The viability of carbon capture at airports using innovative approaches

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Executive summary

- This report examines the feasibility and opportunities for carbon capture, use and storage (CCUS) at airports using innovative new technologies. CCUS provides a range of approaches that could help airports to move towards net zero greenhouse gas (GHG) emissions. CCUS technologies can be categorised into those that depend on engineering, and those that are nature-based. The feasibility and opportunities of both approaches were examined in the context of four case study airports, using GHG emissions data from 2019.

- An important first step for airports to reduce GHG emissions is to understand the extent of their Scope 1, 2 and 3 emissions. Scope 1 emissions are owned and directly controlled by airports, and Scope 2 relate to the emissions associated with electricity use on site. Scope 3 emissions relate to emissions from aircraft and from vehicle use by passengers, and for the four case study airports they are between 10 and 100 times greater than the Scope 1 and 2 emissions.

- Engineering-based CCUS methods include cryogenic separation, calcium looping combustion, solvent-based absorption, physical absorption, membrane separation, and direct air capture (DAC). Many of these techniques require high investments, a long-term commitment and leadership. Some of these approaches may be progressed by airports working with local power stations.

- Many nature-based solutions for carbon capture and storage are well-established with a high technology readiness level. Nature-based solutions can also bring co-benefits such as enhanced biodiversity and landscapes. However, the capacity to scale nature-based solutions within airport landholdings is typically limited, and co-operation with local government and other land owners is likely to be necessary.

- CCUS at airports should be considered as a part of carbon offset scheme and projects. The carbon credit could be awarded, like the Clean Development Mechanism (CDM) and Joint Implementation (JI), under the UNFCCC. This could help to facilitate the investment and finance to cover costs.

- The integration of Hydrogen production generated by renewable energy or low carbon power (Green Hydrogen), SAF production and DAC at airports may be a highly effective solution for improving sustainability.

- Achieving this transformation will require a large investment and long-term policy with strong leadership, which can be operated together with the hydrogen power generation or green fuel to supply aircraft power.

- As a part of the Net Zero 2050 roadmap, the carbon capture, usage and sequestration (CCUS) option should be included along with other energy policies for air transport.

Main Executive Summary

This report examines the feasibility and opportunities for CCUS at airports using innovative new technologies at the request of SITA. We reviewed and analysed the possible CCUS technologies and solutions by two options: (1) engineering and (2) nature-based solutions by examining four case study airports using the baseline of 2019.

Industrial initiatives to reduce greenhouse gas (GHG) emissions by promoting emissions management at airports have been taken by the Airports Council International (ACI) (2008, 2009). Establishing emissions inventories is an important step toward carbon reduction (Transportation Research Board (TRB), 2009; FAA, 2021).

There are various sources of emissions at an airport, ranging from electricity generation through to ground operations. Despite differences in air quality regulations between countries, airport operators are now recording and reporting their Scope 1, 2, or 3 emissions:

Scope 1 emissions come from sources that are owned and directly controlled by the airport. Scope 1 emissions are produced by fuel-powered vehicles owned and operated by the airport, together with stationary sources, for example, heating systems that burn fuel to service the airport. Other sources of Scope 1 emissions are from vehicles used to transport passengers and vehicles used for airport maintenance, airport-related maintenance activities, ground support equipment (GSE) for handling aircraft when they are on the ground, firefighting training and waste disposed of onsite through incineration or treatment (Airports Council International (ACI), 2009).

Scope 2 indirect emissions are those generated from the purchase of electricity to power the various airport facilities and infrastructure. Scope 3 emissions are a result of the activities that are performed by passengers and tenants at an airport. Such emissions include passenger surface access, water supply and wastewater, aircraft jet fuel, staff commute, and waste disposal.

The main emissions at airports belong to Scope 3 and are outside the direct control of the airports. Emissions from passenger surface access are the second largest emission source after aircraft emissions. Although this is not straightforward, the ACI has stated that it is possible that some emissions falling within Scope 3 could be influenced by airports. They play an important role in reducing emissions.

