Operational Efficiencies for Aviation Decarbonisation

March 2025

A report for the Department for Transport by KPMG LLP, Mott MacDonald Ltd. and City St George's, University of London

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Glossary of terms

Airspace Change Organising Group (ACOG)	ACOG's role is to coordinate the Airspace Modernisation Strategy of the UK government, and create a strategic coordinated Airspace Change Masterplan for UK airspace
Automatic Dependent Surveillance–Broadcast (ADS–B)	Aircraft tracking technology using satellite navigation and other sensors to broadcast position and related data to air traffic controllers and other users
Air Navigation Service Provider (ANSP)	An organisation which manages air traffic for a company or within a region or company providing air navigation services to airspace users.
Air Traffic Management (ATM)	Consists of Air Traffic Control, Airspace Management and Air Traffic Flow and Capacity Management to deliver the safe and efficient flow of air traffic.
Artificial Intelligence (AI)	A technology that enables computers to simulate human learning, problem solving and decision making.
Air traffic Controller (ATCO)	Air traffic controllers are people trained to maintain the safe, orderly, and expeditious flow of air traffic in the global air traffic control system.
Auxiliary Power Unit (APU)	A device on an aircraft that provides energy for functions other than propulsion.
Blended wing body (BWB)	An aircraft design with no clear division between the wings and the main body.
Carbon	Greenhouse gas emissions
Continuous Descent and Climb Operations (CDO/CCO)	CDO and CCO are operating techniques that enable aircraft to climb and descend continuously during take-off and landing.
Consistency Ratio (CR)	The consistency ratio is a metric that indicates the consistency between pairwise comparisons.
Exhaust Gas Temperature (EGT)	EGT is the temperature of the turbine exhaust gases as they leave the turbine unit
Estimated cost of abatement (ECA)	A calculation which considers cost, carbon abatement potential and intervention lifetime: $Estimated\ cost\ of\ abatement = \frac{(Unit\ Cost\ \times no.units\ in\ the\ UK)}{(Potential\ CO2e\ abatement\ per\ year\ \times Lifetime)}$
eVTOL	An electric vertical take-off and landing vehicle which uses electric propulsion
Flight Path Angle (FPA)	The angle between the direction of travel of the aircraft, and the horizon. As such, it is equivalent to the
Free route airspace (FRA)	A designated airspace where aircraft can choose their own flight paths between specific entry and exit points, without having to follow pre-defined routes.
Fuzzy logic	A form of many-valued logic that deals with reasoning that is approximate rather than fixed and exact. Unlike classical logic where variables must be either true or false, fuzzy logic allows for truth values to range between 0 and 1, representing the degree of truth. This approach is particularly useful in systems that need to handle

	uncertain or imprecise information, such as control systems in electronics and consumer products.
Ground Power Units (GPU)	A ground-based system to provide electricity to an aircraft whilst it is on the ground
Heating, Ventilation, and Air Conditioning (HVAC)	The use of various technologies to control the temperature, humidity, and purity of the air in an enclosed space.
Internet of Things (IoT)	A network of devices with sensors, software and network connectivity, enabling them to collect and exchange data allowing for automation and optimisation of processes.
Lift to Drag (L/D) Ratio	The L/D ratio is the ratio of two aerodynamic forces, the lift generated at a given speed and drag incurred due to the aircraft's movement through the air.
Multi-criteria analysis (MCA)	A decision-making process that evaluates multiple conflicting criteria in decision making. It is often used in fields where decisions must balance various factors such as cost, benefits, risks, and impacts.
NATS	A provider of air traffic control services to flights within the UK upper airspace.
Near-term/Mid-term/Long-term	For the purpose of this study near-term is defined as interventions which can be implemented within the next 5 years. Mid-term is defined as 5-15 years away and long-term beyond that.
Natural Language Processing (NLP)	A branch of computer science and artificial intelligence (AI) that uses machine learning to allow computers to understand and interact with human language.
OEMs	Companies that design, manufacture and supply essential components and systems to aircraft manufacturers
Pre-conditioned air (PCA)	A ground-based system to provide cooling and ventilation to an aircraft whilst it is on the ground
SESAR	A collaborative project to overhaul European airspace and ATM with the aim pf delivering fully harmonised and interoperable ATM infrastructure across Europe.
Stakeholder	Any individual, group, or organisation that has an interest or concern in a particular project, policy, or decision. Stakeholders can include employees, customers, suppliers, investors, communities, and government agencies, among others
Technology Readiness Levels (TRL)	TRLs are a method used to assess the maturity of a particular technology. They range from TRL 1, where basic principles are observed, to TRL 9, where the technology is proven to work in its final form and under real-world conditions.
tCO_2e (tonnes of CO_2 equivalent)	A metric measure used to compare the emissions from various greenhouse gases based on their global warming potential (GWP). It expresses the impact of different gases in terms of the volume of CO_2 that would generate the same climatic warming.
Transonic Truss-Braced Wing aircraft (TTBW)	A new type of aircraft design that features exceptionally long, slender wings supported by diagonal struts.
UK Aviation	Refers to the civil aviation industry within the United Kingdom (excluding defence), encompassing all aspects of air travel and transport, including commercial airlines, airports, regulatory bodies, and associated services. It plays a significant role in the UK's economy and connectivity.

Contents

1 Executive Summary

1.1 Context

Improvements in operational efficiencies are already playing a crucial role in reducing aviation emissions in the immediate and near-term and will continue to be a key driver in the sector's decarbonisation efforts. Many operators, airports, and Air Navigation Service Providers (ANSPs) are implementing measures that not only help reduce emissions but also bring cost benefits to the industry. As a result of these efficiency gains, CO_2 emissions per passenger in 2019 were 22% lower than 1990 despite an increase in overall passenger numbers.[1] While operational efficiencies are central to near-term progress, other decarbonisation measures, such as the use of Sustainable Aviation Fuel (SAF) and the development of fully electric and hydrogen-powered wide-body and long-range aircraft, will have a substantial impact in the medium to long term. However, many of these breakthrough technologies that achieve zero emissions are still several years away from being commercially viable.

This research seeks to identify, rank, and prioritise both existing and emerging operational efficiency interventions. The ranking is based on an assessment of each intervention's potential for carbon reduction, while also evaluating key factors such as implementation costs, expected timelines for readiness, durability, broader environmental effects, and social implications (referred to as *the impact criteria*). The shortlisted identified interventions are presented in Figure 1.

Evidence was gathered through extensive stakeholder engagement across the industry, as well as thorough reviews of both academic and non-academic literature, to identify interventions and assess their potential impact (*impact assessments*). A multi-criteria analysis (MCA) was undertaken to prioritise the shortlisted interventions wherein invited stakeholders ranked the *impact criteria* based on their own perceived importance. The output of the MCA was then combined with the *impact assessments*, to rank each intervention.

[1] Department for Transport. (2022). '*Jet Zero Strategy: Delivering Net Zero Aviation by 2050*'. Available at: https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050

1 Aircraft Design and Operations

- Improvement in aerodynamics (design and retrofit)
- Lightweight composite materials and cabin equipment/retrofit
- Stabilised approach criteria
- Reduced engine taxi
- Whole life approach to the assets
- Electric propulsion aircraft/support systems
- Hydrogen propulsion aircraft/support systems
- Non-conventional aircraft configurations
- Maintenance scheduling and location

2 Airspace

- Airline flight planning optimisation
- Continuous Climb Operations (CCO) and Continuous
- Descent Operations (CDO)
- Free route airspace (with and without AI enhancements)
- Airspace modernisation (reduced fragmentation of airspaces)
- Real-time data for pilots
- Holding on the ground (with potential for AI enhancement)
- Remote towers

3 Airports

- Electric or assisted taxiing
- Electric and autonomous ground support equipment
- Renewable energy Pre-conditioned air while on the ground (PCA)
- Energy efficiency improvements for buildings

4 Training and Support

- Pilot training
- Data and analytics

Figure 1: Shortlisted interventions for operational efficiencies in aviation

1.2 Summary of research approach

The summary of the research approach is shown in Figure 2. Forty-one potential interventions were identified through stakeholder engagement and an extensive literature review. Using additional stakeholder engagement and professional judgement of the research team, twenty-five shortlisted interventions were selected as interventions for further assessment in this study.

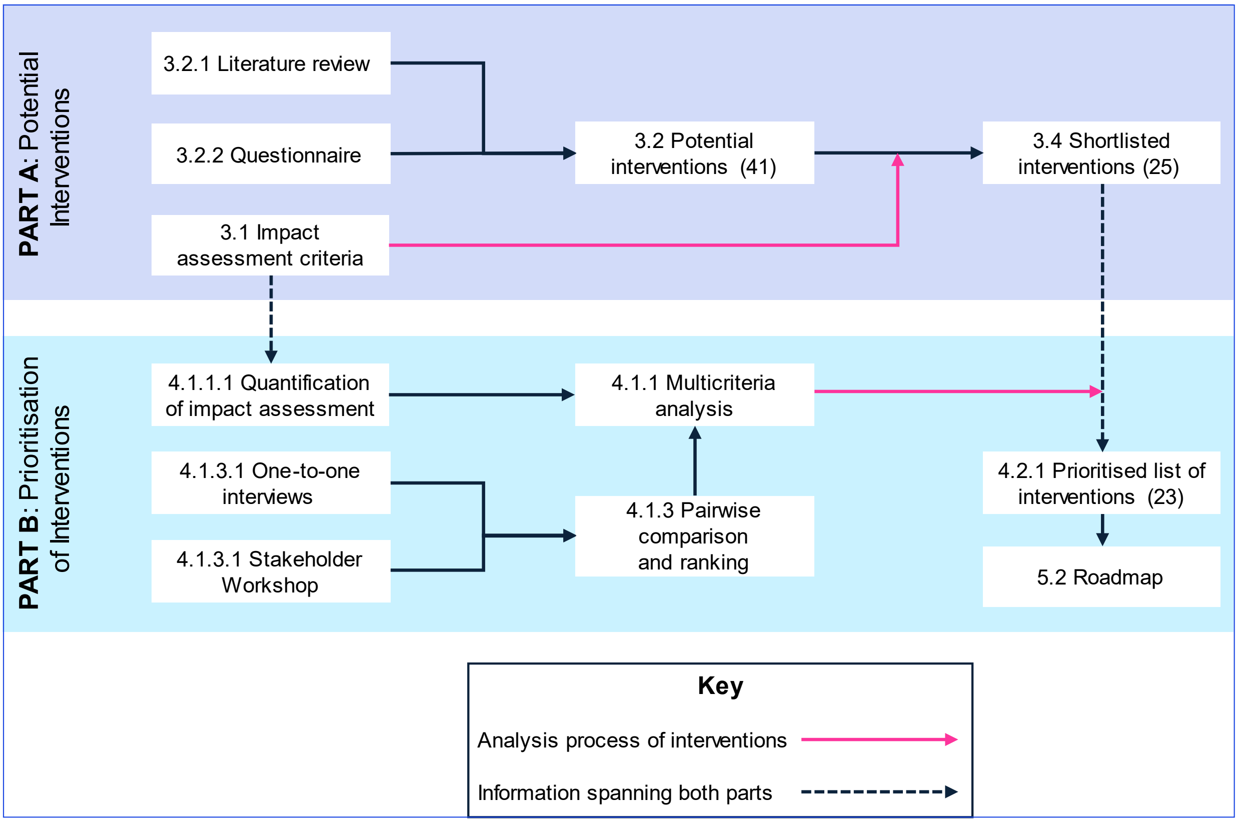


Figure 2: Summary of research approach

1.3 Multi-criteria analysis ranking

A multi-criteria analysis (MCA)[2] was then used to rank these interventions, as shown in Table 1. The focus of this analysis was not to quantify impacts of the interventions, but instead to rank the interventions against each other.

Of the twenty-five interventions, the top twenty-three were identified as viable solutions to deliver operational efficiencies (shown in Figure 1). Stand design was considered of low importance due to overall lower scores across all the *impact criteria*, whilst in-flight refuelling was scored very low across all criteria, with the exception of cost of abatement.

[2] R. Curran, Foundations of Transdisciplinary Engineering Theory: Sustainable Airport Application, Advances in Transdisciplinary Engineering, UCL East, London, 2024, in press.

Table 1: MCA rankings and score

Intervention	Intervention category	Ranking	Score
Improvement in aerodynamics/retrofit	Aircraft design and operation	1	6.06
Airline flight planning optimisation	Airspace	2	5.66
Lightweight cabin equipment	Aircraft design and operations	3	5.60
Electric ground support equipment (GSE)	Airports	4	5.54
Free route airspace	Airspace	5	5.50
Stabilised approach criteria	Aircraft design and operations	6 (Joint)	5.44
Building energy efficiency improvements	Airports	6 (Joint)	5.44
Pre-condition air systems while on the ground (PCA)	Airports	8	5.32
Real-time data for pilots	Airspace	9	5.28
Continuous climb operations (CCO) and continuous descent operations (CDO)	Airspace	10	5.22
Reduced engine taxi	Aircraft design and operations	11	5.12
Whole life approach to aircraft and operations	Aircraft design and operations	12 (Joint)	5.10
Airspace modernisation (reduced airspace fragmentation)	Airspace	12 (Joint)	5.10
Pilot training	Training and support	14	4.98
Electric/hybrid propulsion	Aircraft design and operations	15	4.80
Remote towers	Airspace	16	4.76
Maintenance scheduling	Aircraft design and operations	17	4.74
Holding on the ground: Potentially with Artificial Intelligence (AI)	Aircraft design and operations	18	4.72
Electric or assisted taxi	Airports	19	4.56
Renewable energy	Airports	20	4.56
Non-conventional aircraft configurations	Aircraft design and operations	21	4.42
Hydrogen propulsion	Aircraft design and operations	22	4.34
Data and analytics	Training and support	23	4.18
Stand design	Airports	24	3.90
In-flight refuelling	Aircraft design and operations	25	3.18

1.4 Findings

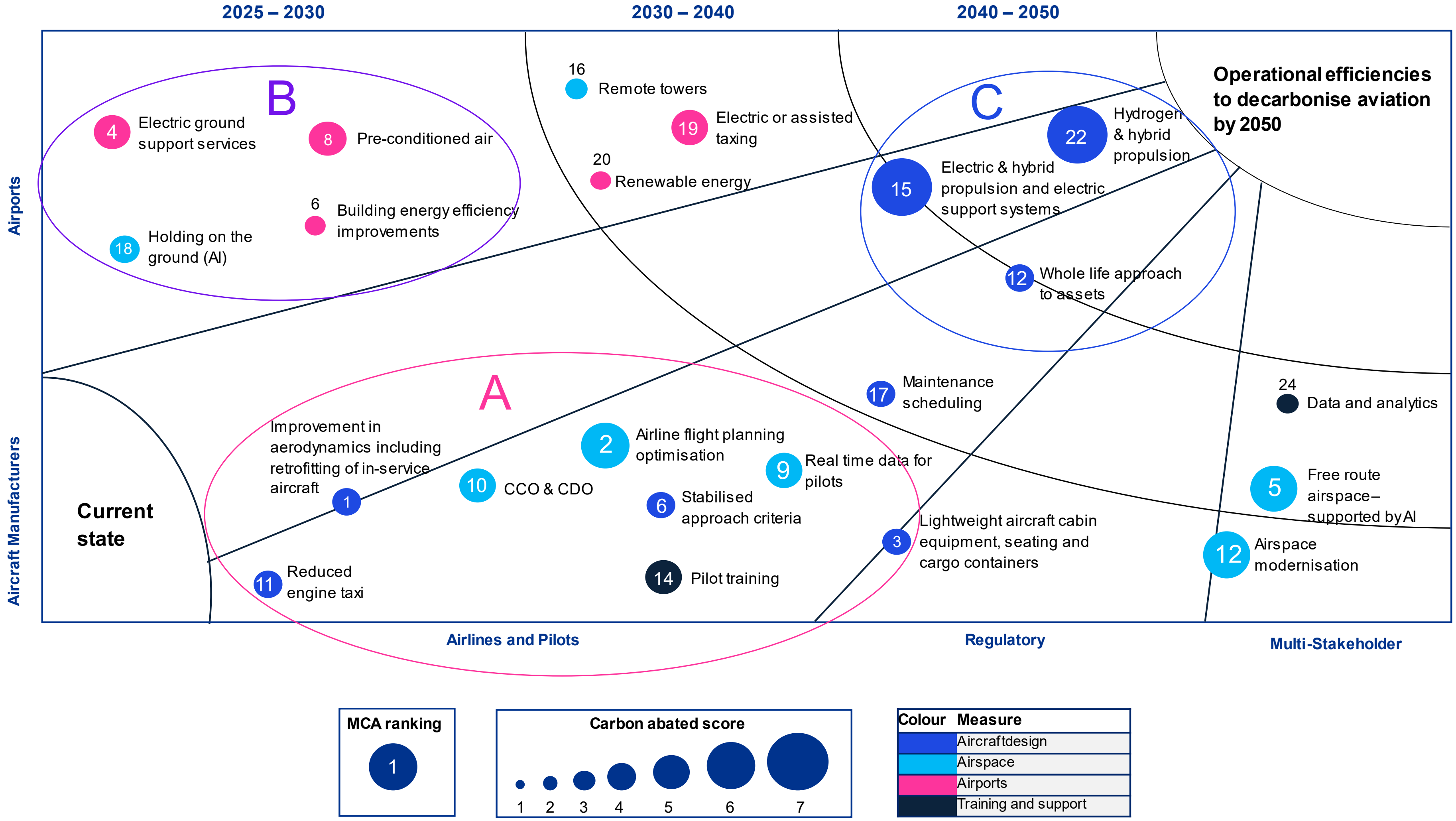
A summary of the findings of this study is as follows:

Finding	Implications
No particularly novel interventions were identified	Stakeholders can be reassured that the academic and non-academic research did not uncover any interventions that are not already being considered. Whilst additional interventions may be developed in the future, current activity should focus on accelerating or implementing those currently being delivered or explored by stakeholders. To accelerate progress, it is crucial to prioritise funding, including trial funding, to support collaboration among stakeholders, with a focus on the integration of technologies and their broader system requirements. A more holistic, systems-level approach is necessary to ensure that interventions are effectively embedded into the aviation sector, leading to long-term decarbonisation success.
Those that were ranked highest on the MCA do not score highly on carbon abatement potential	Of the four interventions ranked highest by the MCA, three scored less than 3/7 on their carbon abatement potential (improvements in aerodynamics, lightweight composites and electric and autonomous ground support equipment), however, these interventions all scored highly on the cost of carbon abated and deliverability demonstrating the importance of ease of implementation to stakeholders.
Th r is no “silv r bull t” to n ar and mid-term decarbonisation	Operational efficiencies in the near to mid-term tend to be lower (relative) cost interventions which have some carbon abatement potential, but the real benefit is in the combination of each of these initiatives to have a much larger grouped impact. The most promising interventions included elements of aircraft design and retrofit, airports, airspace and air operations. All stakeholders involved in aircraft operations therefore have a role to play in near term decarbonisation.
Several interventions are already being delivered or capable of being delivered	Many of the interventions for airports and in aircraft retrofit are already being delivered, such as improvements in aerodynamics and electric ground support equipment. Acceleration of these endeavours and of those near to implementation through the recommended next steps will be key to having the most immediate carbon abatement.
Hydrogen and electric propulsion are important interventions for the long term	Electric and hybrid propulsion was ranked fifteenth and hydrogen propulsion was ranked twenty-second by the MCA, this was primarily due to low deliverability scores. Both interventions however have high carbon abatement potential, and score 5/7 on cost of abatement, which means they are still considered an important intervention, even with a low deliverability score.

1.5 Roadmap

The roadmap in Figure 3 presents the twenty-three viable interventions, mapped against their anticipated implementation timelines. The size of each circle reflects the potential carbon abatement of that intervention, rated on a scale of 1 to 7 (with 1 being the lowest and 7 the highest), indicating its potential impact on decarbonisation. The number within each circle represents the MCA ranking for that intervention, taking into account factors such as cost of abatement, deliverability, durability, and social and environmental impacts. Each intervention is positioned based on both its timeline (2025-2050) and the part of the industry responsible for its delivery. The roadmap, therefore, outlines when each intervention is expected to make an efficiency impact, the scale of that impact, who is responsible for its implementation, and its priority level.

It is important to note that these time points reflect when each intervention is expected to achieve the level of carbon abatement defined in the multicriteria analysis (MCA) or the end state for that intervention. For some interventions, such as a whole-life approach to assets, early carbon reductions may be realised through the reuse and recycling of certain components. Similarly, novel fuels could have a more immediate impact, particularly in auxiliary systems, hybrid propulsion, and smaller, regional aircraft.



Colour	Measure
	Aircraftdesign
	Airspace
	Airports
	Training and support

Figure 3: Roadmap of carbon abatement against time for each intervention

1.6 Next steps

Three distinct areas were identified through the MCA and roadmap.

Interventions in the pink-ringed area (A) represent key priorities for airlines and pilots, all of which were identified as high-impact and achievable in the near term through the MCA. These include interventions requiring aircraft retrofit (such as changes to aerodynamics and lightweighting on board equipment) as well as optimisation of flight planning and ascent and descent operations. While pilot training was ranked 14th in the MCA, it is considered a critical enabler for many of the airline and pilot interventions. As such, it remains a crucial element in driving operational efficiency and decarbonisation efforts.

Interventions in the purple-ringed area (B) represent key priorities for airports, all of which were identified as high-impact actions through the MCA. These interventions include decarbonising airport infrastructure, as well as providing on-ground solutions to aircraft whilst on the ground. While many of these interventions are already being implemented at various airports, the next critical step is accelerating their adoption across the industry to ensure widespread uptake and maximise their potential impact.

Interventions in the blue-ringed area (C) represent longer-term strategies essential for the full decarbonisation of aircraft operations, including alternative propulsion system and employing a circular economy approach to managing assets. Ongoing efforts are required to advance these interventions, while near- and mid-term solutions should be implemented with a clear vision of how they will align with and support the future integration of these longer-term strategies.

Activities around airspace modernisation are included in priority objectives for the CAA and should continue to be delivered to further enhance many of the airline and pilot interventions, by delivering less fragmented airspace.

1.7 Potential actions for consideration

A series of considerations for the government, industry and wider aviation sector to consider were identified to accelerate the delivery of the interventions within groups A and B of the roadmap:

- Developing and piloting performance indicators (in a unified framework) that measure the efficiency of airport and aircraft operations in a comprehensive, system-wide manner, and collaborating with government and industry partners to integrate these efficiency metrics into existing reporting and operational practices.
- Consulting with and obtaining agreement from chief pilots of UK airlines on prioritisation of CCO, CDO and reduced engine taxi, allowing for a consistent approach to operation which does not penalise any operator.
- Giving consideration to changing the tax-free status of aviation fuel, to further incentivise airlines to cut fuel expenditure and prioritise measures which save fuel.
- Encouraging cross-sector collaboration between airports, air traffic management, & technology providers to test and evaluate energy reduction initiatives in real-world conditions and potentially support R&D to assess the scalability of energy-saving initiatives and develop standardised metrics to evaluate their performance.
- Reviewing the current regulatory model for CAA regulated airports to allow for greater investment flexibility and capacity for change control on the grounds of decarbonisation,

reducing the risk that investment in decarbonisation is disincentivised due to fixed funding periods and opposition from airlines based on cost.

- Reviewing current airside operational fleets to identify and replace the largest emitting vehicles.
- Consulting on and introducing airside low emission zones and minimum efficiency requirements for airside equipment.
- Consulting on and introducing a UK standard for Pre-conditioned Air (PCA) usage which penalises / discourages Auxillary Power Unit (APU) usage on stand and sets a minimum connection time from stand arrival.
- Adjusting UK planning laws regarding airspace change, to allow airspace changes to progress through planning faster or with a reduced consultation.
- Establishing financing facilities (e.g. an aviation green infrastructure investment fund) to allow access to aviation specific green finance to accelerate the introduction of low-carbon technology.

Further actions to accelerate the delivery of the interventions in group C include:

- Facilitation of government-led collaborations with industry stakeholders, research institutions, and international partners to ensure alignment on ZEF technology development and deployment.
- Supporting stakeholders to invest in R&D to integrate emerging ZEF solutions into existing aviation systems, ensuring seamless deployment from prototype to commercial operation. This could include implementing trials and demonstration projects to test ZEF technologies at various stages of development, gathering data to inform the broader roadmap and ensure practical feasibility.
- Ensuring that energy infrastructure is in place to enable the transition to electric and hydrogen aircraft, investing in greater energy capacity and resilience.

1.8 Limitations of the research

The analysis and ranking of the various interventions was constrained by limited information, particularly regarding costs, within published data which causes some uncertainty in the result. This lack of data may be partly attributed to the commercial sensitivity surrounding some emerging technologies. The research conducted assessed both qualitative and quantitative data from primary and secondary sources, providing scaled estimates. However, due to gaps in data availability, the interventions could only be ranked rather than fully quantified.

To better understand which interventions offer the most value, further research focused on the Marginal Abatement Cost Curve (MACC) would be beneficial. This additional research should identify which interventions provide the best value for each additional tonne of CO_{2e} reduction. Ultimately, this analysis depends on the availability of cost data within the existing literature.

2 Purpose and approach

2.1 Purpose

The purpose of this research was to identify and assess operational efficiencies for airlines and airports that could have an immediate or near to mid-term impact on emissions, ahead of broader technological and fuel advancements. These operational efficiencies focus on optimising the existing aviation system, including airports, airspace, and aircraft.[3] This report does not aim to provide precise estimates of emissions reductions for each intervention, due to limitations in data availability and the scope of the analysis conducted for this study.

2.2 Scope

The research focused on operational efficiencies that could serve as a critical foundation for achieving meaningful emissions reductions in the short to medium term. The study aimed to identify, assess, and rank activities (grouped by intervention) supported by academic and non-academic literature, as well as stakeholder input, across the following categories:

- Air traffic management
- Aircraft design and operations
- Airport improvements
- Training and support

In addition to near term interventions, some interventions which are applicable in the medium to long term but have a substantial effect on overall sector operation were also included, namely hydrogen and electric propulsion. Whilst these higher impact solutions are developed, continued improvements in operational efficiencies will deliver reduced emissions, with many of the solutions being available today[1], hence forming the main focus of this report.

This report has not included activities outside of the design and operation of existing aircrafts and airports, such as supply chains for alternative fuels or other materials, interventions that do not directly relate to current commercial flight, such as eVTOL or drone operations, and interventions that are unrelated to carbon reduction such as operational or design changes to minimise non-CO_2 (although where evidence exists, non-CO_2 impacts are referenced).

[3] Department for Transport. (2022). '*Jet Zero Strategy: Delivering Net Zero Aviation by 2050*'. Available at: https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050

2.3 Summary of approach and outcomes

The research was conducted in multiple phases, with some running concurrently, allowing for the integration of inputs throughout the process. The methodology was adapted as new findings emerged, particularly in areas where robust quantitative data was limited. Further details of the approach can be found in Part A: The Potential Interventions and Part B: Prioritisation of Interventions. Figure 4 illustrates the methodology, with numbered references corresponding to the relevant chapters where each step is explained.

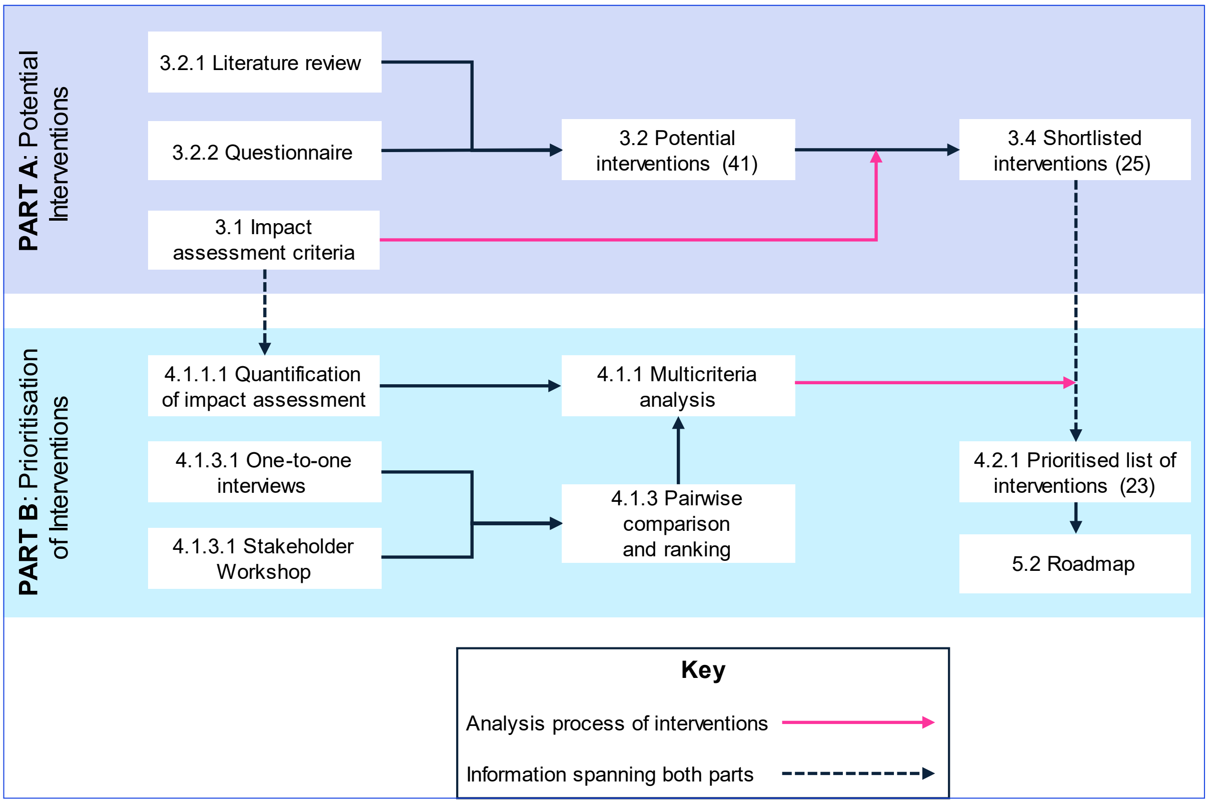


Figure 4: Summary of research approach

3 Part A: The potential interventions

This section outlines the approach used to identify each intervention, evaluating factors such as the likely cost of abatement, deliverability, durability, and environmental and social impacts. Based on this analysis, the most viable opportunities are shortlisted.

3.1 Impact criteria definitions

A method was defined and agreed with DfT, to assess the impact of different interventions prior to undertaking the methodology set out in section 3.2, so that the evidence could be collected at the same time as identifying interventions.

The impact metrics needed were defined under five criteria:

1. **Estimated cost of abatement:** A calculation which considers cost, carbon abatement potential and intervention lifetime:

$$Estimated\ cost\ of\ abatement = \frac{(Unit\ Cost\ \times no.units\ in\ the\ UK)}{(Potential\ CO2e\ abatement\ per\ year\ \times Lifetime)}$$

2. **Deliverability:** The term deliverability refers to the ability of something to be delivered as a result of a development process. It was primarily derived from TRL levels[4]. In the scenario where the intervention was not a technology, the deliverability was based on research and expert opinion
3. **Durability:** This parameter reflects the long-term reliability, effectiveness, and robustness of the measure. It can be defined as "long-term reliability" considering factors including resistance to wear and tear and environmental extremes.
4. **Environmental impact:** The effects that the activities have on the environment, including changes to ecosystems, biodiversity, and natural resources. Common effects include loss of biodiversity, soil degradation, noise, air and water pollution, and climate change
5. **Social impact:** Any significant or positive change that addresses social injustice or challenges - this can include improvements in areas such as health, education, equality, and economic development.

The metrics for each criterion were not rigidly defined at this stage, with the primary focus on gathering evidence for each category. The relevant metrics, both quantitative and qualitative, were later derived from the literature review and questionnaire.

3.2 Identification and shortlisting of potential interventions

The interventions were primarily identified and assessed (including shortlisting) using two mechanisms – a literature review consisting of academic and non-academic searches, and a questionnaire distributed to academics and different operational groups to investigate the most recent ongoing activities.

[4] Aerospace Technology Institute, 2023. *Technology Readiness Levels (TRL)*. [online] Available at: https://www.ati.org.uk/funding/technology-readiness-levels-trl/

3.2.1 Literature review

A rapid evidence review of existing literature on operational efficiencies and their applications in aviation was conducted, with a particular emphasis on identifying opportunities to accelerate carbon reduction in alignment with the 2050 Net Zero target. The rapid evidence review involved scanning through various databases using clearly defined keywords and scope to quickly gather relevant information on the topics. This method was chosen to rapidly synthesise the evidence across the themes in scope, in a resource effective manner.

