "Net zero – the Government target that the UK's total greenhouse gas emissions should be equal to or less than the emissions the UK removed from the environment. This can be achieved by a combination of emission reduction and emission removal."

As part of considering the definition of net zero for this study, a brief review was made of different definitions in the literature, many in the context of different sectors. The different definitions that were identified from this review have been included in Appendix 1.

2. RELEVANT DECARBONISATION TECHNOLOGIES

This section considers the technologies that are available (or are expected to become available in the near future) to support the achievement of net zero for the UK aviation sector by 2040. These technologies are considered in the following sections under three headings:

- Sustainable aviation fuels.
- Zero emission flights.
- Greenhouse gas removals.

The technologies identified are then considered in greater depth, including their applicability to the UK domestic aviation sector, in Section 3.

2.1 SUSTAINABLE AVIATION FUELS

As zero emission aircraft are still in the early stages of development (see sections 2.2 and 3.2), and considering the long lifespans of aircraft (new aircraft entering the market today are likely to still be flying in 2040), the propulsion backbone of aviation is expected to continue to be formed by aircraft with thermal engines using liquid fuels, i.e. kerosene (also referred to as jet fuel). SAF, which is a drop-in kerosene alternative (initially blended with fossil kerosene in varying percentages, eventually expected to be used as pure SAF) is expected to become the primary source of energy to reduce carbon emissions and enable achievement of climate goals in the short- to mid-term (and the net zero 2040 UK domestic goals).

SAF is applicable to all aircraft that burn kerosene (i.e., jet or turboprop aircraft). As such, it is equally applicable to international and the majority of commercial domestic aviation (except for a small number of small, piston-engined, aircraft that use aviation gasoline). The primary drivers for the development and uptake of SAF are from international aviation, as the associated emissions are much greater than for domestic aviation. However, there may be greater potential for UK policy to influence the uptake of SAF on domestic flights than on international flights. Much of the following discussion of SAF and the different options for its production, is, therefore, relevant for both domestic and international aviation.

The Department for Transport's 'Sustainable Aviation Fuels Mandate' consultation targets implementation of a UK SAF mandate from 2025 and suggests a blend of 10% SAF in the UK jet fuel mix by 2030, increasing to between 17% and 32% by 2040 (DfT, 2023c). This is expected to allow jet fuel suppliers to fulfil their obligation outside of the Renewable Transport Fuel Obligation (RTFO). The establishment of minimum sustainability criteria for SAF production (for example, limits on Hydroprocessed Esters and Fatty Acids (HEFA)-drawn fuels to encourage a transition to other pathways, such as alcohol-to-jet fuels, and subsequently power-to-liquid (PtL)[2]) and emphasis on SAF production from waste feedstock (such as commercial waste, steel-mill off-gas and other waste derived oils[3]), drawing from the most recent SAF investment programmes such as Advanced Fuels Fund (AFF) signals the trajectory for feedstock and technology choices. These will potentially influence policy support mechanisms that will need to be put in place to support fuel suppliers.

While the scope of this work is on domestic UK aviation, the rate of maturation of SAF and production pathways over the short- and long-term period are likely to broaden the scope for their long-term application to long-haul flights. A list of SAF technologies, and the associated feedstocks, that are relevant to the UK aviation sector are shown in Table 2-1 and are discussed in detail in section 3.1.

Table 2-1: ASTM approved SAF production pathways that may contribute to reducing emissions from aviation

Technology	Feedstocks	TRL	Availability	UK Domestic applicability	WTW[4] emissions reduction[5]
Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) [6]	Fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils, and greases (FOGs) e.g., tallow, UCO, soybean oil, camelina, jatropha	6-8	2012	Yes	Up to 90% (depending on feedstock)
HEFA-SPK from Algae	Bio-derived hydrocarbons such as algal oils	4-5		Yes, but currently limited to 10% blend, which may	

[2] PtL mandate has been modelled subjected to a scenario analysis. Anticipated targets based on the scale of technology transition (dependent on DAC deployment and technology maturity), between low-supply to optimistic scenario is expected to be set as follows 0.05%-1% by 2030 and between 1.5%-8% (targets by volume of the total fuel use) by 2040 (DfT, 2023c)

[3] All of these are discussed in detail in section 3.1.

[4] "Well-to-wake", i.e. full lifecycle emissions associated with the fuel, including oil extraction (for conventional fuel), plant growth or electricity generation for CO_2 capture ("well"), processing, delivery to the aircraft and exhaust from the aircraft engine ("wake").

[5] Assuming a 100% SAF blend.

[6] Synthetic Paraffinic Kerosene: the terminology applies to all drop-in SAF types.

Technology	Feedstocks	TRL	Availability	UK Domestic applicability	WTW[4] emissions reduction[5]
				make it less attractive	
Biomass Gasification + Fischer-Tropsch SPK	Gasified sources of carbon and hydrogen: Biomass (forestry residues, grasses, municipal solid waste)	6-7	2030	Yes	80% - 90%
Alcohol to Jet SPK (ATJ-SPK)	Agricultural residues (stover, grasses, forestry slash, crop straws), forest residues, corn grain, herbaceous energy crops	6-7	2030	Yes	45% - 66%
Direct Sugar to Hydrocarbon (DSHC)	Sugars from direct sources (e.g., cane, sweet sorghum, sugar beets, tubers, field corn) and indirect sources (e.g., cellulosic sugars)	7	2025	Yes, but currently limited to 10% blend, which may make it less attractive	
Catalytic Hydrothermolysis Jet Fuel (CHJ) SPK	Triglyceride-based feedstocks (plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil)	6	2030	Yes	Up to 80%
Electrofuels (synthetic kerosene) SPK	Hydrogen, carbon (e.g., CO_2 from air)	1-2	2035	Yes	Up to 100% (depending on electricity source)

Source: (Ure, et al., 2022)

Currently, the greatest issues limiting the uptake of SAF by airlines are the lack of processing infrastructure, the limited availability of feedstock and the high price of SAF. These are clearly interrelated. However, given the focus currently on developing the production, supply and market for SAF, it is to be expected that the production capacity and feedstock supply will both increase significantly in the coming years (at least in the countries that are currently leading efforts to develop the relevant capabilities). This will likely reduce the price of SAF; further, airlines are beginning to offer passengers the opportunity to make a financial contribution towards the additional costs of SAF, effectively reducing their carbon footprint in so doing.

In the longer term, current blend limits will prove a barrier to greater SAF uptake. The current certification requirements for SAF (as produced and published by American Society for Testing and Materials (ASTM)) place a maximum blend rate of 50% on the majority of production pathways (and just 10% for the HEFA from algae and DSHC pathways). If the expected SAF mandates (in the EU and potentially other countries) are to be met, it is important that these limits on SAF blend rates are relaxed and, in the longer term, removed (i.e., allowing aircraft to fly on 100% SAF).

Efforts are underway by aircraft and engine manufacturers, and airlines, to test and demonstrate the operation of aircraft using 100% SAF to enable ASTM to draw up new regulations for SAF pathways with no blend limits applied. Examples of such demonstration activities include:

- In 2021, Rolls-Royce tested a business jet engine (the Pearl 700 engine) on a testbed using 100% SAF (Rolls-Royce, 2021). The test demonstrated that the new engine series could run on 100% SAF without any problems.
- In December 2021, United Airlines performed the first passenger-carrying demonstration flight using 100% SAF in one of the General Electric engines of its Boeing 737 Max 8 aircraft (General Electric, 2021). This flight demonstrated the ability to use 100% SAF in the aircraft engine and the confidence in its safety when carrying passengers
- In 2022, the UK Royal Air Force flew one of its Voyager tanker/transport aircraft using 100% SAF in both engines on a 90-minute flight (UK Ministry of Defence, 2022). The aircraft is based on an Airbus A330 passenger aircraft fitted with Rolls-Royce Trent 772 engines. This demonstrated the ability of the full aircraft and engine systems to operate successfully using pure SAF.
- In 2022, Swedish airline Braathens Regional Airlines flew one of its ATR 72-600 regional turboprop aircraft using 100% SAF in both engines, following previous flights in which 100% SAF was used in one engine (Neste, 2022). This demonstrated the ability to use SAF in a smaller, regional aircraft.
- In January 2023, Emirates airlines conducted a test flight of a Boeing 777-300ER aircraft using 100% SAF in one of its GE90-115B engines (Business Traveller, 2023), following an initial test of the fuel in it engine a few days earlier (Aerotime Hub, 2023). This further demonstrated the ability to use 100% SAF in a large, modern airliner.

Building on these tests, the UK Government initiated a competition to support a first flight across the Atlantic (from the UK to the USA) using 100% SAF. Virgin Atlantic was successful in the competition and plan to perform such a flight using one of their Boeing 787 aircraft, flying from London Heathrow to New York John F Kennedy Airport during 2023 (DfT, 2022d). In addition to the use of 100% SAF on the flight (based on waste oils and fats, such as used cooking oil (UCO)), the airline will use carbon removal via biochar credits to offset the residual emissions and deliver a net zero transatlantic flight.

The test and demonstration activities described above are proving the ability to use up to 100% SAF safely in aircraft engines, clearing the way for the introduction of new regulations that will allow its use on commercial flights. This will both provide the legislative conditions to enable the SAF mandates requiring over 50% use of SAF to be met in the future and encourage the market to develop additional production capacity and supply agreements going forwards.

2.2 ZERO-EMISSION FLIGHTS

The terminology “zero-emission flights” refers to ‘aircraft that offer the potential for zero carbon tailpipe emissions’ (DfT, 2022a). At present, the energy sources that are considered under this heading include electricity and hydrogen fuel. In principle, ammonia could also be used as a zero-emission aviation fuel; however, it has some similar problems to hydrogen as a fuel (needing to be stored at low temperatures), while being significantly heavier than hydrogen for the same energy content (as the major contributor to the mass of ammonia is its nitrogen content, which does not provide any energy output when the fuel is combusted). Therefore, this section focuses on the potential of electric and hydrogen-fuelled aircraft.

The focus on electric power for aircraft is on battery electric, while hydrogen is considered under applications using fuel cells and combustion in gas turbine engines. The technologies identified for zero-emission flights, with information on their expected capabilities and relevance to UK domestic aviation, are listed in Table 2-2. The dates of availability and applicability to UK domestic routes presented in the table are based on those identified in the references listed below. However, it should be noted that these are generally the best estimates of the relevant authors and that there is considerable uncertainty associated with the availabilities and capabilities presented.

Table 2-2: Zero-emission flight technologies identified

Technology	TRL	Availability	UK Domestic applicability	WTW emissions reduction
Battery-electric commuter aircraft	7	2024-2025	Routes up to 250km, up to 9 passengers	Up to 100% (depending on electricity source)

Technology	TRL	Availability	UK Domestic applicability	WTW emissions reduction
Battery electric propeller-driven regional aircraft	6	2025-2028	Routes up to 450 km; up to 50 passengers	Up to 100% (depending on electricity source)
Hydrogen-powered commuter aircraft (fuel cell)	5	2030	Routes up to 500 km, 19 passengers	Up to 100% (depending on electricity and hydrogen source)
Hydrogen-powered regional aircraft (fuel cell)	5	2030	Routes up to 1,000 km, up to 80 passengers	Up to 100% (depending on electricity and hydrogen source)
Hydrogen-powered regional aircraft (combustion engine, possibly hybridised with a fuel cell)	2-3	2035	Routes up to 2,000 km, up to 165 passengers	Up to 100% (depending on electricity and hydrogen source)
Hydrogen-powered single-aisle aircraft (combustion engine)	2-3	2040	Routes up to 7,000 km, up to 250 passengers. The capability significantly exceeds that required for UK domestic flights; however, there may be commonality benefits as it would be used for medium range flights to Europe as well. The aircraft may appear too late to have a major contribution to the 2040 net zero target.	Up to 100% (depending on electricity and hydrogen source)
Hydrogen-powered twin-aisle aircraft (combustion engine)	1-2	2040 - 2045	Unlikely to be relevant to UK domestic flights as more appropriate to medium-to-long haul international flights. Also, likely to be too late to contribute to the 2040 net zero target.	Up to 100% (depending on electricity and hydrogen source)

Source: Ricardo elaboration of information from (Lilium, n.d.), (Eviation, n.d.) (Heart Aerospace, 2023), (McKinsey & Company, 2020)

It should be noted that, while the capabilities are presented in Table 2-2 in terms of passenger aircraft, all the aircraft and propulsion types would be equally relevant to freighter aircraft. For context, it is useful to note that similar CAA data to those used for the passenger analysis presented in Section 1.2.1, but providing information on freight carried, shows a total of approximately 73,000 tonnes of freight carried on UK domestic flights in 2022, 1.5% on passenger aircraft and 98.5% on freighter aircraft. For comparison, the total passengers carried on UK domestic routes in 2022 was 15.5 million, giving a total mass of 1.5 million tonnes (assuming a mass of 100 kg per passenger and their bags). Therefore, while the UK domestic air freight sector is important, the total mass carried is only about 5% of that of the passenger sector.

As noted in Table 2-2, the twin-aisle aircraft is not relevant to UK domestic aviation, while the single-aisle aircraft (e.g. a future replacement for current aircraft types such as the Airbus A320neo or Boeing 737Max families) has capabilities (particularly the maximum range) that considerably exceed the requirements for UK domestic flights. It may have relevance in the future, as it would bring commonality with the same types that the airlines will fly on intra-European international flights; however, the expected entry-into-service date is around 2040, so it would play only a small part in meeting the 2040 net zero target for UK domestic aviation.

Therefore, the zero-emission flight technologies to be considered in the remainder of the report are the battery-electric powered commuter and regional aircraft and the hydrogen-powered regional aircraft (both fuel cell and combustion engine propulsion technologies).

2.3 GREENHOUSE GAS REMOVALS

GGRs, also known as NETs, or Carbon Dioxide Removals (CDR), are essential to achieve UK and global net zero targets. The target for reaching net zero in UK domestic aviation by 2040 is unlikely to be reached without GGRs, as low carbon fuels are not zero-emission well-to-wake (WTW), hence resulting in the need to offset remaining emissions. GGRs have therefore been highlighted as a key mechanism to compensate for these residual emissions, hence enabling net zero targets to be reached. In its AR6 Synthesis Report, the Intergovernmental Panel on Climate Change (IPCC) states that the use of GGRs is crucial to offset residual emissions in the aviation sector (Harper, 2023).

GGRs can be broadly categorised into technology-based solutions and nature-based solutions, both involving capture and long-term storage of CO_2, resulting in a net removal of CO_2 from the atmosphere. As GGRs result in a net removal of CO_2 from the atmosphere, the aviation sector can make use of GGRs to offset emissions through various potential market mechanisms, which are discussed in further detail in section 3.3.7.

Technology-based solutions consist of either capturing CO_2 directly from the air, known as DAC, or use of biomass in various conversion processes, combined with capture and storage of the CO_2 which is originally captured during photosynthesis, known as Bioenergy with Carbon Capture and Storage (BECCS). Nature-based solutions make use of increasing organic reactions with rocks or increasing biological uptake of CO_2 in areas such as oceans and soil. An overview of the different GGR methods considered is outlined below.

- **DAC**: Capturing CO_2 directly from the air and subsequently storing the CO_2
- **BECCS:** Use of biomass (including waste biomass) to produce heat, electricity, or various-end products (such as hydrogen, biomethane, biofuels), combined with CO_2 capture and storage
- **Biochar:** Biochar is produced by pyrolysis and subsequently applied to soils
- **Afforestation, reforestation and forest management:** Absorption of CO_2 by growing trees
- **Ocean fertilisation:** Addition of nutrients to the ocean to increase the magnitude of CO_2 uptake
- **Enhanced weathering:** The natural weathering of silicate rocks removes CO_2 from the atmosphere. Enhanced weathering involves milling silicate rocks containing calcium or magnesium, to increase the natural rate of mineral dissolution
- **Ocean alkalinity:** Increasing the concentration of positively charged ions in seawater, resulting in additional uptake of CO_2
- **Soil carbon sequestration:** Land management practices to result in increased soil carbon content
- **Mineral carbonation:** Acceleration of the conversion of silicate rocks to carbonates, resulting in a product which can be used as construction material or for steel production

Table 2-3 below provides an overview of the GGR technologies identified, highlighting the current status of deployment.

Table 2-3. Greenhouse Gas Removal technologies identified

Technology	TRL	Availability	Long-term CO_2 storage potential
DAC	4-6	2026	Dependent on CO_2 storage location
BECCS	5-8	2028 - 2035	Dependent on CO_2 storage location
Biochar	3-6	2030	Long-term storage possible
Afforestation, reforestation and forest management	8-9	Already in use	After 20-100 years will no longer result in net GGR. CO_2 storage only exists while the forests

Technology	TRL	Availability	Long-term CO_2 storage potential
			are alive (i.e., not if cut down, disturbed by forest fires etc)
Ocean fertilisation	1-5	2040+	Carbon can potentially be retained for centuries to millennia
Enhanced weathering	1-5	2040+	Long-term storage possible
Ocean alkalinity	2-4	2040+	Uncertainty in possible reversibility of carbon storage
Soil carbon sequestration	8-9	Already in use	The process is reversible and will eventually reach saturation
Mineral carbonation	3-8	2035	The resulting carbonate minerals are stable

Source: Ricardo elaboration of information from (Royal Society, 2018)

Ocean fertilisation, enhanced weathering and ocean alkalinity are not sufficiently developed and hence not expected to be available in the UK on a commercial scale before 2040, and therefore excluded from further analysis in section 3. Mineral carbonation has a high theoretical global storage potential, as suitable silicates for mineral carbonation are present in large quantities in many areas of the world.

Although soil carbon sequestration is sufficiently developed with a high TRL, alternative challenges arise related to the long-term CO_2 storage potential. One of the main risks for soil carbon sequestration as a GGR method relates to the reversibility of carbon storage, requiring practices to be maintained indefinitely. The uptake of CO_2 will also eventually reach saturation, defined at around 20 years by the IPCC, after which further carbon sequestration decreases to zero.

Afforestation, reforestation and forest management are practices which are already widely implemented and can achieve net-removal of CO_2 at a low cost. The potential for CO_2 removal is intrinsically related to the availability of land, which can be noted as a key challenge when considering competing land-uses for growing crops for food. Captured CO_2 can be stored in forests indefinitely for the lifetime of the trees, however the permanence of this storage can be affected through natural disasters, such as forest fires or drought (Royal Society, 2018). Trees will also become saturated one they reach maturity after around 20 – 100 years depending on the species, after which no further CO_2 will be captured. The Climate Change Committee (CCC) has therefore suggested that afforestation and forest management practices are not likely to largely contribute towards offsets in aviation (Hirst, 2021).To achieve negative emissions from technology based GGRs, captured CO_2 must subsequently be compressed and transported through a CO_2 network to a suitable CO_2 storage site to be injected and permanently stored. Methods of CO_2 transportation consist of road, rail, ship or pipeline transfer. When transporting large volumes of CO_2, pipeline transport is generally the most suitable and lowest cost option.