In addition, the boundary of the emission source is another issue, as an airport is a highly complex environment. Airport operators, together with the ACI's initiatives, have been working to reduce the emissions from airports since 2008. Their explicit policy is that airport operators and different airports will have different journeys to achieve the carbon reduction since each airport has distinctive characteristics and is regulated by different government policies.

ACI selected the year 2010 as a baseline according to the recommendation of ICPP. The baseline emissions for ACI member airports in 2010 was 18.6 million metric tonnes of CO_2, with 10.3% of emissions attributed to Scope 1 sources, and 89.7% of emissions from Scope 2 sources.

In general, the largest source of emissions is from purchased electricity generated off-site at airport (within Scopes 1 and 2). The emission reduction is based on the carbon intensity of the electricity grid and is not something that an airport operator can directly control. However, there is room where airport operators can make their own efforts to generate the electricity in a green way or offsetting the emissions at airport.

Here, we investigate the possible CCUS options at airport in this report. Four case airports were selected to investigate the baseline level of CO_2 emissions and the current reduction measures and identify the challenges for these airports. The following selection criteria were established:

(1) Airport traffic size (Traffic size (super large > 50 million(M) passengers per annum, large >30M, Mid > 5M, Small < 1M)
(2) ACI Carbon Accreditation certified airports or airports with established sustainable policy.
(3) Geographical location: UK, Asia, and the USA.

Four airports were selected: (1) Aberdeen Airport (ABZ, Scotland), (2) London Luton Airport (LTN, England), (3) Indira Gandhi International Airport (DEL, India), and San Francisco International Airport (SFO, USA). The year 2019 is adopted as the baseline for avoiding the significant traffic reduction by the COVID-19 in 2020 and onwards.

Engineering solutions

Six types of process methods were reviewed for engineering CCUS solutions: (1) Cryogenic separation, (2) Calcium looping (CaL) combustion, (3) Solvent based absorption, (4) Physical absorption, (5) Membrane separation, and (6) Direct Air Capture (DAC).

ABZ and SFO airports purchased energy from renewable energy sources to support energy use in airport operation (scope 2 CO_2 emission is completely mitigated). DEL started to use PV system to provide energy for airport to reduce CO_2 emission. All four airports reduced their energy consumption with more efficient monitoring of heating, ventilation, and cooling systems. In addition, case airports have considered the acquisition of low or zero emission vehicles and GSEs. The use of electric powered vehicles which are environmentally more favourable as they reduce vehicle emissions at an airport.

The challenges with the CO_2 capture from Scope 1 and 3 emissions are evident, particularly the capture of CO_2 directly emitted from the combustion of jet engines and fuels for central energy use such as diesel engine, which is widely used in DEL. The current CO_2 capture technologies can be applied to stationary power and heat generation but not possible to abate CO_2 emission from aircraft.

The case airports surveyed recorded CO_2 emissions in the range of 50 kilo tonnes (kT) CO_2 to 100 kT CO_2, emitted from various sources. This indicates the suitability of direct air capture of CO_2 in the airport. Converting CO_2 to jet fuel using renewable energy has been suggested and tested at pilot scale to demonstrate the economic viability of CO_2 utilisation, which provides a technologically feasible option for airport applications.

It could be difficult to capture the CO_2 from aircraft operation directly due to the size and operating conditions of an aircraft and the capture unit, however, if fuel combustion for heating is used on airports, then point-source CO_2 capture could be considered.

Based on the current technology demonstration, it is estimated that 0.4-24.7 km^2 land is required to build the plant to capture 1 Mt CO_2. The land required for the four airport is summarised in Table A below. (1) Luton Airport, as an example, which emits about 100 kt CO_2 per annum. Only a 0.04-2.5 km^2 land size would be required, which is achievable; The economic viability and technical feasibility assessment are key.