The review focused on academic sources, peer-reviewed journals (using Scopus search engine) and industry projects (using Google searches), employing a keyword search methodology to explore various research areas related to operational efficiencies within the Scopus Search engine. The search was organised into key categories: **Air Traffic Management**, **Aircraft Design and Operations**, **Airport Improvements** and **Training and Support**. The gathered literature was then categorised and analysed according to these predefined themes, and evidence identified for each of the five impact areas. A total of 150 global academic and industry reports were collated during this process.

There are some limitations in relying solely on published research: Firstly, there is often a delay between the completion of research and its publication, which means it may not be fully up to date. Secondly, some emerging opportunities may be commercially sensitive and therefore not available in published literature. Therefore, a questionnaire was designed and issued to gather additional insights from academic and industry representatives.

3.2.2 Questionnaire

The focus of the questionnaire was on up-to-date industry and academic insights into ongoing (and desired) activities into operational efficiencies. It also provided additional information to supplement the reviews, for example by providing more detail on priorities and how mitigation measures could be applied operationally. This enabled sourcing of a wide variation of information, evidence and experience from stakeholders, from differing backgrounds within the sector to ensure representation across the industry.

The questionnaire and summary findings can be found in 6.1.

3.3 High-level findings

3.3.1 Impact assessment

Forty-one potential interventions were identified from the literature review and questionnaire with varying potential impacts across the four categories. Using the impact assessment criteria and stakeholder engagement these were reduced to twenty-five for further analysis.

3.3.2 Literature review

In undertaking the review, it was identified that limited data existed. The literature review was therefore expanded to consider additional quantitative and qualitative insights which may assist with the subsequent analysis. It was further identified that impact studies are rare in the literature for interventions that rely heavily on specific design factors such as an airport's layout or size. This makes it challenging to assess the effectiveness of sustainability measures like the implementation of more sustainable aircraft stands or renewable energy solutions as their impact varies significantly depending on the unique characteristics of each.

3.3.3 Questionnaire

Thirty-one individuals responded to the questionnaire on operational efficiencies including academics, airlines, pilots' associations, airport operators, original equipment manufacturers (OEMs), ANSPs, government agencies and consultancies.

In general, the findings from the questionnaire corresponded to those from the literature, with no additional interventions being identified. The questionnaire did however point to challenges the industry is experiencing in investing in and implementing some of the emerging interventions. It also gave additional insights into the current and planned activities within this space, and more detailed understanding as to how data, AI and machine learning can enhance interventions.

As stated in section 3.2.1 limited quantitative data was found within the literature, which was not significantly enhanced by the questionnaire. The data used to understand the impact of each of the criteria used consisted of both qualitative and quantitative evidence from the two data sources.

These assessments removed some of the initially identified interventions, where the metrics were considered unfeasible to implement based on the criteria, and grouped others, resulting in twenty-five assessed interventions. The assessments were agreed with the Department for Transport's Aviation Decarbonisation Policy Unit and in the workshop in November 2024 ahead of the multi-criteria analysis.

3.4 Shortlisted interventions

This subsection details the shortlisted interventions identified using the process described in section 3.2 and the impact criteria assessment (section 3.1). The interventions have been grouped into the four in-scope areas: aircraft design and operation, airspace, airports, and training and support. For each intervention the following structure is followed:

- **Description** of the intervention and planned intentions
- **Summary** of the combined evidence from the literature review and questionnaires on impact, cost and timescales augmented with findings from the workshop and one-to-one interviews.
- **A table summary** of the qualitative and quantitative data used to analyse the interventions. The impact criteria tables have five columns –
  - The first (Estimated Cost of Abatement), provides a summary of why the rating was given, and then evidence of both the cost of the intervention and the potential carbon abated.
  - The second (Deliverability) gives a view of the ease of implementation of each intervention, considering primarily the TRL level of the technology in question.
  - The third column (Durability) gives a view of the lifetime of the intervention and potential degradation over time
  - The fourth (Environmental impact) sets out the anticipated environmental impact of the intervention, considering factors such as waste management, noise pollution and air quality effects.
  - The final column (Social impact) considers how each intervention may affect surrounding communities through factors such as employment opportunities, air quality effects and noise levels.

- It should be noted that **these are not intended to be used to compare between interventions at this stage** (as stated in section 3.3.2 there was a lack of comparable data found), rather to provide a snapshot of the data that was used to assess the intervention and calculate the estimated cost of abatement. Some of the data presented in the tables are an indicative assessment by the authors based on inputs from multiple sources (qualitative and quantitative) and as such no specific reference is provided.

Table 2 shows the qualitative ratings used in assessment of the interventions:

Table 2: Rating system for assessment of interventions

Rating	Description	Estimated Cost of Abatement	Deliverability	Durability	Environmental impact	Social impact
Red	Low rating for the relevant section.	High estimated cost per tonne of carbon abated per unit	Low TRL and ease of implementation	Low durability with short lifetime	Negative environmental effects	Negative effects on surrounding communities
Amber	Moderate rating for the relevant section	Moderate costs per tonne of carbon abated per unit	Medium TRL	Moderate durability	Moderate or minimal environmental effects.	Neutral or moderate effect on surrounding communities
Green	High rating for the relevant section	Low costs per tonne of carbon abated per unit	High TRL, readily implementable	High durability, with a relatively long lifetime	Net positive environmental effects	Positive effects on surrounding communities

3.4.1 Aircraft design and operation

3.4.1.1 Improvement in aerodynamics (design and retrofit)

Description

Advances in aerodynamics and aircraft component weights help reduce drag, improving fuel efficiency and reducing carbon emissions. Key innovations include wing reshaping, smoother surfaces, and retrofitted solutions like riblets and winglets.

Summary of evidence

Riblets

Riblets are small grooves added to an aircraft's surface to reduce drag by up to 5%, leading to fuel savings of up to 10%[5]. Airlines such as All Nippon Airways (ANA)[6] and Lufthansa[7] have already implemented riblets, expecting a fuel consumption reduction of 1-2%, which could save up to 250 tonnes of fuel annually per aircraft and cut CO_2 emissions by up to 800 metric tonnes. Lufthansa Technik[8] estimates 19,000 tonnes of CO_2 reduction across 20+ aircraft using their AeroShark[9] riblets. However, the implementation cost and price for AeroShark is not publicly disclosed.

Winglets

Winglets are the most prominent and in-use retrofitted accessories to reduce fuel consumption. Retrofits started with the B737 in 2001, with implementation costs ranging from £600,000 to £1.42 million per aircraft. It is estimated that winglets save around 380,000 litres of fuel annually per aircraft[10]. The benefits vary based on the aircraft type: older models like the B707 see a 6.5% fuel reduction, while newer models like the B737-800 achieve savings between 4.6% and 10.5%[11]. Despite their effectiveness, retrofitting winglets can be complicated due to the impact on increasing an already large aircraft's wingspan, which may

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[5] Mohsen Jahanmiri. (2011). Aircraft Drag Reduction: An Overview. *Department of Applied Mechanics, CHALMERS UNIVERSITY OF TECHNOLOGY*. https://publications.lib.chalmers.se/records/fulltext/137214.pdf

[6] Luke Bodell. (2024). 1st All Nippon Airways Boeing 777 With Lufthansa AeroSHARK Emissions-Reducing Film Enters Service. https://simpleflying.com/1st-all-nippon-airways-boeing-777-lufthansa-aeroshark-emissions-reducing-film-enters-service/

[7] Guy Norris. (2024). Drag Reducing Riblets To Be Applied To A330. *Aviation Week Network*. https://aviationweek.com/mro/aircraft-propulsion/drag-reducing-riblets-be-applied-a330

[8] Author Unknown. (2024). Cutting emissions with sharkskin technology. *Lufthansa Technik*. https://www.lufthansa-technik.com/en/aeroshark

[9] Author Unknown. (2022). AeroSHARK: inspired by shark skin. *Swiss Magazine*. https://www.swiss.com/magazine/en/inside-swiss/sustainability/aeroshark-how-we-further-reduce-our-carbon-emissions

[10] Author Unknown. (2010). Winglets Save Billions of Dollars in Fuel Costs. *NASA Spinoff*. https://spinoff.nasa.gov/Spinoff2010/t_5.html

[11] David Price. (2022). The impact of winglets on fuel consumption and aircraft emissions. *Cirium Aviation Analytics*. https://www.cirium.com/thoughtcloud/impact-winglets-on-fuel-consumption-and-aircraft-emissions/#:~:text=In%20modern%20aircraft%2C%20winglets%20help,efficiency%20and%20lower%20carbon%20emissions.&text=Winglets%2C%20the%20vertical%20tips%20at,by%20aircraft%20type%20and%20route

conflict with airport infrastructure[12]. In 2022, Boeing introduced a new aircraft, the B777X featuring folding wingtips to address this issue[13].

Engine retrofit

While there is limited data on the average cost of engine retrofitting (as aircraft designs and missions vary widely), replacing engines with lighter, more efficient ones can significantly improve fuel efficiency. For example, replacing engines on a 90-passenger regional jet costs around €20 million[14] but can save £880,000 annually per aircraft, with a 12-14% reduction in fuel consumption[15].

Table 3: Summary of data for improved aerodynamics

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Cost[16]:** Boeing estimate the following costs for a retrofit: ~£884,000 per aircraft retrofit. Based on average cost of: Boeing 737-700/800: ~£585,000 Boeing 757-200: ~£663,000 Boeing 767-300ER/F: ~£1,404,000 **Justification:** The cost estimates for this intervention include only the initial implementation and exclude ongoing maintenance, which is presumed to be minimal, as well as replacement costs. These replacement costs are expected to be borne by the operator. **tCO_2e/year:** Approx. 5million tCO2e per year **Justification:** Emission estimates are based on average assumptions regarding the retrofitting of existing aircraft. The potential aerodynamic improvements, and consequently the fuel and emissions savings, depend

[12] Taylor Rains. (2022). The folding wing tips on Boeing's massive new 777X are a first in commercial aviation. Here's why the plane needs them. *Business Insider*. https://www.businessinsider.com/why-the-new-boeing-777x-needs-folding-wingtips-2022-1#the-airplane-will-not-be-limited-to-which-airports-it-can-operate-out-of-an-issue-the-airbus-a380-faced-after-the-superjumbos-debut-in-2007-7

[13] Vishnu Ravi. (2023). Why does the Boeing 777 have no winglets like the 737 or other commercial airplanes?. *Medium*. https://thewalkingpilot.medium.com/the-boeing-777-why-no-winglets-unveiling-the-mystery-71951614cc16#:~:text=To%20sum%20it%20all%20up,wings%20than%20meets%20the%20eye

[14] Della Vecchia p . Mandorino M. Cusati V. Nicolosi F. (2022) ' Retrofitting Cost Modeling in Aircraft Design' *Aerospace 2022, 9, 349*. https://doi.org/10.3390/

[15] Pierluigi Della Vecchia, Massimo Mandorino, Vincenzo Cusati, Fabrizio Nicolosi. (2022). Retrofitting Cost Modeling in Aircraft Design. *MPDI Aerospace*. https://www.mdpi.com/2226-4310/9/7/349

[16] Aviation Partners Boeing. (n.d.). '*Products List & Prices*.' Available at: https://aviationpartnersboeing.com/products_list_prices.php

Impact metrics	Performance	Description
		on the age of the fleet and the availability of retrofit kits, which can vary between operators.
Deliverability	Good performance	TRL9 - Technology proven in an operational environment
Durability	High performance	Durability is the same as the lifetime of an existing aircraft. It is assumed that retrofits are implemented on an aircraft of around 10 years old. The actual lifespan will depend on the fleet age and upgrade cycles but has been assumed to be 15 years.
Environmental impact	High performance	There is no adverse environmental impact versus standard aviation, apart from potential changes to the manufacturing process.
Social impact	High performance	There is limited negative societal impact with benefits including potential for reduction in noise levels and air pollution around airports from take-off and landing of aircrafts with associated benefits to the local community as a result.

3.4.1.2 Electric propulsion aircraft/support systems

Description

Electric propulsion systems are primarily designed but not limited to reducing carbon emissions through decreasing or entirely replacing kerosene fuel consumption. These systems use electric motors powered by batteries, producing zero direct emissions. In addition to fully electric propulsion, hybrid solutions combining internal combustion engines with electric motors also offer emission reductions and fuel efficiency by using electric power during low-energy phases like taxiing and descent, improving air quality around airports. Electric power is also being used increasingly for auxiliary and support systems in conventional aircraft. These systems are powered by batteries, reducing reliance on fuel.

Summary of evidence

Hybrid-electric aircraft

Hybrid-electric prototypes have been developed by companies like Siemens and Airbus, achieving a 25% reduction in greenhouse gas emissions compared to traditional fuel-powered aircraft[17]. However, retrofitting existing aircraft with electric propulsion faces challenges such as compatibility issues, structural constraints, and the need to integrate electric systems into designs not originally intended for them. As a result, airlines need to consider the most suitable option for their operations to enable optimised aerodynamics, weight distribution, and overall efficiency.

Full electric propulsion

There remain challenges With full electric propulsion   due to the capacity of the batteries' required energy to run the electric engines. For example, commercial aircraft require a

[17] Thomas K. Walker III, Marika Tatsutani, Jonathan Lewis. (2024). Decarbonising Aviation: Enabling Technologies for a Net-Zero Future. *Clean Air Task Force*. https://www.catf.us/resource/decarbonising-aviation-enabling-technologies-net-zero-future/

battery energy density of 750Wh/kg for regional flights and over 1000Wh/kg for long-haul flights (these values may vary widely depending on the specific mission), while current lithium-ion batteries only provide up to 270Wh/kg[18]. As a result, fully electric aircraft are currently limited in size and capacity, with examples like Pipistrel's Velis Electro (2-passenger)[19] and Eviation's Alice (11-passenger)[20] highlighting these limitations.

New aircraft designs are needed for larger, long-haul electric aircraft. Companies like Electric Aviation Group plan to launch hybrid aircraft (e.g., the 70-seater HERA) by 2028, with projected production costs of £4 billion[21]. Other concepts for over 150-passenger aircraft are expected by 2030[22]. However, the energy density of current battery technology is not expected to support mass electric aircraft use in the near term.

Infrastructure and airport upgrades

Electric aircraft require significant infrastructure upgrades. This is already starting to be delivered for electric Vertical Take-Off and Landing (eVTOL) aircraft. For example, Washington airports are implementing charging stations for eVTOL aircraft, with funding requests totalling $10 million[23]. In the UK, 14 airfields already support electric aircraft, with 36 more planning to integrate the necessary infrastructure[24]. Larger electric aircraft will require even more extensive upgrades.

Electrification of aircraft systems

In addition to propulsion, other aircraft systems have the potential to be electrified including, the environmental control systems (ECS), flight control actuators, and braking systems. However, retrofitting electric systems into existing aircraft is difficult due to the complexity of these systems. While electrification may improve operational efficiency, quantifiable data on these benefits is scarce.

Table 4: Summary of data for electric propulsion and support systems

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Cost** Score: 1 (£10m<)

[18] ibid

[19] Author Unknown. (2024). [Landing Page]. *NEBO*. https://www.neboair.co.uk/

[20] Author Unknown. (2024). Fly The Future. *Eviation*. https://www.eviation.com/

[21] Dominic Perry. (2020). UK firm EAG details development roadmap for hybrid-electric regional airliner. *Flight Global*. https://www.flightglobal.com/air-transport/uk-firm-eag-details-development-roadmap-for-hybrid-electric-regional-airliner/139641.article#:~:text=By%20Dominic%20Perry6%20August,to%20bring%20into%20series%20production.

[22] Bright Appiah Adu-Gyamfi, Clara Good. (2022). Electric aviation: A review of concepts and enabling technologies. *Science Direct, Transportation Engineering, Volume 9, 100134*. https://www.sciencedirect.com/science/article/pii/S2666691X2200032X#sec0020

[23] Tom Banse. (2024). Six Washington airports want to charge ahead preparing for electric aircraft. *Washington State Standard*. https://washingtonstatestandard.com/2024/10/03/six-washington-airports-want-to-charge-ahead-installing-electric-airplane-chargers/

[24] Paige West. (2024). Fourteen UK airfields now trailblazing electric aviation. *Electric Specifier*. https://www.electronicspecifier.com/industries/aerospace-defence/fourteen-uk-airfields-now-trailblazing-electric-aviation

Impact metrics	Performance	Description
		This is estimated at ~£4,680,000 per aircraft retrofit. The cost for retrofitting a small regional aircraft with electric propulsion is estimated to be around $4 million USD per aircraft, in addition to associated infrastructure upgrades. Hybrid Propulsion Retrofit: The cost for retrofitting a larger aircraft with hybrid propulsion systems can range from $6 million to $10 million USD per aircraft.[25,26,27] **Justification:** The cost estimation for this technology is based on current prices. While it is expected that battery prices will continue to decrease, the rate of decline is highly uncertain due to factors such as material availability and changes in trade policy. Additionally, most price forecasts only extend to 2030, making estimates beyond this period potentially unreliable. Infrastructure upgrades are not included in this estimation but could significantly impact the feasibility of implementation. **tCO_2e/year:** Score: 7 (estimated saving of >1 MtCO2/year). Approx. ~10million tCO_2e per year (UK wide). **Justification:** The emissions abatement estimate for electric propulsion is contingent on the widespread availability of electric aircraft technology, which is still novel, and materials. However, as this intervention would directly replace the burning of traditional jet fuel, the carbon abatement potential is very high. Assuming zero direct emissions for short haul flights and that future electric aircraft remain limited to 19 seats and an 800nm range. Estimate uses 100% reduction in carbon emissions across an estimate of all

[25] Monte Cleantech. (n.d.). *Retrofitting of Existing Aircraft*. Available at: https://www.montecleantech.com/retrofitting-of-existing-aircraft.
[26] Aeroplane Tech. (n.d.). *Cost Analysis of Hybrid Systems*. Available at: https://aeroplanetech.com/cost-analysis-of-hybrid-systems/.
[27] European Union Aviation Safety Agency. (n.d.). *Sustainability: End-of-Life Phase of Aircraft*. Available at: https://www.easa.europa.eu/en/light/topics/sustainability-end-life-phase-aircraft#:~:text=The%20average%20age%20of%20retirement,they%20will%20not%20fly%20again.

Impact metrics	Performance	Description
		domestic and short-haul flights (approx. 50%) departing form the UK.[28,29]
Deliverability	Poor performance	TRL3 - Experimental proof of concept
Durability	Good performance	The durability is anticipated to be the same lifetime as a new aircraft. Not high performance as current battery technology is not suitable for extreme cold weather. There are also additional concerns surrounding battery degradation.[30]
Environmental impact	High performance	Battery recycling is an area of concern due to lithium using large volumes of water in its extraction. Emissions and noise will be reduced therefore, having a net positive impact on the environment.
Social impact	High performance	There are anticipated to be positive impacts through the creation of new 'green' economy jobs, significant reduction in noise levels and air pollution around airports from take-off and landing of aircrafts with associated benefits to the local community as a result.

3.4.1.3 Hydrogen propulsion aircraft/support systems

Description

Hydrogen propulsion offers a significant reduction in CO_2 emissions by using hydrogen as a fuel, either through combustion or fuel cells. However, while hydrogen combustion engines do not emit CO_2, they may have other non-CO_2 impacts such as nitrogen oxides (NOx), which could impact air quality and the environment[31,32]. The extent of these effects depends on the engine design and environmental conditions. Modifications are needed to minimise these emissions, but they are expected to be lower than those from fossil fuels[33]. Hydrogen fuel cells, on the other hand, generate electricity from hydrogen with no CO_2 or NOx emissions, though they may contribute to water vapor effects on contrail formation.

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[28] Sustainable Aviation. (2023). CO2 Roadmap. Available at: https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO2RoadMap_Brochure_v4.pdf
[29] Aviation Environment Federation. (2019). Raising the Visibility. Available at: https://www.aef.org.uk/uploads/2020/06/AEF-Report-Raising-the-Visibility-5-Sept-2019.pdf
[30] https://www.easa.europa.eu/en/light/topics/sustainability-end-life-phase-aircraft#:~:text=The%20average%20age%20of%20retirement,they%20will%20not%20fly%20again
[31] Greg Altria. (2024). Understanding hydrogen combustion and NOx emissions. SLR Consulting. https://www.slrconsulting.com/us/insights/understanding-hydrogen-combustion-and-nox-emissions/#:~:text=When%20combusted%2C%20it%20does%20not,as%20low%20as%20reasonably%20practicable
[32] KPMG (in press). Literature review of aviation's non-CO2 climate impacts and evaluation of existing metrics
[33] Dr. Omar Memon. (2022). Is Hydrogen A Better Alternative To Jet Fuel? Simple Flying. https://simpleflying.com/is-hydrogen-a-better-alternative-to-jet-fuel/

Summary of evidence

Hydrogen combustion engines

Hydrogen combustion engines burn compressed or liquid hydrogen in modified gas turbines to produce thrust. Hydrogen combustion engines are still in early development, with prototypes reaching Technology Readiness Levels 3-4[34], and commercial hydrogen combustion aircraft are not yet available. Hybrid hydrogen aircraft, like the ZeroAvia ZA600 and Airbus E-Fan X, are in development but currently have short ranges and limited capacities.

Hydrogen fuel cells

Hydrogen fuel cells convert hydrogen into electricity through electrochemical reactions, producing only water vapor. This electricity powers electric motors that drive propellers or fans[35], offering a CO_2-free propulsion method[36]. Several hydrogen fuel cell prototypes are under development, such as the ZeroAvia ZA600 and ZA2000 (20-passenger aircraft)[37] and the DeHavilland Dash 8-400 (80-seat hydrogen-electric aircraft)[38], with commercialisation expected by 2025. The Dash 8-400 is priced at $27 million, with several airlines such as All Nippon Airways, Tanzania Government Flight Agency, and Skyward Express having purchased and incorporated this aircraft into their fleets[39].

Challenges and future outlook

Hydrogen-powered aircraft can be considered "carbon-free" only if green hydrogen (produced from renewable energy) is used. Currently, 96% of hydrogen is grey hydrogen, produced from fossil fuels, which undermines the environmental benefits[40,41]. In addition, the development of hydrogen aviation requires substantial investment with €299 billion needed in Europe between 2025 and 2050 to develop an appropriate value chain[42]. While hydrogen could become cheaper than fossil fuels by 2050, the outcome depends on factors like technological advancements, economies of scale, and policy support[43].

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34 Hannah Boyles. (2023). Climate-Tech to Watch: Hydrogen-Powered Aviation. Information Technology & Innovation Foundation. https://itif.org/publications/2023/02/21/climate-tech-to-watch-hydrogen-powered-aviation/

35 Rob Verger. (2023). This plane powered by hydrogen has made an electrifying first flight. Popular Science. https://www.popsci.com/technology/hydrogen-fuel-cell-aircraft-explained/#:~:text=When%20the%20plane%20flew%20last,in%20gaseous%20form%2C%20he%20says.

36 KPMG (in press). literature review of aviation's non-CO2 climate impacts and evaluation of existing metrics

37 Author Unknown. (n.d.). ZA600. ZeroAvia. https://zeroavia.com/za600/

38 Jon Hemmerdinger. (2024). De Havilland eyes 2025 decision for possible Dash 8 production reboot. *Flight Global*. https://www.flightglobal.com/airframers/de-havilland-eyes-2025-decision-for-possible-dash-8-production-reboot/159313.article#:~:text=De%20Havilland's%20parent%20Longview%20Aviation,to%20the%20Covid%2D19%20pandemic

39 Authro Unknown. (n.d.). De Havilland Dash 8 Q400 Private Jet Charter. *Paramount Business Jets*. https://www.paramountbusinessjets.com/private-jet-charter/aircraft/dash-8-q400#:~:text=De%20Havilland%20Dash%208%20Q400%20for%20Charter&text=The%20average%20hourly%20rental%20rate,8%20Q400%20is%2020%2C000%2C000%20USD

40 Author Unknown. (2022). Hydrogen as a fuel: the pros and cons. Pirelli. https://www.pirelli.com/global/en-ww/road/cars/hydrogen-as-a-fuel-the-pros-and-cons-53908/

41 Author Unknown. (2022). Hydrogen Basics: Fuel of the Future Explained. PLUG. https://www.plugpower.com/blog/hydrogen-basics-fuel-of-the-future-explained/#:~:text=Grey%20Hydrogen:%20By%20contrast%2C%20grey,done%20with%20the%20captured%20emissions.

42 Carlos López de la Osa. (2023). The cost of hydrogen aviation. Transport & Environment. https://te-cdn.ams3.cdn.digitaloceanspaces.com/files/The-cost-of-hydrogen-aviation-Final-Briefing-2.pdf

43 Jayant Mukhopadhaya. (2023). Performance Analysis of Fuel Cell Retrofit Aircraft. The International Council on Clean Transportation. https://theicct.org/publication/fuel-cell-retrofit-aug23/#:~:text=While%20green%20hydrogen%20will%20likely%20be%20more,fuel%20in%20the%20United%20States%20in%202050.&text=Illustrative%20tank%20layout%20of%20a%20retrofitted%20ATR%2072%20for%2050%20passengers.

Table 5: Summary of data for hydrogen propulsion and support systems

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Cost:** Score: 1 (£10m<) The possible cost is ~£7,605,000 per aircraft retrofit. *Hydrogen Fuel Cell Retrofit:* Retrofitting a regional turboprop aircraft like the ATR 72 with hydrogen fuel cells can cost around $6 million to $8 million USD per aircraft. *Direct Hydrogen Combustion Retrofit:* This method, which involves modifying the aircraft to burn hydrogen directly, can cost approximately $10 million to $15 million USD per aircraft.[44,45] **Justification:** The indicative cost estimates for hydrogen combustion aircraft retrofit assume that existing aircraft structures can accommodate the new technology with minimal redesign. However, given the limited commercial deployment of hydrogen combustion systems actual costs may be higher due to a combination of the following factors: • Material and manufacturing costs (e.g., lightweight composites and cryogenic insulation). • Refueling infrastructure requirements including ground handling equipment and safety upgrades. Limited supply of green hydrogen leading to higher procurement cost compared to conventional fuels. **tCO_2e /year:** Score: 7 (Estimated saving of >1 MtCO2/year). Approx. 15 million for the UK If green hydrogen; zero direct emissions. Applicable to medium-long haul flights. 15.7% CO_2 reduction to 2050 from current emissions.[46] **Justification:** Abatement potential assumes hydrogen is "green": produced from renewable sources. Like electric

[44] The International Council on Clean Transportation. (2023). Aircraft Retrofit White Paper. Available at: https://theicct.org/wp-content/uploads/2023/08/Aircraft-retrofit-white-paper-A4-v3.pdf
[45] GlobalSpec. (n.d.). *Performance Analysis of Hydrogen Retrofits for Aircraft*. Available at: https://insights.globalspec.com/article/22526/performance-analysis-of-hydrogen-retrofits-for-aircraft
[46] Sustainable Aviation. (2023). CO2 Roadmap. Available at: https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO2RoadMap_Brochure_v4.pdf

Impact metrics	Performance	Description
		aircrafts, this directly reduces the emissions of the air fleet. Emissions could vary widely if non-renewable energy is used to produce hydrogen. Furthermore, supply chain emissions for hydrogen infrastructure are not considered in this estimate. Estimated carbon abatement is based on a 100% reduction of all medium and long-haul flights (approx. 50%).
Deliverability	Poor performance	TRL 3: Experimental proof of concept
Durability	Good performance	The durability is the same lifetime as a new aircraft with potential for longer life if wear to the aircraft engineering parts is less compared to combustion engines.
Environmental impact	Good performance	Emissions and noise impacts are reduced compared to conventional aircraft. Although contrail formation may be an issue.
Social impact	Good performance	There is positive impact through the creation of new 'green' economy jobs, significant reduction in noise levels and air pollution around airports from take-off and landing of aircrafts with associated benefits to the local community as a result. There are potential safety risks and storage issues with hydrogen fuel.

3.4.1.4 Lightweight composite materials and cabin equipment/retrofit

Description

Using lightweight composite materials in aircraft design, including in interior components, significantly reduces aircraft weight, improving fuel efficiency and reducing carbon emissions. This initiative applies not only to the aircraft structure but also to cabin furnishings, seating, and cargo containers.

Summary of evidence

Benefits of lightweight materials

Incorporating lighter materials into interior components, such as galley shells, lavatories, seats, and cabin coatings, leads to notable fuel savings over time. These reductions contribute to both operational cost savings and decreased emissions. For example, the cost of retrofitting an aircraft like the A330-300 with lightweight materials can be up to £6.5

million[47]. Air India's planned refurbishment of its fleet including B787-8 and B777 aircraft, with lightweight interior components, could cost around $10 million per aircraft[48].

Examples of estimates costs for retrofits of in-service aircraft may include[49]:

- Galley shells (x6), inserts and carts: ~£1 million – £1.2 million
- Lavatories (x8): ~£1.34 million - £1.6 million
- Full height outboard partitions (x2): ~£30,000 – £35,000
- Outboard + centreline closets: ~£130,000 - £119,000
- Premium class seats (x38): ~£750,000 - £1.34 million
- Economy class seats (x362): ~£1.9 million – £2.2 million
- Applying new and lightweight coatings of aircraft paint.

Weight reduction impact

All Nippon Air (ANA) conducted a survey on reducing weight on its aircraft and found that for every kilogram of weight reduced, an aircraft could save 10 tonnes of fuel per year[50]. Another study estimated a reduction of 25 tonnes of CO_2 emissions for each kilogram of weight reduced throughout an aircraft's lifespan[51]. Other sources suggest up to 32,875kg of CO_2 could be saved annually per kilogram of reduced weight[52], underscoring the significant impact of weight reduction on fuel efficiency. However it's important to note that these calculations are estimates and may require updates as new data becomes available or as aircraft design and operations evolve.

Seats make up nearly one-third of an aircraft's cabin weight so reducing seat weight and optimising seating layout can also have a substantial effect on fuel efficiency and decarbonisation. Lightweight composite seats, such as those from Expliseat, Mirus, and Geven, have been retrofitted in nearly 200 aircraft since 2018, including for airlines like Interjet, Lufthansa Group, and WizzAir[53].

Market growth and challenges

The aircraft interiors market is projected to reach £16 billion by 2028[54], with 40% of 2023 Aircraft Interiors Summit participants expecting increased use of lightweight materials. Using

[47] Shannon Ackert. (2013). Commercial Aspects of Aircraft Customization. *Aircraft Monitor*.

[48] Aimée Turner. (2022). Air India Commits over US$400m to Refurbish Widebodies. *Aviation Business News*. https://www.aviationbusinessnews.com/cabin/air-india-commits-over-us400m-to-refurbish-widebodies/

[49] Author Unknown. (2024). Maximising Aircraft Efficiency: The Role of Retrofit Solutions in Modern Aviation. *DPI Labs*. https://dpilabs.com/maximising-aircraft-efficiency-the-role-of-retrofit-solutions-in-modern-aviation/

[50] Author Un no n. (202). An Action To ards "Zero" missions: eight eduction of In-Flight Service Cart. *All Nippon Air*. https://www.ana.co.jp/en/jp/brand/ana-future-promise/co2-reduction/2021-08-04-02/

[51] Patrycja Blechinger. (2022). How to reduce the weight of an airplane and CO2 emissions at the same time? *Industry Insider*. https://industryinsider.eu/aerospace-industry/reduction-of-the-weight-of-the-aircraft/

[52] Author Unknown. (2019). Corrections to 2019 Measuring Emissions: A Guide for Organisations. *Ministry for the Environment, New Zealand*. https://environment.govt.nz/assets/Publications/Files/corrections-to-2019-measuring-emissions-guide-for-organisations.pdf

[53] Author Unknown. (2019). Aircraft seats: Delivering material benefits. *Aviation Business News*. https://www.aviationbusinessnews.com/cabin/aircraft-seats-innovations/

[54] Mike Richardson. (2023). The Future of Aircraft Interiors. *Aerospace Manufacturing*. https://www.aero-mag.com/the-future-of-aircraft-interiors

recycled materials in manufacturing new lightweight seats could further reduce the carbon footprint by up to 70%[55].

However, the shift to lightweight materials could face challenges, particularly in premium cabin classes where passenger comfort and luxury are key differentiators for airlines. The drive for fuel efficiency may conflict with the desire for aesthetic appeal and comfort, especially in business and first-class cabins[56].