CO_2 storage sites consist of geological locations such as deep saline formations, abandoned coal beds and abandoned oil and gas fields, where CO_2 is injected underground for permanent storage. Storage sites must continuously be monitored for leakage, as this affects the total quantities of CO_2 that are permanently stored and reported. The viability of long-term storage for technology based GGRs therefore relies on the suitability of the storage site.

Analysis undertaken by The Energy Technologies Institute identifies a UK CO_2 storage potential of at least 70 Gt; 61 Gt exist in saline aquifers and 9 Gt in depleted oil and gas fields. Most of this storage is located in the Scottish North Sea, East Coast of England, and off the coast of Merseyside (UKSAP, 2011). For CO_2 transport, either truck, rail, ship, or pipelines can be considered. The Feeder 10 pipeline is considered as a valuable option for the UK to transport CO_2 to the North Sea, as it exhibits a significant storage capacity of at least 10 $MtCO_2$/yr and connects Peterhead Port to St Fergus Gas Terminal. However, the project is dependent on whether funding is awarded to convert the old gas pipeline (Technip Energies, 2022).

Nature-based methods such as afforestation and soil carbon sequestration are expected to be essential to remove CO_2 from the atmosphere. However, due to factors such as land constraints and permanence and timescales of CO_2 storage, nature-based solutions must be complemented with engineered GGR solutions, such as DAC and BECCS, in order to capture and store CO_2 at the scale required to reach net zero targets. It may therefore be likely that nature-based GGRs can be utilised more in the short-term, while technology-based

GGRs are still in development and costs are still high, followed by making greater use of technology-based GGRs in the future once nature-based approaches reach their maximum potential.

The global potential of GGR technologies is estimated to be between 100 – 1,000 $GtCO_2$/year by 2100, therefore, there is potential to deploy both nature and technology based GGRs globally, not just in the UK (IPCC, 2019) . This is especially attractive given the role of market-based mechanisms to use removals elsewhere in the world. Possible GGR options that can be utilised to support UK domestic aviation reaching net zero by 2040 therefore include DAC, BECCS, biochar, afforestation, mineral carbonation and soil carbon sequestration.

3. CHARACTERISATION OF RELEVANT TECHNOLOGIES

This section reviews a set of shortlisted technologies across the categories of SAF, ZEF and GGR. The shortlist builds on the identification in analysis in section 2 and the technologies outlined in Table 2-1, Table 2-2 and Table 2-3 to identify those suitable for decarbonising domestic aviation within the short (2030), medium (2035) and long-term (2040) period, as set within DfT's net zero trajectory.

The section includes an overview of each technology, and then a review of suitability based on technological readiness, investment trends, market and policy drivers, and sustainability constraints.

3.1 SUSTAINABLE AVIATION FUELS

To understand the current and future trends in the potential contribution of SAF to decarbonising domestic aviation, the key factors that play a role in influencing their current and future uptake need to be understood. The most acknowledged factors include SAF supply and demand, but it cannot be simply drawn down to these alone. The SAF discussed in the context of this study is 'drop-in' by nature and, as such, is applicable to all aircraft that use kerosene (i.e. jet or turboprop aircraft). Therefore, it is equally applicable to international aviation and the majority of commercial domestic aviation (except for a small number of small, piston-engined, aircraft that use gasoline). The various domestic and international drivers in the background that determine the readiness of SAF candidates for uptake in the UK are discussed in this section.

To support this analysis, key factors have been identified from a review of technical and scientific literature, including government reports and statistics, independent reports, aircraft/engine OEM and airline and aircraft operator updates. Our selected list of SAF candidates (non-crop derived[7]) from Table 2-1 were subjected to the following review parameters:

1. **TRL** – informed by the evidence found on compatibility with the aircraft systems (particularly engines) and domestic production/supply capabilities.
2. **Investment trends** – informed by the evidence of feedstock type-conversion factors, domestic feedstock supply, etc.
3. **Market/policy drivers –** informed by the review of relevant and cross-cutting policies on SAF demand/supply, such as the RTFO, potential UK SAF mandate, UK emissions trading scheme (ETS) and the recent impacts of the Renewable Energy Directive (RED) III proposal from the European Union.
4. **Sustainability constraints** – including impacts from production pathways, anticipated life cycle GHG savings over the medium and long-term period.

Airlines, in collaboration with aircraft/engine OEMs and fuel producers have been attempting test flights with higher blends (up to 100%). While airlines are increasingly asking for SAF to be available in large quantities to decarbonise their operations, actual demand is low under the current conditions due to high current SAF prices: in 2021, only 19 million litres of renewable avtur (SAF) were reported to have been produced in the UK, which makes up 3.2% of all the domestic aviation fuel consumed in the UK[8] (DfT, 2021b). By 2040, estimates by Ricardo indicate that SAF demand in the UK (both domestic and international) could reach 7.1 billion litres (compared to 7.9 billion litres of demand for fossil kerosene also in 2040) (Ricardo, 2021b). To support that

[7] Non-crop derived SAF candidate chosen in compliance with eligible fuel criteria in the UK SAF mandate and the government consultation responses.

[8] Domestic aviation was responsible for 1.4 million tonnes of GHG emission in 2019 (DfT, 2021a). Based on aviation fuel consumption statistics and its correlation with aviation emissions in the UK, domestic aviation fuel consumption is estimated to be 586 million litres in the baseline year 2019.

uptake of SAF, analysis by Ricardo on offtake agreements signed by British airlines shows a total commitment of 32 million litres agreed for the coming decade – since the average duration of an offtake agreement is around six years, virtually none of them already reach 2040. Overall, most OEMs suggest that the current cause for low uptake of SAF is its low market supply (BP, 2022) (KLM Royal Dutch Airlines, 2022). There appears to be a form of reverse causality at play here. The underlying drivers of this cause are explored further below.

3.1.1 Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA)

In the UK context, HEFA-SPK is expected to contribute to immediate aviation decarbonisation through its characteristics of wider feedstock (UCO as a waste feedstock) availability, competitive conversion factor (tonnes of liquid fuel per tonne of feedstock) and an environmentally viable production pathway (DfT, 2021b). With life cycle emissions of 14.6 gCO_2eq/MJ, 50% blends of HEFA-SPK, prevalent in the UK market would lead to an overall reduction of 41% of GHG emissions generated[9]. Despite promising sustainability characteristics, the lack of current commercial scale production, limited demand, and the expensive nature of HEFA-SPK restricts its current rate of uptake. The current market price of HEFA-SPK is three to four times (£14 to £42/GJ of fuel) that of conventional jet fuel and without relevant support mechanisms such as public fund allocation to bridge the price gap between comparator fuels or cutting subsidies for conventional jet fuel, uptake of SAF will prove to be challenging (Royal Society, 2023). Nevertheless, the planned deployment of guidance framework to accelerate fuel approval and production capacities such as the SAF Clearing House[10] (by 2023) and full-scale UK production of HEFA-SPK, is expected to create a supportive landscape for immediate decarbonisation between 2027 and 2035. That said, HEFA uptake could still be limited due to the proposed 'HEFA cap' in the UK SAF mandate to support a diversity of other SAF production routes.

3.1.2 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

FT-SPK is viewed as a next viable option (at TRL 5-6) in overcoming the 'HEFA cap' bottleneck and is currently certified for blending up to 50% for commercial use. While being at a relatively higher end of the price scale (£20-44/GJ of fuel), FT-SPK can be advantageous in the sense of possessing a diverse range of feedstocks, including wastes. FT-SPK can be synthesised from municipal solid wastes (MSW), lignocellulosic waste residue (agricultural/forestry waste) and also from captured CO_2 (waste flue gas, atmospheric CO_2 from carbon capture), using green hydrogen (i.e., hydrogen produced through electrolysis, where the electricity comes from renewable sources), which can significantly lower the resulting SAF's carbon intensity and subsequently the fleet operations. This choice of feedstock is expected to impart a GHG intensity and market price range to the FT-SPK that is being synthesised. Currently, a number of FT-SPK production plants have been planned for deployment or are under construction in the UK (Worley Energy, 2022) (Fulcrum Northpoint, 2022) (Velocys, 2022) and (Royal Society, 2023), while in the US, commercial scale productions have been reported at the Sierra BioFuels plant, successfully producing jet fuel from commercial waste. The challenge to scaling up production levels would be feedstock availability which is discussed in greater detail in section 5. However, the demand for FT-SPK is expected not to exceed 10% after 2040, in accordance with the Sixth Carbon budget for Aviation in the CCC's fuel demand trajectory, due to more stringent carbon targets and the emergence of PtL as much better 'low-to-no' carbon alternative (Climate Change Committee , 2020).

3.1.3 Power-to-liquid (PtL) or synthetic kerosene

Alternatively, FT-SPK can also be produced from green hydrogen and captured CO_2 (also termed generally as 'e-fuels', synthetic fuels or PtL); this is seen as an attractive long-term GHG mitigation option and not restricted by issues relating to feedstock availability and sustainability concerns. While the current reported carbon intensity of the fuel is about 30-40gCO_2eq/MJ, this is based on the current average carbon intensity of electricity generation; the expected reduction of this towards zero in the future will also reduce the carbon intensity of PtL SAF towards zero. While commercial scale production of e-fuels requires 5-8 times the UK's 2020 renewable energy capacity and would be significantly expensive in the current time frame, the trends in grid decarbonisation and integrated production with carbon capture storage (CCS) plants in the future could positively influence the fuel's sustainability (DfT, 2021a). However, full decarbonisation of the UK power systems is not anticipated much before 2035 (BEIS, 2021a). Additionally, policy support through UK SAF

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[9] Life cycle emissions profile for UCO-derived HEFA-SPK based on Life cycle emission values published within ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) eligible fuels specifications (ICAO, 2022).

[10] UK Clearing House, committed to as part of the Department for Transport's Jet Zero Strategy to support SAF producers through the early stages of fuel testing and then to support the development and uptake of military standard sustainable fuels in UK aviation.

mandate and CCC's recommendations on prioritising innovation focus on PtL could favour investor confidence which is expected to accelerate commercialisation of promising and technologically optimal PtL production plants well before 2035 (Climate Change Committee , 2020). There is currently a greater expectation of the promised capability of e-fuels or PtL to deliver net zero in 'hard-to-decarbonise' sectors, as opposed to other SAF candidates. CCC's net zero trajectory for aviation, as a part of its sixth carbon budget, suggests that by 2050, SAF may be able to support net zero transition by only 10% and therefore, recommends prioritising innovation focus and acceleration of PtL fuels for long-term applications. Similar observations and recommendations are also made within the ReFuelEU (European Commission, 2021) and other relevant literature (Ricardo, 2022) (McKinsey, 2022) (ITF, 2023) .

3.1.4 Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK)

ATJ-SPK or Alcohol-to-jet-SPK is a developing technology, currently at a TRL of 5-6. ATJ-SPK can be synthesised from a range of feedstocks including forestry/agricultural waste, flue gas, MSW and atmospheric CO_2/green hydrogen. A selection of processing plants at varying levels of production capacity have been planned for partial to full-scale deployment from 2026 onwards (Nova Pangaea, 2022). However, the seasonal availability of some of the locally derived feedstock and current technological restrictions have led to restrictions on its scale up and potential commercialisation in the short to medium term. Imports of feedstock may not be a feasible option due to the inherently lower conversion efficiency, requiring additional energy expenditure to improve yields. This is likely to impact the life cycle carbon intensity and cost of fuel production (55-78 gCO_2eq/MJ and market price of fuel similar to FT-SPK). This is discussed further in section 4. Any delays in optimisation of this technology (feedstock selectivity and energy efficiency improvements) and its commercialisation are anticipated to render this process counter-productive to the CCC's aviation decarbonisation projections, from a sustainability standpoint.

3.1.5 Other SAF candidates

The other SAF candidates considered are relatively niche pathways, which leads to difficulty in estimating their trajectory for development and deployment. The Catalytic Hydrothermolytic process, currently at a TRL of 5, has been developed and foreseen for application in processing UCO and other FOGs to produce CH-J fuel. The processing pathway and the resulting fuel type have been one of the most recent to be approved under the ASTM D7655 specifications. Similarly to the other fuel types, the production costs are influenced by feedstock costs (source of raw triglycerides, hydrogen, feed water etc.), the CH-J process has been observed to have higher conversion efficiency, with the scope to lower the overall market price of the resulting fuel (Royal Society, 2023). Nevertheless, the currently competitive market for UCO and the lack of evidence on deployment of any CH-J production plant in the UK limits the scope for its consideration in this review. As for other fuel types, particularly the DSHC, the feedstock-pathway configurations introduce difficulties similar to that observed with the ATJ-SPK production processes. The need for sugar-rich feedstocks to deliver higher overall conversion efficiencies are anticipated to increase the overall production costs, which is currently restricted within the UK SAF mandate. A recent study by the Royal Society, has therefore, identified a shift in producer interests in targeting the chemicals and pharmaceuticals sector, as opposed to the aviation fuels in the UK (Royal Society, 2023).

3.1.6 Summary

SAF is favoured as the most-desired solution for short-to-medium term decarbonisation, irrespective of application in domestic or international context, due to their "drop-in" nature and the subsequent relief from potentially added costs of creating disruptive engine technologies and airport infrastructure needed to accommodate new fuel types (e.g., hydrogen fuel cell/combustion engines). The primary drivers for the development and uptake of SAF are from international aviation, as the associated emissions are much greater than for domestic aviation. However, there may be greater potential for UK policy to influence the uptake of SAF on domestic flights than on international flights. An example of such an influence can be found in the significant support for the prioritisation of PtL from 2030s to the long-term in a number of relevant UK policies including UK SAF (DfT, 2023b) and the CCC's Sixth Carbon Budget (Climate Change Committee , 2020), trickling down to revised proposal for an UK SAF mandate (DfT, 2023c), decarbonisation technology roadmaps (DfT, 2021a) and the RTFO guidance (DfT, 2021c). A variety of types of SAF are under development with some already deployed commercially. All of these are still not cost-competitive with fossil-based kerosene, but over time that difference is expected to abate. Table 3-1 summarises the key characteristics of the different pathways under consideration.

Table 3-1: Summary of the different SAF pathways under consideration

Fuel Type	Feedstock sustainability	GHG intensity (gCO2/MJ)	Current fuel price (Relative to the conv. Jet fuel)	Fuel price from 2040 (Relative to the conv. Jet fuel)	Domestic Policy Prioritisation	Long-term viability
HEFA –SPK (UCO-based)	🟢	🟢 14.6	🟠 2-3x	🟠 2x	🟠	🔴
FT-SPK	🟢	🟢 5-13	🔴 3-4x	🟠 2-3.5x	🟢	🟠
ATJ-SPK	🟠	🟠 55-78	🔴 3-4.5x	🟠 2-3 x	🟢	🔴
DSHC	🔴	🟠 72-75	🔴 3-4.5x	🟠 2-3 x	🟢	🔴
CHJ	🟠	-	🟠 1-2x	-	🟢	🔴
PtL	🟢	🟢 31-42 currently, reducing to 0 over time	🔴 6-7x	🟢 1-2x	🟢	🟢

🟢 and 🟢 >> highly favourable in terms of net zero transition
🟠 and 🟠 >> somewhat favourable in terms of net zero transition
🔴 and 🔴 >> not favourable in terms of net zero transition
Sources: (Climate Change Committee , 2020) (ICAO, 2022) (McKinsey, 2022) (ITF, 2023)

3.2 ZERO-EMISSION FLIGHTS

As described in section 2.2, the zero-emission flight technologies considered here are the battery-electric powered commuter and regional aircraft and the hydrogen-powered regional aircraft (both fuel cell and combustion engine propulsion technologies).

3.2.1 Battery-electric aircraft

Battery-electric aircraft offer the potential for zero-emission flight, with no emissions of other pollutants (e.g., oxides of nitrogen (NOx) or particulate matter (PM)) as well as CO_2. However, low weight is critical for an aircraft to be able to fly and, previously, battery technology was not able to provide sufficient capacity (in MJ or kWh, for example) at low enough weight.

More recently, improvements in battery technology have raised the potential for battery-electric aircraft to fulfil some of the future demand for air travel. It is still highly unlikely that technology will enable larger, or longer range, battery-electric powered aircraft, but smaller, shorter-range aircraft are becoming feasible.

Two aircraft types that are of relevance to this study, both of which are in the prototype testing stage, are the Lilium Jet (Lilium, n.d.) and Eviation Alice (Eviation, n.d.). The Lilium Jet aircraft is primarily being developed to fulfil the electric vertical take-off and landing (eVTOL) urban air mobility (UAM) or advanced air mobility (AAM) requirements. However, its capabilities, including seating for 6 passengers and a range of up to 250 km, may allow it to fulfil demand on some shorter routes, such as inter-island flights in the Scottish islands. In some cases, the vertical take-off and landing (VTOL) capability of the aircraft could bring additional benefits in allowing it to operate from locations without longer runways. The Lilium Jet is expected to enter service in the 2024 to 2025 timeframe.

The Eviation Alice aircraft has a more conventional layout, with twin rear-mounted propellers, with seating for 10 passengers and a range of up to 450 km. The prototype first flew on 27 September 2022, and it is expected to enter service in 2027. The aircraft is powered by two 700 kW (about 940 horsepower, greater than the engines on a De Havilland DHC-6 Twin Otter turboprop aircraft, for example) electric motors, giving a claimed maximum cruise speed of 260 knots (481 km/h). This would allow the aircraft to perform many of the flights performed currently by smaller twin-turboprop aircraft.

Larger battery-electric aircraft have also been proposed by, for example, Heart Aerospace (Heart Aerospace, 2023), such as the ES-19, with 19 seats and a 400 km range. However, although the entry into service is projected for 2026, it does not appear to be as far advanced as the other two battery-electric aircraft described.

Between them, the aircraft types described (plus any others that may be developed) would have the capabilities to meet the demand for aircraft of up to 9 and up to 19 seats, as shown in Table 1-1. Although the total demand currently fulfilled by such aircraft types is small (as a percentage of the total UK domestic passenger demand), it can be of vital importance for maintaining connectivity for some smaller communities.

The use of electric aircraft on UK domestic routes will require the installation of electric charging points at any airports that they visit. While this may bring challenges, particularly for more remote airports, the provision of electric supplies, with (potentially) local generation, is a well-understood requirement and likely to be simpler than handling other fuels, such as hydrogen, for example.

3.2.2 Hydrogen fuel cell aircraft

In 2020, the Clean Sky 2 (CS2) and Fuel Cells and Hydrogen (FCH) Joint Undertakings jointly published a report on hydrogen powered aviation, including the identification of potential applications in different categories of aircraft (McKinsey & Company, 2020). The aircraft types described in the report included a hydrogen fuel cell powered commuter aircraft and a similarly powered regional aircraft.