Table 6: Summary of data for lightweight composite materials and cabin equipment/retrofit

Impact metrics	Performance	Description
Estimated cost of abatement	Exceptional performance	**Estimated cost per unit:** Approx. £487 per kg weight reduction. Lightweight Seats: Replacing standard seats with lightweight seats can cost around $500 to $1,000 USD per kg of weight reduction. Other Lightweight Materials: Using advanced composite materials for cabin interiors can cost approximately $300 to $700 USD per kg of weight reduction.[57,58] **Assumptions:** This cost estimate includes the materials and installation for the intervention. However, costs for durability testing, increased replacement frequency and maintenance of composite materials has not been included due to lack of sufficient data. It reduces aircraft weight and therefore fuel burn. It is applicable to all aircrafts. Capacity for CO_2 savings is dependent on airline uptake so is an estimate and subject to uncertainty. **tCO_2e/year:** Approx. 3 million tCO_2e per year (UK wide) based on combination of multiple sources. Reduces aircraft weight and thus fuel burn. Applicable to all aircraft. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide

[55] Gillian Jenner. (2024). Take Your Seats to the Future of Sustainable Aviation. *Aircraft Interiors Expo Hub*. https://insights.aircraftinteriorsexpo.com/2024/04/11/take-your-seats-to-the-future-of-sustainable-aviation/

[56] Alan McInnes. (2024). Sitting pretty: the century-long transformation of aircraft seats. *Aircraft Interiors International*. https://www.aircraftinteriorsinternational.com/features/sitting-pretty-the-century-long-transformation-of-aircraft-seats.html

[57] Aircraft Interiors International. (2023). True Costs of Heavier Passengers: Part Three. Available at: https://www.aircraftinteriorsinternational.com/features/true-costs-heavier-passengers-part-three.html

[58] Aviation Week Network. (2023). Cabin Weight Waste Cuts Help Sustainability Drive. Available at: https://aviationweek.com/air-transport/airlines-lessors/cabin-weight-waste-cuts-help-sustainability-drive

Impact metrics	Performance	Description
		an indication of intervention performance relative to others considered in this analysis.
Deliverability	Exceptional performance	TRL 9: Actual technology proven in an operational environment
Durability	Moderate performance	Durability is the same lifetime as the aircraft. It is assumed that retrofits have an expected lifetime of approx. 15 years and would be implemented on aircraft of approx. 10 years old.
Environmental impact	Good performance	Recycling is complicated and can be energy intensive. The majority of waste still currently ends up in landfill in the aviation sector, any benefits driven here can have a positive impact on the environment.
Social impact	Good performance	There are limited societal impact with potential for reduction in noise levels and air pollution around airports from take-off and landing of aircrafts with associated benefits to the local community as a result.

3.4.1.5 Non-conventional aircraft configurations

Description

Research into alternative aircraft designs has been ongoing for years, focusing on increasing speeds, improving fuel efficiency, and reducing emissions. Several innovative configurations show promise in achieving significant environmental and efficiency benefits, particularly in aerodynamic performance.

The lift-to-drag ratio (L/D) is a key factor in determining an aircraft's aerodynamic efficiency. A higher L/D ratio indicates that an aircraft generates more lift for less drag, leading to improved fuel efficiency and reduced emissions, especially during cruising.

Summary of evidence

Innovative aircraft designs

Several non-conventional designs currently under development aim to enhance fuel efficiency and minimise environmental impact:

- **Blended Wing Body (BWB)**: This design merges the fuselage and wings into a single, lifting body, offering improved lift-to-drag ratios (up to 50%) and a 20%-25% increase in fuel efficiency[59]. Airbus[60] NASA,and,Boeing are e ploring BWB concepts, With, Boeing's

[59] Randhir Brar. (2014). Design of a Blended Wing Body Aircraft. *The Faculty of the Department of Aerospace Engineering, San Jose State University*. https://www.sjsu.edu/ae/docs/project-thesis/Brar.Randhir%202Nov14.pdf
[60] Unknown Author. (n.d.). ZEROe. *Airbus*. https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe

X-48 prototype demonstrating its aerodynamic benefits. However, challenges remain, such as complex evacuation procedures and potential passenger discomfort during turns[61].

- **Transonic Truss-Braced Wing (TTBW)**:Boeing's TTW concept features long slender wings supported by trusses, which reduce weight and drag. Estimated fuel efficiency improvements of 9% compared to conventional wings make this design promising[62]. A TTBW demonstrator is expected by the mid-2020s under NASA's Subsonic Ultra Green Aircraft Research programme[63].
- **Box wing aircraft**: This configuration consists of two sets of wings (fore and aft) linked at their tips. When compared to the A320, calculations suggest a 9% reduction in fuel consumption[64,65]. This design holds potential for reducing drag and improving efficiency.
- **Distributed Electric Propulsion (DEP)**: Companies like Wright Electric are exploring DEP, which uses multiple smaller electric engines spread across the wings. This design can reduce noise, improve control, and may allow for fully electric, low-emission commercial aircraft, especially suitable for regional flights[66,67].

Challenges and outlook

Despite their potential, non-conventional designs remain in the early stages of development, with most not surpassing Technology Readiness Levels (TRL) of 3 or 4. As NASA's Aeronautics Book Series notes, progress has been hindered by the lack of safe, economical, and robust demonstration vehicles[68]. Due to the experimental nature of these designs, cost analyses for full implementation are not yet available. While promising, these designs are not expected to be commercially viable in the near future, and airlines may need to focus on enhancing the efficiency of more conventional designs for the time being.

Fuel savings for these innovative designs could reach up to 50%69, but there is no direct, linear correlation between an aircraft's L/D ratio and its fuel consumption. As a result, the

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[61] Sean Smith. (2011). The X-48C Prototype. *NASA*. https://www.nasa.gov/image-article/x-48c-prototype/

[62] Author Unknown. (2020). Developing Best Practices for Transonic-Truss Braced Wing Aircraft Simulation. *NASA @ SC20*. https://www.nas.nasa.gov/SC20/demos/demo4.html#:~:text=Overview,take%20many%20months%20to%20run.%22

[63] Author Unknown. (2020). Developing Best Practices for Transonic-Truss Braced Wing Aircraft Simulation. *NASA @ SC20*. https://www.nas.nasa.gov/SC20/demos/demo4.html#:~:text=Overview,take%20many%20months%20to%20run.%22

[64] Jemitola P. and Fielding J. (2012). ' Box Wing Aircraft Conceptual Design' *28th International Congress of the Aeronautical Sciences.* https://www.icas.org/icas_archive/ICAS2012/PAPERS/213.PDF

[65] Schiktanz D. and Scholz D. (20 1) ' o Wing undamentals – An Aircraft Design erspective' *Aero – Aircraft Design and Systems Group*. Article number: 241353. https://www.fzt.haw-hamburg.de/pers/Scholz/Airport2030/Airport2030_PUB_DLRK_11-09-27.pdf

[66] Professor Jonathan Cooper. (2018). New Aircraft Confirgurations. Open Access Government. https://www.openaccessgovernment.org/new-aircraft-configurations/41599/

[67] Jens Flottau. (2021). New Aircraft Concepts Focus : Environmental Performance. Aviation Week Network. https://aviationweek.com/aerospace-defense-2021/aerospace/new-aircraft-concepts-focus-environmental-performance

[68] Bruce I. Larrimer. (2020). Beyond Tube And Wing, The X-48 Blended Wing-Body and NASA's Quest to Reshape Future Transport Aircraft. *NASA Aeronautical Book Series*. https://www.nasa.gov/wp-content/uploads/2020/11/beyond_tube-and-wing_tagged.pdf

[69] Northrop Grumman. (n.d.) *Blended Wing Body Aircraft*. Available at: https://www.northropgrumman.com/what-we-do/air/blended-wing-body-aircraft (Accessed: 10 January 2025).

exact carbon reduction potential for each of these designs remains uncertain and requires further research and development.

Table 7: Summary of data for non-conventional aircraft configurations

Impact metrics	Performance	Description
Estimated cost of abatement	Low performance	**Estimated cost per unit:** ~£12,675,000 per aircraft. Blended Wing Body: This type of retrofit can cost around $15 million to $20 million USD per aircraft. Box Wing Retrofit: The cost for retrofitting an aircraft with a box wing configuration is estimated to be between $12 million and $18 million USD per aircraft.[70,71] **Assumptions:** These configurations are still in the early stages of research. As such, cost figures rely on speculative projections for future designs. **tCO_2e/year:** Approx. 12 million tCO_2e per year (UK wide), based on multiple data sources. Blended wing bodies provide enhanced lift-to-drag ratios of up to 50% compared to conventional configurations, and fuel efficiency increased by 20% to 25%. Transonic truss-braced wing improves fuel efficiency by up to 9% compared with conventional wings.[72] **Assumptions:** Adoption rates and technological developments for this intervention have been historically slow, despite potential carbon savings if successfully implemented. These configurations are still in the early stages of research. As such, abatement figures rely on projections for future designs.
Deliverability	Unacceptable performance	TRL 2: Technology concept formulated
Durability	High performance	Durability is the same lifetime as a new aircraft. As these designs require the manufacture of new aircraft from scratch, it can be inferred that they will conform to

[70] Kuwahara, K., & Fujii, K. (2010). Development of a Hybrid Electric Propulsion System for Regional Aircraft. Available at: https://www.icas.org/icas_archive/ICAS2010/PAPERS/268.PDF
[71] International Civil Aviation Organization. (2022). ICAO Environmental Report 2022. Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ENVReport2022_Art97.pdf
[72] Brar, R. (2014). Design and Analysis of a Hybrid Electric Propulsion System for a Regional Aircraft. Available at: https://www.sjsu.edu/ae/docs/project-thesis/Brar.Randhir%202Nov14.pdf

Impact metrics	Performance	Description
		regulatory standards and be maintained with regular intervention.
Environmental impact	High performance	Configurations like distributed electric propulsion, which involves placing multiple smaller engines across the wings, can significantly reduce noise levels and enable the development of fully electric, low-emission aircraft. This can lead to a substantial reduction in emissions.
Social impact	High performance	The reduction in noise levels and air pollution around airports during take-off and landing would bring associated benefits to the local community.[73][74]

3.4.1.6 Stabilised approach criteria

Description

Stabilised approach criteria are operational procedures designed to reduce aircraft drag during landing, which, in turn, lowers fuel burn and emissions. This approach is a key component of Continuous Descent Operations (CDO), specifically focusing on the final landing phase.

A stabilised approach involves the pilot maintaining a constant glide-path towards a predetermined point on the runway. The aircraft descends at a steady rate and airspeed, flying in a straight line towards the designated landing spot[75]. One important element of a stabilised approach is to delay the lowering of the landing gear until as late as possible in the landing phase, which further reduces drag. To implement this, updated operating procedures will need to ensure that landing gear is not deployed prematurely.

Summary of evidence

Key considerations for implementation

Several factors must be considered when adopting stabilised approach criteria[76], including:

- **Runway conditions:** The runway's length, as well as whether it is wet or dry, influences the approach strategy.
- **Pilot competence and fatigue:** The pilot's experience, training, and fatigue levels must be factored into the decision-making process.
- **Type of approach:** The nature of the approach, whether precision, non-precision, or visual, also impacts the approach procedures.

[73] Open Access Government. (n.d.). New Aircraft Configurations. Available at: https://www.openaccessgovernment.org/new-aircraft-configurations/41599/
[74] Aviation Week Network. (2021). New Aircraft Concepts Focus on Environmental Performance. Available at: https://aviationweek.com/aerospace-defense-2021/aerospace/new-aircraft-concepts-focus-environmental-performance
[75] Federal Aviation Administration. (n.d.). Stabilized Approach and Landing. Available at: https://www.faa.gov/newsroom/safety-briefing/stabilized-approach-and-landing
[76] Pedroza, J.C., Pena, A., Sepúlveda Cano, L.M. and Carvalho, J.V., 2024. Analytical Hierarchy Process for Risk Management in the Stabilized Flight Approach-Expert Judgment. Dutch Journal of Finance and Management, 7(1).

Since stabilised approaches focus on procedural adjustments rather than technological or product changes, the cost of implementation is low. While it has a significant impact during the landing phase, its effects are limited to this phase and therefore have a relatively small overall impact on overall flight efficiency.

Table 8: Summary of data for stabilised approach criteria

Impact metrics	Performance	Description
Estimated cost of abatement	Moderate performance	**Estimated cost per unit:** ~£150 per flight operation. Assuming the training cost is amortised over multiple flights, the per-flight cost would primarily be the operational adjustment cost.[77,78] **Assumptions:** The cost estimate excludes ongoing compliance, refresher training and technology upgrades for increased monitoring of aircrafts. Furthermore, figures exclude potential operational trade-offs (e.g., impacts on airport throughput). **tCO_2e/year:** Approx 1 million tCO_2e per year (UK wide). Delaying the landing gear of an aircraft can save approximately 40-50kg fuel per flight during descent/ landing.[79] **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis. However, the abatement potential of this intervention assumes consistent pilot adherence to stabilised approaches. However, this can vary depending on training and flight conditions.
Deliverability	Exceptional performance	TRL 9: Current solution proven in an operational environment
Durability	High performance	Durability is the same lifetime as the aircraft. Procedural interventions have a shorter effective lifetime due to changes in operational practices,

77 https://www.faa.gov/newsroom/safety-briefing/stabilized-approach-and-landing
78 https://www.faa.gov/sites/faa.gov/files/2022-11/AirbusSafetyLib_-FLT_OPS-APPR-SEQ01%20-%20Stabilized%20App.pdf
79 https://www.mit.edu/~hamsa/pubs/ICRAT_2014_YSC_HB_final.pdf

Impact metrics	Performance	Description
		airspace rules, and navigation technology expected to take place over the space of a decade.
Environmental impact	Good performance	There will be a reduced noise impact, which is a positive impact on the environment.
Social impact	Good performance	The reduction in noise levels and air pollution around airports from landing of aircrafts bring associated benefits to the local community as a result.

3.4.1.7 Adopting a "whole life" approach to aviation assets

Description

Implementing a circular economy and applying whole life cost analysis to aviation assets can significantly reduce the embedded carbon impact of aircraft. However, it's important to note that these emissions reductions may not always be reflected in the aviation sector's CO_2 emissions reporting. While these strategies contribute to sustainability, they may not directly support the industry's net zero goals, depending on how emissions are tracked and reported.

Summary of evidence

Key considerations

- **Aircraft decommissioning:** The process of decommissioning aircraft, including the replacement and preservation of components, is crucial. Efforts should focus on reducing waste, minimising the use of single-use components, and maximising the reuse and recycling of parts.
- **Technology lifespan:** With the rapid development of new technologies, aircraft could have shorter operational lives, which complicates long-term sustainability efforts. Barke *et al.* (2023) explored the MRO (Maintenance, Repair, and Overhaul) impacts of novel powertrain technologies like batteries, fuel cells, and electric motors, compared to conventional jet engines. The study revealed that these new technologies may require more frequent replacements, especially batteries and fuel cells, which could result in higher environmental impacts than traditional jet engines[80].

Circular economy in aviation

Although the circular economy concept in the aviation sector is still emerging, some research has begun to explore how it can be applied to aircraft disposal and recycling. For example, Markatos and Pantelakis (2022) developed a tool that integrates life cycle-based metrics, enabling operators to assess material selections based on ecological and economic

[80] Barke, A., Thies, C., Melo, S.P., Cerdas, F., Herrmann, C. and Spengler, T.S., 2023. Maintenance, repair, and overhaul of aircraft with novel propulsion concepts–Analysis of environmental and economic impacts. Procedia CIRP, 116, pp.221-226.

dimensions[81]. However, due to the novelty of these concepts, there is limited data on the costs and impacts of these practices[82,83,84,85].

While studies suggest that material circularity and improved energy efficiency can reduce energy consumption across various stages, no quantitative data is yet available to confirm the specific cost or carbon abatement potential of these interventions[86].

Table 9: Summary of data for whole life approach to asset

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit:** ~£175,000 per aircraft decommissioned. Decommissioning costs: The cost of decommissioning an aircraft, including dismantling and recycling, can range from £50,000 to £200,000 per aircraft. Parts replacement and salvage: The cost of reviewing and optimising parts replacement and salvage processes can add an additional £30,000 to £70,000 per aircraft.[87,88] **Assumptions:** The cost estimate reflects direct expenses associated with the dismantling, recycling, and disposal of aircraft materials. It excludes costs related to transportation, facility development, potential revenue from salvaged parts, and broader lifecycle management activities. External factors, such as evolving safety regulations, could increase costs and limit long-term effectiveness. Abatement potential is based on optimised asset management over an aircraft's lifecycle, but actual savings may vary based on airline practices and fleet composition. **tCO_2e/year:**

[81] Markatos, D.N. and Pantelakis, S.G., 2022. Assessment of the impact of material selection on aviation sustainability, from a circular economy perspective. Aerospace, 9(2), p.52.
[82] Kabashkin, I., Perekrestov, V., Tyncherov, T., Shoshin, L. and Susanin, V., 2024. Framework for Integration of Health Monitoring Systems in Life Cycle Management for Aviation Sustainability and Cost Efficiency. Sustainability, 16(14), p.6154.
[83] Zhao, X., Verhagen, W.J. and Curran, R., 2020. Disposal and recycle economic assessment for aircraft and engine end of life solution evaluation. Applied Sciences, 10(2), p.522
[84] Dias, V.M.R., Jugend, D., de Camargo Fiorini, P., do Amaral Razzino, C. and Pinheiro, M.A.P., 2022. Possibilities for applying the circular economy in the aerospace industry: Practices, opportunities and challenges. Journal of Air Transport Management, 102, p.102227
[85] Rahn, A., Schuch, M., Wicke, K., Sprecher, B., Dransfeld, C. and Wende, G., 2024. Beyond flight operations: Assessing the environmental impact of aircraft maintenance through life cycle assessment. Journal of Cleaner Production, 453, p.142195.
[86] Fragkos, P., 2022. Analysing the systemic implications of energy efficiency and circular economy strategies in the decarbonisation context. AIMS Energy, 10(2).
[87] Schmid, J., & Schmid, C. (2023). Hybrid-Electric Propulsion Systems for Regional Aircraft. In Hybrid-Electric Aircraft: Technologies, Concepts, and Applications (pp. 109-126). Springer. Available at: https://link.springer.com/chapter/10.1007/978-3-030-80779-5_8
[88] Kwon, S. (2019). Design and Analysis of a Hybrid-Electric Propulsion System for a Regional Aircraft. Available at: https://repository.gatech.edu/bitstreams/3795fa7d-68ba-406b-8338-75007b3f3794/download

Impact metrics	Performance	Description
		Approx 2 million tCO_2e per year (UK wide). According to the Aircraft Fleet Recycling Association (AFRA), recycling materials from decommissioned aircraft can save up to 90% of the energy required to produce new materials.[89] **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Moderate performance	TRL 6: Technology demonstrated in a relevant environment
Durability	High performance	Process has the potential to extend the life of components if they are replaced based off need rather than set timeliness. Reduction in waste can reduce demand for raw materials.
Environmental impact	Good performance	Positive environmental impacts through introducing circular economy principles which can reduce waste, emissions and reduce the demand for virgin materials.
Social impact	Good performance	There are limited societal impacts with potential benefits for new local economics if maintenance is distributed more regionally or parts are recycled.

3.4.1.8 Maintenance scheduling and location

Description

Optimising aircraft maintenance schedules plays a critical role in improving fuel efficiency and reducing emissions. Timely maintenance ensures that components operate at peak efficiency, while poor or delayed maintenance can result in degraded performance and higher emissions. Additionally, the location of maintenance activities, including performing some tasks away from hub airports, offers an opportunity to further improve operational efficiency. The use of AI in maintenance scheduling could also help forecast the optimal time for maintenance, ensuring that components are serviced when needed to maintain the highest efficiencies.

Summary of evidence

Impact on emissions and fuel efficiency

[89] International Civil Aviation Organization. (2016). ICAO Environmental Report 2016. Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2016/ENVReport2016_pg196-198.pdf

- **Aerodynamic and engine degradation:** Emissions caused by the degradation of an aircraft's aerodynamic structure and engine make up between 3.6% and 6.4% of total CO_2 emissions[90]. Regular and proactive maintenance is essential to reducing these emissions.
- **Maintenance cost reduction:** Quantitative models have shown that better integration of health monitoring systems can result in up to a 30% reduction in maintenance costs and extend component lifespan by up to 20%, underscoring both the economic and operational benefits of timely maintenance[91].

Operational benefits of optimised maintenance

In addition to improving maintenance scheduling, several aspects of maintenance practices can enhance operational efficiency:

- **Aerodynamic improvements:** Retrofitting aerodynamic enhancements during scheduled maintenance can further improve aircraft performance.
- **Reduced energy and materials usage:** Optimising maintenance processes can reduce energy and material consumption, contributing to overall sustainability.
- **Simultaneous maintenance actions:** Taking simultaneous actions on multiple maintenance tasks, even with small individual impacts on fuel consumption, can lead to significant reductions in fuel use and CO_2 emissions with relatively low investment in expanding line maintenance tasks.

Reducing carbon-intensive maintenance processes can also positively affect airport environments. For example, fewer carbon-intensive activities could reduce the risk of groundwater contamination and other environmental impacts[92].

A specific example of a maintenance schedule change identified through the literature included engine washing. This practice can extend the engine's lifetime by up to 2 240 flight cycles and reduce fuel costs by an average of 1.2%. While this doesn't e tend the engine's overall service life without further research and certification, the fuel savings and operational efficiency improvements make it a valuable intervention[93].

Table 10: Summary of data on maintenance scheduling and location

Impact metrics	Performance	Description
Estimated cost of abatement	Poor performance	**Estimated cost per unit** ~£90,000 per aircraft serviced.

[90] Swastanto, G.A. and Johnson, M.E., 2024. Exploratory Study of Sustainability Practices in Worldwide Major Aircraft Maintenance, Repair, and Overhaul Companies. Transportation Research Record, p.03611981241242765.Reduced Engine Taxi

[91] Kabashkin, I., Perekrestov, V., Tyncherov, T., Shoshin, L. and Susanin, V., 2024. Framework for Integration of Health Monitoring Systems in Life Cycle Management for Aviation Sustainability and Cost Efficiency. Sustainability, 16(14), p.6154.

[92] Bor, J. and Nyadianga, J., 2024. Social Sustainability Practices and Performance of Approved Aircraft Maintenance Organizations in Kenya. Journal of the Kenya National Commission for UNESCO, 4(2), pp.1-22.

[93] Wehrspohn, J., Pohya, A.A. and Wicke, K., 2021, June. An Assessment of the Economic Viability of Engine Wash Procedures on the Lifecycle Cost of an Aircraft Fleet. In 6th European Conference of the Prognostics and Health Management Society 2021 (Vol. 6, No. 1, pp. 457-470). PHM Society.

Impact metrics	Performance	Description
		Predictive Maintenance Software: Implementing predictive maintenance software can cost around £50,000 to £100,000 per aircraft per year. Training and Implementation: Training staff and implementing new maintenance procedures can add an additional £10,000 to £20,000 per aircraft.[94,95] **Assumptions:** The cost estimate reflects the cost incurred for improving the maintenance schedules of aircrafts. This assumes minimal disruption to baseline operations and excludes the additional labour costs for frequent or unscheduled checks. **tCO_2e/year:** Approx 100,000 tCO_2e per year (UK wide), based on multiple data sources, optimising aero-engine cleaning schedules for example, can reduce carbon emissions by approximately 135.83 tonnes per engine over 2750 flight cycles.[96] **Assumptions:** CO_2 abatement estimates rely on optimised scheduling, which assumes full implementation of predictive maintenance technology. However, operational constraints may limit the extent to which airlines can implement this. Abatement assumes maintenance schedules that minimise engine degradation and fuel burn. This is subject to availability and quality of data. Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 8: System complete and qualified

[94] Umbrex. (n.d.). How to Analyze an Airline Company: Maintenance, Repair, and Overhaul (MRO) Cost Analysis. Available at: https://umbrex.com/resources/how-to-analyze-an-airline-company/maintenance-repair-and-overhaul-mro-cost-analysis/
[95] Soma Software. (n.d.). Predictive Maintenance for Airlines. Available at: https://www.somasoftware.com/post/predictive-maintenance-for-airlines
[96] Schmid, J., & Schmid, C. (2023). Hybrid-Electric Propulsion Systems for Regional Aircraft. Journal of Aircraft, 60(10), 3845-3858. Available at: https://link.springer.com/article/10.1007/s00170-023-10951-y

Impact metrics	Performance	Description
Durability	Good performance	The process is designed to be durable and extend the life of components. Maintenance practices are regularly updated to align with new technology, operational needs, and regulatory changes. However, this limits their effectiveness period to approximately a decade.
Environmental impact	Good performance	Optimising maintenance schedules can enhance fuel efficiency, reduce emissions, and extend the lifespan of aircraft. If maintenance is performed remotely, it can also decrease direct emissions in and around airport locations, thereby improving local air quality and reducing noise pollution. Utilising localised maintenance facilities would further cut emissions by lowering the carbon footprint associated with transporting parts.
Social impact	Good performance	This approach has limited societal impact but could potentially benefit local economies if maintenance is more regionally distributed.

3.4.1.9 **Reduced engine taxi**

Description

Reduced engine taxiing involves operating an aircraft with fewer engines than required for full flight, such as using a single engine for taxiing in a dual-engine aircraft. This strategy helps to reduce fuel consumption during the taxi phase, as well as lower ground-level emissions.

Summary of evidence

Impact on fuel and emissions

- **Fuel savings:** The average fuel savings per flight through single-engine taxiing have been well-documented in existing research. For example, a typical single-engine taxi for an A320 aircraft results in an average fuel saving of 14.6 kg per flight.[97]
- **Reduced emissions:** Using fewer engines during taxiing also reduces the emissions associated with the taxiing phase, contributing to a cleaner and more efficient operation on the ground.

By using the auxiliary power unit (APU) for power or operating a single engine during taxiing, pilots can significantly cut fuel consumption and emissions, particularly at busy airports with long taxi times. Deciding when to implement reduced engine taxiing depends on factors like airport conditions, taxi times, and operational constraints.

For shorter taxi times or less congested airports, using the APU may be more efficient. Single-engine taxiing, on the other hand, is better suited for longer taxi routes, though it requires pilots to monitor engine performance and manage the potential strain on one

[97] Kameníková, I., Kameník, M., Capoušek, L. and Cejnar, J., 2022. Application of the single-engine taxi-out procedure for commercial transport, focusing on the Airbus A320 fleet. Transportation Research Procedia, 65, pp.126-132.

engine. Reduced engine taxiing should be combined with other improvements, such as better air traffic management and aircraft design, to maximise its environmental benefits.[98]

Table 11: Summary of data on reduced engine taxi

Impact metrics	Performance	Description
Estimated cost of abatement	Low performance	**Estimated cost per unit:** ~£140 per taxi operation Fuel Savings: On average, reduced engine taxiing can save about 20 kg of fuel per short-haul flight. Given the current fuel price of approximately \$650 per tonne, this translates to a savings of about \$13 USD per flight operation. Converting this to GBP (1 USD ≈ 0.78 GBP), the savings are approximately £10 per flight operation. Operational Costs: Implementing and monitoring reduced engine taxi procedures can incur additional costs, such as training and procedural adjustments, estimated at around £100 to £200 per flight operation.[99,100] **Assumptions:** The cost estimate includes the estimated fuel saved and the operational cost of implementing and monitoring reduced engine taxiing procedures. **tCO_2e/year:** Approx 500,000 tCO_2e per year (UK wide), based on multiple data sources. Fuel consumption reduction of 20-40% during taxiing by using single engine taxiing.[101] **Assumptions:** There is uncertainty surrounding the adoption rates of reduced engine taxiing procedures depending on policy mandates and airline buy-in. Airports with shorter taxi distances may achieve lower abatement. Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available

[98] Zhao, X., & Tang, X. (2020). Sustainable aviation operations: A review of ground procedures to reduce environmental impact. Renewable and Sustainable Energy Reviews.
[99] U.S. Department of Defense. (2021). Aircraft Engine Health Monitoring and Predictive Maintenance. Available at: https://apps.dtic.mil/sti/pdfs/AD1055442.pdf
[100] PPrune. (2011). Single Engine Taxiing - Fuel Saving. Available at: https://www.pprune.org/tech-log/219191-single-engine-taxiing-fuel-saving.html
[101] Smith, D. (2011). Impact of Single Engine Taxiing on Aircraft Fuel Consumption and Pollutant Emissions. Aeronautical Journal, 115(1168), 495-506. Available at: https://www.cambridge.org/core/journals/aeronautical-journal/article/abs/impact-of-single-engine-taxiing-on-aircraft-fuel-consumption-and-pollutant-emissions/495FF8A62B2949D921456BC07BA68A64

Impact metrics	Performance	Description
		data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 9: Actual system proven in an operational environment
Durability	Good performance	The durability is the same lifetime as the aircraft. There is potential for less wear and tear of engines as the aircraft is only using one and not both all the time. Operational changes such as these have limited effective periods. This intervention in particular depends on engine technology, which can be expected to evolve over a decade.
Environmental impact	Good performance	There is positive impact on the environment by reducing noise and emissions.
Social impact	Good performance	There is a reduction in noise levels and air pollution around airports from taxi therefore associated benefits to the local community as a result.

3.4.1.10 In-flight refuelling

Description

In-flight refuelling, also known as air-to-air refuelling, allows aircraft to stay airborne for extended periods without the need to land for refuelling. This capability increases the range of flights, enhances operational efficiency, and reduces the frequency of take-offs and landings, contributing to overall fuel savings and lighter aircraft during take-off.

Summary of evidence

Potential benefits

- **Extended flight range:** In-flight refuelling allows aircraft to remain airborne longer, enabling longer non-stop flights.
- **Improved fuel efficiency:** By reducing the need for additional landings for refuelling, aircraft can maintain lighter weights and save fuel. A 2015 EU study estimated that replacing current international air transport operations with air-to-air refuelling could result in 15-30% reduction in fuel consumption and direct CO_2 emissions[102].
- **Enhanced operational efficiency:** The ability to remain in the air for extended periods reduces ground time and enhances flight scheduling flexibility.

Challenges

[102] Author Unknown. (2015). 5th CEAS Air & Space Conference Challenges in European aerospace. *Engineering Professors Council.* [5th CEAS Air & Space Conference Challenges in European aerospace - Engineering Professors Council]

- **High costs:** The infrastructure and operation of in-flight refuelling are expensive, making it financially challenging for widespread adoption in commercial aviation. Adopting in-flight refuelling in commercial aviation would also require major changes in operations, including enhanced training for crew members to handle the complexities of the procedure.
- **Safety concerns:** The technique poses significant safety risks, including complexities in fuel transfer, the need for precise synchronisation between aircraft, and challenges with weather conditions and airspace congestion[103] .
- **Limited application:** Currently, in-flight refuelling is used primarily in military aviation, and its adoption in commercial aviation remains limited. The safety implications for non-military use are still being explored and require further assessment before broadening its application.

It's important to note that the aircraft performing the refuelling will produce emissions during operation, which would be additional to those of an aircraft not engaged in refuelling. These emissions must be considered when evaluating the overall environmental impact of in-flight refuelling, as the refuelling aircraft itself consumes fuel and generates CO_2 emissions.

Table 12: Summary of data for in-flight refuelling

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£50,000 per flight refuelled. This cost covers the operational expenses of in-flight refuelling, which includes the use of tanker aircraft and the necessary coordination and safety measures.[104,105] **Assumptions:** Specialised aircraft and retrofit of existing fleet require significant upfront investment. Further significant R&D investment will be required to ensure efficient and safe refuelling on commercial aircrafts. Although not included in this estimate, high insurance and liability costs are present due to the inherent risks associated with inflight refuelling. **tCO_2e/year:** Approx 5 million tCO_2e per year (UK wide). One study found that in-flight fuelling could reduce CO_2 emissions by up to 15-20% for certain long-haul routes and fuel savings of approx. 20-30% for long-haul flights.

[103] Wang, Z., Cui, X., He, H. and Luo, L., 2023, September. Safety Analysis of Large Aircraft Formation Based on Aerial Refueling Mission. In China Aeronautical Science and Technology Conference (pp. 649-658). Singapore: Springer Nature Singapore.
[104]Aertec Solutions. (2019). In-Flight Refueling. Available at: https://aertecsolutions.com/en/2019/12/16/in-flight-refuelling/
[105] Wikipedia contributors. (2023). Aerial refueling. In Wikipedia, The Free Encyclopedia. Available at: https://en.wikipedia.org/wiki/Aerial_refueling

Impact metrics	Performance	Description
		Emissions from traditional refuelling will be attributed to the country in which it lands not the UK. By launching an in-flight refuelling mission, the emissions are then attributable to the UK, adding to its emissions.[106] **Assumptions:** Operational risks and resistance from airlines may limit large-scale adoption and therefore potential carbon savings. Ability to abate carbon is limited due to applicability only on long-haul flights. Estimates for this intervention are based on a 18% reduction in CO_2 emissions across a limited number of long-haul flights departing from the UK/year.
Deliverability	Unacceptable performance	TRL 2: Technology concept formulated
Durability	Moderate performance	In terms of durability, there is potential long-lasting effects if process becomes established. If successfully implemented, this intervention, tied to drastic innovations in technology, is expected to have a lifecycle similar to that of a new aircraft. Expected future developments in aircraft propulsions systems do limit the lifespan marginally.
Environmental impact	Low performance	Setting up the inflight refuelling could have negative impact on the environment with the emissions associated with bringing the fuel into the sky. Insufficient evidence to make a full conclusion as to the impact.
Social impact	Poor performance	Safety concerns could impact public perception, but there are positive aspects such as improved efficiency during short layovers and the availability of more direct routes.

3.4.2 Airspace

This section focuses on interventions that can be enabled through changes to airspace regulation as part of broader airspace modernisation efforts. Airspace modernisation refers to global improvements designed to enhance the efficiency of air travel, reduce holding times, and integrate emerging technologies. While this concept is aligned with the goals of

[106] Sustainable Aviation. (2024). Sustainable Aviation: One Year On - Policy Progress Report. Available at: https://www.sustainableaviation.co.uk/wp-content/uploads/2024/05/Sustainable-Aviation-One-Year-On-Policy-Progress-Report.pdf

the UK's Airspace Modernisation Programme[107], it differs from the specific categories outlined by the CAA, as it focuses more on the outcomes of these activities rather than the individual components. Additionally, the interventions discussed here are not entirely mutually exclusive – many can occur simultaneously. By breaking down the interventions in this way, each component can be implemented independently, but many may build upon previous actions. It is important to note that some of the interventions referenced also relate to broader European efforts, which may not always be directly linked to the UK's Airspace Modernisation Programme.

3.4.2.1 Airspace modernisation (reduced fragmentation of airspaces

Description

Interviews with industry stakeholders revealed significant inefficiencies in the management of airspace, particularly across Europe. Airspace is often fragmented along national borders, leading to less efficient flight paths and higher altitudes, both of which contribute to increased fuel consumption and emissions.

Summary of evidence

Challenges and impact of fragmented airspace

- **Inefficiencies and increased fuel consumption:** Airspace is divided by national borders, creating congestion, delays, and unnecessary flight route deviations. These inefficiencies lead to longer flights and higher altitudes, which in turn increase fuel consumption and emissions[108].
- **Non-optimal routing decisions:** Airlines sometimes opt for non-optimal routes due to economic factors. For instance, a flight from Berlin to Milan might take a longer route through Slovenian and Croatian airspace, which is cheaper than flying directly through Italian airspace, even though the longer route leads to higher fuel consumption[109].
- **Congested routes:** Popular routes, such as those from the UK and Northern Europe to the Canary Islands, often suffer from congestion due to holiday traffic[110]. This congestion causes inefficiencies and results in altered flight levels and routes, further increasing fuel burn.
- **Higher costs and delays:** Fragmented airspace leads to higher operational costs and delays, potentially causing one in five flights to face disruptions lasting more than 45 minutes[111].

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[107] Civil Aviation Authority. (n.d.). Airspace Modernisation Strategy. Available at: https://www.caa.co.uk/commercial-industry/airspace/airspace-modernisation/airspace-modernisation-strategy/
[108] Ortner, P., Steinhöfler, R., Leitgeb, E., & Flühr, H., 2022. Air Traffic Simulation and Modeling Framework. 2022 International Conference on Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom), pp. 1-5. https://doi.org/10.1109/CoBCom55489.2022.9880802
[109] OPS Group. (2023). The Three Sisters: Shanwick's Tango Routes. Available at: https://ops.group/blog/the-three-sisters-shanwicks-tango-routes/
[110] OPS Group. (2023). The Three Sisters: Shanwick's Tango Routes. Available at: https://ops.group/blog/the-three-sisters-shanwicks-tango-routes/
[111] Air Traffic Control Group. (2024). 1 in 5 Flights Could Experience Disruption Without UK Airspace Upgrade: New Report Highlights. Available at: https://www.acog.aero/blog/2024/10/10/1-in-5-flights-could-experience-disruption-without-uk-airspace-upgrade-new-report-highlights/

- **Increased emissions:** Longer routes and inefficient flight levels increase CO_2 emissions. Without airspace modernisation, flight delays could increase by over 200%, significantly impacting fuel consumption and emissions[112].

Proposed solutions and areas of development

Eurocontrol has proposed the concept of FUA which would optimise airspace usage by allowing civil and military air traffic to share the same space. This system could reduce congestion and improve flight efficiency. However, the implementation of FUA requires better integration of military air traffic management infrastructure, updated rules and procedures, and enhanced training for pilots and navigational staff to ensure seamless operations. Military flight training also impacts airspace congestion. There is a need to explore how different training schedules and structures can minimise disruptions to civil air traffic, particularly in congested airspace, alongside updated legislation to better define the conditions under which military aircraft can use national airspace[113,114].

No literature was found detailing the cost of implementing these changes or the cost of carbon abatement that could result from this.

Table 13: Summary of data on airspace modernisation (reduced fragmentation of airspace)

Impact metrics	Performance	Description
Estimated cost of abatement	Exceptional performance	**Estimated cost per unit** ~£1,750,000 per airspace sector. This cost covers the modernisation of airspace, including updating its structural design and integrating new aviation technologies. The goal is to improve efficiency, safety, and environmental performance.[115,116,117] **Assumptions:** Major infrastructure upgrades to air traffic control systems, development of interoperable systems for seamless coordination across different airspaces and extensive training required increase the cost of this intervention. **tCO_2e/year:**

[112] Air Traffic Control Group. (2024). 1 in 5 Flights Could Experience Disruption Without UK Airspace Upgrade: New Report Highlights. Available at: https://www.acog.aero/blog/2024/10/10/1-in-5-flights-could-experience-disruption-without-uk-airspace-upgrade-new-report-highlights/

[113] Mostarac N. Reščić AMihetec T. & Nova D. 2022. Flight Training Syllabus Structure mpact on roactive lanning of High-Performance Military Aircraft Pilot Training Operations in Flexible Airspace Structures. Promet. https://doi.org/10.7307/ptt.v34i6.4158

[114] Stanev, H., 2019. CRITERIA AND APPROACHES FOR ASSESSMENT OF THE USE OF AIRSPACE OF THE MEMBER STATES OF EUROCONTROL BY MILITARY AIRCRAFTS. Knowledge International Journal. https://doi.org/10.35120/kij34051415s

[115] Department for Transport. (n.d.). Airspace Modernisation. Available at: https://www.gov.uk/government/publications/airspace-modernisation/airspace-modernisation

[116] Department for Transport. (2018). Upgrading UK Airspace: Strategic Rationale. Available at: https://assets.publishing.service.gov.uk/media/5a80e5bfed915d74e623111b/upgrading-uk-airspace-strategic-rationale.pdf

[117] Civil Aviation Authority. (2023). Airspace Modernisation: A Strategic Framework for the UK. Available at: https://www.caa.co.uk/publication/download/20428

Impact metrics	Performance	Description
		Approx 10 million tCO_2e per year (UK wide), based on multiple data sources. Single European Sky ATM Research (SESAR) programme estimates that optimising air traffic management could reduce CO_2 emissions by up to 10% per flight.[118] **Assumptions:** Carbon saving benefits are dependent on coordination with international air traffic management systems as well as the efficacy of national policy and funding. High initial investment may deter smaller airports from participating, preventing this intervention from abating more carbon. Estimates are based on an assumed 10% reduction in CO_2 emissions across all flights departing from the UK in a year.
Deliverability	Poor performance	Due to politics and territory issues it can be hard to implement. TRL 6: Technology demonstrated in a relevant environment, however issues associated above will influence the MCA.
Durability	High performance	Instability of politics associated with airspace could mean flight plans are disrupted/ inconsistent. It would require new or updated regulations and policy. If successfully implemented, this intervention, tied to major technological shifts is expected to last approximately 20-30 years before significant overhauls are required.
Environmental impact	High performance	There is positive impact on emissions and the environment.
Social impact	Good performance	Additionally, positive outcomes for customers due to less time spent waiting and a quicker journey. There is also potential for less noise impact if operations are smoother, and fewer airplanes are holding or diverted with associated benefits to the local community as a result.

[118] European Commission. (2024). Reducing Air Travel's Climate Effects Requires More Technological Innovation and Carbon Pricing. Available at: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/reducing-air-travel-climate-effects-requires-more-technological-innovation-and-carbon-pricing-2024-12-09_en

3.4.2.2 Remote towers

Remote towers represent a significant advancement in air traffic management (ATM) and air traffic control (ATC) by enabling air traffic services to be conducted from locations away from the airport. This innovation can improve efficiency and safety through the use of digitalisation and automation. Remote towers also offer environmental benefits, as they can be housed in more carbon-efficient buildings or enable the co-location of multiple airport towers at a single site, reducing infrastructure-related emissions.

Currently operational at airports like London City and Dubai, remote towers are still in the early stages of widespread implementation. While their potential is clear, research gaps remain regarding their full capabilities, particularly in quantifying the environmental benefits. No comprehensive assessments currently exist to measure the carbon reductions achieved by the use of remote towers across the aviation sector.

Table 14: Summary of data on remote towers

Impact metrics	Performance	Description
Estimated cost of abatement	Unacceptable performance	**Estimated cost per unit** ~£20,000,000 per airport. The cost includes the installation of remote tower technology, which involves advanced sensor-based control centres, video cameras, and communication antennas. This technology can significantly reduce operational costs for airports.[119,120] **Assumptions:** Costs include initial technology investment but does not account for potential savings associated with staffing changes. Abatement potential is difficult to quantify due to indirect effects on operational efficiency. **tCO_2e/year:** Approx. 7000 tCO_2e per year (UK wide), achieved through energy savings and consolidation of operational activities[121],[122]. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide

[119] NRI Digital. (2022). Remote Air Traffic Control. Available at: https://airport.nridigital.com/air_feb22/remote_air_traffic_control

[120] Grand View Research. (n.d.). Remote Towers Market Report. Available at: https://www.grandviewresearch.com/industry-analysis/remote-towers-market-report

[121] Prokerala. (n.d.) *Airports in United Kingdom*. Available at: https://www.prokerala.com/travel/airports/united-kingdom/#:~:text=There%20are%20144%20Airports%20in,airport%20United%20Kingdom%20etc...

[122] KAMS Global. (n.d.) *Sustainable Air Traffic Control*. Available at: https://kamsglobal.net/sustainable-air-traffic-control/

Impact metrics	Performance	Description
		an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 8: System complete and qualified
Durability	Good performance	Operational lifespan of remote towers will align with upgrades to technology and system dependencies.
Environmental impact	Good performance	Remote towers could potentially reduce noise impact by enabling more efficient airspace operations, leading to optimised flight paths and less disruption for nearby communities.
Social impact	High performance	Remote towers could potentially reduce noise impact by enabling more efficient airspace operations, leading to optimised flight paths and less disruption for nearby communities.

3.4.2.3 Continuous Climb Operations and Continuous Descent Operations

Description

Continuous Climb Operations (CCO) and Continuous Descent Operations (CDO) are advanced flight techniques designed to optimise aircraft trajectories, reducing fuel consumption, emissions, and noise. By avoiding level-offs during climb and descent, these methods minimise fuel usage, improving efficiency during take-off and landing.

Summary of evidence

Potential benefits and challenges

Both CCO and CDO have demonstrated significant environmental benefits, including substantial reductions in CO_2 emissions and noise pollution around airports[123,124]. While these operations are being implemented worldwide by various Air Navigation Service Providers (ANSPs), their full potential is limited by challenges such as managing aircraft trajectories in high-density airspace, particularly during descent[125]. To overcome this, procedures like Fixed Flight-Path Angle (Fixed-FPA) descent have been proposed to

[123] Díaz, M., Comendador, V., Carretero, J., & Valdés, R., 2020. Environmental benefits in terms of fuel efficiency and noise when introducing continuous climb operations as part of terminal airspace operation. *International Journal of Sustainable Transportation*, 14, pp. 903 - 913. https://doi.org/10.1080/15568318.2019.1651924
[124] Del Pozo Domínguez, M., Leonés, J., Morales, M., & Astorga, R., 2023. Assessing the environmental impact of Continuous Descent Operations based on Quick Access Recorder and surveillance data. *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, pp. 1-9. https://doi.org/10.1109/DASC58513.2023.10311191
[125] Toratani, D., Wickramasinghe, N., Westphal, J., & Feuerle, T., 2020. Feasibility study on applying continuous descent operations in congested airspace with speed control functionality: Fixed flight-path angle descent. *Aerospace Science and Technology*, 107, pp. 106236. https://doi.org/10.1016/J.AST.2020.106236

improve trajectory prediction and speed control, making CDOs more feasible in congested areas[126].

Trajectory planning and optimisation

Efficient trajectory planning is crucial for the successful implementation of CCOs and CDOs. Multi-objective optimisation models have been developed to generate conflict-free and economical trajectories, balancing factors such as fuel consumption, trip time, and collision probability[127]. Techniques like the Non-dominated Sorting Genetic Algorithm with Elitist Strategy (NSGA-II) and the Chebyshev–Gauss–Lobatto (CGL) Pseudospectra Method have been employed to optimise these trajectories[128,129]. Furthermore, innovative control methods, such as iterative learning control, are being explored to improve the precision of trajectory tracking and enhance overall air traffic management efficiency[130].

Table 15: Summary of data on CCO and CDO

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Estimated cost per unit** ~£99 per flight, which includes the implementation and monitoring of Continuous Climb Operations procedures, which could lead to fuel savings and reduced emissions.[131132] **Assumptions:** The initial investment required is minimal as this intervention largely involves changes to operational procedures rather than to technology or physical infrastructure. Training costs, increased air traffic management costs are partially offset by cost savings associated with decreased fuel burn (and emissions). **tCO_2e/year:**

[126] Toratani, D., Wickramasinghe, N., Westphal, J., & Feuerle, T., 2020. Feasibility study on applying continuous descent operations in congested airspace with speed control functionality: Fixed flight-path angle descent. *Aerospace Science and Technology*, 107, pp. 106236. https://doi.org/10.1016/J.AST.2020.106236
[127] Yang, L., Li, W., Wang, S., & Zhao, Z., 2021. Multi-Attributes Decision-Making for CDO Trajectory Planning in a Novel Terminal Airspace. *Sustainability*. https://doi.org/10.3390/SU13031354
[128] ibid
[129] Díaz, M., Comendador, V., Carretero, J., & Valdés, R., 2020. Environmental benefits in terms of fuel efficiency and noise when introducing continuous climb operations as part of terminal airspace operation. *International Journal of Sustainable Transportation*, 14, pp. 903 - 913. https://doi.org/10.1080/15568318.2019.1651924
[130] Buelta, A., Olivares, A., & Staffetti, E., 2022. Iterative Learning Control for Precise Aircraft Trajectory Tracking in Continuous Climb and Descent Operations. *IEEE Transactions on Intelligent Transportation Systems*, 23, pp. 10481-10491. https://doi.org/10.1109/tits.2021.3094738
[131] Civil Aviation Authority. (n.d.). CAP1075. Available at: https://www.caa.co.uk/our-work/publications/documents/content/cap1075/
[132] Schmid, J., & Schmid, C. (2023). *Hybrid-Electric Propulsion Systems for Regional Aircraft*. In *Hybrid-Electric Aircraft: Technologies, Concepts, and Applications* (pp. 485-504). Springer. Available at: https://link.springer.com/chapter/10.1007/978-981-16-8154-7_28

Impact metrics	Performance	Description
		Approx 1.5 million tCO2e per year (UK wide). **Assumptions:** CO_2 abated by this intervention varies significantly between airports and operational contexts. This estimate is likely subject to a large degree of uncertainty. CO_2 abatement excludes potential delays in air traffic caused by prioritising continuous operations. Feasibility for widespread deployment limited at airports with congested airspace, somewhat limiting potential carbon savings of this intervention. Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 8: System complete and qualified
Durability	Good performance	Effective in reducing fuel burn and emission production but may require training if pilots have not used these techniques and may not be applicable to all aircraft types. Procedural changes like CDO/CCO will evolve with airspace rules and technology, resulting in an effective period of around a decade.
Environmental impact	Good performance	CCOs and CDOs improve fuel efficiency therefore burning less fuel, produce fewer emissions and reduce noise levels.
Social impact	Good performance	A reduction in noise levels and air pollution around airports from take-off and landing of aircrafts with associated benefits to the local community as a result is anticipated.

3.4.2.4 Airline flight planning optimisation

Description

Flight planning optimisation aims to create the most efficient flight routes to minimise fuel consumption, reduce flight times, and improve overall operational efficiency. This involves

[133] EUROCONTROL. (n.d.). Continuous Climb and Descent Operations. Available at: https://www.eurocontrol.int/concept/continuous-climb-and-descent-operations

real-time adjustments to flight plans based on weather conditions, air traffic, wind patterns, and ensuring that aircraft carry the optimal amount of fuel, reducing weight and improving fuel efficiency.

Summary of evidence

Optimising flight levels

Optimising flight levels is crucial for fuel savings. A study by NATS found that flying 2,000 feet below the optimal level could increase fuel burn by up to 7%[134]. Aircraft generally perform better at higher altitudes, where thinner air reduces drag. However, the ability to achieve optimum flight levels is often influenced by external factors, such as air traffic control restrictions, as this is not solely under the pilot's control.

Cost Index (CI) and cruising speed optimisation

The Cost Index (CI) [135] is a critical tool in balancing fuel consumption and flight time. CI represents the ratio between the cost of fuel and the cost of time, with a lower CI resulting in slower speeds and reduced fuel consumption (these are the main two cost drivers for airlines as shown in Figure 5). Airlines adjust their CI to find an optimal balance, but sub-optimal CI values are often used. Optimising CI can lead to a 1-3% cost reduction, primarily due to fuel savings, especially when fuel prices are high[136].

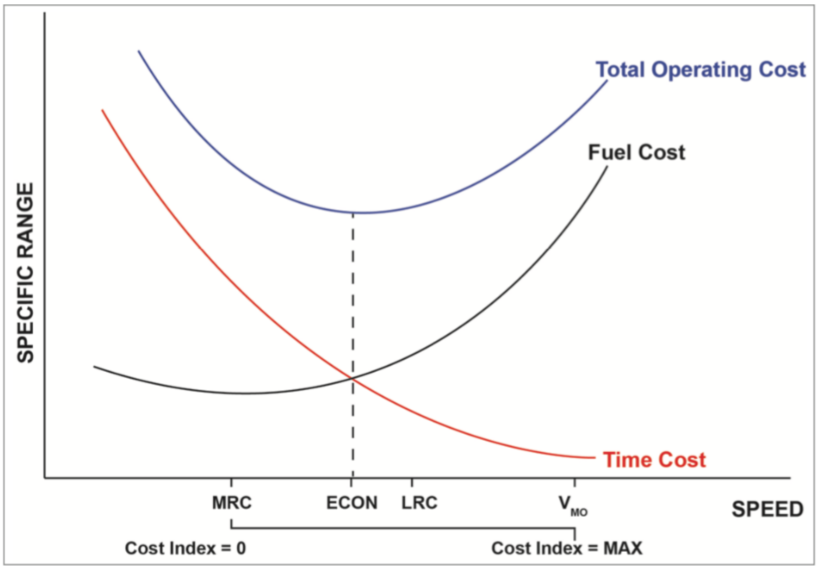

Figure 5: Cost Index and most economical speed[137]

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[134] NATS. (2013). NATS Swatch Book. Available at: https://www.nats.aero/wp-content/uploads/2013/05/11001_NATS_Swatch-book_Online_Linked_240413_HS.pdf
[135] Cook, A.J. and Tanner, G., 2015. *European airline delay cost reference values*. EUROCONTROL Performance Review Unit.
[136] Aircraft Commerce, 2018. 08-A/C ANALYSIS-feature. Accessed 27/02/25.
[137] IVAO Documentation Library, 2023. Cost Index | IVAO Documentation Library. Accessed 27/02/25

Contrail avoidance and environmental impact

Optimising flight paths also plays a role in avoiding contrails, a significant yet often overlooked factor in sustainability models. Re-routing to avoid contrails may lead to slight increases in fuel consumption. However, research indicates that the extra fuel burn from minor trajectory changes is minimal and would not significantly affect overall fuel efficiency[138].

Challenges and considerations

- **External factors:** Air traffic control structures and procedures often restrict the ability to fly at optimum levels, as flight paths are heavily influenced by air traffic management.
- **Optimisation confidence:** There is a need for greater confidence in flight planning technology to ensure accurate calculations of the optimal fuel load and fuel efficiency gains.
- **Safety:** While flight planning optimisation can improve fuel efficiency, safety remains the priority in aviation, and any changes to flight plans or operational practices must ensure safety levels are maintained or improved. SESAR (2025) state that ATM evolution, including those related to flight panning will maintain, or, where possible improve safety levels[139].

Table 16: Summary of data on airline flight planning optimisation

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£150 per flight This cost includes the use of advanced flight planning systems to optimise routes, taking into account variables such as weather and air traffic. This can lead to fuel savings and reduced emissions.[140,141] **Assumptions:** Costs incurred from implementing this intervention include the investments in data collection infrastructure and staff training. As this intervention requires minimal investment in physical infrastructure, its costs are comparatively low. **tCO_2e/year:** Approx 3 tCO_2e per year (UK wide). (IATA) estimates that optimising flight routes can reduce fuel consumption by up to 10%.

[138] KPMG (in press). Literature review of aviation's non-CO2 climate impacts and evaluation of existing metrics

[139] Author Unknown. (2025). European ATM Master Plan. *SESAR Joint Undertaking*. *SESAR Master Plan 2025.pdf*https://www.globalfastenernews.com/how-many-fasteners-in-a-boeing-777-global-fastener-news-usa/

[140] McKinsey & Company. (n.d.). A Better Approach to Airline Costs. Available at: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/a-better-approach-to-airline-costs

[141] International Air Transport Association. (n.d.). Airline Cost Benchmarks at Your Fingertips. Available at: https://www.iata.org/globalassets/iata/programs/distribution-mailings/acmg_airline_cost_benchmarks_at_your_fingertips_external.pdf

Impact metrics	Performance	Description
		Assumptions: The estimated 10% reduction in fuel consumption per flight is influenced by factors such as flight distance and specific route characteristics. Long-haul flights may experience more significant savings compared to shorter routes due to differing operational dynamics. Additionally, unforeseen factors like weather conditions and airspace restrictions can impact fuel savings. However, given the scalability of this intervention, substantial carbon savings are achievable.
Deliverability	High performance	TRL 8: System complete and qualified
Durability	High performance	Instability of politics associated with, and complexity of planning airspace could mean flight plans are disrupted at short notice/ inconsistent. It would require regulations, and monitoring. Software-driven interventions typically require updates or replacements within a decade.
Environmental impact	High performance	There are positive impacts on emissions and the environment.
Social impact	Good performance	There are positive outcomes for customers with less time spent holding and a quicker journey. Also, potential for less noise impact if operations are smoother and fewer airplanes are holding or diverted with associated benefits to the local community as a result.

3.4.2.5 Real time data for pilots

Description

Integrating real-time data into airport operations is a critical intervention for enhancing operational efficiency, reducing fuel consumption, and lowering emissions. By providing pilots with access to live data such as weather updates, fuel tracking, and air traffic conditions, they can make informed decisions that optimise flight planning and performance.

Summary of evidence

Benefits of real-time data

- **Optimised flight planning:** Real-time data allows pilots to proactively adjust flight routes, altitude, and speed, which can lead to significant fuel savings and emission reductions.

- **Efficiency improvements:** According to SESAR, real-time data integration can result in a 3.5% improvement in operational efficiency[142].
- **Contrail avoidance:** Real-time data can also be used to avoid contrail formation, which contributes to environmental sustainability[143].
- **Proactive adjustments:** Having immediate access to relevant data enables pilots to make prompt adjustments to avoid delays and optimise fuel usage.

Current challenges and opportunities

- **Data overload:** While pilots have access to some real-time data, a key challenge is avoiding data overload. Ensuring that pilots receive only actionable insights is crucial to improving decision-making without overwhelming them.
- **Underutilisation of technology:** During stakeholder interviews, it was noted that many of the technologies enabling real-time data-driven decisions already exist but are underutilised in practice.

One area where real-time data is effectively utilised is in communication systems between ground controllers and aircraft. Data link communication (the transmission of messages between aircraft and ground systems) has already improved operational efficiency, particularly in airspaces such as the North Atlantic, where it is mandated.

Table 17: Summary of data on real time data for pilots

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Estimated cost per unit** ~£50,000 per system installed (plus pilot and ANSP training). This cost includes the installation of real-time data systems that provide pilots with up-to-date information for flight planning. These systems can enhance situational awareness and improve operational efficiency.[144,145] **Assumptions:** Costs exclude infrastructure upgrades for data sharing or potential cyber security risks associated with real-time communication systems. **tCO_2e/year:** Approx 3 million tCO_2e per year (UK wide).

142 Author Unknown. (2025). European ATM Master Plan. *SESAR Joint Undertaking.* *SESAR Master Plan 2025.pdf*https://www.globalfastenernews.com/how-many-fasteners-in-a-boeing-777-global-fastener-news-usa/
143 KPMG (in press). Literature review of aviation's non-CO2 climate impacts and evaluation of existing metrics
144 Garmin. (n.d.). *FlyGarmin Support: Pricing*. Available at: https://fly.garmin.com/fly-garmin/support/pricing
145 L3Harris Technologies. (n.d.). SRVIVR25 Series Cockpit Voice and Flight Data Recorders. Available at: https://www.l3harris.com/all-capabilities/srvivr25-series-cockpit-voice-and-flight-data-recorders

Impact metrics	Performance	Description
		(IATA) estimates that optimising flight routes can reduce fuel consumption by up to 10%.[146] **Assumptions:** The effectiveness of this intervention depends on the willingness of pilots to adjust operations and the availability of quality real time data. This estimate is based on a 2.5% reduction in CO_2 emission across all flights departing the UK in a year.
Deliverability	Good performance	TRL 7: System prototype demonstration in an operational environment
Durability	Good performance	The new technology is assumed to be sufficiently durable and up-to-date, capable of interacting with other necessary software. However, it may require additional training for users to adapt to the newer technologies and software. Its effectiveness also depends on airspace management and political factors that enable short-notice flight planning. Typically, software-driven interventions require updates or replacements within a decade.
Environmental impact	High performance	There are positive impacts on emissions and the environment.
Social impact	Good performance	Positive outcomes for customers due to less time spent waiting and a quicker journey. There is also potential for less noise impact if operations are smoother, and fewer airplanes are holding/ diverted with associated benefits to the local community as a result.

3.4.2.6 Free route airspace (with and without AI enhancements)

Description

Free Route Airspace (FRA) is an advanced air traffic management concept that enables aircraft to plan and fly direct routes between defined entry and exit points. This approach aims to improve operational efficiency, reduce environmental impact, and provide greater flexibility in flight planning. FRA has been successfully deployed in various regions, including two tranches by NATS in the UK, one in Scotland and another across the Southwest[147].

[146] International Civil Aviation Organization. (n.d.). CONOPS for Free Route Airspace (FRA) Implementation in AFI Region. Available at: https://www.icao.int/WACAF/Documents/APIRG/APIRG%2024/Appendices/Appendix%203E%20CONOPS%20for%20Free%20Route%20Airspace%20%28FRA%29%20implementation%20in%20AFI%20Regiontion%20-Final.pdf

[147] NATS. (2023). NATS Deploys Once-in-a-Generation Airspace Upgrade. Available at: https://www.nats.aero/news/nats-deploys-once-in-a-generation-airspace-upgrade

While both FRA and Airspace Modernisation aim to enhance the efficiency of air traffic management, the key difference lies in their scope and implementation. FRA focuses specifically on enabling aircraft to fly the most direct route possible between entry and exit points, reducing flight path deviations. In contrast, Airspace Modernisation involves a broader overhaul of air traffic management systems, which may include updates to infrastructure, procedures, and technologies, with the goal of improving overall airspace capacity, safety, and efficiency, beyond just direct routing.

Summary of evidence

Benefits of free route airspace

- **Efficiency improvements:** By allowing airlines to fly more direct routes, FRA reduces the distance flown, which in turn decreases the amount of fuel needed. This also leads to lighter aircraft, further improving fuel efficiency.
- **Environmental impact:** FRA has demonstrated significant environmental benefits, including reductions in fuel consumption, CO_2 emissions, and nitrogen oxides (NOx) emissions.

Challenges

- **Airspace management:** The implementation of FRA can introduce complexities in airspace management, particularly in high-density regions. The freedom to choose flight paths requires careful planning to prevent conflicts between aircraft and ensure safe operations[148,149].
- **Advanced planning strategies:** To fully harness the benefits of FRA, advanced planning strategies and models are needed to manage air traffic effectively and minimise risks in complex airspaces[150]. These strategies are essential for optimising airspace use while ensuring safety.

Research gaps and future considerations

- **Complexity of airspace management:** While FRA holds great potential, its implementation in high-complexity airspace is challenging. Further research is required to develop better strategies for managing these environments.
- **Technological innovation:** Leveraging technological advancements, such as Artificial Intelligence (AI) enhancements, could significantly improve airspace management and help navigate the challenges of FRA. AI could help predict and manage flight trajectories more effectively, optimising fuel usage and reducing delays.
- **Need for robust mathematical foundations:** Establishing robust mathematical models and optimisation techniques is necessary to evaluate and refine FRA systems, ensuring their environmental benefits are maximised in various airspace conditions.

148 Gencoglu Y. & Başpınar, B . 2023. Free outing in High-Complexity Airspace: Impact Assessment for Environment and Aviation Stakeholders. Journal of Aerospace Information Systems. https://doi.org/10.2514/1.i011203

149 Itoh, E., Tominaga, K., Schultz, M., & Duong, V., 2023. Untangling Complexity in ASEAN Air Traffic Management through Time-Varying Queuing Models. Aerospace. https://doi.org/10.3390/aerospace11010011

150 Gencoglu Y.,& Başpınar B. 202 . Free Routing in high -Complexity Airspace: Impact Assessment for Environment and Aviation Stakeholders. Journal of Aerospace Information Systems. https://doi.org/10.2514/1.i011203

Table 18: Summary of data on free route airspace

Impact metrics	Performance	Description
Estimated cost of abatement	Exceptional performance	**Estimated cost per unit** ~£500,000 per flight sector adjusted. This cost covers the adjustment of airspace to allow for free route operations, which can reduce flight times and fuel consumption by enabling more direct routing.[151,152] **Assumptions:** Subject to transitional period where both traditional and free route systems must operate simultaneously, resulting in increased costs. **tCO_2e/year:** Approx 8 million tCO_2e per year (UK wide). Free route airspace and improving air traffic management and aircraft operations can facilitate an emissions reduction of 6%.[153] **Assumptions:** Emissions savings are contingent on regulatory approval and international collaboration to establish free route airspace corridors. Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Low performance	TRL 5: Technology validated in a relevant environment
Durability	High performance	Durability is impacted by political instability related to airspace management which could lead to disrupted or inconsistent flight plans, necessitating robust regulations and policies. Given the complexity and scale of this intervention, it is anticipated to have a lifespan of 20-30 years.

[151] International Civil Aviation Organization. (n.d.). CONOPS for Free Route Airspace (FRA) Implementation in AFI Region. Available at: https://www.icao.int/WACAF/Documents/APIRG/APIRG%2024/Appendices/Appendix%203E%20CONOPS%20for%20Free%20Route%20Airspace%20%28FRA%29%20implementation%20in%20AFI%20Regiontion%20-Final.pdf
[152] Destination 2050. (2021). Destination 2050 Report. Available at: https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf
[153] Destination 2050. (2021). Destination 2050 Report. Available at: https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf

Impact metrics	Performance	Description
Environmental impact	High performance	There are positive impacts on emissions and the environment.
Social impact	High performance	There are positive outcomes for customers with less time spent waiting and a quicker journey. Potential for less noise impact if operations are smoother, and fewer airplanes are holding/ diverted with associated benefits to the local community as a result.

3.4.2.7 Holding on the ground (with potential for AI enhancement)

Description

Holding aircraft on the ground at the departure airport, instead of airborne holding at the arrival airport, can significantly reduce fuel consumption and emissions.

Summary of evidence

Potential benefits

- **Fuel savings:** Ground holding has been shown to be a more fuel-efficient method compared to airborne holding. For instance, reducing the average stack holding time at Heathrow by just two minutes per aircraft can save up to 23,000 tonnes of fuel annually, equating to £14 million in savings for airlines[154].
- **Environmental impact:** Reducing airborne holding can help lower carbon emissions, which are typically higher during airborne waiting periods due to increased fuel burn.