In both cases, the expectation was that the fuel cell would generate electricity, which would be used to power propellers via electric motors. The conceptual designs exploited a benefit of electric powered propellers for aircraft propulsion, in that the aircraft can use multiple motor-propeller combinations (e.g., 12 motor-propeller units per aircraft), giving overall improvements in efficiency.

The fuel cell powered commuter aircraft is expected to seat 19 passengers with a 500 km range and a cruise speed of 500 km/h. As shown in Table 1-1, the use of aircraft with up to 19 seats on UK domestic flights is currently limited to flights of less than 350 km distance, so the additional range capability of the hydrogen fuel cell aircraft would not bring immediate advantages over an electric aircraft of a similar size in terms of routes that can be served. One advantage that it could bring, however, would be a reduction in the number of airports that would need to be equipped with recharging/refuelling infrastructure, as the aircraft would be able to complete a round trip of up to 500 km without refuelling at the intermediate airport.

The larger fuel cell powered aircraft in the CS2/FCH report is designed for 80 passengers with a 1,000 km range and a cruise speed of Mach 0.44 (about 490 km/h at an altitude of 25,000 ft or 7,620 m). From Table 1-1, this capability would serve up to 15% of passenger demand for UK domestic aviation (if the seating was stretched to 100 seats, to match the size categories in Table 1-1; alternatively, if limited to 80 seats, the number of flights of such aircraft would need to be increased slightly to capture the full potential demand).

As noted above, the CS2/FCH report considered conceptual aircraft in a range of sizes. Currently, there are a limited number of hydrogen-fuelled aircraft under development:

Under Project Fresson, a consortium of companies, led by Cranfield University, is retrofitting a Britten-Norman Islander aircraft with a hydrogen fuel cell system. The standard Islander is powered by twin piston engines and has up to 9 passengers. The conversion to hydrogen fuel cell power is expected to reduce its range to about 250 km. The design approach includes mounting the hydrogen fuel tanks externally, under the wing, to preserve the seating capacity. The initial flight of the converted aircraft is expected in 2023. While the project is mainly targeted at a demonstration of the feasibility of hydrogen fuel cell powered flight, it may also show the feasibility of retrofitting in-service aircraft of a type that is widely used for short haul flights, which could lead to a more rapid take-up of the technology than would be achieved with all-new designs.

Similarly, ZeroAvia is developing a hydrogen fuel cell system for propeller-driven aircraft. Their initial application was to replace one of the engines on a Dornier 228 aircraft with the hydrogen fuel cell system, while retaining one conventionally fuelled engine. The modified aircraft achieved its first flight on 19 January 2023 (Canary Media, 2023). Building on the successful demonstration of the fuel cell system, ZeroAvia have announced plans to inaugurate the first commercial flights using a fully hydrogen powered aircraft on flights from Rotterdam The Hague in 2025 (Flight Global, 2023). Like the Project Fresson approach, the ZeroAvia plans include retrofitting hydrogen fuel cell systems on existing aircraft (as well as the Dornier 228, they also envisage retrofitting larger turboprop aircraft, such as the ATR-72 and Bombardier Dash-8 later in the decade), enhancing the potential take-up of the technology for short-haul flights.

3.2.3 Hydrogen combustion aircraft

The CS2/FCH report also includes concepts for larger aircraft types, which use gas turbine engines (similar to current turboprop and jet engines, but with much-modified combustion systems) burning liquefied hydrogen fuel. The report includes a regional jet aircraft powered by a hybrid propulsion system and medium and long-haul aircraft powered by hydrogen-fuelled gas turbines. As noted in section 2.2, the twin-aisle, long-haul aircraft is not relevant for UK domestic aviation, while the single-aisle, medium-haul aircraft would be relevant for much of the UK domestic routes, but it is not expected to enter into service until towards 2040, reducing the impact that it can have delivering net zero for UK domestic aviation by 2040.

The proposed regional jet aircraft uses a combination of a hydrogen-fuelled gas turbine engine, with electric power to drive the engine’s fan. The electric power would be produced using a hydrogen fuel cell system; thus, all the energy would be derived from the hydrogen fuel.

More recently, Airbus has also launched its ZEROe concept, including three aircraft concepts using liquefied hydrogen fuel (Airbus, 2020). The three concepts target zero-emission aircraft powered by gas turbine engines burning hydrogen fuel, with the initial entry into service being in the 2035 timeframe. The concept aircraft include a turboprop aircraft carrying up to 100 passengers with a range of 1,000 nautical miles (1,852 km), a long-range jet aircraft carrying up to 200 passengers with a range of 2,000 nautical miles (3,704 km) and a blended wing-body design with the same capacity and range capability as the long-range jet aircraft. The designs include internal storage tanks for the liquified hydrogen fuel, located behind the fuselage rear pressure bulkhead in the turboprop and long-range jet concepts and in the lower wing structure for the blended wing-body.

In November 2022, Airbus announced a fourth concept aircraft type under its ZEROe family. This time using hydrogen fuel cell power sources included in engine “pods” (co-locating the fuel cell and electric motor), also using propellers in a turboprop-style layout (Airbus, 2022). First flight for a demonstrator unit, to be attached to an Airbus A380 aircraft, is planned for 2026.

Of the concepts shown by Airbus, only the turboprop aircraft (whether powered by hydrogen-fuelled gas turbines or fuel cells) has real relevance for UK domestic flights (the long-range jet aircraft might be relevant if the final design is closer to current single-aisle aircraft, such as the Airbus A320neo family, rather than the twin-aisle aircraft such as the Airbus A330neo or Boeing 787 family). The estimated initial entry into service is 2035, which would allow these designs to contribute to reaching the net zero target for 2040, but with only a relatively minor impact due to the limited fleet penetration by that date.

3.2.4 Summary

Concepts being developed for future zero-emission flight technology include battery-electric, hydrogen fuel cell and hydrogen combustion aircraft. The three types of propulsion system concepts have different capabilities and, hence, may contribute differently to the UK achieving its net zero target for domestic aviation by 2040.

Battery-electric aircraft are likely to be restricted to a maximum of 19 seats (based on the aircraft types under development), with ranges of up to 400 km. Although this capability corresponds to only a small percentage of current UK passenger demand, it matches the requirements for many of the short-range flights by small aircraft essential for providing connectivity to small communities.

Hydrogen fuel cell aircraft may provide additional capability, up to 80 seats and 1,000 km range for example, which would allow them to be used for about 15% of current UK domestic passenger demand.

Hydrogen combustion engine powered aircraft have the potential to meet the requirements of the longer UK domestic routes, whether they use propellers or jet engines. However, the technology is not as far advanced as the other types considered and the expected entry into service dates of 2035 to 2040 mean that they are unlikely to contribute significantly to meeting the net zero target for 2040.

The focus of the analysis has been on passenger transport; however, the technologies would be equally applicable to freighter versions of the aircraft types (indeed, many of the smaller aircraft would be easily convertible from passenger to freight carriage, depending on the requirements at the time)

3.3 GREENHOUSE GAS REMOVALS

To understand the potential of GGRs to support UK domestic aviation, key influencing factors for accelerating the development of GGR technologies have been reviewed. Specific parameters include the TRL, resource requirements, monitoring, reporting and verification (MRV) requirements, costs, market developments, availability in the UK, and the policy and regulatory landscape. As outlined previously, GGRs will be required to reach net zero in the aviation sector. Therefore, significant efforts are underway to develop GGRs in the UK, with efforts focusing on feasibility studies, as well as deployment of pilot and commercial scale GGR facilities. A high-level review of GGR case studies was therefore also undertaken, with the aim of using case studies as a means to consider further market developments.

3.3.1 BECCS

The BECCS process chain consists of biomass production, biomass conversion, CO_2 capture, transport and storage. There are a wide range of biomass feedstocks which can be used, with some examples including forestry residues, sawmill residues, solid recovered fuels (SRF), perennial energy crops, straw, waste wood, food waste and by-products. Biomass conversion processes refer to converting biomass feedstocks into energy, with methods consisting of combustion, pyrolysis, gasification, anaerobic digestion, and fermentation. The aforementioned biomass conversion technologies are all well-established and commercially available.

There are also a range of CO_2 capture approaches available, where the most advanced are post-combustion capture, pre-combustion capture and oxy-fuel combustion capture. GGRs are at various stages of development, and hence have different timelines approaching commercial readiness. A benefit of post-combustion capture systems is the ability to retrofit onto existing plants, hence allowing for emissions to be captured for existing plants in faster timescales than constructing entirely new BECCS plants.

In general, different CO_2 capture approaches are applied to different biomass conversion processes, also resulting in different end products. The TRL of BECCS varies depending on the specific pathway, ranging from TRL 3 to TRL 9, with BECCS bioethanol having the highest TRL.

Different combinations of biomass conversion and CO_2 capture approaches have varying degrees of maturity, hence BECCS technologies can be categorised by their different applications and end-products:

- **BECCS Power:** Use of CCS in power stations to produce electricity (and possibly heat in a combined heat and power plant) which use biomass feedstocks as a fuel source
- **BECCS Industry**: Use of CCS in industrial facilities, such as cement, paper pills and distilleries, which use biomass feedstocks as a fuel source
- **BECCS Energy from Waste:** Use of CCS in Energy from Waste (EfW) plants which use biomass waste as a feedstock
- **BECCS Hydrogen:** Production of hydrogen with biomass feedstocks and CCS
- **BECCS Biomethane:** Production of biomethane with biomass feedstocks and CCS
- **BECCS Biofuels:** Production of biofuels with biomass feedstocks and CCS

Biomass feedstocks used in BECCS can have significant land requirements associated with feedstock production. Estimates for land requirements range from 0.03 to 0.06 ha/tCO_2. BECCS EfW makes use of biogenic wastes as a feedstock, hence providing less adverse effects from land use than other BECCS power/CHP applications (Royal Society, 2018).

Effective monitoring, reporting and verification (MRV) of the emissions reduction achieved through BECCS plants requires the inclusion of life cycle emissions in the scope of the analysis. This must consider the environmental impacts of biomass feedstock production, as well as monitoring of the CO_2 storage site.

Drax Power Station in the UK is currently operating two pilot scale BECCS facilities on two side streams of one of their biomass boilers in North Yorkshire. The pilot scale facilities (one based on chemical absorption and the other based on Molten Carbonate Fuel Cell (MCFC), technology) became operational in 2019 and 2020 respectively, capable of capturing a total of approximately 1.3 tonnes of CO_2 per day. Further plans are underway, aiming to reach commercial scale operation on one of the 600 MW boilers by 2027 (Drax, 2022).

There is also ongoing work to develop a BECCS EfW plant at Redcar Energy Centre in Northeast England, with commercial operation planned for 2025. The plant will be designed to capture 400 ktCO_2/year (Redcar Energy Centre, 2023). Other key projects include Kew Projects Ltd pilot plant aiming to use gasification to produce hydrogen and capture 50 ktCO_2/yr by 2025-2030 increasing to 24 MtCO_2/yr by 2040 (BEIS, 2022a), and Future Biogas, who plan to construct up to 25 new biogas plants with CCS and retrofit 20 existing sites with CCS (The Association for Renewable Energy & Clean Technology, 2021).

The scale of GGR deployment in the UK is uncertain; however, modelling carried out by the CCC (Climate Change Committee , 2020) does provide some detailed insights. Technologies seen as low-hanging fruits, such as BECCS EfW, BECCS Biomethane, and BECCS Biofuels, can be easily retrofitted with CCS and deliver negative emissions of 16.4 MtCO_2/yr by 2050. Technologies that are expected to take longer to develop, such as BECCS Power, BECCS Hydrogen, and BECCS Industry, are capable of achieving negative emissions of circa 36.5 MtCO_2/yr by 2050 (Climate Change Committee , 2020).

3.3.2 DAC

DAC involves removing CO_2 directly from the air, followed by transport and storage of CO_2. Ambient air is drawn in and contacted with special sorbents, using adsorption or absorption processes to separate the CO_2 from the air. The CO_2 is later regenerated with heat and water to release the CO_2 in a high purity stream.

DAC processes have high energy requirements due to the low concentrations of CO_2 in air. It is important that the energy required for DAC plants is supplied from renewable sources, hence maximising the potential for negative emissions to be achieved. DAC plants can therefore be co-located with industrial processes that emit waste heat, or with renewable energy generation such as solar and wind plants, thereby reducing costs as well as increasing the negative emissions potential. Passive DAC processes will have lower energy requirements than active contacting processes; however, they require much more significant quantities of land area. Land area for active DAC processes is predominantly made up of the area for the DAC infrastructure, as well as for the renewable energy generation infrastructure.

In terms of MRV requirements, elements in a DAC system that require effective monitoring consist of the life cycle impacts of the material and energy inputs, the quantity and efficiency of capture and the integrity of CO_2 storage (Royal Society, 2018). It is expected that DAC plants will have less complex MRV and GHG accounting methods than BECCS plants, as DAC is a closed system, where biomass feedstocks do not need to be considered, unlike BECCS.

There are currently no DACCS plants operating in the UK; however, there are approximately 20 operating worldwide. The key projects in operation include Carbon Engineering's pilot plant located in Canada, which captures 365 tCO_2/yr to produce e-fuels, and Climework's Orca plant located in Iceland, which is the world's first commercial DAC plant that captures 4,000 tCO_2/yr for storage (IEA, 2022b). So far, there is only one commercial DAC plant in the UK that is expected to be installed in the next decade; named Storegga, which will be operated by Carbon Engineering and capture 0.5-1 MtCO_2/yr by 2026. However, there is potential for further deployment, with the CCC estimating a total capture rate of 5 MtCO_2/yr by 2050 (Climate Change Comittee, 2020).

Airbus have partnered with 1PointFive, who are currently building a DACCS facility in Texas which is capable of removing up to 1 million tonnes of CO_2 from the atmosphere. It is anticipated that the plant will be running in 2040, and over 4 years will provide Airbus with 400,000 tons of carbon removal credits. Several airlines have signed letters of intent to discuss purchasing carbon credits, achieved through DAC, to offset their emissions; these airlines include Air Canada, Air France-KLM, Virgin Atlantic, LATAM Airlines, easyJet, Lufthansa Group, and International Airlines Group (IAG) (Air Insight Group, 2022).

3.3.3 Biochar

Biochar, a coal-like substance, is formed during pyrolysis, a biomass conversion method involving thermal decomposition of biomass feedstock in the absence of oxygen. The CO_2 from the biomass feedstock is stored in the biochar, which is subsequently added to soil to stabilise organic matter. The CO_2 can therefore be stored in the soil, while also providing improvements to soil quality and fertility.

The TRL of biochar is approximately 3-6, being an established method that is not widely applied. Slow rates of uptake predominantly relate to competing land use for biomass feedstocks; as with BECCS, biomass use for biochar will compete with land used to grow food crops. Use of biomass for biochar also competes with use of biomass for BECCS, as it may be argued that biomass feedstocks should be prioritised for use in BECCS, the more advanced technology of the two.

Although application of biochar onto soil provides positive benefits, biochar has also been found to decrease soil surface reflectivity, subsequently increasing soil surface temperature, possibly resulting in reduced positive climate change effects of applying biochar to soils (Royal Society, 2018).

To verify that biochar has been applied to the soil, an appropriate MRV procedure will need to be outlined which accounts for uncertain storage permanence and the varying decomposition rates of biochar depending on the choice of feedstock and temperature.

There are currently no operating biochar facilities in the UK; however, there are a number of demonstration scale projects in Australia, China, and Europe, which cover the pyrolysis of various wastes and residues. At present, the biochar is sold as a by-product of the pyrolysis process, with the production of biofuels, syngas, and bio-oil being prioritised. There are some sites in Canada and Europe which produce biochar and subsequently burn it onsite for heat and power, which eliminates the GGR potential of the product (IEA, 2022a) and (Bioenergy ExCo, 2023). Analysis by the Royal Society indicates that biochar deployment could reach 5 $MtCO_2$/yr by 2050 (Royal Society, 2018), depending on resource constraints and competition with BECCS technologies.

3.3.4 Afforestation, reforestation and forest management

Afforestation, reforestation and forest management are various land based GGRs that consider carbon removals through woodland expansion and forest management. They are based on the principle that by increasing forest area, the amount of CO_2 absorbed from the atmosphere increases. The technology readiness level (TRL) of afforestation is 9 as it is robust, well evidenced, and already widely practiced throughout the world (Element Energy, 2021)

Deployment of afforestation and reforestation has several limiting factors; these include land availability, the supply of tree seed and saplings, and capacity to plant large areas. Further, there are sustainability issues associated with this GGR, such as risk of biodiversity loss, greater water demand, and land competition with food production. Afforestation is already commercially deployed in the UK, and there is potential to grow existing capacity with afforestation targets. However, to meet these targets, early deployment is required, along with appropriate selection of tree species, planting age, and yield class, as these factors directly affect carbon sequestered (Element Energy, 2021).

An appropriate MRV procedure will need to be outlined to verify woodland expansion and forest management; this should be long-term, and take into account the area, as well as characteristics, such as age, of the trees planted.

Reforestation has been successfully deployed in the UK, an example being Forest Carbon, who have led the way in developing woodland creation for carbon capture. Since 2006, Forest Carbon have aided in the planting of approximately 10.3 million new trees in 220 new woodlands, removing over 2.1 million tonnes of CO_2e from the atmosphere (Forest Carbon, 2023).

Air New Zealand's FlyNeutral programme, allows passengers to voluntarily offset 100% of the carbon generated from their flight. Although FlyNeutral enables Air New Zealand to purchase carbon credits from certified international projects, the airline also uses the FlyNeutral contribution to support reforestation, restoration, and regeneration of New Zealand's native trees (Air New Zealand, 2023).

3.3.5 Soil carbon sequestration

Soil carbon sequestration is a GGR method that considers how the carbon content of soil can be increased through land-use or land-management change. It is more relevant to agricultural land use, and hence has greater impact on cropland and grassland. The deployment of soil carbon sequestration takes place predominantly on agricultural land used for food production, as well as temporary and permanent grassland. It involves either applying compost/crop residues to fields, reducing soil disturbance by switching to low-till or no-till practice, changing planting schedules, or managing grazing of livestock (Element Energy, 2021).

The technology readiness of soil carbon sequestration as a GGR was assessed to be TRL 8. There are several reasons as to why the TRL is not higher, and this is mainly due to a lack of consensus on the magnitude and effectiveness of land use and management change. Furthermore, this GGR encompasses a complex range of potential management practices that are dependent on socio-economic and environmental context (Element Energy, 2021).

Several MRV protocols already exist for sequestering carbon in agricultural soils as a climate change mitigation strategy, however, these relate to a limited number of practices, such as cover crops, reduced tillage, and crop rotation. Despite the establishment of these protocols, there are associated MRV challenges, as the changes in soil can be relatively small in magnitude per unit area and slow to be fully achieved. Furthermore, after approximately 20 years, soil becomes saturated, and once saturated, it is assumed that land will require indefinite maintenance to avoid CO_2 being re-emitted. Therefore, cost-effective, long-term measurement of changes in soil carbon is required as part of a successful MRV procedure.