Role of AI in enhancing ground holding

While ground holding can be achieved without AI, predictive modelling powered by AI could further optimise operations by improving the accuracy of predicting destination airport capacities and traffic flow. This would enable better planning and coordination, reducing the likelihood of unnecessary airborne holding. However, it's important to recognise that while AI could optimise fuel efficiency, its own carbon footprint, due to the computational power required, may limit the overall carbon savings. Thus, the net carbon benefit of AI-driven improvements might be modest.

Challenges and considerations

- **Air traffic management:** Effective implementation of ground holding requires real-time data and communication between departure and arrival airports. The ability to anticipate delays and adjust schedules accordingly is key to optimising fuel savings and minimising emissions.
- **Passenger experience:** One challenge with ground holding is the passenger perception. Holding passengers at the airport, while typically more fuel-efficient, may be viewed negatively compared to holding aircraft in the air. This needs to be balanced with the convenience of not having planes circling in the air.

[154] Author unknown. (n.d.). Ten steps to flight efficiency. *NATS.* 11001_NATS_Swatch-book_Online_Linked_240413_HS.pdf

- **Airport capacity and network resilience:** The capacity of the departure airport to accommodate aircraft while on the ground is another factor. There is a potential impact on airport infrastructure, especially when considering high traffic volumes and operational delays. Additionally, improving network resilience is critical to ensuring the success of ground holding interventions[155].

Stakeholder discussions emphasised the value of delaying departures until the optimal moment to prevent aircraft from being placed into hold at arrival airports. By timing departures carefully, airlines can avoid inefficient airborne holding and reduce the risk of fuel burn associated with poor weather or congestion at the destination airport.

Table 19: Summary of data for holding on the ground

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£200 per flight delayed. This cost includes the implementation of AI systems to manage ground holds, reducing the need for airborne holding and improving overall efficiency.[156,157] **Assumptions:** This cost estimate assumes an average cost to implement AI scheduling and manage delays. Cost includes the opportunity cost associated with the plane not being in the air at its scheduled departure time. Therefore, the cost estimate is revised upwards to reflect this. **tCO_2e/year:** Approx 150,000 tCO_2e per year (UK wide), based on multiple data sources At Oslo-Gardermoen airport, implementing ground delays for short flights was found to yield potential CO_2 emissions reduction by around 5-10% per flight. This intervention relies on widespread adoption and only applicable to a small proportion of flights, thus the emissions estimate is revised down.[158] **Assumptions:** The abatement potential depends on widespread adoption of AI systems and efficient communication

[155] R. Curran, Foundations of Transdisciplinary Engineering Theory: Sustainable Airport Application, Advances in Transdisciplinary Engineering, UCL East, London, 2024, in press.
[156] Cox, I. J. (2019). The Impact of Air Traffic Control on Airline Operations. Available at: https://aa222.stanford.edu/wp-content/uploads/2019/04/cox.pdf
[157] Aviation Today. (2022). AI in the Sky: How Artificial Intelligence and Aviation are Working Together. Available at: https://interactive.aviationtoday.com/avionicsmagazine/may-june-2022/ai-in-the-sky-how-artificial-intelligence-and-aviation-are-working-together/
[158] Schmid, J., & Schmid, C. (2012). Hybrid-Electric Propulsion Systems for Regional Aircraft. Available at: https://www.icas.org/icas_archive/ICAS2012/PAPERS/797.PDF

Impact metrics	Performance	Description
		across airports globally. This figure is also dependent on future air traffic levels. Emissions savings estimates for this intervention are based on a 7.5% reduction in CO_2 per flight. It is assumed these savings are applicable to a percentage of all aircraft departing from the UK in a year.
Deliverability	Low performance	TRL 5: Technology validated in a relevant environment
Durability	Good performance	AI systems are rapidly evolving. Software-driven interventions typically require updates or replacements within a decade.
Environmental impact	Good performance	There will be reduced time spent in a holding stack, leading to associated drop in emissions and noise at arrival airport, potential for small increase in pollution at host airport if aircraft remains on site / holding for longer.
Social impact	Good performance	There are positive outcomes for customers with less time spent holding and a quicker journey. Additionally, potential for less noise impact if operations are smoother and fewer airplanes are holding/ diverted with associated benefits to the local community as a result.

3.4.3 Airports

Airports, while contributing a smaller percentage to the overall carbon footprint of aviation compared to flight operations, have significant potential to decarbonise their operations. This potential is driven by a range of existing technologies that can be implemented to reduce emissions and improve sustainability. Ground operations therefore represent another vital area for improving efficiency and reducing energy consumption.

3.4.3.1 Stand design

Description

Optimising the allocation and design of airport stands offers significant potential to improve operational efficiency and reduce fuel consumption. This can be achieved by reducing taxi distances for aircraft, which leads to less time spent on the ground and decreased fuel burn. Stand design considerations include the physical layout of stands, apron configurations, and operational processes that support efficient aircraft movements.

Summary of evidence

Key components of stand design

- **Stand allocation and positioning:** The way stands are allocated and their positioning within the airport layout plays a crucial role in minimising taxi times. Efficient positioning of stands can reduce the distance aircraft need to travel from the gate to the runway and vice versa, leading to substantial fuel savings and time efficiency.

- **Flexible stand systems**[159]**:** The design of flexible systems for stand allocation helps adapt to operational disturbances, such as changes in demand or unexpected delays. These systems can optimise the use of available space, adjusting to varying needs and minimising inefficiencies.
- **Energy use considerations:** In addition to the operational aspects, stand design also includes considerations for energy use, particularly for heating and lighting. Sustainable energy management can contribute to overall environmental impact reduction at airports.

Case study

A notable example of stand design optimisation comes from Shenzhen Airport[160], where a two-stage optimisation model was applied to improve stand allocation and ground support vehicle scheduling. The results were promising:

- **Taxi distance reduction:** Taxi distances were reduced by 20.4%, which directly translates to fuel savings and reduced emissions.
- **Increased vehicle utilisation:** Vehicle utilisation increased by 37.5%, enhancing operational efficiency and reducing idle times.

While the potential for improving efficiency through better stand design is clear, there is limited evidence on the overall scale of efficiency savings across different airports and operational contexts. Further studies are needed to understand the broader impacts of stand design changes and to identify the most effective strategies for different airport layouts.

Table 20: Summary of data for stand design

Impact metrics	Performance	Description
Estimated cost of abatement	Poor performance	**Estimated cost per unit** ~£100,000 per stand modified. This cost includes the reallocation and prioritisation of aircraft stands, which can involve redesigning stand layouts, updating signage, and implementing new operational procedures to optimise stand usage.[161,162] **Assumptions:** Due to the broad variety of modifications attributable to this intervention, cost is difficult to estimate. Specific stand configurations and existing operational practices will all influence the extent to which effective modifications are possible. Due to the broad variety of

[159] Skorupski, J. and Żarów, P., 2021. Dynamic management of aircraft stand allocation. Journal of Air Transport Management, 90, p.101964.

[160] MDPI, 2023. Optimization of Stand Allocation and Ground Support Vehicle Scheduling at Shenzhen Airport. MDPI Electronics, [online] 14(23), pp. 1-16. Available at: https://www.mdpi.com/2076-3417/14/23/11407

[161] Quadrant 2 Design. (n.d.). How Much Does an Exhibition Stand Cost?. Available at: https://www.quadrant2design.com/how-much-exhibition-stand-cost/

[162] Standsbay. (n.d.). How Much Does It Cost to Build an Exhibition Stand?. Available at: https://standsbay.com/blog/how-much-does-it-cost-to-build-an-exhibition-stand/

Impact metrics	Performance	Description
		modifications attributable to this intervention, CO_2 abatement is difficult to estimate. Specific stand configurations and existing operational practices will all influence the extent to which effective modifications are possible. **tCO_2e/year:** Estimated at 200,000 tCO_2e per year (UK wide). Efficient journeys have the potential to reduce fuel burn during taxi. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Good performance	TRL 6: Technology demonstrated in a relevant environment
Durability	Moderate performance	With the anticipated continued growth in the number of flights and passengers, it is likely that airports will need to undergo some level of reconfiguration to accommodate this increase.
Environmental impact	Moderate performance	There are potential air quality and noise benefits if planes are held on stand rather than taxiing or have a shorter taxi.
Social impact	Moderate performance	There could be improvements in local health conditions (through improved air quality and noise reduction).

3.4.3.2 Pre-conditioned air while on the ground (PCA) – reducing the need for auxiliary power units (APUs)

Description

Pre-conditioned air systems (PCAs) provide essential cooling and ventilation for aircraft while they are on the ground, significantly reducing the need for auxiliary power units (APUs), which burn fuel. When an aircraft is parked at an airport gate, a flexible duct or tube connects the aircraft to the PCA unit. The PCA system regulates the temperature and humidity inside the aircraft ensuring passenger comfort without relying on the aircraft's

APU[163]. By replacing APUs with PCAs, fuel consumption is minimised, leading to reductions in CO_2 emissions and noise pollution during ground operations.

Summary of evidence

Potential benefits

- **Fuel and emissions reduction:** PCA systems can result in up to a 90% reduction in fuel and energy consumption compared to using APUs[164]. OEMs (Original Equipment Manufacturers) of PCA units claim up to 97% savings in CO_2, NOx, and particulate matter (PM10) emissions[165].
- **Cost savings:** By eliminating the need for aircraft APUs during ground operations, airlines can reduce operational costs and fuel consumption. For example, an APU can burn up to 120kg of jet fuel per hour for narrow-bodied aircraft and up to 300kg per hour for wide-body aircraft[166]. PCA systems provide a more sustainable and cost-efficient alternative. Investment is already underway at airports such as LHR to invest in PCA infrastructure[167].

Integration with Ground Power Units (GPUs) and Fixed Electrical Ground Power (FEGP) units

- **Ground Power Units (GPUs):** GPUs supply electrical power to the aircraft while on the ground, complementing PCA units. By using both PCA and GPU, the need for an aircraft's APU is nearly eliminated leading to a significant reduction in fuel consumption and emissions.
- **Fixed Electrical Ground Power (FEGP):** FEGP units are permanently fixed to airport gates and draw power directly from the airport's electric grid, unlike mobile GPUs that can be diesel-powered. When used in combination with PCA and GPUs, FEGPs contribute to a near-zero emission footprint during aircraft ground operations.

Case studies

Studies at Zurich Airport showed a dramatic reduction in CO_2 emissions during ground operations using FEGPs alongside APUs, GPUs and PCAs. For short-haul missions, emissions dropped from 337kg per hour to just 0.7kg per hour, while for long-haul flights, CO_2 emissions decreased from 758kg per hour to 1.2kg per hour[168].

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[163] Author Unknown. (2017). Ground Cooling, Pre-Conditioned Air Systems (PCA). *Cavotec Inspired Engineering*. https://www.cavotec.com/uploads/2017/11/07/flyercavotec-pca05102017ld.pdf
[164] Author Unknown. (n.d.). PCA (Pre-conditioned Air) and 400 Hz, Aircraft Ground Energy System AGES. *Inox-Steel Technology*. https://www.istinox.ch/en/products/airport-systems/#:~:text=The%20energy%2Defficient%20alternative%20to,ramp%20noise%20level%20drops%20considerably.
[165] Author Unknown. (n.d.). Preconditioned Air Unit (PCA) – ZEPHIR. *Adelte The Boarding Company*. https://www.adelte.com/airports/preconditioned-air-zephir/
[166] Unknwn Author. (2021). APU Maintenance Management and the Aftermarket. *Aircraft Commerce, Maintenance & Engineering.* https://www.aircraft-commerce.com/wp-content/uploads/aircraft-commerce-docs/General%20Articles/2021/139_MTCE_A.pdf
[167] Author Unknown. (n.d.). Fly Quieter and Greener. *Heathrow*. https://www.heathrow.com/company/local-community/noise/making-heathrow-quieter/fly-quieter-and-greener
[168] Unknown Author. (2018). Aircraft Ground Energy Systems At Zurich Airport. *Zurich Airport*. https://media.flughafen-zuerich.ch/-/jssmedia/airport/portal/dokumente/das-unternehmen/politics-and-

Several airports, particularly in Europe, have adopted these close-to-zero emission alternatives, including PCA, GPU, and FEGP systems[169]. Munich Airport has committed €5.6 million EUR to implement eGPUs, while €307,000 EUR has been allocated for replacing diesel-powered GPUs at Frankfurt Airport with eGPUs by 2040[170,171].

Challenges and considerations

The cost of implementing PCA, GPU, and FEGP systems can vary depending on factors such as existing airport infrastructure, local energy consumption capabilities, and specific project requirements. This can lead to significant cost disparities between airports, as seen with Munich and Frankfurt's different funding levels.

The effectiveness of these systems depends on airport infrastructure and available energy supply. Furthermore, the transition from older systems to newer, greener technologies may require significant investments and careful planning to ensure smooth integration.

Table 21: Summary of data for PCA

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£30,000 per aircraft stand. This cost covers the installation and operation of pre-conditioned air units, which provide fresh, temperature-controlled air to parked aircraft, reducing the need for onboard auxiliary power units (APUs) and lowering emissions.[172,173] **Assumptions:** This cost estimates the expense of installation and operation of PCA units. Any additional training required by ground handling staff or other airport staff is not considered. **tCO_2e/year:** Approx 1 million for the UK. PCA units if supplied with renewable energy can reduce APU usage and lead to a significant carbon

responsibility/environmental-protection/technische-berichte/2018_zrh_aircraft-ground-energy-system.pdf

[169] Samantha Payne. (2023). GPUs: The Only Way is Sustainable. *Ground Handling International*. https://www.groundhandlinginternational.com/content/features/gpus-the-only-way-is-sustainable/

[170] Jake Adams. (2024). Munich Airport Implements eGPU Technology for Sustainable Energy Supply. *Travel Wires*. https://www.travelwires.com/munich-airport-implements-egpu-technology-for-sustainable-energy-supply

[171] Angelika Heinbuch, Miriam Leich. (2024). Frankfurt Airport Modernises Ground Power Supply. *Fraport*. https://www.fraport.com/en/newsroom/press-releases/2024/q1/frankfurt-airport-modernizes-ground-power-supply.html

[172] ITWGSE. (n.d.). Pre-Conditioned Air. Available at: https://itwgse.com/pre-conditioned-air/

[173] Adelte. (n.d.). Preconditioned Air Zephyr. Available at: https://www.adelte.com/airports/preconditioned-air-zephir/

Impact metrics	Performance	Description
		saving compared to a non-PCA operation. Their impact is best felt on wide-body aircraft with a longer turnaround time.[174] **Assumptions:** CO_2 abatement is reliant on replacing existing APUs with cleaner electrified PCA units. This figure is heavily influenced by airline uptake. Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Good performance	TRL 7: System prototype demonstration in an operational environment
Durability	Good performance	They are highly effective at reducing aircraft emissions on the ground. However, require regular maintenance and training. PCA systems have a mechanical lifespan tied to infrastructure and technology and are typically replaced/upgraded every 15-20 years.
Environmental impact	Good performance	There will be reduced noise and air pollution at the airport, which could help support improvements in biodiversity.
Social impact	Good performance	Potential for improvements in local health conditions through improved air quality.

3.4.3.3 Electric or assisted taxiing

Description

Electric or hybrid-electric taxiing systems utilise electric motors or auxiliary systems to move aircraft on the ground, eliminating the need for main engines during taxiing. This shift significantly reduces fuel consumption, resulting in lower ground-level emissions and improving operational efficiency. Aircraft can taxi with engines off, typically at speeds of around 25 knots, which is faster than traditional taxiing speeds[175]. In addition to electric taxiing, technologies like pushback tugs or "taxi bots" can provide initial taxiing power.

[174] Adelte. (n.d.). Preconditioned Air Zephyr. Available at: https://www.adelte.com/airports/preconditioned-air-zephir/#:~:text=All%20components%20are%20designed%2C%20manufactured,available%20to%20enhance%20PCA%20operations
[175] Taxibot International. (n.d.). Taxibot International. Available at: https://taxibot-international.com/

Summary of evidence

Summary of evidence Potential benefits

- **Fuel savings and emissions reduction:** By replacing fuel-intensive engine taxiing with electric motors, fuel consumption is significantly reduced, and emissions during taxiing are lowered. Innovations like taxi bots also reduce the operational energy demands of aircraft. Air India projects that the use of taxi bots at Delhi and Bengaluru airports could save approximately 15,000 tonnes of fuel over three years[176]. At Schiphol Airport in the Netherlands, taxiing with taxi bots has been shown to reduce fuel consumption by about 50%, with potential savings of up to 65% when taxiing to the Polderbaan runway[177].
- **Operational efficiency:** Electric taxiing allows for immediate taxiing after pushback and enables aircraft to taxi with engines off. This reduces wait times, eliminates bottlenecks, and improves overall ground operations. Aircraft can be moved using systems like pushback tugs or taxi bots, reducing the reliance on main engines for ground movement.

Technological innovations

The Electric Green Taxiing System (EGTS), developed by Honeywell and Safran, enables aircraft like the Airbus A320 to move on the ground using electric motors, rather than relying on the aircraft's jet engines. This system provides up to 4% total fuel savings per flight, which can contribute to a 75% reduction in carbon emissions during taxiing[178]. The EGTS results in annual savings of between $20,000 and $50,000 per aircraft[179]. Despite the additional weight of the electric motors, another study indicates a potential 3% reduction in fuel consumption per flight[180].

The implementation of electric taxiing systems such as the EGTS has an initial cost ranging from $250,000 to $1,000,000, depending on the aircraft type. While the initial investment can be high, the long-term savings in fuel and emissions make it a cost-effective solution for airlines committed to sustainability[181].

Table 22: Summary of data for electric or assisted taxiing

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£150 per aircraft taxi operation. This cost includes the use of electric or assisted taxiing systems, which reduce fuel consumption and

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[176] Air India. (2023) 'Air India to save 15,000 tonnes of jet fuel in 3 years with TaxiBot operations at Delhi and Bengaluru airports', Air India Newsroom, 13 April. https://www.airindia.com/in/en/newsroom/press-release/taxibot-jet-fuel-savings.html
[177] Schiphol Group. (2020) 'Sustainable taxiing uses half the fuel of standard taxi process', *Schiphol Newsroom*, 15 April. Available at: https://news.schiphol.com/sustainable-taxiing-uses-half-the-fuel-of-standard-taxi-process/
[178] Shuang Sun, Yu Liao, Shuo Ding, Yinte Lei, Song Li, Zhijie Hu, Hualong Dong. (2023). Analysis of the Application and Benefits of Aircraft Electric Wheel Systems during Taxi and Take-Off. WILEY Online Library, *International Transactions on Electrical Energy Systems*. https://onlinelibrary.wiley.com/doi/10.1155/2023/3118713
[179] Shuang Sun, Yu Liao, Shuo Ding, Yinte Lei, Song Li, Zhijie Hu, Hualong Dong. (2023). Analysis of the Application and Benefits of Aircraft Electric Wheel Systems during Taxi and Take-Off. WILEY Online Library, *International Transactions on Electrical Energy Systems*. https://onlinelibrary.wiley.com/doi/10.1155/2023/3118713
[180] P.C. Vratny, U. Kling. (2018). IMPACT OF ELECTRIC TAXIING ON HYBRID-ELECTRIC AIRCRAFT SISING. *Bauhaus Luftfahrt e.V*. https://www.dglr.de/publikationen/2019/480115.pdf
[181] Parth Vaishnav. (2017). Costs and Benefits of Reducing Fuel Burn and Emissions from Taxiing Aircraft, Low-Hanging Fruit? *Center for Climate and Energy Decision Making*. https://www.google.com/search?q=cedm+center&rlz=1C1RXQR_enJP929JP929&oq=cedm+center&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg80gEIMTc2N2owajeoAgCwAgA&sourceid=chrome&ie=UTF-8

Impact metrics	Performance	Description
		emissions during ground operations by using electric motors or other assistive technologies.[182,183] **Assumptions:** Electric taxi will reduce jet fuel usage during taxi and can also facilitate other carbon saving. This intervention results directly in less jet fuel being burned during an aircraft's ground operations. However, only a small quantity of aircraft emissions is produced while taxiing, limiting the impact of this intervention. **tCO_2e/year:** Approx 2 million tCO_2e per year (UK wide), based on multiple data sources. Electric taxi will reduce jet fuel usage during taxi, can also facilitate other carbon saving. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Low performance	TRL 5: Technology validated in a relevant environment
Durability	Moderate performance	The new technology is assumed to be sufficiently durable, provided that it receives the correct and regular maintenance. This ensures that the technology remains reliable and effective over its intended lifespan, minimising the risk of failures and maximising its operational efficiency.
Environmental impact	Good performance	Electric equipment provides an air quality benefit and electric vehicles are quieter in operation. However, there are potential environmental risks from raw materials required in battery production.

[182] Aviation Today. (2019). Electric Taxiing Systems: Past, Present, and the Possible Future. Available at: https://interactive.aviationtoday.com/avionicsmagazine/may-2019/electric-taxiing-systems-past-present-and-the-possible-future/

[183] Urban Air Mobility News. (2023). Unit Economics Suggest Cost of Traveling by Electric Air Taxi Should Drop Precipitously. Available at: https://www.urbanairmobilitynews.com/market-analysis/unit-economics-suggest-cost-of-traveling-by-electric-air-taxi-should-drop-precipitously/

Impact metrics	Performance	Description
Social impact	Good performance	Could lead to improvements in local health conditions through improved air quality.

3.4.3.4 Electric and autonomous ground support equipment

Description

Electric and autonomous Ground Support Equipment (GSE) offers significant opportunities to improve operational efficiency at airports and reduce carbon emissions. By replacing traditional internal combustion engine (ICE) vehicles with electric or hydrogen-powered alternatives, airports can significantly reduce fuel consumption and lower greenhouse gas emissions. Additionally, autonomous GSE can optimise driving patterns, reducing the need for human intervention and further increasing operational efficiency.

Summary of evidence

Examples of electric and autonomous GSE

- **Electric GSE:** Electric-powered vehicles such as towing tractors (used for towing aircraft) and luggage vehicles are already in use at some airports. These vehicles help eliminate the use of diesel-powered engines, resulting in cleaner operations.
- **Autonomous GSE:** Autonomous technologies are being applied to cargo tugs and container loaders, optimising routes and operations. Automation can also lead to carbon savings by improving driving efficiency and reducing fuel usage through more consistent and precise driving patterns. Various airports are already trailing autonomous vehicles, such as automated employee cars at Gatwick Airport and baggage trucks with Aurrigo. These trials aim to further explore how autonomous GSE can contribute to airport decarbonisation.

Challenges and considerations

- **Infrastructure and investment:** The electrification of GSE requires significant infrastructure investments, including the establishment of electric charging stations at airports. This infrastructure is crucial for supporting the transition to electric vehicles and ensuring operational continuity. While electric GSE is commercially available, the implementation of the necessary infrastructure, especially for large-scale operations, remains costly and complex.
- **Collaborative efforts:** The electrification of GSE across airports and airlines requires collaboration between multiple stakeholders. Operational arrangements, varying infrastructure, and investment requirements need to be harmonised to ensure smooth adoption and scaling of electric and autonomous vehicles.

British Airways has already initiated efforts to overhaul airport equipment, investing in lower-carbon replacements to reduce emissions from their ground operations[184]. DHL Express UK has committed £16 million GBP to support East Midlands Airport in

[184] Author Unknown. (2024). British Airways overhauls airport equipment at Heathrow with multi-million-pound investment to help reduce emissions. *British Airways Media Center*. https://mediacentre.britishairways.com/news/18032024/british-airways-overhauls-airport-equipment-at-heathrow-with-multi-million-pound-investment-to-help-reduce-emissions

achieving its 2038 decarbonisation goals, demonstrating an ongoing investment in green technologies at the airport level[185].

Table 23: Summary of data for electric and autonomous ground support equipment

Impact metrics	Performance	Description
Estimated cost of abatement	Exceptional performance	**Estimated cost per unit** ~£160,000 per GSE unit installed. This cost covers the purchase and installation of electric ground support equipment, such as baggage tractors and belt loaders, which offer lower operating costs and reduced emissions compared to traditional gas-powered equipment.[186,187] **Assumptions:** The cost covers the purchase and installation of electric ground support equipment, which offer a lower operating cost, and reduced emissions compared to traditional gas-powered equipment. The potential CO_2 savings are based on replacing diesel-powered equipment and will vary depending on the size of airports existing fleet. **tCO_2e/year:** Approx 1.5 million tCO_2e per year (UK wide). Electric GSE vehicles and machines will reduce scope 3 emissions at airports. Scope to reduce further still if switch to renewables which is potential future opportunity. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 8: System complete and qualified

185 Craig Waters. (2023). DHL Express invests £16m in electric ground service equipment at East Midlands Airport. *Aviation Business News*. https://www.aviationbusinessnews.com/cargo/dhl-express-invests-16m-in-electric-ground-service-equipment-at-east-midlands-airport/

186 Flytek GSE. (2022). The Financial Impact of Switching to Electric Ground Support Equipment. Available at: https://flytekgse.com/2022/01/06/the-financial-impact-of-switching-to-electric-ground-support-equipment/

187 Idaho National Laboratory. (n.d.). Cost-Benefit Analysis of Electric Ground Support Equipment at Airports. Available at: https://avt.inl.gov/sites/default/files/pdf/airport/GSECostBenefitSmall.pdf

Impact metrics	Performance	Description
Durability	Good performance	Requires collaboration with energy providers, EV charge point providers and relies on available space within airport grounds. Its lifespan is dependent on battery technology and operational wear and tear.
Environmental impact	Good performance	Electric equipment provides an air quality benefit and electric vehicles are quieter in operation. Potential environmental risk from raw materials required in battery production.
Social impact	Good performance	Possible improvements in local health conditions through improved air quality.

3.4.3.5 Energy efficiency improvements for buildings

Description

Energy efficiency interventions for airport buildings focus on reducing overall energy consumption and minimising environmental impact. Key strategies include, energy-efficient lighting for terminals, runways, and other airport buildings, efficient heating, ventilation, and air conditioning (HVAC) systems to optimise temperature control and the use of renewable energy sources where possible, to further reduce reliance on fossil fuels.

Summary of evidence

Energy consumption in airport buildings

A significant portion of energy usage in airport buildings stems from HVAC systems, particularly in terminal buildings. Studies have identified that HVAC systems can account for up to 50% of total energy consumption in some airport terminals[188]. In warmer climates, much of this energy is used for cooling, while in colder climates, heating also contributes significantly.

A case study at Erzurum Airport in Turkey showed that through implementing energy-saving strategies, energy consumption could be reduced by 57.24%, and CO_2 emissions could be cut by 48.79%, from 6.3 GWh/year to 2.7 GWh/year, and emissions from 1.9 million kg/year to 0.9 million kg/year[189].

Challenges

Quantifying the precise energy savings and emissions reductions across airports can be challenging due to the varied size, age, and infrastructure of existing airports. The potential for energy savings varies greatly across different airports, especially in the UK, where

[188] Xianliang, G., Jingchao, X., Zhiwen, L. and Jiaping, L., 2021. Analysis to energy consumption characteristics and influencing factors of terminal building based on airport operating data. Sustainable Energy Technologies and Assessments, 44, p.101034.
[189] Yildiz, O.F., Yilmaz, M. and Celik, A., 2022. Reduction of energy consumption and CO2 emissions of HVAC system in airport terminal buildings. Building and Environment, 208, p.108632.

existing facilities differ significantly in their age and design[190]. The types of energy-saving strategies that can be implemented will depend on the specific characteristics of each airport.

Sustainable design and opportunities

There is also potential for improving energy efficiency in new airport infrastructure. Sustainable design practices can reduce embodied carbon (the carbon footprint associated with the materials and construction of buildings). When planning for new buildings, it is important to consider whole-life costs of assets, integrating both operational and construction emissions in decarbonisation plans[191].

Table 24: Summary of data for energy efficiency improvements for buildings

Impact metrics	Performance	Description
Estimated cost of abatement	Moderate performance	**Estimated cost per unit** Varies depending on size and building requirements. Average of ~£75,000 per building retrofit. This cost includes various energy efficiency measures such as insulation, lighting upgrades, and HVAC system improvements. The exact cost can vary depending on the size and condition of the building.[192,193] **Assumptions:** Exact costs will depend on the building age, size, and current energy efficiency levels. The efficacy of efficiency measures will vary by building based on factors such as age, and size. However, in comparison to other interventions the capacity for emissions reductions is relatively small. **tCO_2e/year:** Approx 100,000 tCO_2e per year (UK wide). Can reduce energy usage up to 85% of original use e.g. LEDs.
Deliverability	Outstanding performance	TRL 9: Actual system proven in an operational environment
Durability	High performance	Upgrading to energy efficient buildings would use high-performance materials which incorporate the most up to date technological developments e.g., LED lighting

[190] Mott MacDonald (in press), Zero Emissions English Airports Target Further Analysis.
[191] KPMG (in press), Transition to zero emission and climate resilient airports. Opportunities for UK supply chain.
[192] UK Green Building Council. (n.d.). Home Retrofit Investment Calculator. Available at: https://ukgbc.org/resources/home-retrofit-investment-calculator/
[193] Department for Business, Energy & Industrial Strategy. (2022). Domestic Cost Assumptions: What Does It Cost to Retrofit Homes. Available at: https://www.gov.uk/government/publications/domestic-cost-assumptions-what-does-it-cost-to-retrofit-homes

Impact metrics	Performance	Description
		now lasts 25 times longer than traditional bulbs. More energy efficient buildings place less strain on the buildings systems (heating, lighting etc.) and therefore reduce maintenance needs, and wear and tear.
Environmental impact	Good performance	There are positive environmental impacts through improved air quality with transition away from gas boilers.
Social impact	Good performance	Reducing energy demand is a positive societal outcome for local grid energy management. Spare capacity can also help facilitate the transition to other electric infrastructure on the airport e.g. electric GSE. Airports may act as local energy hubs with wider community benefits.

3.4.3.6 Renewable energy

Description

Airports present significant opportunities to generate, store, and utilise renewable energy. Key renewable energy sources include, solar power, wind energy, hydrogen plants and small modular reactors (SMRs). To fully support the transition to renewable energy, airports will also need supporting infrastructure such as, hydrogen storage facilities and batteries for energy storage. These systems can help airports become more self-sufficient and potentially sell any unused electricity back to the grid, depending on the scale of energy generation and airport needs.

Summary of evidence

Current industry efforts and case studies

There has been substantial progress in integrating renewable energy across airports globally, with several successful projects demonstrating the potential impact of such initiatives:

- **Solar energy:** Many airports are turning to solar power as a primary renewable energy source. Brisbane Airport's photovoltaic (PV) solar system alone is projected to reduce CO_2 emissions by 8,000 tonnes annually[194].
- **Trigeneration systems:** Melbourne Airport has implemented a trigeneration system, which is estimated to reduce CO_2 emissions by 920,000 tonnes over 15 years[195].
- **Wind energy:** Schiphol Airport in the Netherlands is powered entirely by Dutch wind energy and is taking steps to eliminate its dependence on natural gas[196].
- **Solar arrays and 100% renewable goals:** Denver International Airport has installed large-scale solar arrays, with plans to achieve 100% renewable energy by 2030.

[194] Baxter, G., 2021. Mitigating an airport's carbon footprint through the use of "green" technologies: The case of Brisbane and Melbourne Airports, Australia. International Journal of Environment, Agriculture and Biotechnology, 6(6), pp.29-39
[195] Baxter, G., 2021. Mitigating an airport's carbon footprint through the use of "green" technologies: The case of Brisbane and Melbourne Airports, Australia. International Journal of Environment, Agriculture and Biotechnology, 6(6), pp.29-39
[196] Sustainability Magazine. (n.d.). Top 10 Net-Zero Strategies from the World's Busiest Airports. Available at: https://www.sustainability-magazine.com/content/top-10-net-zero-strategies-from-the-worlds-busiest-airport

Similarly, Los Angeles International Airport (LAX) aims for 100% renewable energy and carbon neutrality by 2046, exploring on-site power generation options[197].

Challenges in transitioning to renewable energy

While renewable energy adoption is progressing, airports still face challenges in fully transitioning:

- **Reliance on National Grid:** A significant portion of an airport's energy still comes from the national grid, which may not always be powered by renewable sources. This reliance complicates the transition, as airports often have limited control over the broader national energy mix.
- **Infrastructure requirements:** Developing the necessary infrastructure to support renewable energy, such as energy storage systems, hydrogen storage, and grid integration, requires considerable investment and planning.
- **UK planning system:** The UK planning system can present significant obstacles to the transition. Strict planning regulations and lengthy approval processes for new energy infrastructure can delay projects, making it challenging to implement renewable energy solutions in a timely manner. The need for coordination with local authorities, regulatory bodies, and stakeholders further complicates the process, potentially hindering the speed at which airports can transition to cleaner energy sources.