Soil carbon sequestration has been deployed in America, Australia, Europe, and the UK, although there is limited evidence of efficacy in the UK context. The Soil Inventory Project, a non-profit based in America, conducted a study on the regenerative farming methods, such as no-till agriculture, cover crops, and crop rotation on a 500-acre farm, and it was estimated that they successfully sequestered more than 100 tonnes CO_2/year (Morgan Stanley, 2021).

3.3.6 Mineral carbonation

Mineral carbonation as a GGR technology relies on the mineralisation reaction, whereby alkaline earth metals such as magnesium or calcium from silicate materials react with CO_2 to form stable carbonate rocks. The reaction process occurs naturally and has a slow reaction rate when observed over geological time scales, however, through the deployment of industrial processes, this can be sped up (Thonemann, et al., 2022). Mineral carbonation can be distinguished into in-situ (below the surface) and ex-situ (above ground). In-situ carbonation involves the injection of CO_2 into silicate-rich permeable rock, where conversion into carbonates occurs. Ex-situ refers to the exposure of crushed rocks, such as mine tailings or industrial wastes, on the Earth's surface to CO_2 rich gas, resulting in the production of a stable carbonate mineral (Royal Society, 2018).

There are large resource requirements for mineral carbonation, for example, ex-situ carbonation has significant water requirements to enhance reaction rates, and if additional mining is pursed, vast areas of land will be required. Both ex-situ and in-situ methods have high energy demands, however, when taking into account energy consumption and full life cycle, more CO_2 emissions are produced from ex-situ carbonation than removed in most cases. Other limitations include scalability, cost, as well as the fact that a carbon capture technology is necessary in conjunction with mineral carbonation (Royal Society, 2018).

Neither in-situ nor ex-situ carbonation have yet been pursued at a sufficient scale, hence there are no MRV protocols currently established. An appropriate MRV should give similar credit to in-situ carbonate as conventional geological CO_2 storage, particularly if it to be incentivised. It should also be noted that in-situ carbonation doesn't require long term monitoring for potential CO_2 leakages due to the CO_2 being chemically bound in the mineral matrix (Thonemann, et al., 2022). The products of ex-situ carbonation can be easily measured; therefore, it should not be challenging to establish an appropriate MRV protocol to account for the captured carbon (Royal Society, 2018). The UK, Iceland, and the USA are some of the few countries that have successfully deployed mineral carbonation as a GGR method. Carbon8 is a company based in the UK who have commercialised small scale ex-situ carbonation; their technology captures CO_2 from point sources, which then becomes an ingredient to carbonate industrial residues. The CarbFix project demonstrates in-situ carbonation in Iceland by injecting CO_2 into basalts, however, this is only at a scale of 0.01MtCO_2 (Royal Society, 2018).

3.3.7 Policy and regulatory environment

The UK Government has highlighted the commitment to incentivise, and support engineered GGRs in the UK Net Zero Strategy, including the deployment of 5 MtCO_2/year of engineered GGRs by 2030, with a potential increase to 23 MtCO_2/year by 2035, in line with the pathway provided for Carbon Budget 6 (2033-2037) (HM Government, 2021). In line with commitments, several advancements have been made in ensuring that commercial investment in GGRs is incentivised, through development of a policy and regulatory landscape. The approach consists of first supporting early commercial deployment, primarily through grant funding programmes, followed by moving towards a market-based framework for GGRs. Although advancements have been made, the deployment of GGRs must be accelerated if net zero targets are to be reached, as there are still several barriers that exist. Further details on barriers to deployment of GGRs are outlined in section 4.3.

To date, most funding schemes focus on providing grant funding towards capital costs of GGR technologies, hence reducing upfront costs for investors. A notable funding programme is the DAC and GGR Innovation Competition, a £100 million investment, providing grant funding for research and development of early-stage

GGR technologies (BEIS, 2022a). Several pilot scale projects are in development in the UK after receiving funding from the DAC and GGR Innovation Competition, consisting of BECCS hydrogen, DACCS and biochar.

Additional UK policy support includes the CCS Infrastructure Fund (CIF), a £1 billion investment, providing grant funding for capital costs for CO_2 T&S infrastructure, as well as the Industrial Carbon Capture (ICC) Business Model, providing capital grant funding for CCS projects and support for operational expenses, including T&S fees (BEIS, 2022c).

In recent years the UK Government has released several consultations on GGR business models, aiming to accelerate investment into GGRs. Current business models focus on engineered GGRs. GGR business models are still in development and hence there is uncertainty in the future policy landscape for GGRs; however, the UK Government has highlighted initial thoughts on proposed business models for GGRs. Firstly, it has been recognised that business models should be technology neutral, and not favour any specific GGR technologies over others, as it is anticipated that a broad range of GGRs will need to be deployed to reach net zero targets. Additionally, although it is also expected that GGRs may be able to be implemented outside of the UK at lower costs, the UK is committed to incentivising GGR deployment in the UK in line with net zero commitments (BEIS, 2022c).

There are already some existing revenue streams for GGRs, such as through voluntary carbon markets, however these are still fairly immature and are predominantly focussed on emissions avoidance projects or nature based GGR options. In more recent years, there has been a greater focus on engineered negative emissions credits in voluntary carbon markets, with multiple corporations announcing purchase agreements and partnerships to support engineered GGR projects (BEIS, 2022c). It is expected that voluntary markets will not be sufficient to support the scale of GGR deployment required to support net zero targets, hence other policy mechanisms are being explored.

In the UK Government's latest GGR business model consultation, it was highlighted that the current intention is to focus on supply-side interventions, possibly through the introduction of a contracts-based business model, with the three leading options consisting of a Negative Emissions Contract for Difference (CfD), a Negative Emissions Payment, and a Negative Emissions Guarantee (BEIS, 2022c). The consultation highlights that market demand for negative emissions is expected to increase over time, however currently, market prices may not be sufficient to sustain and promote the wide scale deployment of novel GGR technologies. UK Government intends to provide a response to the consultation in 2023, setting out a detailed policy proposal on the design and implementation of a GGR business model (BEIS, 2022c).

It is anticipated that, in the longer-term, demand-side interventions can be used to further incentivise GGRs through incorporation in compliance markets. Options could include a Carbon Takeback Obligation, requiring obligated companies to compensate for a fixed percentage of their remaining emissions through purchase of negative emissions credits, or the inclusion of negative emissions credits in the UK ETS (BEIS, 2022c). Emissions from hard-to-abate sectors, including aviation, would therefore be able to offset a portion of their emissions by purchasing negative emissions credits (BEIS, 2022c)

In March 2022, the UK ETS Authority launched a call for evidence on the potential role of the UK ETS in providing long-term markets and demand for GGRs. Areas that are being explored include the eligibility criteria, accounting requirements, and timings for the inclusion of GGRs in the market (BEIS, 2022c). Inclusion of GGRs in the UK ETS require robust MRV methods to be developed, as well as ensuring that GGRs are not used as an alternative to decarbonisation and instead utilised as a mechanism to support reaching net zero after decarbonisation options have first been implemented.

Advancements in CO_2 transport and storage (T&S) infrastructure are required to accelerate the deployment of GGRs; however, the costs of T&S infrastructure are high. Currently, there are ongoing plans in the UK to develop CO_2 T&S infrastructure, with a focus on shared infrastructure that can be used by multiple emitters located within industrial clusters in the UK. This provides opportunities for plants capturing CO_2 to use this shared infrastructure, hence distributing capital costs. Transport and storage operating costs can also be minimised by locating GGR facilities close to T&S infrastructure, hence reducing the total distance the CO_2 must travel to reach the storage location.

The UK has recently proposed a Transport & Storage Regulatory Investment model (TRI Model) (BEIS, 2022a), published in 2020 with several updates proposed throughout 2020-2022, highlighting a proposed model for utilisation of shared T&S infrastructure. The model also highlights how dispersed sites outside of industrial clusters can make use of the model. A 'user pays' economic model has been proposed, in which a Transport and Storage Services provider (T&SCo) will be awarded an economic license to design, build, own and operate a transport and storage network, in return for receiving revenue through charging fees to users of the transport and storage network. T&SCo is expected to be responsible for ensuring the long-term storage of CO_2, and hence the T&SCo would bear the risk of CO_2 leakage (BEIS, 2022b).

3.3.8 Summary

Although there are no commercial scale BECCS, DACCS or biochar plants available in the UK, it is evident that the deployment of GGRs is accelerating, with pilot plants being planned in the UK as well as operational in other countries worldwide. DACCS is expected to be commercially available in the UK by 2026, followed by BECCS in 2028 and biochar in 2030. Afforestation is already a widely used GGR method. Different GGR options have varying resource requirements, and hence this will influence the degree to which each option is deployed in the future, considering factors such as land availability for biomass feedstocks and availability of renewable energy. Further improvements are expected in the future to drive down costs and provide energy efficiency improvements.

Policy and regulatory support for GGRs is also accelerating, with the UK Government providing a wide range of support through grant funding schemes for capital costs, as well as funding schemes to provide subsidies for operating expenses, including T&S costs. The UK Government is also exploring options for technology-based GGR business models, T&S business models, and methodologies for MRV of negative emissions achieved through GGRs. The UK Governments GGR business model consultants have only covered engineered GGRs to date. Current policy support aims to incentivise all GGRs equally, as there is current uncertainty in the future landscape of GGR deployment, hence the UK Government does not wish to favour any technologies at the current time.

T&S infrastructure is also a crucial element towards enabling wide-scale deployment of GGRs. The availability of T&S infrastructure in the UK is growing, with the Government focusing on developing industrial clusters that can utilise shared T&S infrastructure, hence reducing costs for individual investors.

A summary of the different GGR options is outlined in Table 3-2 below.

Table 3-2: Comparison of GGR technologies

Technology	Cost, £/tCO_2	Land requirements, ha/tCO_2	UK indicative scale 2050, MtCO_2/year
DACCS	160 - 470	0.0003	25
BECCS	80 - 230	0.03 – 0.06	50
Biochar	14 - 130	<1	5
Afforestation, reforestation and forest management	2 - 23	0.1	15
Soil carbon sequestration	4 - 20	Applied to existing cropland so does not require additional land	10
Mineral carbonation	15 - 240	In-situ: Applied to natural rock deposits/underground reservoirs, hence no additional land requirements. Ex-situ: Requires potential additional land for mining, or storage of the carbonated product, but is not a limiting factor.	Theoretical potential is effectively limitless

Source: (Royal Society, 2018) (Vivid Economics, 2019)

4. POTENTIAL BARRIERS AND CHALLENGES

This section discusses the main barriers that the UK and the different stakeholders will face in implementing the different technologies under discussion in this study (SAF, ZEF and GGR).

4.1 SUSTAINABLE AVIATION FUELS

While several pilot and demonstrator scale SAF plants have been developed and are operating or planned for commercial deployment, there are a limited number of SAF suppliers at a commercial scale in the UK (the only one being Phillips 66 at Humberside). This stems mainly from the lack of demand, fuelled by underlying factors which we discuss in this section. An overview of a selection of SAF candidates, in the UK context, provided a wider coverage of some of the key parameters and their extent of influence on the overall sustainability on the topic of analysis. In this section, we will dive deeper into these parameters, identify the independent factors and interlinkages between some of the factors in terms of relevant policy, technical and infrastructure systems. This will provide insights into the perceptions of SAF as a whole and the subsequent impact on industrial and societal acceptance as a key solution to aviation decarbonisation.

Global market factors – Demand for air travel in the UK plummeted significantly (by 90% in 2020 and by 60% in 2021) with the onset of travel restrictions from the global pandemic in 2020 (House of Commons Transport Committee, 2021). This tilted the playing field for aviation in general, including any plans for its decarbonisation through SAF deployments, particularly among risk-averse stakeholders (e.g., investors, OEMs and airline operators). The use of SAF in UK aviation has been reported only since 2021; however, the current consumption rates amount to merely 0.15% of the conventional fuel consumption rates from 2019 levels. The introduction of a strategic SAF mandate, targeting the most promising candidates for immediate intervention (2025 onwards), is expected to improve the forecast scenarios and potential investor confidence. That said, SAF investors are also aware of the dynamic and the risk-averse nature of the aviation sector where assets with long-term investment cycles are determined based on the profitability of their lifetime operation.

Policy factors – While mechanisms like the UK SAF Clearing House, which are anticipated to support and expedite SAF testing and certifications is set to be launched mid-2023 (University of Sheffield, 2023a), the current lack of specifics on supporting frameworks to bridge SAF premiums and lack of roadmaps on SAF development, deepens the perception of investment in SAF refineries as a 'high risk'. This is further fuelled by other factors including lack of mandated, coherent guidance on the anticipated support mechanisms (planned for provision through the SAF mandate). These uncertainties could blur the lines in the anticipated reporting requirements and perceived risks to the fuel producers/suppliers and has also been raised as a key concern in the stakeholder consultation responses to the UK SAF mandate (DfT, 2022c). Nevertheless, recent developments reported in the second consultation of the SAF mandate, published in April 2023, discusses some of the key aspects directly contributing to fuel sustainability criteria including the implementation of RTFO-equivalent sustainability reporting, method of GHG accounting when calculating tradeable credits, electricity criteria addressing the inclusion of "additionality[11]" etc (DfT, 2023c). Use of a mature policy framework is encouraging from the angle of both the SAF's sustainability and on the overall grid-decarbonisation measures. The UK SAF mandate and its consultation responses discuss the importance of support mechanisms such as a CfD[12] to support fuel suppliers through offtake volume and price certainty. Additionally, there are indications of implementing a "buy-out" mechanism that is expected to support suppliers by discharging their mandate obligations in case where they are unable to fulfil their obligated supply target. The "buy-out" prices are anticipated to be set at a level that makes it more feasible for the suppliers to produce SAF, compared to opting to 'buy-out'. However, some of the revenue generated through this mechanism is expected to provide a crucial level of price support by future proofing against price fluctuations in the fuels market thus lowering the incidence of 'dead-weight' costs being transferred to the consumers (DfT, 2023c) .

Technical compatibility and related restrictions – SAF operation and compatibility studies, including component testing and demonstration flights, have been undertaken since 2015 and are ongoing. While all the SAF candidates are certified 'drop-in' alternatives, to date ASTM has approved a maximum of only 50% blends to ensure seamless on-board performance of the fuel blends. This performance is analysed through a series

[11] Additionality is defined as is renewable (or nuclear) energy that would not have been available to the grid in the absence of power demand from the SAF plant in question.

[12] CfD is a price support mechanism that corresponds to an arrangement or private law contract between the sustainable fuel producers and potential investors to support SAF production by providing price and offtake volume certainty to suppliers. This is expected to provide significant boost to the incentive for investment into UK SAF industry.

of laboratory, rig, component, and engine testing by the certification bodies, to measure the chemical and physical properties of the fuels in question, including their fuel handling properties, tribological properties after fuelling and during on-board operation (e.g., fuel storage, distribution, combustion, valve sealing, lubrication, and other interaction relative to the aircraft component systems). Unlike conventional jet fuel, neat SAF (100%) naturally lacks aromatics, which by aircraft fuel specifications, must form a minimum of 8% by volume, to ensure elastomer sealing and prevent fuel leaks. While this can be an environmental benefit, since aromatics are directly related to high soot formation and contrails, this proves to be a safety and performance implication. Additionally, SAF testing is majorly carried out on new models of engines, and there is the possibility that some of the existing fleet might never be compatible with 100% SAF blends. Therefore, SAF consumption, in particular higher blends, requires additional investigations, which can prove to be time and resource intensive.

Global feedstock market – It is generally not feasible to import SAF feedstock for the production of transport fuels due to a range of factors. CORSIA[13] currently incentivises countries to develop their own climate policies, which are expected to rely partly on their domestic feedstocks. This could lead to maximum utilisation of domestic waste and residue both in the EU and globally, increasing competition for the feedstock and limiting any scope of exports. For example, the UK currently depends on China for 62% of its UCO imports. But China is currently establishing a strong future vision for incorporating SAF production and transport decarbonisation targets into its wider climate policies (IEA, 2021). In addition to the difficulties associated with market-wide competition for SAF feedstock, supply chain uncertainties through climate-induced crop failures and geo-political instabilities also pose further feedstock-supply challenges. That said, fundamentally, imports of feedstock (depending on feedstock type and source location) may also prove to be infeasible due to the inherent energy expenditures and subsequent impact on the overall sustainability of the resultant fuel.

Limited range and supply of domestic feedstocks - A study by the Royal Society on SAF resource availability demonstrated a selection of domestically sourced oil-rich feedstocks such as rapeseed, miscanthus and poplar that could be used to replace the current demand for conventional jet fuel in the UK. While SAF production using bio-oil from these oil seeds appeared feasible, the amount of arable land required to cultivate these oil crops is likely to introduce issues pertinent to the sustainability of the resulting fuels. Any additional measures to convert their residual biomass (lignocellulosic residue) into SAF could be energy intense with relatively lower conversion efficiency (tonne of jet fuel per tonne of dry biomass). UCO is a feedstock that is produced in reasonable quantities in the UK (250 million litres in 2021), but the competition for its use is significant. For example, sectors such as animal feed or cosmetics also make use of UCO, and the amounts available for SAF production might thus be limited (DfT, 2023d). There is also competition for UCO from road transport, which uses this feedstock to produce HVO biodiesel for road and off-road machinery applications. The UK fulfils its additional demand primarily through imports, the future challenges of which were discussed in an earlier bullet point. More sustainable resources that are limited in supply for SAF production but have current application in other sectors such energy generation are municipal solid waste and sewage, are both low in GHG intensity and could prove to be additional sources of feedstock. The renewable content of the municipal solid waste in the UK is estimated at 40Mt and sewage at 1.4 million tonnes per year with a majority used in other sectors (composting and heat generation) (Royal Society, 2023). However, the heterogenous nature of these feedstock types and the current technological limitations need to be addressed to improve their productivity. Another key barrier to these feedstocks includes potential deviation from some of the existing uses in other sector (agriculture, energy generation, etc) and the lack of systematised framework for their collection and homogenisation, with the currently reported plants are either at conceptual or pilot stage. In the long-term, some of the key sources of feedstock for e-fuel production, waste gases, CO_2 from atmosphere (sourced through carbon capture) and green hydrogen may be more feasibly sourced from within the UK. However, to achieve this, current and medium-term renewable energy capacities need to be scaled up to cater for the future accelerated demands for captured CO_2 and green hydrogen, which is faced with severe competition from other sectors such as food and beverage, residential, and surface transport sectors (see sections on GGR, namely 3.3 and 4.3).

Production costs and underlying drivers – The ‘drop-in’ nature of the SAF candidates support plans for the use of existing conventional fuel infrastructure for the fuel distribution and handling. However, one of the biggest challenges to SAF commercialisation and market uptake are the costs associated with its production. SAF production is influenced by capital, operational and regulatory costs. Currently, there are fund allocations and investment roadmaps to support the SAF plant deployment, including the concluded GFGS, the Advanced

[13] CORSIA or Carbon Offsetting and Reduction Scheme for International Aviation is a global market-based mechanism that is dedicated to mitigating international aviation-related CO_2 emissions through co-operative approaches, as opposed to the national or regional regulatory framework operating in silos.

Fuel Fund which allocated £165 million to accelerate commercialisation of SAF plants between 2022 and 2025, and the establishment of the SAF Clearing House to streamline transition of, or upscaling, SAF production. From the production perspective, feedstock costs and the energy expenditure determine the market price of the resulting fuel. For industrial acceptance, focus must be put on driving the fuel costs down as they make up roughly 17-32% of an airline's operating costs (IATA, 2022). The impact of competition for feedstock, feedstock imports, conversion factors (tonnes of fuel per tonne of dry biomass) and the resulting energy expenditure have been discussed in relevant sections above. While this may be true for SAF candidates considered for short and medium-term application, PtL fuel, which is approximately six to seven times more expensive, is expected to make promising long-term solution for domestic aviation decarbonisation, supplemented by an accelerated deployment of renewable energy infrastructure as discussed above. This is expected to pose additional financial challenges through investment needs into innovation, scale-up and additional infrastructure costs.

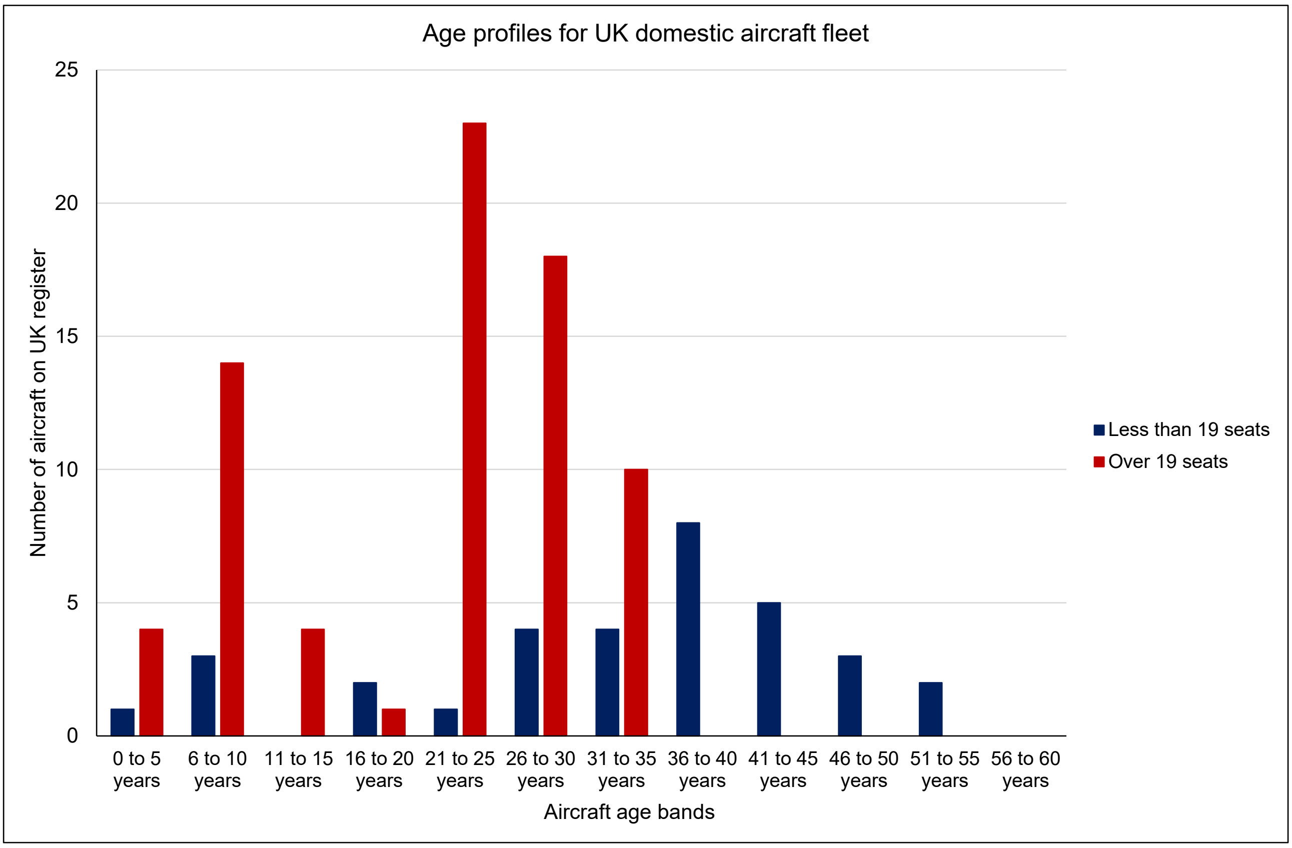
Sustainability-related concerns – Increasing demand for UCO, and its unregulated channels of import worldwide, has led to suspicions of illegal blending of virgin (i.e. not waste) oil to bulk up UCO supplies at source (DfT, 2021c). The lack of a well-defined framework to support the traceability of UCO feedstocks is expected to lead indirectly to additional environmental concerns and a potential food vs. fuel crisis. Agricultural residues have a current significant demand profile as bedding for animals, feed and, particularly, soil conditioners to ensure the return of nutrients (from the dry biomass) back to the arable land post-cultivation. From the perspective of land use, the study also highlighted the demand of nearly 30-70% of UK agricultural land (depending on feedstock and subsequently the fuel-type) for the cultivation of these energy crops. Diversion of agricultural residue from soil re-integration also introduces land-use emissions in the range of 50-70 gCO_2/MJ of jet fuel, on top of the overall life cycle GHG emissions which could have a direct impact on GHG accounting schemes within the proposed UK SAF mandate. Besides the requirements within the RTFO guidance, there are currently no regulatory frameworks that can assure sustainability or support the traceability of the feedstocks for SAF supplied to the UK. This is a key sustainability-oriented challenge to societal and industrial SAF acceptance.

4.2 ZERO-EMISSION FLIGHTS

Deployment of aircraft of ZEF will face a number of implementation barriers for aircraft manufacturers, airlines and airports.

Slow fleet replacement rate and long investment cycles of aircraft – Aircraft are capital-intensive, long-lived assets – usually flying for more than 20 years, with analysis of the current fleet used on UK domestic flights showing some smaller aircraft with over 35 years of age (see Figure 4-1). That means that aircraft entering the UK market now will still likely be flying in 2040. The longevity of the fleet means that it takes longer for airlines to introduce newer, more sustainable aircraft into service. This can be compounded by the time it takes aircraft to pass rigorous national and international safety standards, a particular issue for new design aircraft using novel fuels or energy sources, such as may be the case for zero emission (battery electric or hydrogen powered) aircraft. In principle, carbon pricing, such as through the UK ETS, should incentivise airlines to renew their fleet more rapidly (and to take up zero emission options when they become available). However, the aircraft manufacturing industry has recently been facing challenges in meeting production schedules and has a substantial backlog in orders (e.g. (Airbus, n.d.)), reducing the ability of airlines to renew their fleets as rapidly as they might wish.

Figure 4-1: Age profiles for UK domestic aircraft fleet



Source: Ricardo analysis based on CAA's G-INFO database.

Airlines' limited capacity to absorb extra costs – The airline industry is highly competitive, with thin profit margins (when compared to other sectors), and high capital and operational expenditures. This limits the capacity of airlines to absorb additional costs derived from decarbonisation measures, such as additional purchase costs for battery-electric of hydrogen fuel cell aircraft or increased fuel costs arising from the use of SAF instead of conventional fuel. Those issues are compounded by the limited scale of some of the airlines focusing on the UK domestic market for the majority of their operations, which further limits their ability to invest. Furthermore, those additional costs are likely to be passed on to air transport users – given the sector's low margins, increases in costs are generally passed through to consumers (Ricardo, 2021a) – which may have an impact on demand. The COVID-19 pandemic worsened the financial situation of airlines[14], further limiting their capacity to invest in zero emission aircraft.

Technology uncertainty – Given the long investment cycle of aircraft, aircraft manufacturers and airliners are generally very risk averse. This means that the industry may defer investment until a technology becomes a clear frontrunner and can be deployed at scale. This could delay the introduction of ZEF, as there will be lack of demand for manufacturers to develop technologies (as airlines wait for a more settled technology landscape), creating a "chicken-and-egg" situation. This could impact aspects such as developments in battery technology, resulting in initial battery-electric aircraft being less competitive or the establishment of standards for refuelling/recharging aircraft (see also next bullet point).

Lack of airport infrastructure – Whether for battery electric or hydrogen-powered aircraft, specialised infrastructure will be required at airports to enable ZEF[15]. Sufficient deployment of refuelling infrastructure in airports is essential to enable such technologies. As with the last point, however, the uncertainty in respect of

[14] The pandemic also contributed to the demise of a prominent airline which mostly served the domestic UK market, Flybe.

[15] For example, battery-electric aircraft will require charging capability, likely at every stand (including remote ones). "Rapid" charging at higher power rates will impose demands on the grid, at a time where demands are already increasing given the increasing electrification of more aspects of the UK economy (from road vehicles to heating in buildings). For hydrogen-powered aircraft, there will be a need for facilities to transport and store green hydrogen, and in the case of larger airports potentially manufacture green hydrogen on site (which would also have impacts on the grid). For more on these challenges with airport infrastructure see the final report for Project NAPKIN (Project NAPKIN, 2022) and the ZEFI roadmap (Connected Places Catapult, 2022).

the likely infrastructure frontrunner adds an additional layer of complexity. A clear roadmap on technology choices and development of standards for refuelling/recharging will be key to plan infrastructure needs accordingly. Aircraft equipped with new technology will also require new safety procedures at airports, with all that entails, including certification of procedures, new equipment, and training of personnel.

4.3 GREENHOUSE GAS REMOVALS

An increasing number of GGR pilot scale projects have commenced or are planned in upcoming years. It is therefore evident that the deployment of GGRs is accelerating, however several challenges and barriers still exist, and hence must be overcome to reach the quantity of carbon removal required to reach net zero targets. Challenges and barriers exist in the areas of technical, economic, infrastructure, environmental, social, policy and regulatory. Certain barriers are apparent across all GGR methods, whereas there are also technology-specific barriers only applicable to certain GGR methods. As most GGRs are still in development, barriers must first be overcome to enable GGRs to reach the scale of deployment required to reach net zero targets. This section therefore explores key challenges to accelerating the development of GGRs, followed by barriers that exist in creating a long-term market for GGRs. Further detail of key considerations required for inclusion of GGRs in the UK ETS is outlined in section 5.3.

Technical – Several technological barriers exist across all the different GGR options; however, efforts are underway to further develop these technologies, which will enable deployment at an increasing scale and consequently reduce costs. A common limitation for technology based GGRs is the high energy requirements associated with their operation; this is most notable for oxy-combustion capture, post-combustion capture and DACCS, all of which are particularly energy intensive. DAC is much more energy intensive than other GGR options.

The large energy demand for oxy-combustion capture arises from the use of air separation units required to produce a pure stream of oxygen needed for combustion, whilst for DACCS, it is a result of the need to process dilute concentrations of CO_2 form the atmosphere. Pre-combustion capture also exhibits high energy requirements due to the cleaning of syngas from biomass gasification (e.g., Sulphur oxide (SOx) and NOx removal), as most gas cleaning methods are not substantially efficient on a large scale. For solvent-based post-combustion capture systems, which are the most advanced post-combustion capture technologies, the largest challenge relates to the high energy penalty associated with solvent regeneration. The electricity demand for technology based GGRs should be met using renewable energy where feasible; this will subsequently increase the demand for renewables, which creates further challenges, as outlined in section 5.1.

Nature based GGRs on the other hand do not exhibit high energy requirements, nor significant technical challenges; however, technical challenges do arise regarding the MRV process. It is harder to quantify nature based GGRs, for example, during soil carbon sequestration, changes in soil can be relatively small in magnitude per unit area and slow to be fully achieved, consequently requiring highly sensitive technology to detect such changes, which is yet to be commercially available. As there are barriers associated with quantifying the efficacy of nature based GGRs, it makes it more challenging to determine the scale at which these methods need to be deployed to reach the net zero target set for UK domestic aviation.

Infrastructure – The most cited barrier for technology GGRs is the need to develop CO_2 transport and storage infrastructure; this must be prioritised if GGRs are to be successfully deployed at large scale in the short timeframes necessary. CO_2 transportation predominantly takes place via pipeline, shipping, rail, or truck, with pipelines being favoured for transporting over moderate distances (100 - 500km) or of large quantities (1 - 5 Mt), whilst shipping is better suited for longer journeys (over 2,400km).

The establishment of CO_2 transport infrastructure ensures a substantial cost, especially on a small scale, however, the cluster approach, where infrastructure is shared, allows economies of scale benefits to be incurred through the reduction of costs and risk associated with the operation of a full supply chain. If an emitter is not in close proximity to these clusters, it will incur increased operational costs due to the requirement to transport CO_2 to the storage site or existing clusters. The UK Government has recognised the importance of considering dispersed sites and their accessibility to the CO_2 transport and storage network. As a result, the UK government is considering how to incorporate non-piped sources of CO_2 under several business model (BEIS, 2022b).

Resource requirements – The large-scale deployment of BECCS not only involves changes in current land use, but also has significant land requirements. By dedicating vast regions to the production of energy crops, it creates potential conflict between food and fuel production, which may impact the price of agricultural commodities. Regardless of the feedstock used, there are considerable land requirements, ranging from 0.03 – 0.06 ha/tCO_2. Furthermore, by implementing these changes to land use, it may lead to reduced biodiversity as well as species loss. For BECCS to be deployed in the UK at scale, biomass will need to be imported to meet the demand. The import of feedstock creates challenges relating to emissions accounting; therefore, it is essential that policy and MRV frameworks are established that include how to account for imports. Moreover, relying on the import of biomass to meet the UK's demand further complicates the challenges, as other countries with decarbonisation targets will likely require imported biomass, resulting in competition due to the increased demand and limited supply. Alternatively, countries producing biomass may begin to prioritise domestic use, again, reducing the amount of biomass available for importing.

Different GGR technologies have varying land use requirements, for example sufficient space between units is needed when employing DACCS to limit the effects of local CO_2 depletion; this is essential, as local CO_2 depletion negatively impacts vegetation and wildlife. Biochar is another example, where land is required to first grow the biomass feedstock, and then another area is needed for spreading, which has potential to lead to land competition issues. Afforestation requires large land areas, which is consequently a limiting factor for deployment. Furthermore, competition for land may limit deployment and expansion, or lead to indirect land use change emissions elsewhere. As there is a barrier to the scale at which nature based GGRs can be deployed, after a period of time, other GGRs may have to be utilised to continue meeting the net zero target.

The growth of energy crops requires large volumes of water, approximately 60m^3/tCO_2. There is an additional water demand for the operation of BECCS, with the exact demand varying depending on the specific technology. Whilst certain GGRs like biochar do not use large quantities of water and are said to improve the water-holding capabilities of soil, for other technologies such as DACCS, water plays a more pivotal role in their operation (Royal Society, 2018). For all variations of DACCS, regeneration of the capture agent requires water, as well as heat and low pressure. Another example is the use of oxy-combustion with BECCS power; this process has high water requirements due to the production and processing of the biomass fuel. The deployment of BECCS will increase water demand, which may lead to a rise in water prices and in some cases negatively impact wildlife due to the diversion and reduction of available fresh water.

High energy intensity can be observed across multiple technology based GGR technologies, however, is most evident for BECCS power, mainly due to the use of air separation units required for oxy-combustion, or during post-combustion capture due to the relatively low concentration of CO_2 in the flue gas that must be separated. DACCS also presents high energy demands, particularly for high temperature systems that require approximately 900°C to regenerate the sorbent. The large energy demands ideally need to be met using renewable energy sources; if using fossil fuel derived energy, there will be a reduction in the overall negative emissions achieved.

Economic – Economic barriers to the deployment of technology based GGRs exist to a large extent due to the high capital costs associated with the upfront investment. The addition of CCS increases the capital investment required, which could be seen as increasing investment risk, particularly due to the uncertainties surrounding current policy and lack of transport infrastructure. There are a variety of abatement costs associated with GGRs, considering that many are at various stages of development, and how these are highly dependent on both technology and project. Further factors impacting capital investment include site scale and location.

Apart from the high CAPEX involved, there are high operational costs associated with technology based GGRs that arise from feedstock (biomass) and/or energy requirements. This is most prevalent for DAC, which requires the construction of large capture units to process and extract the dilute concentrations of CO_2 in the air (~400 ppm) and consumes significant heat and power. The cost estimates for BECCS are highly dependent on electricity sales price, feedstock cost, plant lifetime, and efficiency. Frequently observed efficiencies of BECCS plants are estimated at 22%, with some reaching 33%; however, it is believed that there is potential to improve to approximately 38% which is comparable to typical figures of coal-fired power plants (35 – 41%).

For post-combustion carbon capture, the large energy penalty associated with solvent generation is another example of the high operating expenditure involved with technology based GGRs. It is believed that the key barriers to technology based GGR deployment are financial, on account of lack of policy incentives to make the high capital and operational costs of GGRs attractive, as well as the lack of stable revenue streams for the provision of negative emissions. Although the economic barriers associated with land based GGRs are significantly lower than that of technology based GGRs, there are accompanying costs such as labour, as well as long term monitoring and maintenance.

To help mitigate this barrier, the UK government announced in the spring budget that there will be £20 billion available for CCUS, including partnerships and funding for educational institutions to develop GGR technologies.

Supply chain – The increased demand for negative emissions will result in an increase in the demand for carbon capture equipment. It can therefore be expected that the number of suppliers will need to increase to meet this demand to avoid significant supply chain barriers. In recent years, the number of companies offering carbon capture solutions has increased rapidly, with major companies including Aker Carbon Capture, Climeworks, Carbon Engineering, Carbix, Carbon Clean, amongst others.

At present, there is a lack of a carbon capture equipment supply chain within the UK, as there are a limited number of companies locally manufacturing such equipment. Carbon Clean Solutions is a notable company headquartered in the UK providing modular DACCS systems, however, it is unclear whether their equipment is manufactured in the UK. Importing equipment will aid in resolving this barrier, although, additional challenges may arise due to Brexit, particularly when importing from Europe, such as significant shipping delays. Other noteworthy companies in the UK include Carbogenics and Carbon Infinity, both start-ups that have developed biochar and DACCS technologies, respectively (Trendafilova, 2022). The U.S. and Canada appear to be leading the way with number of companies providing carbon capture equipment, as illustrated by Carbon Engineering, LanzaTech and Svante. Whilst in Europe, countries such as Norway, Denmark, Switzerland, and the Netherlands dominate, with companies including Aker Carbon capture, Climeworks, and CO_2 Capsol.