Table 25: Summary of data for renewable energy

Impact metrics	Performance	Description
Estimated cost of abatement	Unacceptable performance	**Estimated cost per unit** ~£1,500 Per kW installed. This cost covers the installation of renewable energy systems such as solar panels or wind turbines. The cost can vary based on the type of renewable energy technology and the scale of the installation.[198,199] **Assumptions:** This cost covers the installation of renewable energy systems. However, due to differences in the generation capacity of airports (type of renewable technology deployed and the scale of the installation), this figure is largely indicative. It also assumes the availability of renewable energy resources, which can vary regionally and due to other external factors. Whilst renewable energy generated at airports will provide up to a 100% reduction in fossil

[197] Sustainability Magazine. (n.d.). Top 10 Net-Zero Strategies from the World's Busiest Airports. Available at: https://www.sustainability-magazine.com/content/top-10-net-zero-strategies-from-the-worlds-busiest-airport

[198] Department for Business, Energy & Industrial Strategy. (2023). Electricity Generation Costs 2023. Available at: https://assets.publishing.service.gov.uk/media/6556027d046ed400148b99fe/electricity-generation-costs-2023.pdf

[199] House of Lords Library. (n.d.). *Renewable Energy Costs*. Available at: https://lordslibrary.parliament.uk/renewable-energy-costs/

Impact metrics	Performance	Description
		energy produced, the wider decarbonisation of the UK grid is already underway. The electricity "imported" into airports, is likely to be clean in the near future. Therefore, the potential carbon savings from on-site renewables is relatively small. **tCO_2e/year:** Approx 100,000 tCO_2e per year (UK wide).[200] Up to 100% carbon savings vs fossil fuels at an operational level, not including cradle or grave emissions. Offset against current grid intensity.[201] **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	High performance	TRL 8: System complete and qualified
Durability	High performance	Requires collaboration with energy providers, EV charge point providers and relies on space within airport grounds. Renewables, such as wind, would likely need to be sourced elsewhere. The lifespan of renewables can vary but range from 20-40 years.
Environmental impact	Good performance	Renewable energy offers significant environmental benefits over fossil fuel-based energy production, particularly in improving air quality. However, there is also potential impact to local biodiversity with certain renewable technologies e.g. windfarms. They may also be perceived negatively by public if intrusive.
Social impact	Moderate performance	Potential improvements in local health conditions through improved air quality.

[200] National Renewable Energy Laboratory. (2013). Renewable Energy Technologies: Cost Analysis and Market Assessment. Available at: https://www.nrel.gov/docs/fy13osti/57187.pdf
[201] World Resources Institute. (n.d.). Setting the Record Straight About Renewable Energy. Available at: https://www.wri.org/insights/setting-record-straight-about-renewable-energy#:~:text=The%20useful%20lifespan%20of%20renewable,from%2025%20to%2040%20years

3.4.4 Training and support

3.4.4.1 Data and analytics

Description

To achieve more efficient airport and airline operations, detailed data and analytics are crucial. A systems-wide approach is needed to identify inefficiencies, communicate findings to stakeholders (such as airlines and airports), and understand how technology can be implemented and utilised to improve operations.

Summary of evidence

Challenges in data integration

One of the key challenges in implementing data and analytics is building trust and ensuring the explainability of systems. The effective sharing of data in accessible formats is key to operational efficiency. For instance, to enable timely decision-making during flights (e.g., route changes), data must be clear and actionable for pilots, taking all relevant variables into account.

For these long-term solutions to succeed, it is essential to invest in training for stakeholders to understand how the systems work and their functional performance, including training and implementation around the use of blockchain technology to ensure data integrity and security[202,203,204].

Emerging data and analytical tools

Several innovative tools can enhance the efficiency of operations. AI and machine learning technologies have shown promise in identifying high-emission areas and enabling targeted interventions. For example, AI can spot inefficiencies, allowing airports and airlines to make data-driven decisions for emissions reductions. However, it's important to consider the environmental impact of these technologies when evaluating their overall effectiveness[205]. Cloud computing solutions can also facilitate comprehensive emissions tracking and reporting[206], and big data can enable proactive strategies for targeted emissions reduction[207].

The current aviation systems often fail to provide trusted data provenance, immutability, transparency, auditability, and traceability. Blockchain technology offers a potential solution by providing secure, decentralised traceability and transparency without relying on a trusted third party. Key applications for blockchain in aviation include, digitising crew certificates, securing customer loyalty programmes and enhancing Maintenance, Repair, and Overhaul

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[202] Degas, A., Islam, M., Hurter, C., Barua, S., Rahman, H., Poudel, M., Ruscio, D., Ahmed, M., Begum, S., Rahman, M., Bonelli, S., Cartocci, G., Di Flumeri, G., Borghini, G., Babiloni, F., & Aricó, P., 2022. A Survey on Artificial Intelligence (AI) and eXplainable AI in Air Traffic Management: Current Trends and Development with Future Research Trajectory. Applied Sciences. https://doi.org/10.3390/app12031295
[203] Zhong, J., 2021. Heading Toward Trusted ATCO-AI Systems: A Literature Review. **. https://doi.org/10.31224/osf.io/t769b
[204] Ahmad, R.W., Salah, K., Jayaraman, R., Hasan, H.R., Yaqoob, I. and Omar, M., 2021. The role of blockchain technology in aviation industry. *IEEE Aerospace and Electronic Systems Magazine*, *36*(3), pp.4-15.
[205] United Nations Environment Programme. (2023). AI Has an Environmental Problem. Here's What the World Can Do About It. Available at: https://www.unep.org/news-and-stories/story/ai-has-environmental-problem-heres-what-world-can-do-about
[206] Hasan, M.R., Islam, M.Z., Sumon, M.F.I., Osiujjaman, M., Debnath, P. and Pant, L., 2024. Integrating artificial intelligence and predictive analytics in supply chain management to minimize carbon footprint and enhance business growth in the USA. Journal of Business and Management Studies, 6(4), pp.195-212.
[207] Arinze, C.A., Ajala, O.A., Okoye, C.C., Ofodile, O.C. and Daraojimba, A.I., 2024. Evaluating the integration of advanced IT solutions for emission reduction in the oil and gas sector. Engineering Science & Technology Journal, 5(3), pp.639-652.

(MRO) operations. Training in blockchain technology will be crucial for these applications to be fully realised across the industry[208].

While indicative costs for data and analytics-driven interventions have been outlined (see the table below), actual costs will vary depending on the type of data and analytics employed and the specific intervention being supported.

Table 26: Summary of data for data and analytics

Impact metrics	Performance	Description
Estimated cost of abatement	Good performance	**Estimated cost per unit** Approx. £7,500 per report generated. This cost includes the use of data analytics tools to identify inefficiencies and generate reports for airlines and airports. The cost can vary based on the complexity of the analysis and the data sources used.[209,210] **Assumptions:** Cost figures exclude any potential costs incurred due to additional data privacy requirements or cyber security challenges. System requires robust systems and training which are likely to vary across airlines/airports. In comparison to other interventions, the estimated CO_2 abetment is relatively small. **tCO_2e/year:** Approx 100,000 tCO_2e per year (UK wide). This is more of an enabling feature. **Assumptions:** Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Good performance	TRL 9: System complete and qualified

[208] Lopes, D.P., Rita, P. and Treiblmaier, H., 2021. The impact of blockchain on the aviation industry: Findings from a qualitative study. *Research in Transportation Business & Management*, *41*, p.100669.
[209] RapidOps. (n.d.). Cutting Costs with Data Analytics. Available at: https://www.rapidops.com/blog/cutting-costs-with-data-analytics/
[210] Wolniak, M., & Grebski, M. (2024). The Impact of Data Analytics on the Efficiency of Airline Operations. Management Papers, 26(1), 184-198. Available at: https://managementpapers.polsl.pl/wp-content/uploads/2024/01/184-Wolniak-Grebski-3.pdf

Impact metrics	Performance	Description
Durability	Good performance	May require constant updating and improvement as interventions are introduced. Software-driven interventions typically require updates or replacements within a decade.
Environmental impact	Moderate performance	Interventions to improve efficiency can drive positive environmental outcomes with less noise and air pollution.
Social impact	Poor performance	Potential adverse impacts with issues around access to data and GDPR.

3.4.4.2 Pilot training

Description

Pilot training is essential for encouraging efficient operations and promoting behavioural change in aviation. While technology can enhance system efficiencies, both industry stakeholders and research indicate that training and pilot behaviour are key drivers in accelerating aviation decarbonisation.

Summary of evidence

Focus of training

The training should go beyond teaching pilots how to achieve operational efficiencies; it must emphasise why these efficiencies are crucial for sustainability. Currently, the aviation industry tends to prioritise economic benefits and safety over environmental concerns, with limited focus on operational changes that could drive sustainability.

Encouraging pilots to prioritise fuel savings and sustainable practices will be essential for decarbonising the sector. Research has shown that pilots tend to believe the cruise phase offers the greatest potential for fuel savings, whereas ground operations are often overlooked[211]. This highlights the need for targeted training to challenge existing perceptions and encourage more sustainable behaviours.

Human factors in training

To maximise operational efficiency while ensuring safety, pilot training must incorporate human factors considerations. Key elements to focus on include, managing cognitive and physical demands during training and operations, ensuring pilots can make informed decisions for sustainability and designing systems and training programmes that accommodate human capabilities.

As aviation technology continues to evolve, addressing gaps in personnel competencies will be vital to maintaining both safety and efficiency. Developing a taxonomy of human

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[211] Hong, J., Park, W., & Ryoo, C., 2021. An Autonomous Space Navigation System Using Image Sensors. International Journal of Control, Automation and Systems, 19, pp. 2122 - 2133. https://doi.org/10.1007/s12555-020-0319-7

performance issues will help bridge the gap between advancing technology and human capabilities[212].

Cost and abatement estimates

While indicative figures for the cost of training and abatement potential have been provided (see the table below), actual costs will vary based on the scope and depth of training provided and the specific training methods and tools implemented.

Table 27: Summary of data for pilot training

Impact metrics	Performance	Description
Estimated cost of abatement	High performance	**Estimated cost per unit** ~£15,000 per pilot trained. This cost includes enhanced training programmes focused on efficient operations, which can lead to fuel savings and reduced emissions. The cost can vary based on the duration and content of the training programme. **Assumptions:** This cost estimate included enhanced training, which could lead to fuel savings and reduced emissions. The cost is expected to vary depending on the duration and content of the programme. Figures subject to variability due to differences in the quality and consistency of training programs across airlines. Standardisation would help to mitigate this. **tCO_2e/year:** Approx 500,000 tCO_2e per year (UK wide). There is less of a direct impact on CO_2 but a greater understanding as to sources - more of an enabling feature. The estimate is revised down as to avoid the problem of double counting: (i.e., allocating carbon benefits to the training which have already been counted by other interventions). Additionally, this intervention is only effective in conjunction with other interventions. **Assumptions:**

[212] Tikanashvili, N. and Kopyt, A., 2022, November. Modern Technologies & Human Performance Taxonomy in Air Traffic Management Development. Polish and Georgian Case Studies. In 2022 New Trends in Aviation Development (NTAD) (pp. 233-236). IEEE.

Impact metrics	Performance	Description
		Due to lack of available data, emissions estimations for this intervention are based on informed assumptions derived from industry standards and publicly available data. These estimates are intended solely to provide an indication of intervention performance relative to others considered in this analysis.
Deliverability	Good performance	TRL 9: Actual system proven in an operational environment
Durability	Good performance	Training may require frequent updating. Pilot training must evolve with new technology and operational requirements. So much like software-driven interventions, pilot training will typically require updates or replacement within a decade.
Environmental impact	Good performance	Interventions to improve efficiency can drive positive environmental outcomes like less noise and air pollution.
Social impact	Moderate performance	Potential improvements in local health conditions through improved air quality and noise reduction.

3.4.5 Artificial intelligence and machine learning

Both the literature review and the responses to the questionnaire frequently cited artificial intelligence and machine learning as opportunities to enhance the impact of many of the interventions identified. AI, for example can be used to enhance or complement many of the proposed interventions including holding on the ground and free route airspace. Indeed, AI is included as a development priority within SESAR (Single European Sky ATM Research, 2025) to enable the next generation of airport platforms[213]. The integration of AI and other emerging technologies such as cloud computing, big data, and the Internet of Things (IoT) into ATM systems is still in its nascent stages but all will have a role to play in future aviation operations and result in smarter, more efficient ATM systems. These have been identified as enhancements to specific interventions throughout the text, where the evidence supports its implementation.

[213] Author Unknown. (2025). European ATM Master Plan. *SESAR Joint Undertaking.* [SESAR Master Plan 2025.pdf](https://www.globalfastenernews.com/how-many-fasteners-in-a-boeing-777-global-fastener-news-usa/)https://www.globalfastenernews.com/how-many-fasteners-in-a-boeing-777-global-fastener-news-usa/

4 Part B: Prioritisation of interventions

This section details how the identified interventions were prioritised by considering the relative importance of emissions impact, cost and time to implementation. The analysis was undertaken using a multi-criteria analysis (MCA) combining the findings from the impact assessment (described in section 3.1) with activities to determine the relative importance or weighting of the five criteria (pairwise comparison) through further stakeholder engagement.

4.1 Approach

4.1.1 Multi-criteria analysis

A multicriteria analysis (MCA) was adopted to rank the twenty-five potential interventions identified in Section 3. The results of this MCA allow for interventions to be prioritised based on their feasibility, relative estimated cost, and potential impact on carbon savings, identifying interventions with the biggest potential to achieve operational efficiencies.

Due to the limited published quantitative data on the impacts and costs of the identified interventions it was not viable to undertake an economic analysis of pursuing investment of the interventions. Instead, an MCA was chosen as the most suitable method for this analysis. In the Treasury Green Book, multi-criteria analysis (MCA) is an alternative when defining alternative analysis than one that defines monetary values for all the major costs and benefits when economic analyses are impractical due to lack of available data. It is a tool that can be used to assess the value and relative importance of an operation, technology or process and uses a hybrid approach.

The impact assessment criteria defined in section 3.1 were used as the basis for assessing the potential impact and feasibility of the interventions which were then quantified, as described in section 4.1.1.1 (the "score"). Using the methodology described in section 4.1.3**.** the relative importance of each criterion was e stablished (the "criterion eight"). Jointly this provided a final score for each intervention:

$$\begin{aligned} Final\ Score\ =\ & (\text{ECA Weight x ECA Score}) + (\text{Deliverability Weight x Deliverability Score}) \\ & + (\text{Durability Weight x Durability Score}) \\ & + (\text{Environment Weight x Environment Score}) + (\text{Social Weight x Social Score}) \end{aligned}$$

4.1.1.1 Quantification of the impact assessment

Section 3.4 describes the breadth of the qualitative and quantitative data which was used to understand the impact of each intervention, including the challenges with identifying comparable data. To enable ranking and conduct the MCA, a rating of 1-7 was applied to each of the criteria. The evidence used to apply the scoring criteria are defined in Table 28, which were reviewed and agreed in a workshop with DfT in December 2024.

Table 28: Scoring criteria

Criteria	Definition
Estimated cost of Abatement	Derived from the cost of the intervention and the CO_2 abated (both described below) by the approach described in section 3.1. **Cost** The cost of implementing the intervention per unit e.g. per aircraft where data is available. Where no cost information is available the scores are based on "Expert judgment"/"Stakeholder Consultation". **CO_2 abated** The tonnes of CO_2 abated per year (or other time-based metric) where data is available. For interventions with insufficient quantitative data, defining ranges were based on expert opinion: For sector wide the scores applied were (e.g. > 1 MtCO2/year => High (score 5), 0.1 - 1 MtCO2/year => Medium (score 3), 0.1< MtCO2/year =>Low (score 1) The recommended scores for cost of abatement were: • High = 7 • High Medium = 6 • Medium High = 5 • Medium = 4 • Medium Low = 3 • Low Medium = 2 • Low = 1
Deliverability	The term deliverability refers to the ability of something to be delivered as a result of a development process. Deliverability was assessed by combining qualitative literature review insights, stakeholder engagement and expert judgement The scores were based on current/current perceived TRL level[214]: TRL 1: Basic principles observed and reported TRL 2: Technology concept formulated TRL 3: Experimental proof of concept TRL 4: Technology validated in a lab TRL 5: Technology validated in a relevant environment TRL 6: Technology demonstrated in a relevant environment TRL 7: System prototype demonstration in an operational environment TRL 8: System complete and qualified TRL 9: Actual system proven in an operational environment In the scenario where the intervention was not a technology, the deliverability was based on research and expert opinion and

[214] Aerospace Technology Institute, 2023. *Technology Readiness Levels (TRL)*. [online] Available at: https://www.ati.org.uk/funding/technology-readiness-levels-trl/

Criteria	Definition
	readiness against a "systems readiness level" directly aligned to TRL criteria. The scores that aligned with TRL criteria were: • TRL 1-2 = 1 • TRL 3-4 = 2 • TRL 5 = 3 • TRL 6 = 4 • TRL 7 = 5 • TRL 8 = 6 • TRL 9 = 7
Durability	This parameter reflects the long-term reliability, effectiveness, and robustness of the measure. It is defined as "long-term reliability". This was scored based on a mix of qualitative judgement from the literature and expert opinion. The following were used as scoring criteria and assessed by combining qualitative literature review insights, stakeholder engagement and expert judgement: • Resistance to wear and tear – Interventions that are materials dependent are scored based on the general durability of the base material (composites/ metals etc) and/or based on available data for similar technologies already implemented at commercial scale – Where the interventions are implementing procedures or software etc which are not / are less reliant on materials and therefore more resistant to wear and tear the received highest scores. • Environmental resistance (how resistant the intervention is to diverse operational conditions / extreme weather etc.) Durability was scored as follows: • Not material dependent and not affected by extreme environmental/weather condition, and no to very low level of getting affected by security/safety threats = 7 • Not material dependent and not affected by extreme environmental/weather condition, but can be affected by security/safety threats = 5 • Not material dependent, but could be affected by extreme environmental/weather condition, and/or by security/safety threats = 3 • Material dependent and could be affected by extreme environmental/weather condition, and/or by security/safety threats = 1
Environmental Impact	Environmental impact encompasses the effects that human activities have on the environment, including changes to ecosystems, biodiversity, and natural resources. Common effects

Criteria	Definition
	include loss of biodiversity, soil degradation, noise, air and water pollution, and climate change. These were primarily derived from stakeholder engagement and expert judgement. Three types of impact were included and assessed by combining qualitative literature review insights, stakeholder engagement and expert judgement: • Direct vs. Indirect: Direct impacts cause immediate changes, while indirect impacts may take longer to manifest. • Temporary vs. Permanent: Temporary impacts are short-lived, whereas permanent impacts have long-lasting effects. • Reversible vs. Irreversible: Reversible impacts can be mitigated or restored, while irreversible impacts cause permanent damage Environmental impacts were scored from 1-7 as follows: • Major negative impact = 1 • Moderate negative impact = 2 • Minor negative impact = 3 • No impact = 4 • Minor positive = 5 • Moderate positive impact = 6 • Major positive impact =7
Social Impact	Social impacts refer to the significant, positive or negative changes that occur in society because of specific actions, projects, or policies. These impacts can affect individuals, communities, and broader societal structures. Significant positive impacts are those that address social injustice or challenges - this can include improvements in areas such as health, education, equality, and economic development. The following types of impact were included and assessed by combining qualitative literature review insights, stakeholder engagement and expert judgement: • Direct Impacts: Immediate effects on individuals or communities, such as job creation or improved access to healthcare. • Indirect Impacts: Secondary effects that occur over time, such as economic growth resulting from improved infrastructure. And were considered both positively and negatively: • Positive Impacts: Benefits such as increased quality of life, reduced poverty, and enhanced social cohesion. • Negative Impacts: Adverse effects like displacement, social inequality, or environmental degradation. Examples of Social Impacts include: • Economic: Job creation, increased income levels, and economic development. • Health: Improved healthcare access, reduced disease prevalence, and better mental health outcomes.

Criteria	Definition
	• Education: Increased literacy rates, better educational facilities, and higher educational attainment. • Environmental: Enhanced sustainability practices, reduced pollution, and conservation of natural resources. • Community: Strengthened social networks, improved public safety, and greater community engagement. The scores for social impact were designated as follows: • Major negative impact =1 • Moderate negative impact = 2 • Minor negative impact = 3 • No impact = 4 • Minor positive = 5 • Moderate positive impact = 6 • Major positive impact =7

4.1.2 Estimated cost of abatement

The Estimated Cost of Abatement (ECA) considers costs, carbon abatement potential and the intervention lifetime. The ECA for each intervention was estimated using a combination of public reports and expert judgement and assume average market conditions.

This report uses the provided cost estimates as high-level indicative figures, and as such, they should be considered as approximate rather than definitive.

Each intervention was assigned an indicative unit cost, e.g., per aircraft, per flight, depending on the available data. This approach was chosen based on the availability of data within the literature. There was insufficient detail within the literature to provide more granular data.

This process made cost estimates comparable with available data on carbon abatement potential, which was also derived from a combination of public reports and expert judgement. The calculation below was used:

$$Estimated\ cost\ of\ abatement = \frac{(Unit\ Cost\ \times no.units\ in\ the\ UK)}{(Potential\ CO2e\ abatement\ per\ year\ \times Lifetime)}$$

Where lifetime is based on the lifetime of the intervention with a minimum of ten years and a maximum of twenty-five years and the number of units means the relevant quantity in the UK (e.g. number of aircraft for aircraft interventions, number of flights for airspace, and number of aircraft stands for stands).

A top-down approach was taken to estimate CO_2e emissions abated. The value for tCO_2e/flight the total emissions attributed to UK aviation and dividing that by the number for departing flights per year. This was combined with a value for fuel burn. Additional data values were derived where possible from established data.

Scores of one to seven were applied as per the Estimated Cost of Abatement bands. Interventions with an Estimated Cost of Abatement less than or equal to 2GBP/tCO_2e

received a score of seven, while those with an Estimated Cost of Abatement of greater than 100GBP/tCO_2e received a score of one.

Scoring Key	Scoring Description	Scoring Bands
1	Unacceptable performance	X > £100.00
2	Poor Performance	£50.00 < X < £100.00
3	Low Performance	£25.00 < X< £50.00
4	Moderate Performance	£10.00 <X < £25.00
5	Good Performance	£5.00< X < £10.00
6	High Performance	£2.00< X < £5.00
7	Exceptional Performance	X < £2.00

Figure 3 shows the plot of intervention cost against carbon abatement. Those interventions above the line have a higher cost per carbon abated than the average whilst those below the line deliver better carbon savings per pound than the average. The cluster of interventions in the lower left-hand corner highlight that there is no silver bullet to decarbonising operations in the UK. It presents, visually, the idea that the combination of many "smaller" interventions can aggregate to have a large impact on carbon emissions.

This analysis resulted in the identification of three potential outliers:

- In-flight refuelling results in an increase in the UK's aviation carbon emissions. Traditional refuelling emissions are attributed to the landing country, but in-flight refuelling emissions are attributed to the UK, raising its overall emissions.
- Investing in renewable energy has a high Estimated Cost of Abatement, partly because the electricity grid is already undergoing significant decarbonisation. As the grid becomes less reliant on fossil fuels, the additional carbon reduction achieved by renewable energy investments at airports diminishes. Consequently, the overall carbon abatement potential may be reduced by the broader decarbonisation efforts in the UK.
- As identified in Figure 6, non-conventional flight aircraft configurations have extremely high estimated cost relative to its carbon abatement potential. This stands to reason as these configurations are still in the early stages of research (TRL 2) and would require enormous investment to progress beyond this stage. Historically, adoption rates and technological developments for this intervention have been slow, despite potential carbon savings if successfully implemented. To better understand how the maturity and economic aspects of this intervention, and others at an early stage of development, may change through its future stages, an economy of scale assessment could be undertaken to identify the point at which increased production leads to a lower average cost per unit.

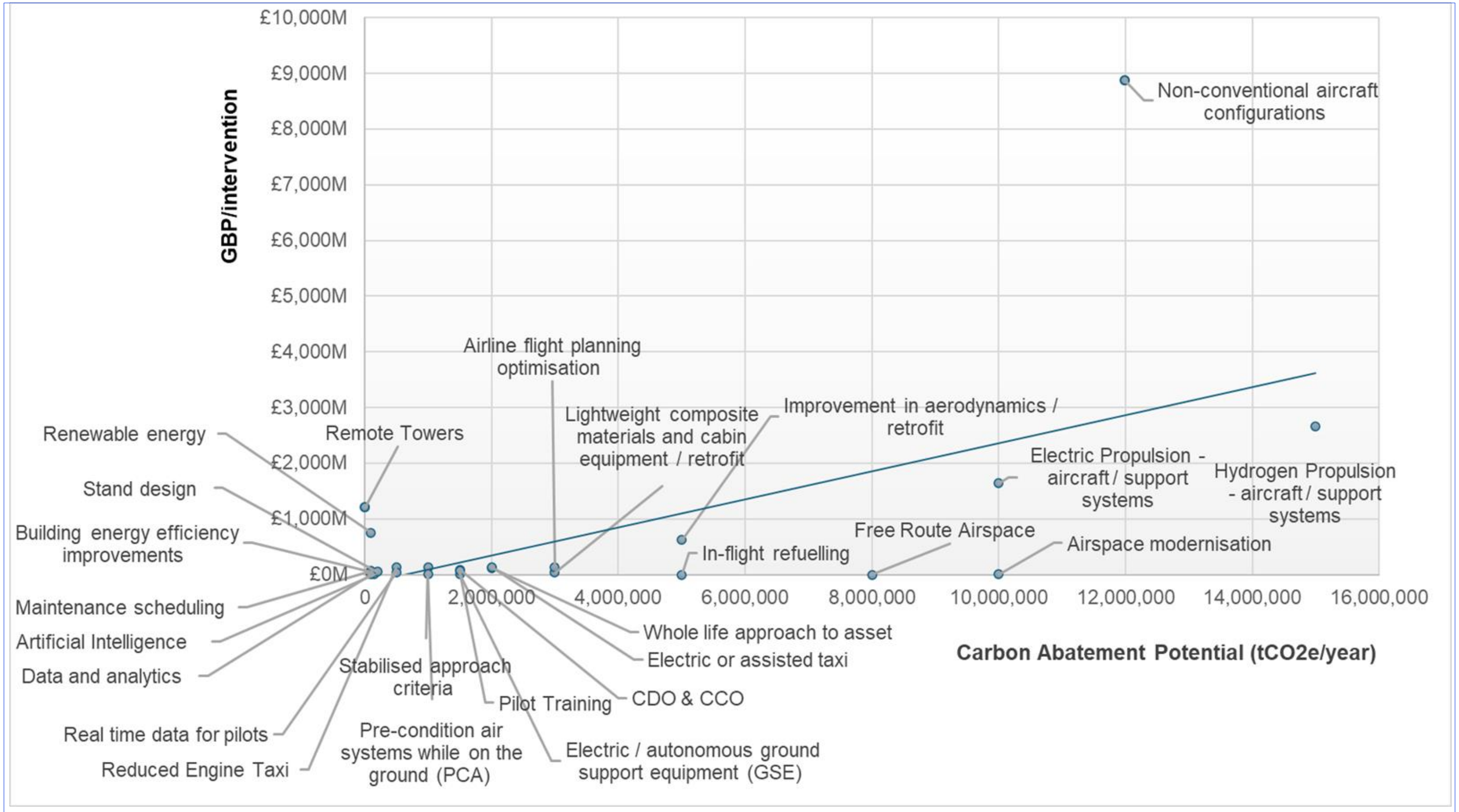

Figure 6: Estimated cost vs. carbon abatement potential per year

4.1.3 Determining the relative importance of the criteria

4.1.3.1 Pairwise comparison and ranking & stakeholder workshop

To determine the relative importance of criteria and thus their weighting for the MCA, a pairwise comparison matrix was designed to allow stakeholders to compare each criterion against every other. This approach simplifies the wider decision-making process by breaking it down into a series of comparisons. Through these comparisons, a weight is calculated for each criterion based on their relative importance and rankings are established based on the outcomes of these direct matchups.

Responses were recorded using a nine-point intensity scale set out below.

Table 29: Pairwise comparison scoring guidance

How important is criteria A relative to B	Preference index
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Absolutely more important	9

The initial pairwise comparison exercise was undertaken during a workshop held on 29th November 2024. Of the 30+ representatives at the workshop, organisations represented included airports, airline operators, pilots, academics, consultants, Government Bodies and NGOs. During the workshop respondents were assigned to groups of approximately 3-4 people - the groups were designed such that there were a mix of stakeholders in each group. In each group, participants were first asked to complete the pairwise comparison independently, and then discussions were initiated to agree a consensus score for each criteria comparison.

After the workshop, some of the attendees were contacted by email to provide further information on and validation of the scores they provided.

4.1.3.2 Ranking process and one-to-one interviews

Sixteen one-to-one interviews were conducted after the workshop with the dual aims of further validating the pairwise comparisons and collecting further qualitative insights into the current status of the interventions. Whilst the pairwise comparison was the primary methodology for capturing stakeholder criteria weightings, a simplified ranking exercise was used in the one-to-one interviews. While the pairwise method offers a mathematically rigorous approach to deriving weights, its complexity can lead to inconsistencies if participants are unfamiliar with the method. A simplified ranking process was introduced to allow stakeholders to express their preferences more intuitively by ranking them in order of importance and mitigate the potential risk of bias.

This dual approach of workshops and interviews, aided in ensuring that all stakeholders' perspectives were captured and validated by providing an additional layer of clarity and served to cross-check the results of the pairwise analysis.

4.1.3.3 Analysis

The scores collated were converted to weights using the Analytic Hierarchy Process (AHP). To validate the results of the AHP, the Consistency Ratio (CR) was assessed. The CR is a measure used to evaluate the consistency of the results of the pairwise comparison exercise, ensuring that consistency in pairwise comparison within the AHP is not arbitrary. A CR of less than 10% is generally acceptable in statistics and indicates a reasonable level of consistency in the pairwise comparison[215]. If the CR exceeds 10%, then it suggests inconsistency in the scoring and that the comparisons should be reviewed with stakeholders and where necessary, revised. The CR was assessed to be 8.6%, which indicated a sufficient level of consistency in the results.

4.1.3.4 Purpose of the analysis

This methodology does not imply absolute accuracy of individual results of the pairwise comparison, rather it ensures that each result is no more or less reliable than another and robust given the constraints, enabling the subsequent MCA and ranking exercise to be undertaken.

4.2 Results

4.2.1 MCA outputs – Prioritised list of interventions

The output of the MCA ranked the twenty-five interventions, based on the combination of the scores and the pairwise comparisons and is shown in Table 30.

Table 30: MCA rankings and score

Intervention	Intervention category	Ranking	Score
Improvement in aerodynamics/retrofit	Aircraft design and operation	1	6.06
Airline flight planning optimisation	Airspace	2	5.66
Lightweight cabin equipment	Aircraft design and operations	3	5.60
Electric ground support equipment (GSE)	Airports	4	5.54
Free route airspace	Airspace	5	5.50
Stabilised approach criteria	Aircraft design and operations	6 (Joint)	5.44
Building energy efficiency improvements	Airports	6 (Joint)	5.44
Pre-condition air systems while on the ground (PCA)	Airports	8	5.32
Real-time data for pilots	Airspace	9	5.28
Continuous climb operations (CCO) and continuous descent operations (CDO)	Airspace	10	5.22

[215] Reich, Y., & Pindyck, R. S. (1987). *Learning, spillovers, and technical change: The case of electric vehicles*. *Management Science, 33*(11), 1383–1394. https://doi.org/10.1287/mnsc.33.11.1383

Intervention	Intervention category	Ranking	Score
Reduced engine taxi	Aircraft design and operations	11	5.12
Whole life approach to aircraft and operations	Aircraft design and operations	12 (Joint)	5.10
Airspace modernisation (reduced airspace fragmentation)	Airspace	12 (Joint)	5.10
Pilot training	Training and support	14	4.98
Electric/hybrid propulsion	Aircraft design and operations	15	4.80
Remote towers	Airspace	16	4.76
Maintenance scheduling	Aircraft design and operations	17	4.74
Holding on the ground: Potentially with Artificial Intelligence (AI)	Aircraft design and operations	18	4.72
Electric or assisted taxi	Airports	19	4.56
Renewable energy	Airports	20	4.56
Non-conventional aircraft configurations	Aircraft design and operations	21	4.42
Hydrogen propulsion	Aircraft design and operations	22	4.34
Data and analytics	Training and support	23	4.18
Stand design	Airports	24	3.90
In-flight refuelling	Aircraft design and operations	25	3.18

Since these categories all have different investment streams and priorities, as well as implementation timescales and complexities, the MCA ranking does not provide detail on how to actually implement these different interventions. This will be more complex than going from ranking 1 to 25 in order, but it provides a starting point to develop a roadmap. To review the implementation process for the interventions, the following sections look at the score breakdown by intervention. Each intervention is assessed against the 5 criteria and allocated a score out of 7.