Another significant supply chain limitation is the shortage of skills within this industry, resulting in an inability to develop the market in line with demand. This compounded with the lack of suppliers, creates consequential barriers for deployment.

Finally, there are also issues around the supply chain for CO_2 storage, including lack of suitable fabrication yards in the UK, and competition for skilled workers with other major projects that are likely to happen at the same time as CCS deployment, such as offshore wind, oil and gas decommissioning and hydrogen transport and storage.

Afforestation and reforestation rely directly on the supply of tree seeds and saplings; therefore, if there is any disruption in the supply chain, this would greatly affect deployment and hence the ability to reach net zero targets.

Social – Bioenergy feedstock is typically of lignocellulosic nature, for example wood and agricultural residues, which are unlikely to compete with food supply; however, they may cause issues relating to land-use change. Energy crops on the other hand, have already caused serious socio-economic problems in several countries, in particular over land tenure and loss of ecosystem services. There are also societal concerns relating to land-use change, especially in cases where energy crops are grown on agricultural land or existing woodland is used for biomass supply.

A study on the perception of BECCS was recently undertaken in the UK, where a large majority (79%) of participants stated that prior to the experiment they knew little to nothing about BECCS (Bellamy, et al., 2019). It was also concluded that after learning about BECCS, there were no participants who were strongly opposed to it, with more overall support shown. The unfamiliar nature of GGRs may cause apprehension to its wide scale deployment.

As with BECCS, there are societal concerns and resistance of nature based GGRs regarding land-use change on the scale that would be required, as well as biodiversity loss and altered water use, however, this is most relevant to afforestation.

Regulatory – Currently the costs of GGRs are prohibitively high, resulting in economic barriers to their widescale deployment. The UK Government are proactively considering the most appropriate support to limit such barriers; however, support has been limited to date. Therefore, further financial incentives are necessary to provide stakeholders with greater long-term clarity and revenue certainty. As highlighted previously, the UK Government has outlined that the current intention is to focus on supply-side interventions, followed by introducing demand-side interventions in the longer term. However, there is still overall uncertainty into the final approach that will be taken.

Additionally, the requirement to have effective MRV standards in place is another key challenge. Most notably, to be classed as negative emissions, the total quantity of CO_2 permanently removed and stored must be greater than the total quantity of CO_2 emitted to the atmosphere. The simplicity of measuring the amount of carbon captured and stored varies throughout the various GGR technologies, with some requiring periodic monitoring. The implementation of robust procedures to account for permanence of storage of CO_2 is also necessary for both biological (e.g., soil or trees) and geological storage (e.g., sub-surface geological formations) pathways. This is because permanence of storage, associated risk of reversal, and cost of monitoring varies. Currently, there is uncertainty surrounding MRV framework in the UK relating to GGRs, as several important factors still need to be considered, such as:

- Avoiding double counting; including accountability and accuracy to ensure a removal is not credited twice.
- Additionality: proving the removal activity is additional to what was already occurring, in the absence of the GGR intervention
- Establishment of independent regulatory body

There is also a need to establish a certification scheme to verify the credibility of the negative emissions.

Competition from other sectors – In addition to the aviation sector, there are other key sectors, such as industry, which are expected to require the use of GGR offsets to account for residual emissions. There will therefore be direct competition with the UK domestic aviation sector for use of GGRs in other sectors.

4.4 COST ESTIMATIONS

To understand, at a high level, the potential cost implications of achieving net zero for domestic aviation in 2040, some initial estimates have been made of the costs associated with the different measures described in this report.

The assumptions associated with the calculations are described in Table 4-1.

Table 4-1: Assumptions for high-level cost calculations

Category	Assumption	Value
Overall demand		
Air travel demand in 2040	Domestic travel grows from current levels in line with demand growth in 2017 DfT UK aviation forecasts. Growth rate derived from data provided for 2040 and 2016 and 2030 (linearly interpolated to 2020). (DfT, 2017)	Demand (passenger distance flown) grows at 0.75% per annum, applied from 2022 to 2040.
Baseline emissions in 2040	Growth to 2040 in line with UK domestic aviation demand growth rates derived from 2017 DfT UK aviation forecasts (DfT, 2017). Applied to “current” emissions from Jet Zero Strategy (DfT, 2022a)	Growth rate of 0.75% per annum, applied from 2022 to 2040. 1.40 million tonnes CO_2 current value, growing to 1.60 million tonnes by 2040
Sustainable aviation fuels		
Total SAF consumption	Total fuel consumption (in kerosene equivalent terms) derived from baseline CO_2 emissions in 2040 and CO_2 emissions factor of 3.15[16]. SAF responsible for all fuel consumption except hydrogen above	96.4% total energy consumption in 2040 428,343 tonnes SAF
SAF price premium	Average values for 2040 used in (Ricardo, 2022), derived from those in (European Commission, 2021)	£738 per tonne premium
Zero emission flight		

[16] Note that, unlike battery-electric and hydrogen-fuelled aircraft, no acquisition costs are included for larger aircraft, as they will be the same types as those without the measures described here, but will use SAF rather than kerosene to reduce emissions.

Category	Assumption	Value
Battery electric aircraft	Replace entire UK fleet of small turboprops[17] by 2040. Grow fleet numbers from 2022[18] in line with UK domestic aviation demand forecasts (DfT, 2017).	33 aircraft in current fleet, increasing to 38 aircraft by 2040
Battery electric aircraft price	Price premium for battery electric taken from (Ricardo, 2022), with the price scaled by the ratio of maximum take-off mass between a Dornier 228 (small turboprop aircraft) and an Airbus A320neo (the aircraft type for which the electric option was originally identified)	£502,000 per aircraft
Hydrogen fuel cell aircraft	Entry into service from 2030; number in fleet in 2040 the same as the current UK fleet of larger turboprops and small regional jets[19] of less than 10 years of age, grown in line with UK domestic aviation demand forecasts (DfT, 2017).	21 aircraft by 2040
Hydrogen fuel cell aircraft price	Price premium for “Liquid hydrogen + fuel cell propulsion” aircraft from (Ricardo, 2022)	£2,782,000 per aircraft
Hydrogen fuel consumption in 2040	Aircraft category of 20 to 100 seats, up to 750 km range is currently responsible for approximately 15% of demand; assume also 15% of emissions. Only the aircraft of up to 10 years age in 2040 will be hydrogen fuelled (others will have been replaced by conventionally-fuelled aircraft before 2030) Energy consumption of hydrogen fuel cell aircraft (per passenger-km) is the same as that of a conventionally-fuelled aircraft.	6,701 tonnes of hydrogen in 2040
Hydrogen fuel price	Price for 2040 from (Ricardo, 2022)	£2,218 per tonne
Greenhouse Gas Removals		
SAF lifecycle emissions	WTW reduction relative to conventional fuel as per assumptions included in DfT Sustainable Aviation Fuels Mandate consultation stage cost-benefit analysis (DfT, 2023e)	70% reduction relative to conventional fuel
Emissions to be removed	Remaining 30% emissions from SAF (30% total SAF consumption, converted to CO_2 at 3.15 emissions factor)	463,057 tonnes
GGR costs	Average of prices in Table 3-2, weighted by the UK indicative scales for the different technologies	£172 per tonne CO_2

Based on these assumptions, high-level estimates have been made of the resulting costs (more details of the cost calculations are provided in Appendix 3). For aircraft acquisitions (for battery-electric and hydrogen fuel cell aircraft) the calculations were for the total fleet of aircraft operating in 2040, independently of when they were delivered. For other costs (fuel, GGR) the calculations covered just the costs incurred in 2040, as these are what is required to deliver on the net zero target in 2040.

Note that while, as described in Table 4-1, the additional costs all fall on the aircraft owners and operators (airlines), this description is not intended to suggest that they should be responsible for managing all the different cost elements. The progression towards net zero is the responsibility for the whole domestic aviation sector and managing the additional costs would be expected to be a collaborative effort.

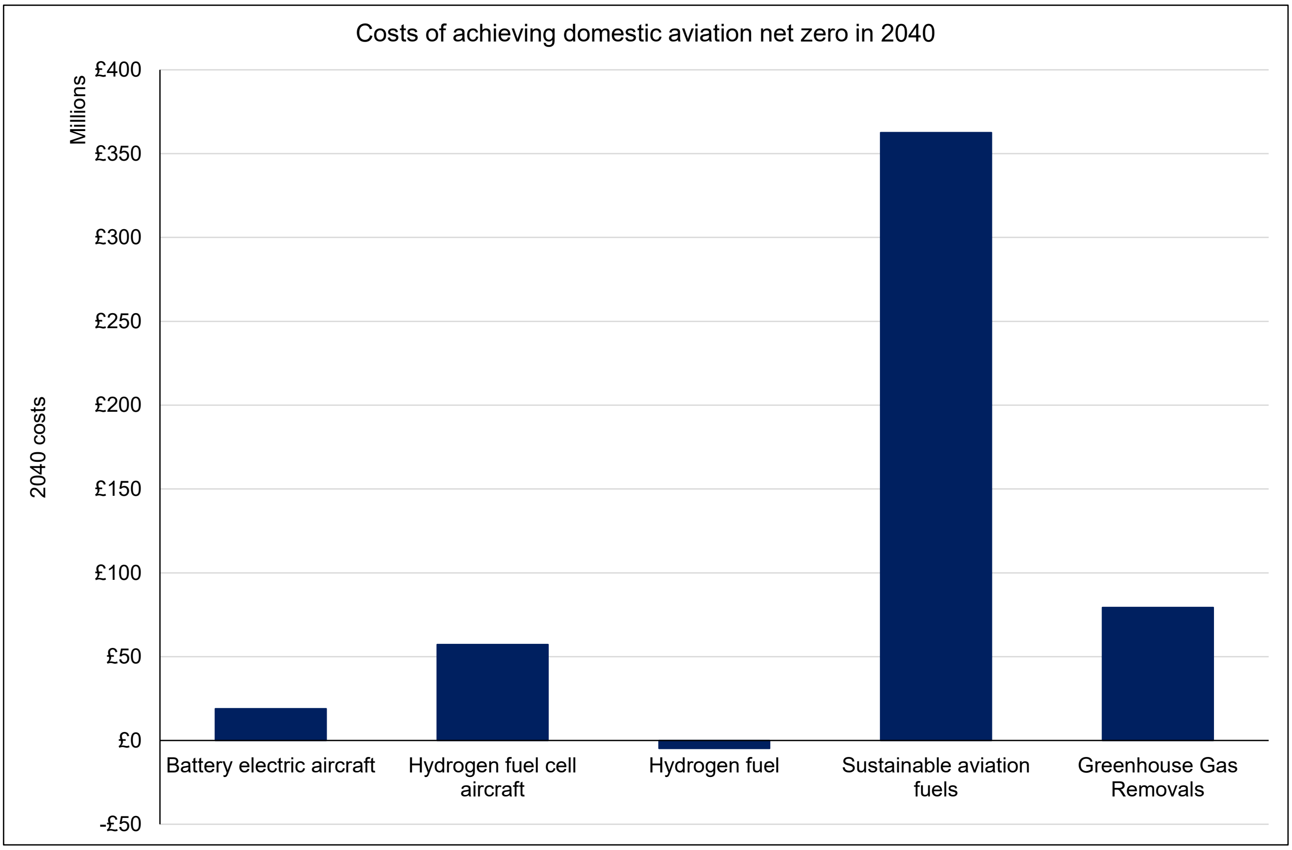
[17] Britten Norman Islander, De Havilland Canada/Bombardier/Viking Air DHC-6 Twin Otter, Dornier Do-228

[18] Numbers of small turboprop aircraft in current fleet extracted from G-INFO database, hosted by UK CAA (CAA, n.d.)

[19] ATR-42, ATR-72, Saab SF340, Jetstream 41, Embraer EMB-135, EMB-145, Fleet numbers extracted from G-INFO database, hosted by UK CAA (CAA, n.d.)

Overall, the total cost estimate for 2040 was approximately £513 million[20], split across the different categories as shown in Figure 4-2.

Figure 4-2: Estimated costs for net zero in 2040, by cost category



The premium for SAF (i.e. the increase in costs due to using SAF rather than fossil kerosene) is clearly the dominant cost element in these results, at approximately £363 million. Conversely, the assumed price for hydrogen (per unit of energy) is lower than that of kerosene in 2040, therefore the cost impact is slightly negative. Other costs (acquisition of battery-electric and hydrogen aircraft, purchase of GGR “offsets”) are significant, but much lower than SAF.

This estimated impact of SAF on costs is based on an average SAF price of £1,706 in 2040, representing an approximately 75% increase over conventional fuel (£966, both prices based on the values used in (Ricardo, 2022), which were based on those for the ReFuel EU Aviation Impact Assessment study (European Commission, 2021)). According to IATA (IATA, 2022), since 2020, fuel has accounted for between 18.7% and 30.1% of airlines’ operating expenses, so such an increase in fuel price would equate to an increase of between 14.0% and 22.6% in their operating costs. Those figures are global values, including both domestic and international aviation; it might be expected that the percentage of operating costs formed by fuel for domestic airlines could be lower (as flight distances are shorter) and, further, the impact of fuel costs would be offset somewhat by carbon pricing (and the expectation that SAF would be exempt). Nonetheless, the results suggest that the uptake of SAF to meet net zero by 2040 would result in a significant increase in airlines’ operating costs.

As noted above, the costs shown for battery electric and hydrogen fuel cell aircraft are the additional costs to operators when purchasing these aircraft (compared to the costs of fleet replacement with conventional aircraft). As such, these are incurred (approximately uniformly) over the period between the initial entry into service of the type (about 2025 for battery electric aircraft and 2030 for hydrogen fuel cell aircraft) and 2040. The fuel and GGR costs shown, however, are solely those incurred in 2040. In reality, these additional fuel costs are likely to increase gradually over time, as SAF represents a progressively greater proportion of fuel supply and greater greenhouse gas removals are purchased. Taking an assumption of linear growth to reach

[20] All cost values presented here are in 2022 GBP.

the values shown for 2040 provides the cumulative costs to 2040 (discounted to 2022 at different discount rates) shown in Table 4-2.

Table 4-2: Estimated cumulative additional costs to 2040 under different categories, discounted to 2022 at different discount rates (millions of GBP)

Discount rate	Battery-electric aircraft	Hydrogen fuel cell aircraft	Hydrogen fuel costs	Sustainable aviation fuels	GGR	Total
0%	18.9	57.3	-26.1	2,900.7	635.3	3,586.2
3%	13.8	38.6	-16.8	1,967.4	430.9	2,433.9
6%	10.3	26.5	-11.0	1,365.2	299.0	1,690.0
9%	7.9	18.4	-7.3	968.1	212.0	1,199.2

It is important to note that there is significant uncertainty associated with all of the cost projections presented above. They are based on best available estimates of future costs, but all the technologies considered are quite new and there is no experience of their implementation to base cost projections on. Further, the developments of the costs over time (for fleet replacement, fuel purchase or GGR purchase) are based on simple linear projections rather than detailed fleet modelling.

5. RECOMMENDATIONS ON POTENTIAL POLICY INTERVENTIONS REQUIRED FOR NET ZERO UK DOMESTIC AVIATION

The results of the analysis undertaken in this study allow for several high-level non-technical policy recommendations in respect of technology, legislation and funding that could be actioned to enable net zero domestic aviation. These policy recommendations are organised by the three groupings of key technologies discussed elsewhere in the report.

5.1 SUSTAINABLE AVIATION FUELS

5.1.1 SAF prioritisation

Prioritisation of synthetic fuels – As they offer the greatest potential for emissions reduction (potentially up to 100%), the prioritisation of research and development and investments need to be on these synthetic fuels, in view of addressing technological and sustainability (environmental and economic) challenges associated with their production – including carbon capture infrastructure in the UK (see section 5.3) and ensuring targets for green electricity supply in the UK can be met (see section 5.1.3).

UK SAF Clearing House – Establish a clear, coherent framework for its operations (timelines, specifications, data requirements and flow of processes/subprocesses) that interacts with the UK SAF mandate, particularly its approaches to monitoring the sustainability/eligibility criteria of the SAF candidates. In addition, UK Clearing House's engagement and coordination with the OEMs (drawing upon novel fuel specifications and current standards operation in aviation technologies) and other key stakeholders (distribution and ground handling) of the aviation sector could be used to accelerate cross-industry cooperation in steadily repurposing/ adapting existing domestic technologies and infrastructure ready for current and higher blends of SAF uptake/ use.

UK ETS criteria – Aviation GHG monitoring over the medium and long-term period require periodic review, including updates of the Emission Reduction Claim Criteria. UK ETS could engage with the UK SAF Clearing House and its potentially vast network of aviation stakeholders to monitor developments in SAF compatibility trajectories within aviation technologies and ground handling technologies. This could be used to update or develop more stringent sustainability requirements pertaining to SAF.

Sustainability assurance and traceability – The sustainability criteria to qualify the eligibility of feedstocks and SAF candidates need to be aligned with international best practices. Particularly, these requirements must also cover the sustainability characteristics of the imported feedstocks through appropriate tools or certification systems that assure the true 'waste' nature of the feedstock. This will help overcome unintended negative impacts related to 'bulking up' of waste feedstocks with virgin mix at source location or sourcing of feedstock which may qualify as 'eligible' at source locations but transition to unsustainable when being transported over long-distances.

Technical compatibility for 100% SAF blends – Support the international efforts to certify aircraft engines up to 100% SAF use. Enabling the use of higher SAF blends which in turn can augment the current decarbonisation efforts and create additional demand for SAF.

5.1.2 Emergent pathways and fuel price mitigation

Emergent Pathways – Develop additional strategies to accelerate support for promising emergent SAF technologies and FOAK (First-of-a-Kind) projects. While the UK Government supports SAF infrastructure deployment partially through capital grants and through CfDs, additional support could be given through loan guarantee programmes backed by the government to help project financial case and reduce overall project risks.

Fuel price gap – The high-level estimates of costs have indicated that the additional costs due to SAF use are the dominant additional cost for the domestic aviation sector in 2040. Therefore, it is vital to establish clear strategies or mitigation measures on how revenue certainty mechanisms can help bridge the price gap between the price of the current fuel and market price of SAF. This needs to be established through the review, assessment and alignment of the various revenue certainty mechanisms discussed in UK SAF mandate including performance-oriented production tax credit[21] and blenders tax credit[22] and through taxation of conventional jet fuel. While the second consultation on the SAF mandate discusses the significance of "buy-out" mechanism to partly bridge the price gaps (DfT, 2023c), further information on how this is to be realised within the support framework need to be furnished.

5.1.3 Overarching recommendations

More stringent SAF mandate for domestic aviation – Given the need to rely on SAF to reach net zero domestic aviation by 2040, a separate, more stringent, SAF mandate for domestic aviation could be considered, potentially reaching close to 100% by 2040 – this contrasts to the 17% to 32% being considered for the UK aviation sector as whole for the same year. To ensure that greater uptake of SAF will lead a high level of emission reduction on a WTW basis (thus less need to rely on GGR to achieve net zero), consideration should also be given to a high requirement of synthetic fuels within that mandate for domestic aviation.

Considering this is an ambitious task, key stakeholders other than fuel suppliers (to whom the proposed SAF mandate applies), such as airline operators may need to be considered to share a part of the obligation towards SAF targets, though their contribution would be from a demand angle, as opposed to the proposed policy focusing solely on the fuel supply side. In practice, for airlines operating both domestic and international flights, they would be subjected to a SAF mandate which could amount to a weighted average of the core SAF mandate and the domestic SAF mandate across the wider network[23].

Consideration should be given, however, not only to the practically of having a subset of airlines that is subjected to a different SAF mandate, but also to other potential negative impacts of such a mandate including the additional domestic SAF demand (thus putting even more pressure on costs), the additional administrative and operational burden of this additional, more complicated, mandate, and unintended financial impacts on specific routes and geographies (and relevant passengers). On this last point, as noted in section 4.4, additional costs with SAF will represent 80% of the total costs needed to achieve net zero domestic aviation in 2040, so there is a need to ensure that the push for net zero does not lead to detrimental impacts on demand and that UK domestic aviation continues to guarantee the necessary connectivity levels in the country (see also Appendix 2).

Decarbonisation of the electrical grid – Decarbonisation of the grid by 2035 as per the government's strategy (BEIS, 2021a) is essential to ensure the sustainability of SAF produced in the UK and allow for the shift towards synthetic fuels. It also supports the development of relevant infrastructure to generate relevant inputs (CO_2 and H_2) locally than relying on future imports.

5.2 ZERO-EMISSION FLIGHTS

For ZEF, the crucial aspects will be to support the development of aircraft and to support their deployment in the UK domestic market.

Development of zero emission aircraft is a multinational endeavour, so unilateral action from the UK may need to be accompanied by wider international activity. Nevertheless, the UK has a thriving aerospace industry with the presence of most of the established aircraft manufacturers, as well as new entrants into the field of zero emission aircraft. The UK can support these by continue to support R&D in the UK, with initiatives such as the Aerospace Growth Partnerships Strategy for Net Zero (AGP, 2022).

For the deployment of these aircraft into the market and actually achieving zero emission flights, several policy actions can be considered.

Financial incentives – A high-level estimate of costs for zero-emission aircraft for domestic flights in 2040 gives a total additional cost of approximately £76 million across the replacement of 56 aircraft between 2025 and 2040, with the majority of the increased costs occurring between 2030 and 2040 when hydrogen-fuelled regional aircraft become available. Tax breaks and financial incentives could be given to airlines for the purchase of zero emission aircraft in this period. Attention should be given to ensure that these tax breaks are not set up in such a broad way that they would apply for the purchase of aircraft that airlines would purchase

[21] An incentive (provision of credit against taxes) targeted at fuel producers who meeting specific criteria, within a defined timescale (for example 20 years), producing a certain type of fuel (SAF, in this case).

[22] An incentive targeted at fuel producers that blend a certain type of fuel (SAF in this case), and it provides a credit against taxes

[23] That is, in practice, airlines operating both international and domestic flights would have a slightly higher mandated blend to take into account both

normally. Applying the same caveats, scrappage schemes to incentivise fleet replacement are another way to support a more rapid uptake of zero emission aircraft (Kaminski-Morrow, 2020). In considering such schemes, it will be important to take account of whether the manufacturing sector could produce sufficient aircraft to meet any expedited fleet turnover scenario. Although a scrappage scheme (or similar) could, in principle, bring forward the renewal of the fleet with ZEF aircraft, the need to put the new types into production, with potential challenges associated with the new technology, may mean that most of the renewal (and hence the need for support) will occur towards 2040.

Supporting use of zero emission aircraft on PSO routes – As noted in section 1.2.1.2, the first markets where ZEF will be possible will be thin routes with low passenger numbers. Many of these routes operate on a PSO basis (namely those serving Scottish islands, with funding coming from the Scottish government (Hendy, 2021)). This combination of factors could create an opportunity to include requirements for zero-emission aircraft in appropriate PSOs (with appropriate level of support), spurring investment in these aircraft and earlier rollout than if only market forces were at play. It is likely that this would require greater levels of subsidy to these routes, either at national level or by the devolved administrations.

Airport policy measures – Finally, an identified barrier for the deployment of zero emission aircraft relates to airport infrastructure (see section 4.2). The UK government is currently consulting on the details of a 2040 Zero Emission Airport Target in England (DfT, 2023a). As part of that overall strategy for airports, there would be a need to ensure that policies exist to accommodate airport's role in supporting ZEF, and that airports supply the necessary infrastructure for operators to not to be constrained in their operation of ZEF because of lack of airport infrastructure. Upstream from that deployment of infrastructure, policy can support, likely in conjunction with international partners, the development of standards for airport infrastructure and its interaction with zero emission aircraft, certification of said airport infrastructure, safety procedures, etc. The Government funded the development of a Zero Emission Flight Infrastructure Standards Action Plan published in March 2023; however, continued activity from industry will be required on this. Contributing to the development of understanding of the required infrastructure upgrades, and the development of policy, the Connected Places Catapult is delivering the Zero Emission Flight Infrastructure (ZEFI) programme (Connected Places Catapult, 2023). Recently, the focus of the ZEFI programme has concentrated on the requirements for hydrogen-fuelled aviation, reflecting the limitations identified on the extent to which battery-electric aircraft will be deployed.

5.3 GREENHOUSE GAS REMOVALS

As many GGR options are still in developing stages, policy interventions are needed to support the development and deployment of GGRs, hence allowing them to be readily available for use as an offset mechanism within the UK domestic aviation sector. Policy interventions considered here therefore include a combination of general recommendations that will enable the development of GGRs, as well as UK domestic aviation specific recommendations. As UK domestic aviation is a key sector that is anticipated to make use of GGRs as an offset mechanism, the sector can showcase support and commitment to supporting development and investment in GGR options. Policy suggestions may also apply to international aviation, however the UK domestic aviation market is specifically considered within these recommendations.

Provide support to accelerate the deployment of GGRs – Further policy incentives should be developed to address the short and longer-term financial barriers to widescale GGR deployment. In the shorter term, the financial barrier to investment in GGR infrastructure needs to be addressed through the establishment of policy incentives that aid in funding the construction of GGRs. Direct capital funding and investments have been the focus to date during the early stages to mitigate the high costs to investors of establishing new infrastructure. Further funding support should focus on mitigating uncertainties in revenue, hence providing longer-term revenue certainty to GGR investors.

The UK Government has highlighted that a likely suitable policy option is through the introduction of a contract-based mechanism, with three potential mechanisms consisting of a Negative Emissions CfD, Negative Emissions Payment and Negative Emissions Guarantee. In all cases, negative emissions credits can be available to be purchased, such as in voluntary markets, with the Government providing revenue stability and bearing some of the risk associated with low market prices. This can therefore support deployment of GGRs, hence increasing availability of negative emissions credits that can be purchased by the UK domestic aviation sector.

As the projects shift away from pilot scale into commercial scale, market-based mechanisms are required to drive demand in the longer-term for GGRs. Incorporating GGRs into regulatory frameworks and carbon trading schemes will create a long-term demand and stable revenue stream for the production of negative emissions. This will therefore provide a platform for the UK domestic aviation sector to purchase negative emissions credits to offset residual emissions, through a ‘polluter plays’ model. With time, less reliance on subsidies is anticipated to be required as negative emissions market prices increase.

Inclusion of GGRs in the UK ETS - A key option currently being explored for a market for GGRs is inclusion within the UK ETS. In comparison with CORSIA, the UK ETS is specifically targeted at UK emissions and will include the domestic aviation sector (which CORSIA will not). Consideration should be given to supporting increased demand for GGRs through their inclusion within the UK ETS. This would encourage the UK domestic aviation sector to invest in GGR technologies, hence supporting an increase in the demand for GGRs to offset residual emissions. However, current uncertainties surrounding the inclusion of GGRs into the UK ETS still remain. At this time there are no additional benefits of achieving negative emissions compared to capturing and storing CO_2 captured from fossil sources. In order for the incorporation to be successful, there are key barriers and considerations that must be explored.

- The core differences in different GGR options must be recognised and accounted for. Key differences to consider include the variations in long-term storage, likelihood of carbon leakage and overall costs for each GGR option. GGR methods such as afforestation will have a shorter long-term storage potential and lower overall costs, whereas methods such as DACCS will have a greater long-term storage potential and higher implementation costs.
- It must be ensured GGR offsets are not used as an alternative to decarbonisation, but only as an option to offset emissions which cannot be reduced through decarbonisation measures. The UK aviation sector should therefore first introduce quantities of SAF and ZEF to the maximum potential, followed by utilising GGR offsets solely for any residual emissions. In the latest GGR business model consultation (BEIS, 2022c), the UK Government highlighted that their approach to GGR deployment is to ‘incentivise negative emissions to balance emissions from hard-to-abate sectors, ensuring that GGRs are not deployed as a substitute for emissions reduction and do not reduce the pressure to decarbonise’.
- The historic prices of carbon in the UK ETS will incentivise the cheapest GGR options, and the price is currently not high enough to support expensive GGR technologies. Inclusion of GGRs in the UK ETS without any other supporting policy will likely result in the most support for nature-based options. Consideration should therefore be given as to what supporting policy is needed to enable inclusion of all GGRs in the UK ETS.
- Determination as to whether or not GGR credits should be treated as entirely interchangeable with conventional carbon permits.
- MRV challenges must be overcome in order to protect the integrity of the UK ETS. A robust MRV framework must be in place for each GGR technology, as well as the establishment of a regulatory body to verify the quantity of negative emissions achieved and hence, available negative emissions credits.
- Determination of how to consider co-benefits for certain GGRs must also be considered. For example, certain nature-based approaches may have wider environmental benefits such as improved biodiversity.
- Interaction with Article 6 of the Paris Agreements must be explored. Article 6 of the Paris Agreement allows countries to cooperate to achieve emissions reduction targets; countries could therefore transfer carbon credits obtained in other countries and make use of them towards their own emissions reduction targets.

Develop a robust MRV framework for each GGR option – For a GGR approach to be credibly carbon negative, there needs to be a means of quantifying its ability to remove more GHG emissions than it creates, and permanently storing it. Therefore, a robust MRV framework must be developed for each GGR option to ensure genuine climate benefits. The implementation of a rigorous MRV framework is important from both a carbon accounting and CO_2 liability perspective and is also essential to allow for the integration of GGRs into carbon markets. Ownership of the credits needs to be clearly defined as well as the establishment of a certification scheme for negative emissions credits. An MRV framework should therefore also have a mature governance framework for GHG accounting and accountability. Calculated negative emissions achieved as well as reported must be carefully reviewed to ensure that negative emissions are not double counted by the organisations involved.

Provide support to accelerate the deployment of CO_2 T&S infrastructure – As the deployment of technology based GGRs is inherently linked to the availability of CO_2 T&S infrastructure, significant efforts should be focused on developing T&S infrastructure and ensuring the correct business models are in place to provide certainty and incentivise investment.

Confirm a stance on the sustainability of the use of biomass and biomass imports – Establish regulatory frameworks that addresses the sustainability issues associated with use of biomass and/or imports for GGR usage. The regulatory framework or payment structure should account for life-cycle emissions of biomass, as well as other sustainability criteria such as biodiversity. Large-scale deployment of BECCS in the UK will require significant biomass imports, therefore, it is essential that safeguards are in place to ensure this does not adversely affect the UK sustainable development goals.

Alignment with other aviation offset schemes – When developing any policies related to GGR in the context of UK domestic aviation, consideration should be given to other offset schemes already in existence. Notably, CORSIA is an international agreement which the UK is a part of, and which has specific requirements for offsets related to international aviation. Given that many of the airlines operating domestic flights in the UK also fly routes where CORSIA will apply, to reduce the regulatory burden on those airlines a minimum level of convergence with CORSIA should be considered, notably in terms on what types of offsets will be allowed domestically[24].

UK domestic aviation engagement in ongoing developments – The UK domestic aviation sector should showcase demand for GGRs, through actively engaging in communications related to planned UK Government support and market developments. While the UK Government is still developing planned GGR business models, the UK domestic aviation sector can seek to show support and encouragement for GGRs, such as through directly investing in GGR technologies. The negative emissions achieved from these facilities can therefore be earmarked for the domestic aviation sector, thereby also supporting to ensure that the negative emissions credits are available to support the sector reaching net zero targets. However, this rests on the UK Government developing the necessary MRV methodologies and a negative emissions credit certification scheme.

6. CONCLUSIONS

This section summarises the main key findings of the study.

6.1 SUSTAINABLE AVIATION FUELS

The use of SAF will be crucial for net zero domestic aviation to be achievable by 2040. This is due to long replacement cycles of current aircraft, combined with the fact that zero emission aircraft are still in their early stages of development. This means that **drop-in SAF will be necessary for almost the entirety of the UK domestic aviation market** to decarbonise.

Some SAF technologies are already **technologically mature and available in the market**. SAF **can reduce WTW emissions up to 100%** (for synthetic kerosene). While in the coming years biofuels will have a preponderance in SAF production, to fully decarbonise the sector, widespread usage of synthetic kerosene will be required. Currently, the use of these SAF on aircraft are limited to 50% blends (i.e., the fuel used is a mixture of up to 50% SAF and the rest fossil-based kerosene). Aircraft and engine manufacturers are now working to increase that limit to 100% (i.e., aircraft running solely on SAF), allowing for the **full benefits of SAF to be realised**. This is expected to become certified for current and future aircraft well in advance of 2040.

Some of the main barriers related to the widespread use of SAF relate to the **availability and sustainability of (some of) the SAF feedstocks** (including the availability of enough renewable energy for producing synthetic kerosene). **The price of SAF** for airlines vis-à-vis conventional jet fuel will also be a barrier – however, as production of SAF scales up the price differential between all types of SAF (including, crucially synthetic kerosene) and fossil kerosene is expected to reduce, **making the transition to SAF less costly**.

To overcome these barriers, several policy interventions can be considered. For one**, prioritisation should be given to the production and use of synthetic kerosene**, which will involve actions on carbon capture infrastructure (see also section 6.3 on GGR) in the UK and on the supply of renewable energy. In the short

[24] For more details on eligible offsets under CORSIA see ICAO (2023).

and medium-term, efforts must be made to firm-up and synchronise the diverse responsibilities between the UK SAF Clearing House and the UK ETS to realise the goals and underlying objectives of the UK SAF mandate. This is crucial to ensure the promise of SAF supply needed for UK domestic aviation decarbonisation by 2040, as per the scenarios in the UK SAF mandate. More crucially, to facilitate this decarbonisation, there is a need to ensure appropriate **sustainability assurance and traceability** (for which the UK SAF Clearing House could play a role) to ensure that the use of SAF does indeed lead to reductions in carbon emissions for the UK aviation sector.

6.2 ZERO EMISSION FLIGHTS

While ZEF, i.e., flights using zero emission aircraft using energy carriers such as electricity and hydrogen, have high levels of potential in the very long term (2050 onwards), in the period considered for this study (i.e. up to 2040), **ZEF applicability in the UK domestic market will be limited** (only around 15% of current domestic passengers fly on routes where zero emission aircraft are likely to be used by 2040). ZEF could, however, become commonplace by 2040 on flights providing connectivity to many of the UK remotest regions (as they generally use smaller aircraft). This will bring challenges of its own, namely in terms of **airport charging and refuelling infrastructure**, and the **supply of electricity and/or hydrogen** to the aircraft. Overall, there is also a need to ensure that barriers with **technology uncertainty** are removed, as that will be a constraint for airlines wishing to invest in zero emission aircraft.

Policy could play a key role in supporting the earlier deployment of ZEF. Working with our international partners, the UK can push for the development of **appropriate standards and certification procedures** for zero emission aircraft and associated airport infrastructures (e.g., charging standards for battery electric aircraft) – this will also support the burgeoning UK industry investing in the sector. As the role of airports in the Jet Zero strategy is further developed, attention needs to be put on the **need to ensure that airport infrastructure capable of supporting ZEF is appropriately considered** on any airport development strategies. Finally, as ZEF will primarily be used initially on very thin routes, some of which operate under publicly funded PSOs (with funding coming either from the UK government or the devolved administrations), consideration should be given to the inclusion of requirements for **zero-emission aircraft in appropriate PSOs**, with appropriate levels of funding.

6.3 GREENHOUSE GAS REMOVALS

For the UK domestic aviation sector to reach net zero emissions, GGR are likely to be needed – by 2040 it is expected that some drop-in SAF will not be zero-emission WTW, thus **there will be a need to offset remaining emissions**. GGR can be **nature-based or technology-based**, with the latter expected to more significantly contribute to large scale, long-term CO_2 removal and thus more likely to be useful to support the Jet Zero goals for domestic aviation. The UK Government has highlighted the commitment to incentivise, and support engineered GGRs in the UK Net Zero Strategy, and significant efforts are already underway to develop GGRs in the UK, with efforts focusing on feasibility studies, as well as **deployment of pilot and commercial scale GGR facilities**.

As with the other technologies analysed in the study, several barriers remain to be overcome with GGR. These include the **electricity requirements** (an issue also faced by synthetic kerosene) as many of these processes are very energy intense, the need to **develop CO_2 transport and storage infrastructure across the UK, land requirements, and high capital and operational costs**. The UK domestic aviation sector will also face **competition from other sectors** for the use of GGRs to offset residual emissions, which is of particular importance as the target for net zero in UK domestic aviation is earlier than in other sectors.

Multi-pronged policy support is needed across all these barriers, including **direct capital support shifting towards market-based mechanisms** as technologies mature for both GGR production and T&S infrastructure. The UK Government is developing a contract-based business model for early GGR projects and exploring the role of voluntary and compliance markets (such as the UK ETS), as a long-term market framework for GGRs. In order to develop the role of GGRs in voluntary and compliance markets, key steps must first be undertaken, including development of an **MRV methodology** for each GGR and a negative emissions certification scheme with an independent regulatory body. The creation of a **capable regulatory framework** must address issues such as the sustainability of different GGR technologies and adequate carbon accounting. The UK domestic aviation sector can seek to showcase support and demand for GGRs, through mechanisms such as directly investing in GGRs, thereby the resulting negative emissions can be utilised to offset residual emissions from the UK domestic aviation sector. However, this is reliant on the UK Government developing an MRV methodology and negative emissions certification scheme.

Finally, as GGR will be used in aviation offset schemes beyond UK domestic aviation (notably CORSIA), it will be important that there is a **minimum level of alignment** between policies that are developed at national level and those implemented internationally. This would help reduce the regulatory and financial burden to the airline industry.