4.2.1.1 MCA results for aircraft design and operation

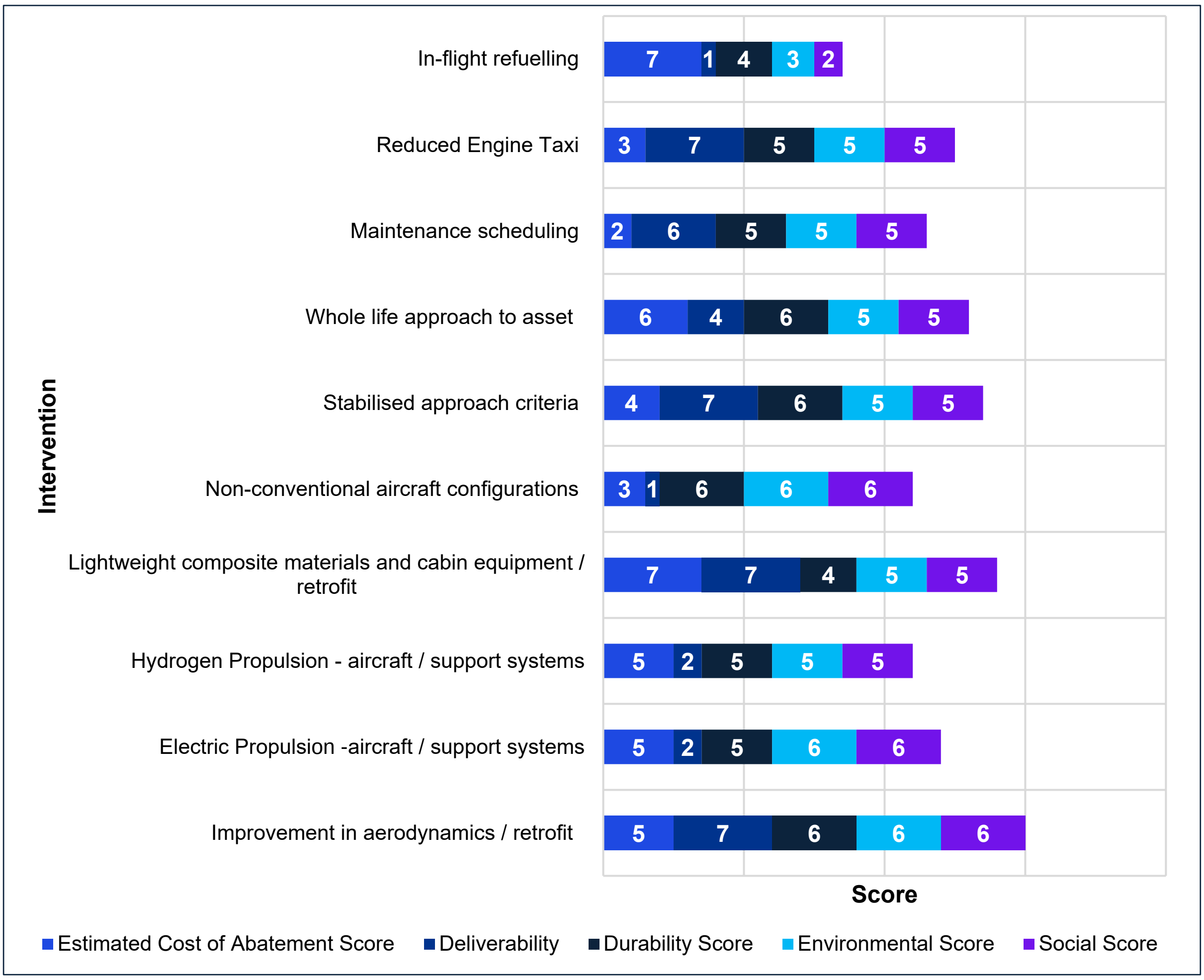

Figure 7: MCA breakdown for aircraft design and operation interventions

Each impact criterium is assessed on a score of 1-7. The score given is shown in each box for each criterium.

Improvements in aerodynamics was identified as the most important intervention, scoring the highest of the assessed intervention. The results from the MCA and the breakdown indicate that the interventions are split into three groups:

- Those with highest deliverability scores (6-7) and highest (6-7) estimated cost of abatement score most highly on the MCA
- Those with highest deliverability (6-7) and mid-high (4-5) estimated cost of abatement rank towards the middle of the MCA
- Those with lower deliverability scores (2-4) and high estimated cost of abatement scores (5) rank towards the end of the MCA.

The scores indicate that the following interventions are relatively easy to implement in terms of cost and deliverability, resulting in real carbon benefits soonest, and are already being used within the industry:

- improvement in aerodynamics/retrofit
- stabilised approach criteria

- reduced engine taxiing
- lightweight cabin equipment.

Combining existing aircraft maintenance and upgrades focused on improving the aerodynamics of the aircraft and using light weight cabin equipment could accelerate these activities. Similarly encouraging the use of a stabilised approach and reducing the use of the engine taxing by, for example, using single engine taxing and active use of available ground support equipment, such as electric tugs where available, could also be accelerated through airline procedures and agreed approaches between airports and airlines to make additional immediate savings.

Results across durability, environmental and social are broadly similar between the interventions (all scoring between 4 and 6), however those interventions with an expected long time to implementation (greater than ten years) are most poorly scored and require long term investments and development to deliver carbon impacts.

In-flight refuelling scored low across all categories, other than estimated cost of abatement and scored the lowest priority in the MCA.

4.2.1.2 MCA results for airspace

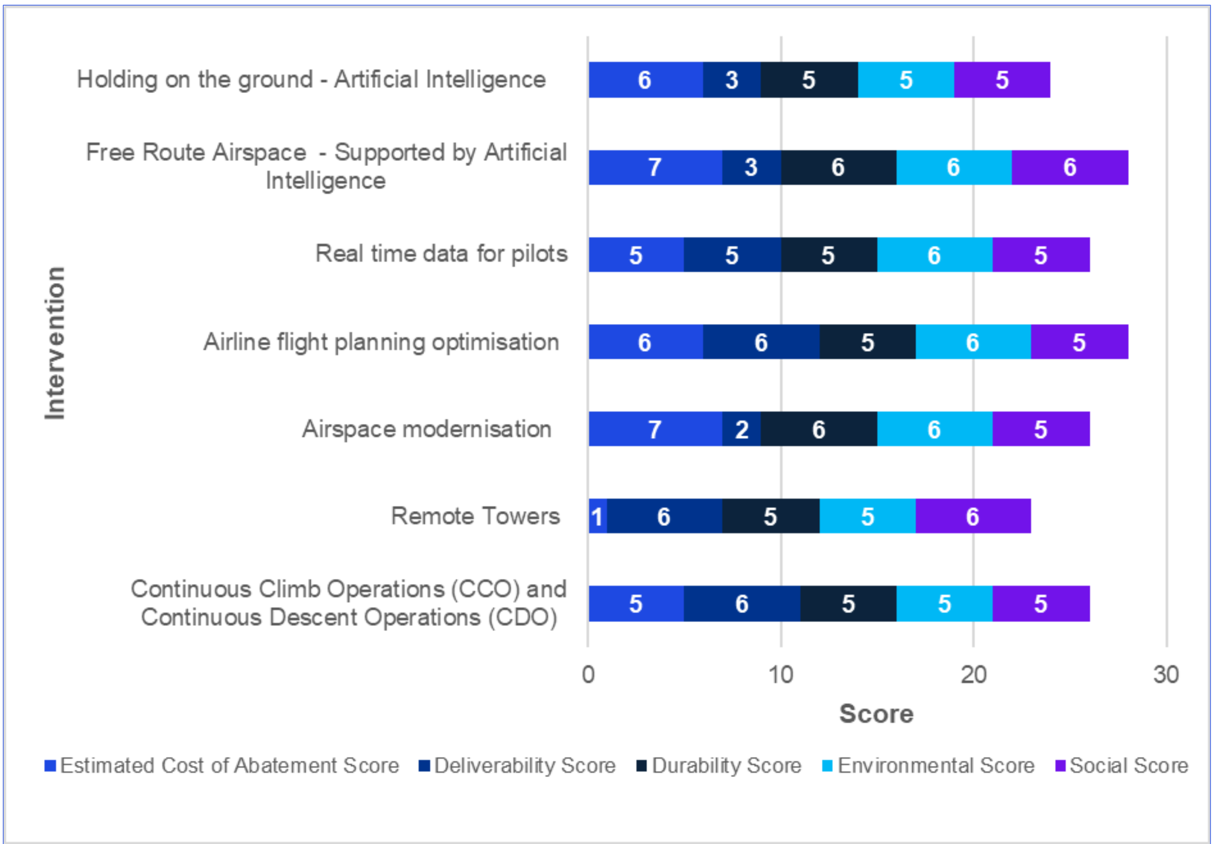

Figure 8: MCA breakdown for airspace

Each impact criterium is assessed on a score of 1-7. The score given is shown in each box for each criterium

Some airspace interventions were identified as important interventions, with airline flight optimisation, free route airspace, real time data for pilots and CDO & CCO all scoring highly.

Like the aircraft design and operation interventions, three of the four highest scoring interventions also scored highly on deliverability. With high estimated cost of abatement scores and high deliverability these should be considered priority near-term interventions.

Free route airspace, however, was only given a score of 3 but its higher rating across all other categories presented it as the fifth most important intervention, with expected UK wide implementation point between 2030 and 2040. This demonstrates that, whilst near term interventions are generally the priority for the industry looking to deliver operational efficiencies, there is still an understanding that for enhanced efficiencies effort and investment still needs to be towards these impactful mid-term opportunities.

Remote towers scored poorly on estimated cost of abatement. Whilst Remote Towers have high deliverability and other impacts, their potential carbon abatement is lower than many of the other interventions, as it is solely linked to potential future sharing of towers or increasing efficiencies within the tower environment, a very small component of aviation emissions.

4.2.1.3 MCA results for airports

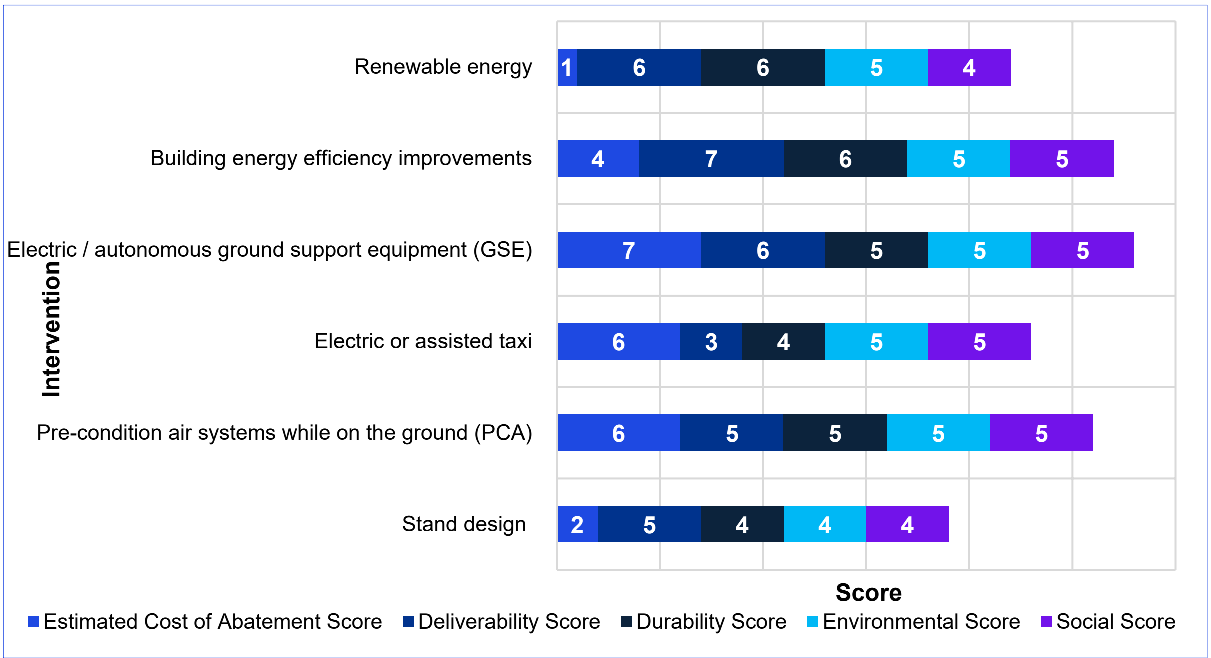

Figure 9: MCA breakdown for airports

Each impact criterium is assessed on a score of 1-7. The score given is shown in each box for each criterium.

Most of the airport interventions, except for electric taxiing, scored highly on deliverability. On ground interventions (be they related to running an airport or ground operations) are easier to implement, due to fewer challenges with new technologies, such as the need for significant increase in energy density. The cost of abatement scores for electric ground equipment (GSE, PCA and electric taxi scores) were also high due to the relatively low cost of these interventions. It should be noted however that each of these interventions only impact efficiencies during ground-based operations, and so have a small overall carbon impact, when viewed as a percentage of the overall UK aviation footprint.

GSE, PCA and buildings were the top three interventions within the airports category. Building energy efficiencies has a low estimated cost of abatement score, however the ease of implementation and high scores on all other criteria mean that it is relatively easy to implement in the near term. GSE scores highly across all categories, whilst PCA similarly is assessed with similar high scores. Both of these interventions therefore imply they are both easy, and beneficial to implement in the near term. There are however wider dependencies on each of these on the grid's decarbonisation (or renewable energy) and a need for the airports and airlines to collaborate on delivering these interventions, especially GSE and PCA.

Renewable energy scored poorly on the estimated cost of abatement due to the high implementation costs and decreasing levels of carbon abatement over time due to the decarbonisation of the grid. However, renewable energy will have a significant overall impact on operational efficiencies, whether it is sourced locally or directly from the grid, as the majority of airport infrastructure and equipment will require electricity to operate by 2050.

4.2.1.4 MCA results for training and support

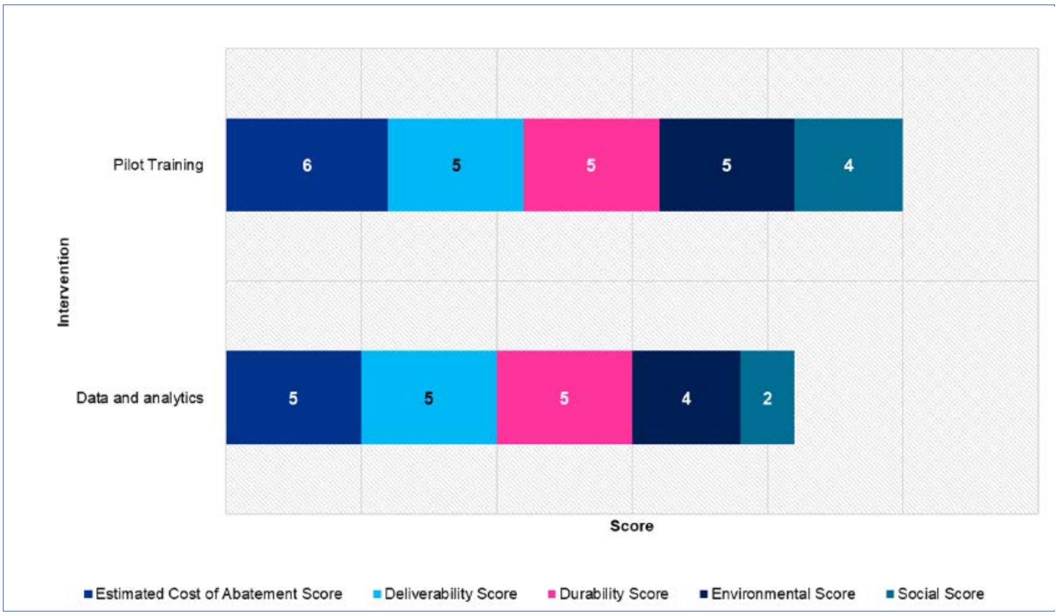

Figure 10: MCA breakdown for training and support

Each impact criterium is assessed on a score of 1-7. The score given is shown in each box for each criterium. The scores used for the MCA for cost of abatement are indicative, however costs and carbon abated could vary significantly depending on the training delivered.

Training and support interventions were ranked independently in the MCA although they can also be seen as enablers for many of the other interventions. They were considered to be low priority with training ranked 14 and data and analytics 23 out of 25. Data and Analytics scored low on social score due to risks and challenges around data sharing and data security.

4.3 Sensitivity analysis

To ensure the data used in the multi-criteria analysis is robust and supports the conclusions of this report, a sensitivity analysis was undertaken. The full details of this analysis are available in the appendix.

5 Conclusion and roadmap

5.1 Summary

This document has provided the outputs from a literature review and associated stakeholder engagement which sought to identify practices and opportunities which have the potential to minimise emissions from aviation operations and assess the feasibility and readiness of these for implementation across the sector.

A shortlist of twenty-five interventions have been identified and prioritised using a multi-criteria analysis (MCA). The outputs of this MCA should be further analysed to support actors in the industry and government, informing decision-making on policy design and delivery priorities.

Following the MCA, twenty-three of the twenty-five interventions were considered as viable interventions. Many of these interventions are already being implemented by the industry, although there is potential to accelerate their implementation through prioritised funding, collaboration among stakeholders and ensuring a systems-level approach to these solutions – these include aerodynamic improvements, lightweight composite material and stabilised approach criteria and energy efficiency for airport buildings. Other interventions, such as electric and hydrogen propulsion and airspace modernisation, despite being of a low technology (or systems) readiness level, are already in various stages of research and development. It should be noted, however that many of the cost inputs used are inherently uncertain. Whilst they were necessary for this research some of the findings may need to be approached with caution due to the lack of information availability. The outcome of this approach was a ranked, rather than quantified list of interventions.

The research found that airlines, airports and ANSPs are already investigating and exploiting the known and viable means of reducing emissions. The research did not find any new viable interventions that airline operations organisations (airlines, airports, aircraft manufacturers and ANS) ar en't already a ar e of and e ploring to differing degrees. At this stage, the research recommendations centre around accelerating the implementation of known interventions rather than considering additional solutions. That is not to say that additional interventions may not be identified in the future, but none were defined by this research.

The potential interventions are at varying levels of readiness for implementation. There remain, for those at a low technology or systems readiness level, outstanding development needs that will need to be addressed before they can progress to commercial implementation. The needs identified include pathways to standardisation of technical solutions, the need for pilot projects, and mechanisms to make solutions commercially viable. Pilot projects are needed to demonstrate the viability of some technologies and solutions which are near-ready for commercial use, including low-carbon or electric ground equipment, and its associated infrastructure.

5.2 Roadmap

The roadmap shown in Figure 11 is an overview of the industry stakeholders and the corresponding operational efficiencies that they have the agency to accelerate to achieve the goals for aviation sector decarbonisation. The size of each circle represents the potential carbon abatement of that intervention (on a 1-7 scale, with 1 being the lowest and 7 the highest), and therefore the potential impact against the decarbonisation metric. The number within each circle shows the MCA rank for that intervention, therefore considering the cost of abatement, deliverability, durability, social and wider environmental impact. Each intervention is plotted against both time and the part of the industry involved in delivery. The roadmap therefore describes when interventions should deliver an efficiency impact, how much that impact is, who should be delivering them and their priority. Timelines should be read as indicative points in time where this acceleration could be achieved, with operational efficiencies evolving with technology over time.

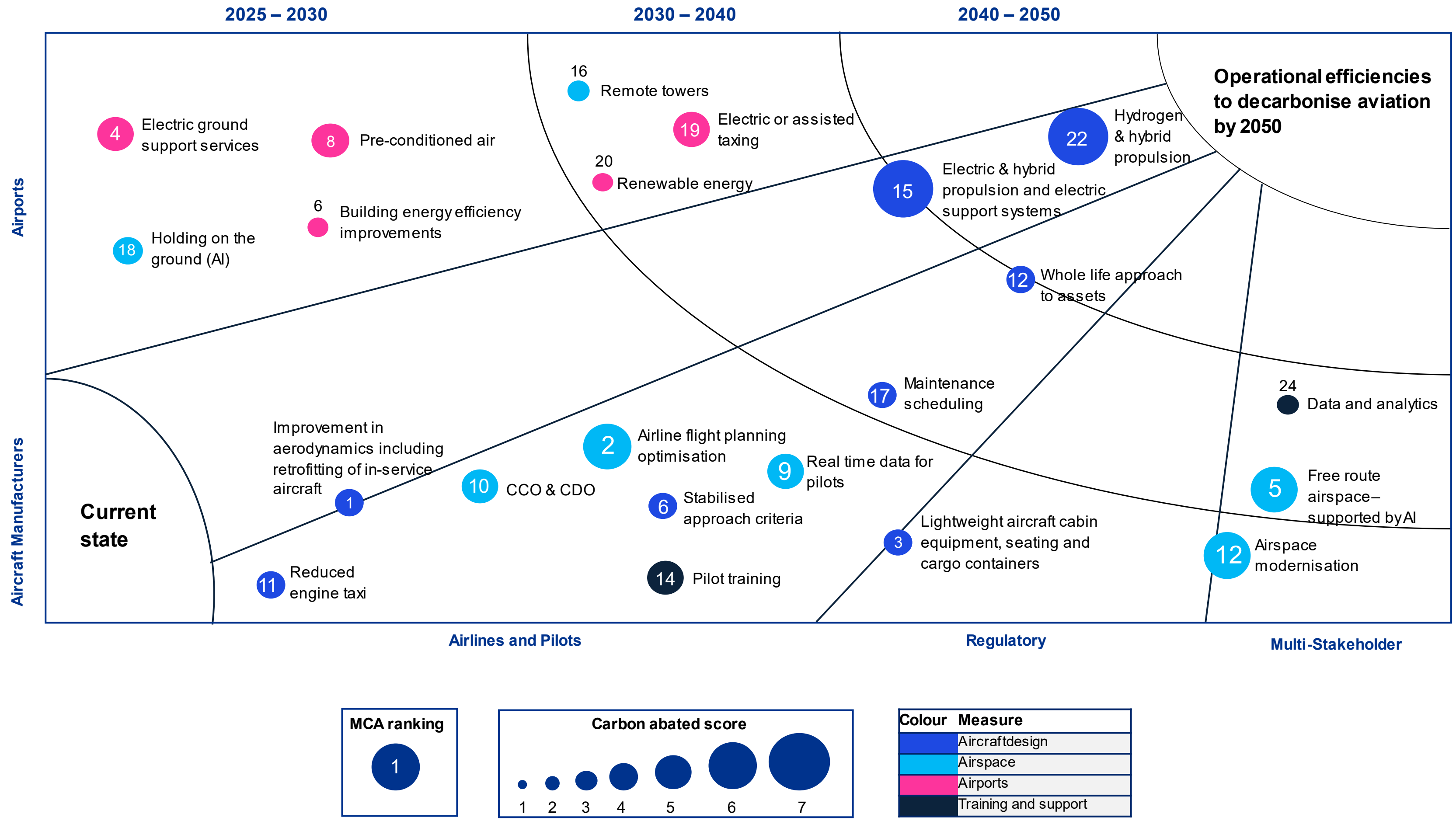

Figure 11: Roadmap

5.3 Priority interventions

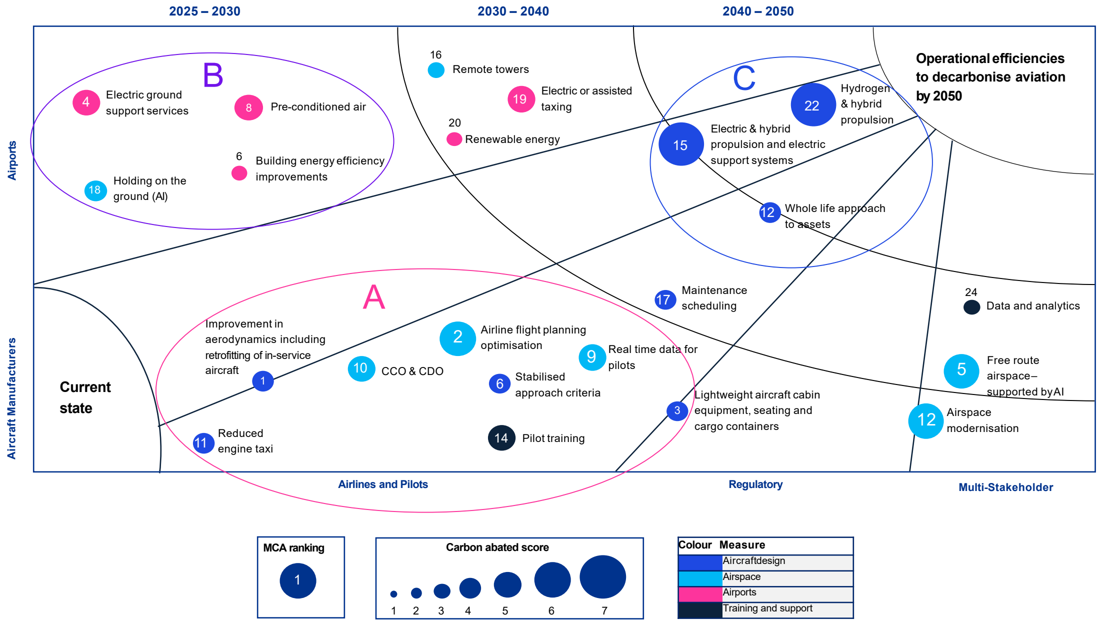

Figure 12: Priority interventions

As identified during the analysis, there is no silver bullet to decarbonising aviation operations in the UK, more so that a combination of many "smaller" interventions can aggregate to have a large impact on carbon emissions – this is demonstrated by the majority of interventions deliverable by 2030 having a relatively low carbon abatement. Many of these interventions are being delivered today; however, activities need to focus on their acceleration.

Further considering who should implement such interventions highlights three key areas, as shown in Figure 12.

Group A (pink): Interventions related to pilots and airlines

All of the interventions (with the exception of pilot training) in this group were ranked within the top ten priority actions by the MCA, and therefore through the analysis perceived as key interventions. These should be prioritised by airlines, pilots and supporting actors (manufacturers and regulators) to either accelerate, or further explore to implement for impact on operational efficiencies. Whilst pilot training ranked less well on the MCA, almost all these interventions require pilot training and acceptance to deliver their efficiencies and so should be delivered alongside those interventions.

Current actions being delivered by some pilots and airline groups, which could be accelerated by consistent prioritisation and application are:

- Stabilised approach criteria
- Airline flight planning optimisation
- CCO and CDO.

Two interventions related to aircraft efficiency (improvements in aerodynamics and lightweight aircraft cabin equipment) are also being implemented across many airlines.

Potential actions include:

- Developing and piloting performance indicators (in a unified framework) that measure the efficiency of airport and aircraft operations in a comprehensive, system-wide manner, and collaborating with government and industry partners to integrate these efficiency metrics into existing reporting and operational practices.
- Consulting with and obtaining agreement from chief pilots of UK airlines on prioritisation of CCO, CDO and reduced engine taxi, allowing for a consistent approach to operation which does not penalise any operator.
- Giving consideration to changing the tax-free status of aviation fuel, to further incentivise airlines to cut fuel expenditure and prioritise measures which save fuel.

Group B (purple): Interventions related to airports

Similarly, all of the interventions in this group scored in the top ten priority actions by the MCA. Most of these interventions will have a lower absolute efficiency impact to other interventions, as they are solely related to airport buildings and ground operations, but the relative ease and cost of implementation makes these attractive interventions for near term impacts. hils t airports ma e up a small percentage of the UK’s overall aviation carbon footprint, there still exists a good opportunity to accelerate decarbonisation.

A series of considerations for the government and wider aviation sector to consider were identified to accelerate the delivery of the interventions within groups A and B of the roadmap:

- Encouraging cross-sector collaboration between airports, air traffic management, & technology providers to test and evaluate energy reduction initiatives in real-world conditions and potentially support R&D to assess the scalability of energy-saving initiatives and develop standardised metrics to evaluate their performance.
- Reviewing the current regulatory model for CAA regulated airports to allow for greater investment flexibility and capacity for change control on the grounds of decarbonisation, reducing the risk that investment in decarbonisation is disincentivised due to fixed funding periods and opposition from airlines based on cost.
- Reviewing current airside operational fleets to identify and replace the largest emitting vehicles
- Consulting on and introducing airside low emission zones and minimum efficiency requirements for airside equipment.
- Consulting on and introducing a UK standard for PCA usage which penalises / discourages APU usage on stand and sets a minimum connection time from stand arrival.
- Adjusting UK planning laws regarding airspace change, to allow airspace changes to progress through planning faster or with a reduced consultation.
- Establishing financing facilities (e.g. an aviation green infrastructure investment fund) to allow access to aviation specific green finance to accelerate the introduction of low-carbon technology.

Group C (blue): Future higher impact interventions

Whilst the focus of the research was on near to mid-term interventions, complete efficiencies cannot be achieved without the future implementation of these three interventions.

Consideration should therefore not only be given now into developing these interventions further, but also how they can be adopted within the air operations environment.

A whole-life approach to assets, including second and third life, through circular economy approaches should also be considered in the nearer term, as some benefits could be gained as reuse and recycling of some components could be achieved sooner. Similarly, whilst full electric propulsion is not likely to be available for many years for larger and long-distance aircraft, the use of hybrid technologies and electric auxiliary systems could be implemented much sooner.

A series of considerations for the government and wider aviation sector to consider were identified to accelerate the delivery of the interventions within groups A and B of the roadmap:

- Facilitation of government-led collaborations with industry stakeholders, research institutions, and international partners to ensure alignment on ZEF technology development and deployment.
- Supporting stakeholders to invest in R&D to integrate emerging ZEF solutions into existing aviation systems, ensuring seamless deployment from prototype to commercial operation. This could include implementing trials and demonstration projects to test ZEF technologies at various stages of development, gathering data to inform the broader roadmap and ensure practical feasibility.
- Ensuring that energy infrastructure is in place to enable the transition to electric and hydrogen aircraft, investing in greater energy capacity and resilience.

Additional priorities

Further priority areas are those related to airspace modernisation and the enabling of free route airspace. Airspace modernisation is already a central strategy for the Department for Transport (DfT) and the Civil Aviation Authority (CAA), with the expectation that it will deliver significant operational efficiencies.

Another area of importance is the role of renewable energy in delivering efficiency savings. Whilst is scored poorly on the MCA (ranked twenty out of twenty-five), this is just a reflection on the long timescales and the high costs associated with implementation. However, for the aviation sector to achieve operational efficiency and ultimately reduce emissions to net zero, the transition to renewable energy sources, such as hydrogen or electric power, remains essential.

5.4 Research gaps and limitations

The analysis and prioritisation of the different interventions was impacted by limited information (especially relating to cost) within published data. To understand more fully which interventions offer the best value, additional research to understand the potential Marginal Abatement Cost Curve (MACC) of different interventions would help. This research should identify which offer the best value at the margin of delivering an additional tonne of CO_2 reduction. This research, however, ultimately relies on the availability of cost data within the existing literature.

Aviation organisations who will be involved in the delivery of these interventions are not, however, delaying effort into decarbonisation activities due to the lack of data. Better data could therefore be collected in parallel with implementation (or trials) in many cases, rather than waiting for additional evidence before proceeding.

6 Appendices

6.1 Appendix 1: Questionnaire

6.1.1 Full list of questions in the Questionnaire

Section 1: Personal Information
We will only collect and store your data for the purpose of this research and will only store the data for as long as needed to complete the project. Personal and commercial data will only be visible to the project team, consisting of researchers from City University of London, KPMG and Mott MacDonald and will be limited to that project team. *Any reporting on the outputs of the data will be anonymised and collated, and unless otherwise agreed (through follow up interviews) no personal data will be included in the final report.* *For further information on the project and purpose, please contact the Programme Lead Jenny Millard (jenny.millard@kpmg.co.uk) or the individual you received the request from.* *You have the right to withdraw your consent at any time, up to the point of reporting. Please email jenny.millard@kpmg.co.uk.* **Question 1:** What is your full name **Question 2:** What organisation do you work for **Question 3:** What is your job title **Question 4:** How many years of experience do you have in your field **Question 5:** Please include any references and links to your own works within the last 5 years (both published, in press, in preparation and in research phase) that may be relevant to aviation decarbonisation (this can be scholarly articles, interviews, conference papers, theses, publications, research papers, etc.)
Section 2: Focus Area
In October 2021 IATA members resolved to deliver net zero aviation by 2050. The ambition to deliver a net zero aviation sector by 2050 was also reflected in the 2022 setting by ICAO of a Long-Term Aspirational Goal for Net Zero Carbon Emissions. A number of industry and government documents frame the delivery of net zero aviation through the lens of multiple decarbonisation measures being pursued in parallel. There is also recognised uncertainty over the exact future potential of some measures and evidence gaps over the aviation sector's impact on the climate. The Department for Transport (DfT) is seeking independent advice on the key evidence gaps and research necessary to enable the aviation sector to deliver its net zero 2050 ambition. The following areas have been identified as priority measures: **Question 1:** As per the decarbonisation measures noted below, what areas do you have insights on? (Select all that apply) ☐ **System Efficiencies:** • Improving the efficiency of existing aviation systems, including airports, airspace, and aircraft. • Optimising flight paths and airspace management.