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APPENDIX 1 DEFINITIONS OF NET ZERO

As part of considering the definition of net zero for this study, a brief review was made of different definitions in the literature, many in the context of different sectors. Possible high-level definitions of net zero that have been identified include:

- Net zero refers to the balance between the amount of greenhouse gas produced and the amount removed from the atmosphere (National Grid, n.d.)
- Net zero refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal out of the atmosphere (Net Zero Climate, n.d.)
- Net zero means cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance. (United Nations Net Zero Coalition, n.d.)
- Net zero emission means that all man-made greenhouse gas emissions must be removed from the atmosphere through reduction measures, thus reducing the Earth's net climate balance, after removal via natural and artificial sink, (see: What are negative emissions?), to zero. (My Climate, n.d.)
- "A Net Zero city or region will set and pursue an ambitious 1.5°C-aligned science-based target for all emissions sources covered within the BASIC+ reporting level of the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC). Any remaining hard-to-decarbonise emissions can be compensated with certified greenhouse gas removal (GGR)."

  "To reach a state of net zero emissions for companies implies two conditions:

  - To achieve a scale of value-chain emission reductions consistent with the depth of abatement achieved in pathways that limit warming to 1.5°C with no or limited overshoot and;
  - To neutralise the impact of any source of residual emissions that remains unfeasible to be eliminated by permanently removing an equivalent amount of atmospheric carbon dioxide." (Carbon Trust, 2023)

At its highest level, the different references suggest that net zero is a balance between emissions of greenhouse gases (GHG) to the atmosphere and those being removed from the atmosphere. However, the more ambitious definitions, such as those from the UN and the Carbon Trust, include an element of maximising reductions in emissions first, then using removals to deliver the net zero balance.

In the context of aviation, with its reliance on high energy density (liquid) fuel, it is challenging to eliminate carbon-containing fuels and, hence, carbon dioxide (CO_2) emissions in the engine exhausts, particularly for medium and long-haul flights. Therefore, the emissions reductions need to include the absorption of CO_2 from the atmosphere as part of the fuel production process, whether by plants used in biofuel production, including intermediary products such as UCO, or via technologies such as direct air capture (DAC) as part of the production of electrofuels ("e-fuels" or "synthetic fuels"). This balance can be included by considering aircraft emissions as "well-to-wake" (WTW) emissions, including the emissions from the fuel production process (which may be negative for the greenhouse gas absorption by plants and DAC systems).

APPENDIX 2 OTHER ISSUES TO CONSIDER TO ACHIEVE NET ZERO DOMESTIC AVIATION

In this appendix several other aspects that could impact the ability of UK domestic aviation to reach net zero by 2040 are briefly discussed.

Connectivity, in particular to remote regions – Some of UK's most remote regions rely on domestic air transport to maintain connectivity with the wider UK and, in many cases, it is the only viable mode of transport for both passengers and freight. For these communities, air transport plays a crucial role in enhancing economic opportunities and the ability of these regions to retain and attract population, tourists and investment. As measures such as SAF, ZEF and GGR are applied throughout the UK domestic air market, this could lead to increased costs for airlines that are then passed through to consumers – given the sector's low margins, increases in costs are generally passed through to consumers (Ricardo, 2021a). This would then lead to a reduction of demand (either no travel or switch to other modes[25]), that could lead to cuts to air services as they become unprofitable for airlines to operate (Ricardo, 2021a). This is an area that should be given particular attention, given the crucial role of domestic aviation for some communities, taking into account the legal and regulatory framework in place (e.g., in terms of what routes qualify for PSOs procedures).

Competitiveness of UK airports and airlines – Pressure for the UK domestic aviation sector to reach net zero ahead of international markets could impose burdens on UK airlines and airports that could potentially jeopardise their competitive position vis-à-vis their peers. For airlines operating in the UK and abroad (which is the case for some of the airlines operating in the UK domestic market), decarbonisation measures would impose additional costs on a portion of their routes, reducing their overall profits and placing them at a disadvantage on routes between the UK and a third country (OECD/IEA, 2008). For airports, the issue is one of hub-switching. A portion of the UK domestic traffic are connecting passengers, i.e., passengers flying a domestic flight to a hub airport (usually in London) and then continuing their journey onwards to a third country. If decarbonisation measures on domestic flights lead to an increase in their costs vis-à-vis flights to neighbouring countries, passengers might choose to connect to a different flight in a foreign airport (like Paris or Amsterdam) instead of connecting in the UK (Adler, et al., 2022). This would be detrimental for the position of UK hub airports against the ones in the EU and beyond. These effects could also constitute a form of carbon leakage, if these new international trips replace domestic trips that would have lower emissions – the overall effect is unclear and would need to be studied further to assess the true impact.

Air traffic management (ATM) – ATM modernisation will support UK domestic aviation reaching net zero by 2040. When fully implemented by 2040, the CAA vision for ATM in the UK will enable a more efficient use of the airspace (CAA, 2023). This will not only increase capacity, but will enable aircraft to follow more efficient flightpaths, which lead to lower fuel burn and lower emissions on each flight. Without these improvements, increasing congestion in UK airspace could lead to increases of up to 12% of CO_2 emission per flight (domestic and non-domestic) by 2030 (ACOG, 2022). This shows the crucial role that ATM modernisation will have in supporting the Jet Zero strategy goals.

Non-CO_2 impacts – One of the priorities of the Jet Zero strategy, the non-CO_2 impacts of aviation[26], is of growing interest amongst researchers and policy makers. This is because they can represent up to two-thirds of aviation's contribution to climate change (EASA, 2020) (Klöwer, et al., 2021). However, their impact is still subject to much debate, and the non-CO_2 impacts of aviation on climate are eight times more uncertain than those resulting from CO_2 (Lee, et al., 2021). One area of particular uncertainty relates to the non-CO_2 impacts of the use of SAF (Teoh, et al., 2022). Given the relevance of SAF in achieving the Jet Zero goals, understanding these impacts and ways to mitigate them (both technically and from a policy perspective) will be crucial in avoiding a situation where CO_2 emissions reach net zero, but where the climate impact of UK domestic aviation is still significant due to non-CO_2 emissions.

[25] In general, it is considered that demand for domestic aviation in Europe is relatively elastic (Intervistas, 2007), likely due to the fact that alternatives by ground transport common. Changes in 2023 in the Air Passenger Duty charged on domestic flight (a reduction from £13 to £6.50 per passenger) has seen claims by airlines that the number of domestic passenger could increase as much as 31% (Amin, et al., 2023), showing the impact of relatively changes in the price of air travel could have on demand for domestic flights. However, for many remote regions ground transport might not be available, which might lead to some trips simply not happening (i.e., not replaced by a trip by land) if prices raise considerably.

[26] Which can be defined as "[the] non-CO_2 emissions of gases and aerosol particles affect atmospheric composition and cloudiness, adding to the overall climate impact from the sector's CO_2 emissions" (Lee, 2018). The first in-depth analysis of these impacts was done in 1999 by the IPCC (Penner, et al., 1999).

APPENDIX 3 COST CALCULATION DETAILS

Section 4.4 presents the results of high-level estimations of the costs associated with the implementation of the measures described in this report. This appendix presents the details of those calculations.

Section 4.4 includes a table of the assumptions used in these cost estimations as Table 4-. That table is repeated here (Table 10-1), and after the table the details for different categories of costs are provided.

Table 10-1: Assumptions for high-level cost calculations

Category	Assumption	Value
Overall demand		
Air travel demand in 2040	Domestic travel grows from current levels in line with demand growth in 2017 DfT UK aviation forecasts. Growth rate derived from data provided for 2040 and 2016 and 2030 (linearly interpolated to 2020). (DfT, 2017)	Demand (passenger distance flown) grows at 0.75% per annum, applied from 2022 to 2040.
Baseline emissions in 2040	Growth to 2040 in line with UK domestic aviation demand growth rates derived from 2017 DfT UK aviation forecasts (DfT, 2017). Applied to “current” emissions from Jet Zero Strategy (DfT, 2022a)	Growth rate of 0.75% per annum, applied from 2022 to 2040. 1.40 million tonnes CO_2 current value, growing to 1.60 million tonnes by 2040
Sustainable aviation fuels		
Total SAF consumption	Total fuel consumption (in kerosene equivalent terms) derived from baseline CO_2 emissions in 2040 and CO_2 emissions factor of 3.15[27]. SAF responsible for all fuel consumption except hydrogen above	96.4% total energy consumption in 2040 428,343 tonnes SAF
SAF price premium	Average values for 2040 used in (Ricardo, 2022), derived from those in (European Commission, 2021)	£738 per tonne premium
Zero emission flight		
Battery electric aircraft	Replace entire UK fleet of small turboprops[28] by 2040. Grow fleet numbers from 2022[29] in line with UK domestic aviation demand forecasts (DfT, 2017).	33 aircraft in current fleet, increasing to 38 aircraft by 2040
Battery electric aircraft price	Price premium for battery electric taken from (Ricardo, 2022), with the price scaled by the ratio of maximum take-off mass between a Dornier 228 (small turboprop aircraft) and an Airbus A320neo (the aircraft type for which the electric option was originally identified)	£502,000 per aircraft
Hydrogen fuel cell aircraft	Entry into service from 2030; number in fleet in 2040 the same as the current UK fleet of larger turboprops and small regional jets[30] of less than 10 years of age, grown in line with UK domestic aviation demand forecasts (DfT, 2017).	21 aircraft by 2040

[27] Note that, unlike battery-electric and hydrogen-fuelled aircraft, no acquisition costs are included for larger aircraft, as they will be the same types as those without the measures described here, but will use SAF rather than kerosene to reduce emissions.

[28] Britten Norman Islander, De Havilland Canada/Bombardier/Viking Air DHC-6 Twin Otter, Dornier Do-228

[29] Numbers of small turboprop aircraft in current fleet extracted from G-INFO database, hosted by UK CAA (CAA, n.d.)

[30] ATR-42, ATR-72, Saab SF340, Jetstream 41, Embraer EMB-135, EMB-145, Fleet numbers extracted from G-INFO database, hosted by UK CAA (CAA, n.d.)

Category	Assumption	Value
Hydrogen fuel cell aircraft price	Price premium for "Liquid hydrogen + fuel cell propulsion" aircraft from (Ricardo, 2022)	£2,782,000 per aircraft
Hydrogen fuel consumption in 2040	Aircraft category of 20 to 100 seats, up to 750 km range is currently responsible for approximately 15% of demand; assume also 15% of emissions. Only the aircraft of up to 10 years age in 2040 will be hydrogen fuelled (others will have been replaced by conventionally-fuelled aircraft before 2030) Energy consumption of hydrogen fuel cell aircraft (per passenger-km) is the same as that of a conventionally-fuelled aircraft.	6,701 tonnes of hydrogen in 2040
Hydrogen fuel price	Price for 2040 from (Ricardo, 2022)	£2,218 per tonne
Greenhouse Gas Removals		
SAF lifecycle emissions	WTW reduction relative to conventional fuel as per assumptions included in DfT Sustainable Aviation Fuels Mandate consultation stage cost-benefit analysis (DfT, 2023e)	70% reduction relative to conventional fuel
Emissions to be removed	Remaining 30% emissions from SAF (30% total SAF consumption, converted to CO_2 at 3.15 emissions factor)	463,057 tonnes
GGR costs	Average of prices in Table 3-2, weighted by the UK indicative scales for the different technologies	£172 per tonne CO_2

Battery-electric aircraft

A review of the G-INFO UK aircraft fleet database, hosted by the CAA (CAA, n.d.), for aircraft types of less than 19 seats that would be used on commercial flights identified the following number of aircraft (Table 10-2).

Table 10-2: Aircraft suitable to be replaced with battery-electric aircraft registered in the UK

Aircraft type (code)	Number aircraft
BN2A	5
BN2B	16
DHC6	5
DO228	7
Total	33

It was assumed that these aircraft could all be replaced by battery-electric types by 2040. Further, it was assumed that the number of aircraft would increase in line with the forecast increase in demand for domestic aviation.

Table 72 of the DfT aviation forecasts (DfT, 2017), give seat-distance flown values for UK domestic aviation under a baseline case as:

- 22,345 million kilometres in 2016.
- 26,681 million kilometres in 2040.

Combining these two figures gives an average annual growth rate of 0.75%. As these forecasts were derived prior to the COVID-19 pandemic, it is assumed that the resulting growth rate can be applied to the current (post-COVID-19) demand for long-term forecasts.

Applying this growth rate to the 33 aircraft currently in service gives 38 battery electric aircraft in service by 2040.

The Ricardo study on *Investment Scenario and Roadmap for Achieving Aviation's European Green Deal Objectives by 2050* (Ricardo, 2022) identified a price premium of €7,057,832 per aircraft for a battery-electric aircraft. However, that was for an Airbus A320-size aircraft. Therefore, the price was scaled by the ratio of the maximum take-off masses (MTOM) of a Dornier 228 (6.4 tonnes, (Homeland Security Technology, undated)) and an Airbus A320 (79 tonnes, (Airbus, n.d.)), to give a price premium of €571,774, or £501,952 (using an exchange rate of 0.8779 for April 2023 (xe.com, 2023)).

Multiplying this price premium by the 38 aircraft required by 2040 gives a total additional cost (over that required to purchase conventional aircraft) of **£18.95 million**.

Hydrogen fuel cell aircraft

The calculations of the additional purchase costs of hydrogen fuel cell aircraft follows a similar approach to that of battery electric aircraft. In this case, the current fleet is that of the larger turboprops and smaller regional jets in the G-INFO database. As hydrogen fuel cell aircraft are expected to start to become available in 2030, all such aircraft in service in 2040 will be less than 10 years old. Therefore, the assessment considers the number of relevant aircraft in the current fleet less than 10 years of age.

Relevant aircraft types in the G-INFO database are shown in Table 10-3 below.

Table 10-3: Aircraft suitable to be replaced with hydrogen fuel cell aircraft registered in the UK

Aircraft type (code)	Number aircraft	Number aircraft less than 10 years old
ATR42	7	2
ATR72	30	16
Jetstream 41	14	0
SF340	6	0
EMB135	2	0
EMB145	15	0
Total	74	18

Of 74 aircraft of relevant size and type in the current UK fleet, 18 (24.3%) are less than 10 years of age. Projecting these values to 2040, again in line with the DfT demand projections, suggests that the fleet in 2040 will consist of 85 aircraft, of which 21 will be less than 10 years of age and hence may potentially be hydrogen fuel cell aircraft.

The European aviation Green Deal study identified a price premium for a hydrogen fuel cell aircraft of €3,168,634 or £2,781,698. Multiplying the expected number of fuel cell aircraft[31] by this price premium gives a total additional cost for purchasing hydrogen fuel cell aircraft between today and 2040 of **£57.28 million**.

As described above, the calculations for the additional purchase costs of battery-electric and hydrogen fuel cell aircraft were for the costs associated with the aircraft that will be in service in 2040. As such, they represent total expenditure over the period from 2025 (for battery-electric aircraft) or 2030 (for hydrogen fuel cell aircraft) to 2040. The other costs described below, for fuel consumption and for GGR, are just for the costs associated with aircraft operations in 2040.

[31] When deriving the cost values, the calculation uses the detailed growth rates and, therefore includes a non-integer number of aircraft (20.591 aircraft); the numbers of aircraft are presented here as integer values for simplicity.

Hydrogen fuel costs in 2040

The current total CO_2 emissions from domestic aviation is quoted as 1.40 million tonnes in the Jet Zero Strategy (DfT, 2022a). Applying the average growth rate in demand of 0.75% per annum (identified above) to this gives a forecast 1.601 million tonnes of CO_2 emissions in 2040 (as a baseline value).

As shown in Table 1-, 14.9% of the total UK domestic RPK is performed by aircraft of a size suitable for replacement by hydrogen fuel cell aircraft (those from 20 to 100 seats). Applying this percentage to the emissions identified above indicates that 238,536 tonnes of CO_2 emissions would be attributed to these aircraft in 2040 in the baseline case. This corresponds to 75,726 tonnes of conventional aviation fuel (using the emissions factor for conventional aviation fuel of 3.15 kg/kg).

As described above, 24.3% of the aircraft in the fleet are less than 10 years of age and it is assumed that the same percentage of the fleet in 2040 will be less than 10 years of age and, hence, could be hydrogen fuel cell types. Applying this percentage to the baseline fuel consumption in 2040 gives 18,420 tonnes of aviation fuel. Using an assumption of constant energy requirement (i.e. the hydrogen fuel cell aircraft will require the same fuel energy as the aircraft type it replaces[32]), this quantity of aviation fuel corresponds to 6,701 tonnes of hydrogen consumed in 2040[33].

The aforementioned study from Ricardo (Ricardo, 2022) calculated fuel costs, including a conventional fuel price of €1,100 (£965.7) per tonne, and hydrogen price of €2,218 (£1,947.2) per tonne in 2040. Applying these unit prices to the quantities of conventional fuel and hydrogen presented above gives a **reduction** in cost for hydrogen fuel of **£4.74 million** in 2040.

SAF costs in 2040

As noted above, the estimated total emissions from UK domestic aviation in 2040 is 1.601 million tonnes of CO_2 in the baseline case. This would correspond to a fuel consumption of 508,426 tonnes of fuel. As the relevant aircraft are small and fly only short routes, it is assumed that the contribution of aircraft that may be battery-electric in 2040 is very small. The equivalent conventional fuel consumption of the hydrogen fuel cell aircraft is 18,420 tonnes; therefore, the remaining 490,006 tonnes of fuel would need to be replaced by SAF (in a scenario in which all kerosene fuel used on domestic flights is SAF by 2040).

The aforementioned study from Ricardo (Ricardo, 2022) included prices for fossil kerosene (€1,100 or £965.67 per tonne in 2040) and a range of SAF types, with an average of €1,942.90 (£1,705.64) per tonne in 2040. Multiplying the price per tonne of SAF by the SAF consumption in 2040 (above) gives a total cost of £835.78 million, which would be £473.19 for the same quantity of fossil kerosene. The difference between the two costs gives an additional cost of **£362.59 million** in 2040 for using SAF instead of fossil kerosene.

GGR costs in 2040

The estimated consumption of SAF in 2040 is 490,006 tonnes. As shown in the assumptions table (Table 10-1), it is assumed that SAF offers an average 70% reduction in CO_2 emissions compared to conventional fuel. Therefore, the net emissions from SAF would be 463,057 tonnes CO_2.

The average price for GGR, shown in Table 3-, is £172 per tonne CO_2.

Therefore, the total costs for removing the residual emissions using GGR would be **£79.41 million** in 2040.

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[32] It is likely that a hydrogen fuel cell plus electric motor will be more efficient than a turboprop gas turbine engine. Conversely, the fuel tanks and systems for liquefied hydrogen are likely to be substantially larger than those for conventional fuel, leading to greater structural mass and aerodynamic drag. There is, therefore, significant uncertainty in the assumption that the energy requirements for the two aircraft types will be the same.

[33] The energy density of kerosene is taken as 43.69 MJ/kg (Staffell, 2011), while that for hydrogen is taken as 120.087 MJ/kg (The Engineering Toolbox, 2005)