- Implementing new technologies for fuel efficiency and emissions reduction.
- Aircraft operational efficiencies (drag-reduction, fuel optimisation, non-conventional aircraft design, etc...)
- Modernising airport infrastructure and operations.

 Sustainable Aviation Fuels (SAF):

- Developing and scaling up the production of sustainable aviation fuels.
- Investing in research and development of new SAF technologies.
- Creating a supportive policy framework for the adoption of SAF.
- R&D involving SAFs, Biofuels, hybrid propulsion systems, alternative propulsion systems, etc...

 Zero Emission Flight:

- Developing and commercialising zero-emission aircraft technologies, such as electric and hydrogen-powered aircraft.
- Investing in research and development of new zero-emission aircraft technologies.
- Creating a supportive policy framework for the adoption of zero-emission aircraft.

 Markets and Removals:

- Developing and implementing effective carbon markets for aviation.
- Investing in greenhouse gas removal technologies to offset residual emissions.
- Exploring innovative financing mechanisms for carbon reduction projects.

 Influencing Consumers:

- Raising awareness of sustainable aviation options among consumers.
- Providing consumers with information and tools to make informed choices about their travel.
- Encouraging the adoption of sustainable aviation practices by consumers.
- Addressing consumer incentives

 Addressing Non-CO2 Impacts:

- Researching and understanding the non-CO2 impacts of aviation, such as noise and contrails.
- Developing and implementing mitigation strategies for non-CO2 impacts.

Section 3: Operational Efficiencies

Operational efficiencies refer to improving the efficiency of our existing aviation system, including airports, airspace, and the aircraft we use. This approach focuses on optimising existing technologies and practices to reduce emissions and improve overall sustainability.

This section of the questionnaire explores the potential of system efficiencies to contribute to aviation decarbonisation. We will investigate various aspects, including:

- **Optimising flight paths and airspace management:** This involves finding the most efficient routes for aircraft to fly, reducing fuel consumption and emissions.
- **Implementing new technologies for fuel efficiency and emissions reduction:** This includes exploring and adopting new technologies that can improve the efficiency of aircraft engines and operations.
- **Aircraft operational efficiencies:** This encompasses various strategies to reduce fuel consumption during flight, such as drag reduction, fuel optimisation, and exploring non-conventional aircraft designs.

- **Airport efficiency:** This includes measures such as optimising ground handling procedures, reducing taxi times, and improving energy efficiency in airport facilities.

Operational efficiencies are considered a crucial foundation for achieving significant emission reductions in the short to medium term. They provide a more efficient environment for the development and implementation of future low and zero-emission technologies. By continuously improving the efficiency of our aviation system, we can significantly reduce emissions while paving the way for a more sustainable future for aviation.

Part A of this section aims to identify the potential for implementing operational efficiency measures at airports and by aircraft in-flight to achieve accelerated carbon savings by 2040. **Part B** is focused on R&D to understand research gaps and opportunities within operational efficiency.

PART A: OPERATIONAL EFFICIENCIES

Question 1: How are you specifically contributing to the decarbonisation of aviation through operational efficiencies? Please highlight any existing strategies or sustainability plans you'd li e to flag.

Question 2: Which technologies are you currently investing in or researching to help achieve your decarbonisation goals?

Question 3: Which decarbonisation measures related operational efficiency are your main focus for delivering before 2030?

Question 4: Which decarbonisation measures related operational efficiency are your main focus for delivering before 2050?

Question 5: What are the main barriers to achieving greater operational efficiencies that improve decarbonisation performance in your sector?

☐ Regulatory constraints

☐ Financial limitations

☐ Technological gaps

☐ Lack of stakeholder engagement

☐ Other – If you face other barriers not listed above, please provide a brief explanation.

Question 6: le ase rate the follo ing sta tement "The current regulatory environment ma e s it easy to implement operating efficiencies" (= Strongly disagree; 7 = Strongly agree)

Question 7: Please explain your score

Importance of technology and potential for system efficiencies

Question 1: What role do you think technology will play in achieving your decarbonisation goals?

Question 2: What are the new technologies you believe to be crucial for the successful achievement of your decarbonisation goals? (Open-ended)

Question 3: Which areas of your business currently lack the technological solution to decarbonise?

Question 4: Do you believe that the technology gap can be successfully bridged in time for your decarbonisation goals? (1 = highly disagree; 7 = highly agree)

Question 11: Please rate the potential for improved operational efficiencies in the following areas before 2030 (1 = low; 7 = high):

☐ Airline flight operations

☐ Airline maintenance

- ☐ Airline flight planning
- ☐ Airport aircraft ground operations
- ☐ Airport support and maintenance operations
- ☐ Airport terminal operations
- ☐ Airport landside and accessibility operations
- ☐ Airport air traffic control
- ☐ Air traffic flow management
- ☐ Other – Please specify additional areas if applicable.

Engagement and collaboration

Question 1: How do you engage with other stakeholders (airlines, regulators, technology providers) to help drive operational changes that support carbon savings? (Open-ended)

Question 2: How would you rate the level of engagement with other stakeholders? (1 = not engaged at all; 10 = very engaged)

Question 3: Do you have suggestions on additional efforts you want to see in other stakeholders? (Open-ended)

Investments and Financial Infrastructure

Question 1: What investments or financial infrastructures are being implemented to fund the transition from current operations to decarbonisation practices? (Open-ended)

Question 2: Are there any funding gaps or financial barriers slowing down the transition to decarbonised aviation?

Question 3: So far, how much financial investment have you made in your decarbonisation strategy, or any other similar sustainability plan?

- ☐ <0.5% of revenue
- ☐ Between 0.5% and <1% of revenue
- ☐ Between 1% of revenue and <2%
- ☐ More than 2% of revenue
- ☐ N/A

Question 4: What are the main results or impacts from the investments? (i.e., what have you achieved?) (Open-ended)

Question 5: How willing are you to continue financing in these same areas, considering the past return? (1 = very unlikely; 7 = very likely)

PART B: R&D IN OPERATIONAL EFFICIENCIES

Current and recent projects (last 5 years)

Question 1: For your ongoing and recently completed projects related to operational efficiencies within the last 5 years, please complete the following details

Field	Information needed
Project name	
Source of funding	
Fund amount (project level)	
Partners	
Development state	Select from the following dropdown options: • Concept/ early stage

	• Proof of concept • Prototype • Pilot testing • Near commercialisation • Deployed in market • Academic research

Question 2: For any projects where you applied for funding but were unsuccessful, or applications here y ou're a ait ing feedbac please provide the follo i ng details:

Field	Information needed
Project name	
Source of funding	
Requested funding amount (project level)	
Proposed partners	
Status	Select from the following dropdown options: • Lost • Awaiting outcome
Feedback received	Select from the following dropdown options: • Not relevant to the call • Budget • Approach • Not innovate enough • Other (open text)

Exploring research gaps in systems efficiencies

Question 3: What research areas within operational efficiencies do you believe would be beneficial to explore further?

Question 4: What is preventing you, or the industry from exploring these areas? (e.g. funding, applicable existing research, lack of industry priority etc.)

Question 5: Looking beyond 2030, what future research priorities in operational efficiencies do you think should be given prominence?

Current status of R&D

Question 6: Which areas of operational efficiencies do you feel are currently prioritised within the industry and what stage of development are they? Please indicate the stage of development for each. (E.g. concept/early stage, near commercialisation etc.)

Question 7: In your opinion, who should hold primary responsibility for conducting research and developing solutions to decarbonise aviation? Please select all that apply.

☐ Airlines

☐ Airports

☐ Aircraft manufacturers

☐ Aviation regulatory bodies

☐ Research institutions/universities

- ☐ Government (national and local)
- ☐ Private research organisations and consultancies
- ☐ Other – Please specify.

Question 8: What new findings, evidence, or methodologies have emerged that could lead to unrealised carbon savings in aviation? Please provide details.

Challenges in implementing R&D

Question 9: Please rate the significance of the following challenges for implementing R&D in operational efficiencies in your sector:

(1 = insignificant; 7 = very significant)

- ☐ Regulatory constraints
- ☐ Financial limitations
- ☐ Technological gaps
- ☐ Lack of stakeholder engagement
- ☐ Other – If you face other barriers not listed above, please provide a brief explanation.

Question 10: What additional support, tools or resources do you believe would help overcome the barriers you face in advancing operational efficiency in your sector?

6.1.2 Questionnaire outputs

No of Responses: 44

Respondents to the questionnaire included experts across the industry value chain and academia, below is a summary of the types of organisations that employ questionnaire respondents.

University/Academia	10
Airline/Pilots Association	9
Consultancy/NGO	7
Airport/Airport Operator	4
Fuel producer	4
Government Agency/Multilateral agency	5
OEM	3
Others	2

The following were the responses to the question "As per the decarbonisation measures noted below, what areas do you have insights on?" (one respondent can provide insights in multiple themes)

Market and Removals	Operational Efficiencies	Sustainable Aviation Fuels	Zero Emission Flights	No response
10	31	27	21	1

6.1.3 Summary of key themes from questionnaire responses

The following summarises some of the key thematic findings from the questionnaire, highlighting responses from various participating organisations.

Airspace/Air Traffic Management

Airlines	**Routing, scheduling, and descent approaches:** Most airlines said they are researching various aspects of in-flight operations to achieve greater operational efficiencies such as continuous descent approaches, optimised operational flight plans and shortening flight paths. **Engagement with NATS:** A few airlines mentioned that they engage regularly with NATS on route optimisation techniques.
Airports / airport operators	**Landing and take-off cycle**: Only one respondent from the airports group mentioned they are researching optimisation techniques for landing and take-off cycles through techniques such as PBN, NADP1, NADP2, Steeper approach, etc.
Consultancy / NGOs	**Inefficiencies in Air Traffic Management (ATM):** A sole respondent from the group mentioned about significant inefficiencies stating "There are still a lot of inefficiencies When n it comes to air traffic management. Emissions are also poorly priced, giving airlines still not enough financial incentive to choose the most climate optimised flight path".
Government agency / Multilaterals	**Free routing/airspace:** A sole respondent stated about researching free routes to achieve operational efficiencies in airspace operations.
OEM	**Collaboration with airlines:** A sole respondent from the group mentioned collaborating with airlines to identify key opportunities in airspace modernisation.
Other	**Free route space:** Only one respondent, an ANSP (NATS) mentioned they are actively working to improve the operational efficiency of air traffic, primarily through airspace modernisation, including the delivery of free route airspace. **Arrival and separation techniques, queue management**: The ANSP (NATS) also mentioned about implementing advanced arrival separation techniques, improvement of queue management to reduce low level holding, and support of our customers. In addition, it mentioned about achieving significant improvements to queue management prior to 2030.

Airport ground operations/Passenger Operations

Airports / airport operators	**Taxiing operations:** Most respondents mentioned they are undertaking initiatives to reduce taxi out times such as the A-CDM initiative and exploring use of fixed ground power units and preconditioned air systems. **Airport heating/cooling requirements**: A sole respondent mentioned they are looking at technologies and pathways to cease burning of fossil fuels for airport and vehicle heating required for daily operations

Aircraft engine/designs for fuel efficiency

University / Academia	**Aircraft Engine and Design:** A few respondents from the group mentioned about various technologies they are researching to improve engine efficiency, aircraft design. A sole respondent mentioned about collaborating with OEMs for developing innovative designs for fuel efficient aircrafts. Some key technologies mentioned were high-aspect ratio wing technologies.
OEM	**Aircraft Engine and Design:** Most respondents stated that they are researching various aspects of aircraft and engine designs with the objective of achieving operational efficiencies. Some key technologies mentioned were gas turbine efficiency improvements and inflight refuelling technology

Implementation of Robotics and AI for achieving operational efficiency

Airlines	**Robotics and AI:** A few airlines have indicated their interest in exploring AI technologies to enhance operational efficiencies. Notably, key technologies mentioned include the integration of AI in flight scheduling for real-time optimisation and the use of digital twin technology.
Airports / airport operators	**Implementation of AI:** A sole respondent stated further research is required for implementation of AI in airport operations.

Barriers to achieving operational efficiencies for airspace operations

Airlines	**ANSP Coordination**: A sole respondent stated that airspace design and coordination is a key barrier for achieving airspace modernisation. **European Sky:** A sole respondent stated that “officialisation of a Single European Sky” is required for achieving greater efficiencies in airspace operations.
Other	**ANSP Operations:** A sole respondent stated that “The business struggles with a lack of SME availability (particularly as far as controllers are concerned) that can be released from Operations to support development and validation activities. As ATCO training takes a considerable time, this is not expected to change for some time, even if financial limitations were eased”

Hydrogen propulsion and allied infrastructure

Consultancy / NGOs	**Alternative fuels**: A few respondents stated that further research is required on Hydrogen storage (on aircraft, and at the airport) and hydrogen refuelling technologies for implementation of zero emission flights.
University / Academia	**Hydrogen Research Hub**: A sole respondent stated that it is developing a liquid hydrogen research hub focused on Hydrogen production, liquefaction, storage, distribution, refuelling, ground operations for the aviation sector.
OEM	**Commercialisation**: A sole respondent stated that it plans to commercialise hydrogen powered aircrafts; however, it has cited technological gaps as a reason for widespread commercialisation.
Other	**Hydrogen and hybrid systems:** A sole respondent, an insurance provider, stated that it is collaborating with stakeholders to develop insurance products for hydrogen and hybrid system, associated infrastructure for hydrogen production to help the sector become a key enabler for decarbonisation initiatives in aviation.

6.2 Appendix 2: Sensitivity Analysis

Sensitivity analysis is a critical component in evaluating the robustness of rankings, especially when considering varying stakeholder preferences and changes in key assumptions. This process involves systematically altering the scores or weights assigned to different criteria to observe how these changes impact the overall rankings.

Because the ranking is calculated based on a score and a weight, we tested the sensitivity of the ranking for both changes in scores and weights in turn.

6.2.1 Sensitivity test on scores

Due to the lack of quantitative data publicly available to inform the work there a level of uncertainty exists regarding the scores assigned, with professional judgement being used throughout the study. Due to the required judgement it's possible that scores could be out by a factor of one, or more. Based on past experience, one was chosen as the basis for the sensitivity test as this was the expected to be the most likely factor the analysis was out by. This was considered to be sufficient, given that this is an initial high level ranking exercise with subsequent analysis being required to produce an investment roadmap.

6.2.1.1 Changing all scores by a factor of one at the same time

The first sensitivity test undertaken was to understand the impact if a single scoring criteria was increased by one for each intervention and is shown in Table 30. The scores on the left of the table show the original baseline scores for each criterium, adjusted by weight, with the baseline rating provided in the rating column. The score for one intervention was then increased by 1. For example, for an intervention the original score for deliverability might be 7 out of 10. Deliverability has a weight of 15.7% and therefore the weighted score is 1.01. Adding one to the score, 7 would become 8 and the weighted score will become 1.26. This was repeated taking each of the scoring criteria in turn. The right-hand columns show the ranking of the intervention if all the scores of that criteria are increased by one. It is important to remember that the outcome of the MCA is the ranking of the list of interventions, therefore it is important to understand the impact of the sensitivity test on the baseline ranking.

Ranking is shown as the outcome, as the overall assessment is whether the ranking will change if the scores increase by one. The analysis shows that there is some sensitivity of the ranking of electric or assisted taxi and renewable energy interventions which are ranked 19th and 20th. According to this test, the order of the other interventions is relatively robust to small changes in scores occurring across the criteria and it is unlikely that there would be large changes in the scores at the time of undertaking the MCA.

Table 31: Sensitivity test – changing scores

ID	Intervention	ECA	Deliverability	Durability	Enviro. Impact	Social Impact	Total Score	Original rating	NEW RATING with changes to respective criteria				
									ECA	Deliverability	Durability	Enviro. impact	Social
1.2	Electric/hybrid propulsion	0.8	0.44	0.8	1.68	1.08	4.8	16	16	16	16	16	16
1.3	Hydrogen propulsion	0.8	0.44	0.8	1.4	0.9	4.34	22	22	22	22	22	22
1.4	Lightweight cabin equipment	1.12	1.54	0.64	1.4	0.9	5.6	3	3	3	3	3	3
1.5	Non-conventional aircraft configurations	0.48	0.22	0.96	1.68	1.08	4.42	21	21	21	21	21	21
1.6	Stabilised approach criteria	0.64	1.54	0.96	1.4	0.9	5.44	6	6	6	6	6	6
1.7	Whole life approach to asset	0.96	0.88	0.96	1.4	0.9	5.1	12	12	12	12	12	12
1.8	Maintenance scheduling	0.32	1.32	0.8	1.4	0.9	4.74	17	17	17	17	17	17
1.9	Reduced engine taxi	0.48	1.54	0.8	1.4	0.9	5.12	11	11	11	11	11	11
2.1	CDO & CCO	0.8	1.32	0.8	1.4	0.9	5.22	9	9	9	9	9	9
2.2	Remote towers	0.32	1.32	0.8	1.4	1.08	4.92	15	15	15	15	15	15
2.3	Airspace modernisation	1.12	0.44	0.96	1.68	0.9	5.1	12	12	12	12	12	12
2.4	Airline flight planning optimisation	0.96	1.32	0.8	1.68	0.9	5.66	2	2	2	2	2	2
2.5	Real-time data for pilots	0.8	1.10	0.8	1.68	0.9	5.28	8	8	8	8	8	8
2.6	Free route airspace	1.12	0.66	0.96	1.68	1.08	5.5	5	5	5	5	5	5
2.7	Holding on the ground: Artificial Intelligence (AI)	0.96	0.66	0.8	1.4	0.9	4.72	18	18	18	18	18	18
2.8	In-flight refuelling	1.12	0.22	0.64	0.84	0.36	3.18	25	25	25	25	25	25
3.1	Stand design	0.32	1.10	0.64	1.12	0.72	3.9	24	24	24	24	24	24

ID	Intervention	ECA	Deliverability	Durability	Enviro. Impact	Social Impact	Total Score	Original rating	NEW RATING with changes to respective criria				
									ECA	Deliverability	Durability	Enviro. impact	Social
3.2	Pre-condition air systems while on the ground (PCA)	0.96	1.10	0.8	1.4	0.9	5.16	10	10	10	10	10	10
3.3	Electric or assisted taxi	0.96	0.66	0.64	1.4	0.9	4.56	19	19	**20**	19	19	19
3.4	Electric ground support equipment (GSE)	1.12	1.32	0.8	1.4	0.9	5.54	4	4	4	4	4	4
3.5	Building energy efficiency improvements	0.64	1.54	0.96	1.4	0.9	5.44	6	6	6	6	6	6
3.6	Renewable energy	0.16	1.32	0.96	1.4	0.72	4.56	20	20	**19**	20	**19**	**19**
4.1	Data and analytics	0.8	1.10	0.8	1.12	0.36	4.18	23	23	23	23	23	23
4.2	Pilot Training	0.96	1.10	0.8	1.4	0.72	4.98	14	14	14	14	14	14

6.2.1.2 Changing scores individually

The analysis undertaken in section considered the impact if all of the scores in a criterium were out by 1, however it is also important to consider the impact if only one of the scores was out by 1. A sensitivity test was therefore carried out on the 25 interventions to see how much each intervention's score must decrease before the ranking changes. The 25 interventions are categorised into three groups according to the estimated timeline of realisation to ascertain if the ranking would impact the outcomes of the study. The three groupings are short term, medium term and long term. The output of each sensitivity analysis is shown in Table 32.

Short term group:

These are interventions which can be implemented within the timeframe of 1 to 5 years. The interventions identified as short term are varied in their rank position including the highest ranked (position number 1) and the near-lowest ranked (position number 24).

A decrease of one point in the intervention score under the five criteria leads to a change in ranking position by up to 5 places. The interventions are most sensitive to the environmental impact criteria which has both the highest criteria weight and low variability in the scores for the environmental criteria within this group.

Looking at each criterion in turn:

- **Improvement in aerodynamics/retrofit** intervention requires a decrease in intervention score of at least two points under the different criteria for a change in ranking position from first to at worst fourth. This therefore has low sensitivity as it still remains relatively high in the rankings.
- **CDO and CCO** is most sensitive to environmental impact, dropping four position places from tenth to fourteenth, whilst for the other criteria its rank changes to thirteenth.
- **Stabilised approach** is also sensitive to environmental impact as a change of one point in this intervention score changes its rank by three places to its worst position of ninth.
- **Reduced Engine taxi** exhibits sensitivity to deliverability and environmental impact criteria where a one-point decrease in intervention score changes its rank position from eleventh to fifteenth.
- **Optimised flight planning** ranks second. A one-point change in intervention score under both the estimated cost of abatement and durability criteria changes it to fourth.
- **Free route airspace changes** the rank from fifth to either seventh under the least sensitive or eight in the most sensitive criteria.

Medium term group:

This group comprises interventions with a likely implementation point of five to fifteen years away. For the estimated cost of abatement criteria, a change of one point reduction in the intervention score changes the rank position by at least one place.

The electric/hybrid propulsion intervention, which currently ranks fifteenth, has large sensitivity to environmental impact and social impact where the rank position changes to twentieth based on a score change of 1.

Long term group:

This group comprises interventions likely to have an implementation point more than fifteen years away. These interventions include hydrogen propulsion, whole life approach to asset and in-flight refuelling. A single score change for almost all interventions in this group causes a change in the rankings from between 1 and 3 places (except for in-flight refuelling which remains at 25). Whilst this does demonstrate sensitivities, hydrogen propulsion remains between 21st and 23rd place.

Table 32: Ranked Interventions by timeline

Ranked interventions by timeline		Baseline	ECA		Deliverability		Durability		Environmental		Social	
Timeline	**Intervention**	Original ranking	*Decrease to Intervention Score*	**New ranking**	*Decrease to Intervention Score*	**New ranking**	Decrease to Intervention Score	**New ranking**	*Decrease to Intervention Score*	**New ranking**	*Decrease to Intervention Score*	**New ranking**
Short (1-5 years)	Improvement in aerodynamics/ retrofit	1	*from 5 to 2*	**3**	*From 7 to 5*	**2**	From 6 to 3	**3**	*From 6 to 4*	**4**	*Reduced to 3*	**4**
	Lightweight cabin equipment	3	*from 7 to 6*	**5**	*from 7 to 6*	**7**	from 4 to 3	**5**	*from 5 to 4*	**7**	*from 5 to 4*	**7**
	Stabilised approach criteria	6	*from 4 to 3*	**8**	*from 7 to 6*	**8**	from 6 to 5	**7**	*from 5 to 4*	**9**	*from 5 to 4*	**8**
	Maintenance scheduling	17	*from 2 to 1*	**18**	*from 6 to 5*	**20**	from 5 to 4	**18**	*from 5 to 4*	**20**	*from 5 to 4*	**18**
	Reduced engine taxi	11	*from 3 to 2*	**14**	*from 7 to 6*	**15**	from 5 to 4	**14**	*from 5 to 4*	**15**	*from 5 to 4*	**14**
	CDO & CCO (Continuous Descent Operations & Continuous Climb Operations)	10	*from 5 to 4*	**13**	*from 6 to 5*	**13**	from 5 to 4	**13**	*from 5 to 4*	**14**	*from 5 to 4*	**13**
	Remote Towers	15	*from 2 to 1*	**16**	*from 6 to 5*	**18**	from 5 to 4	**16**	*from 5 to 4*	**18**	*from 6 to 5*	**16**

Ranked interventions by timeline		Baseline	ECA		Deliverability		Durability		Environmental		Social	
	Airline Flight Planning Optimisation	2	*from 6 to 5*	**4**	*from 6 to 5*	**5**	from 5 to 4	**4**	*from 6 to 5*	**7**	*from 5 to 4*	**5**
	Real-time data for pilots	9	*from 5 to 4*	**10**	*from 5 to 4*	**13**	from 5 to 4	**10**	*from 6 to 5*	**13**	*from 5 to 4*	**11**
	Free route airspace	5	*from 7 to 6*	**7**	*from 3 to 2*	**8**	from 6 to 5	**7**	*from 6 to 5*	**8**	*from 6 to 5*	**7**
	Holding on the ground: Artificial Intelligence (AI)	18	*from 6 to 4*	**21**	*from 3 to 2*	**20**	from 5 to 3	**21**	*from 5 to 4*	**20**	*from 5 to 4*	**20**
	Stand design	23	*from 2 to 1*	**24**	*from 5 to 1*	**25**	from 1 to 1	**24**	*from 4 to 1*	**25**	*from 4 to 1*	**24**
	Pre-condition air systems while on the ground (PCA)	8	*from 6 to 5*	**13**	*from 5 to 4*	**14**	from 5 to 4	**13**	*from 5 to 4*	**15**	*from 5 to 4*	**13**
	Electric ground support equipment (GSE)	4	*from 7 to 6*	**7**	*from 6 to 5*	**7**	from 5 to 4	**7**	*from 5 to 4*	**8**	*from 5 to 4*	**7**
	Building energy efficiency improvements	6	*from 4 to 3*	**8**	*from 7 to 6*	**8**	from 6 to 5	**7**	*from 5 to 4*	**9**	*from 5 to 4*	**8**
	Data and analytics	24	*from 5 to 2*	**24**	*from 5 to 3*	**24**	from 5 to 3	**24**	*from 4 to 3*	**24**	*from 2 to 1*	**23**
	Pilot Training	14	*from 6 to 5*	**15**	*from 5 to 4*	**16**	from 5 to 4	**15**	*from 5 to 4*	**18**	*from 4 to 3*	**15**

Ranked interventions by timeline		Baseline	ECA		Deliverability		Durability		Environmental		Social	
Medium (5-15 years)	Electric/hybrid propulsion	16	*from 5 to 4*	**18**	*from 2 to 1*	**18**	from 5 to 4	**18**	*from 6 to 5*	**20**	*from 6 to 5*	**20**
	Non-conventional aircraft configurations	21	*from 3 to 2*	**22**	*None*	**21**	from 6 to 5	**22**	*from 6 to 5*	**23**	*from 6 to 5*	**22**
	Airspace modernisation	12	*from 7 to 6*	**14**	*from 2 to 1*	**15**	from 6 to 5	**14**	*from 6 to 5*	**15**	*from 5 to 4*	**15**
	Electric or assisted taxi	19	*from 6 to 5*	**21**	*from 3 to 2*	**21**	from 4 to 3	**21**	*from 5 to 4*	**22**	*from 5 to 4*	**23**
	Renewable energy	20	*from 1 to 1*	**20**	*from 6 to 5*	**21**	from 6 to 5	**21**	*from 5 to 4*	**22**	*from 4 to 3*	**21**
Long (15+ years)	Hydrogen propulsion	22	*from 5 to 4*	**23**	*from 2 to 1*	**22**	5 to 4	**23**	*5 to 4*	**23**	*5 to 4*	**23**
	Whole life approach to asset	12	*from 6 to 5*	**14**	*from 4 to 3*	**15**	from 5 to 4	**14**	*from 5 to 4*	**15**	*from 5 to 4*	**15**
	In-flight refuelling	25	*25*	**0**	*25*	**0**	25	**0**	*25*	**0**	*25*	**0**

6.2.2 Sensitivity test on weights

A sensitivity test on the weighting was also undertaken. Weighting has been used as there are different perceptions of importance of the criteria: Estimated Cost of Abatement, Deliverability, Durability, Environmental, Social.

The weights used in the baseline were an average between weights derived by stakeholders through one-to-one interviews (independent of each other) and weights derived by workshop (where discussion was had) as shown in Table 33.

Table 33: Weights derived by method of collection

	W(stakeholder)	W(workshop)	W(average)
ECA	**22.1%**	7.7%	14.9%
Deliverability	**29.5%**	15.7%	22.6%
Durability	**15.6%**	14.3%	14.9%
Environmental Impact	**23.0%**	34.8%	28.9%
Social Impact	**9.8%**	27.5%	18.7%

In this sensitivity test the average weights were exchanged with W(stakeholder) and W(workshop) to understand what differences in weight assumptions would do to the ranking.

Table 33**.** presents the baseline ranking alongside columns that depict the rankings following our sensitivity tests, which vary the weights. **W(stakeholder)** represents weights collected from individuals independently, without discussion. **W(workshop)** represents weights derived from group discussions during the workshop. For the baseline, the weights were averaged to mitigate personal biases and group think. This sensitivity test reveals the potential outcomes when either weighting scenario is applied.

The lowest and highest rankings observed among the sensitivity tests were then examined to understand the variance. Where the ranking exhibits high variance due to changes in weights (which are influenced by subjectivity), this sensitivity is highlighted.

Table 34: Sensitivity test – changing weights

ID	Intervention	Baseline	W(stakeholder)	W(workshop)	Top	Bottom	Average variance
1.1	Improvement in aerodynamics/retrofit	1	1	1	1	1	0
1.2	Electric/hybrid propulsion	16	21	13	21	13	8
1.3	Hydrogen propulsion	22	22	22	22	22	0
1.4	Lightweight cabin equipment	3	2	7	7	2	5
1.5	Non-conventional aircraft configurations	21	23	16	23	16	7
1.6	Stabilised approach criteria	6	5	4	6	4	2
1.7	Whole life approach to asset	12	13	15	15	12	3
1.8	Maintenance scheduling	17	16	17	17	16	1
1.9	Reduced engine taxi	11	11	11	11	11	0
2.1	CDO & CCO	9	8	12	12	8	4
2.2	Remote towers	15	15	9	15	9	6
2.3	Airspace modernisation	12	14	10	14	10	4
2.4	Airline flight planning optimisation	2	3	3	3	2	1
2.5	Real-time data for pilots	8	9	6	9	6	3
2.6	Free route airspace	5	7	2	7	2	5
2.7	Holding on the ground: Artificial Intelligence (AI)	18	17	19	19	17	2
2.8	In-flight refuelling	25	25	25	25	25	0
3.1	Stand design	24	24	23	24	23	1
3.2	Pre-condition air systems while on the ground (PCA)	10	10	14	14	10	4
3.3	Electric or assisted taxi	19	19	21	21	19	2
3.4	Electric ground support equipment (GSE)	4	4	8	8	4	4

ID	Intervention	Baseline	W(stakeholder)	W(workshop)	Top	Bottom	Average variance
3.5	Building energy efficiency improvements	6	5	4	6	4	2
3.6	Renewable energy	20	20	20	20	20	0
4.1	Data and analytics	23	18	24	24	18	6
4.2	Pilot Training	14	12	18	18	12	6

6.2.2.1 Conclusion of sensitivity test

Improvement in aerodynamics/retrofit (ranked 1), Hydrogen propulsion (ranked 22), Reduced engine taxi (ranked 11), In-flight refuelling (ranked 25) and Renewable energy (ranked 20) were not sensitive to changes in weights from the average weights to the stakeholder or workshop weights. This means we have good confidence that the ranking of these are appropriate despite changes in weighting assumptions.

The results, however, show significant variation of ranking for Electric/hybrid propulsion, non-conventional aircraft configurations, Remote towers, Data and analytics, Pilot training, Lightweight cabin equipment and Free route airspace as a result of changes in weights. The result is that the ranking of these particular interventions should be considered carefully, since they easily change based upon weight changes.

Some variance was found for the remaining interventions.

Weights are inherently subjective because they are developed by steering groups tasked with making judgments on the relative importance of various criteria. To mitigate bias, we used the average of two distinct weighting approaches: one derived from participants independently, without any discussion, and another derived from group discussions. This averaging method was intended to smooth out individual biases and groupthink.

However, our sensitivity tests have demonstrated that the criteria rankings are highly sensitive to the values assigned by those participating in the weighting exercise. This sensitivity indicates that the rankings can vary significantly based on the subjective inputs of the contributors.

Therefore, the conclusions of this report regarding the relative prioritisation of the interventions should be considered with the caveat that they are informed by the average weighting methodology used in this study. It is important to acknowledge that the prioritisation is influenced by the subjective nature of the weights assigned during the exercise. Consequently, the findings should be interpreted with an understanding of the potential variability introduced by the different weighting scenarios.

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