Table A The land required and operating cost (USD) for the case study airports using DAC technology

	Aberdeen (ABZ)	Luton (LTN)	Delhi (DEL)	San Francisco (SFO)
Scope 1 (CO2 tonnes)	5,513	2,966	4,310	17,456
Scope 2 (CO2 tonnes)	0	4,981	59,195	0
Scope 3 (CO2 tonnes)	66,436	278,268	1,887,426	1,680,125
Total CO2 (tonnes)	71,749	286,125	1,950,931	1,697,581
Scopes 1 and 2				
Direct Air Capture (required land area for plant) (m^2)	2.2-136	3.2-196	25-1,568	7-431
Total cost (USDM) *	3.7-5.8	5.2-8.4	42-67	11.4-18
Cost (USD) per passenger	1.2-1.9	0.3-0.5	0.6-0.96	0.2-0.3
Total emissions (incl. Scope 3)				
Direct Air Capture (required land area for plant) (km^2	0.29-17.8	0.11-7.1	0.78-48.2	0.68-42
Total cost (USDM)	47-75	187-300	1,278-2,045	1,112-1,779
Cost (USD) per passenger	16-25	10-17	19-30	19-31

Note: cost refers to the operating cost (excluding the infrastructure investment).
Note 2: exchange rate: 1 GBP= USD1.31

Nature based solutions

Nature-based solutions for emissions mitigation include tree planting, wetland restoration and creation, the application of soil amendments, and green walls and roofs. Many technologies can be combined for additional carbon sequestration, and some have co-benefits through increasing biodiversity, flood risk management, or wastewater treatment. Some technologies can bring trade-offs (for example increased birds at wetland sites) which may require mitigation activities.

The potential for carbon sequestration using available open land for selected techniques is investigated and summarised by case airport in Table B. In general, nature-based solutions are likely to make a small but significant contribution to reducing emissions. For example, woodland planting across 20% of the open land at

Aberdeen airport, combined with wetland creation on a further 20%, and biochar application across the entire area would potentially reduce emissions by 374-1157 t CO_2e yr^{-1}, equivalent to 7-21% of Scope 1 emissions, or 0.5-1.6% of total CO_2 emissions. The use of off-setting or twinning approaches would potentially result in much greater emissions reduction due to an increase in available land area.

Table B Indicative levels of carbon sequestration using nature-based solutions, if they could be applied to 20% of the available open land on the airport estate

Approach	Emission reduction (t CO_2e ha^{-1} y^{-1})[b]	Total emissions reduction (t CO_2e y^{-1})[b]			
		Aberdeen (ABZ) 110 ha	Luton (LTN) 140 ha	Delhi (DEL) 51 ha	San Francisco (SFO) 136 ha
Woodland planting [a]	12.0	264	336	122	326
Low density agroforestry [a]	3.7	81	104	38	101
Plant hedges [a]	0.7	15	20	7	19
Bioenergy carbon capture and storage (BECCS) [a]	0-5.8	0-128	0-162	0-59	0-158
Wetland restoration or creation [a]	0.4-18.0	9-396	11-504	4-184	11-490
Biochar addition[b]	4.6-22.6	101-497	129-632	46-230	125-615
Rock weathering[b]	7.0	154	196	71	190

[a]: Assuming techniques are applied to 20% of available land to minimise impacts on airport operations.

[b]: The assumption is that the application of biochar and rock weathering would not be annual

Feasibility heatmap

Various CO_2 capture technologies for airport operation are summarised as a heatmap in Table C. In general, there are a number of commercially ready technologies for capturing CO_2 from the point source. These technologies can be used to capture CO_2 from the combustion of diesel engines for central energy production as widely deployed in DEL. These technologies can also be applied to greater scale coal/natural gas-powered plants for CO_2 capture, with the electricity produced being purchased by airport such as practised by SFO and ABZ.

Membrane technology is suitable for small scale point-source CO_2 capture but still requires development to increase efficiency and thus reduce cost. Capturing Scope 1 and 3 emissions is the most challenging faced by all the four airports studied. Although still in the early stage of development, direct air capture seems to be a feasible option for CO_2 capture for the airport applications, given the flexibility in location and the relatively small total amount of CO_2 emissions (less than 1 million tonnes from scopes 1 and 3 in all the four airports).

Table C Indicative CO_2 capture technologies heatmap for airport operation

CO_2 capture technologies	TRL	Scalability	Cost	Performance is Scope 1-3 CO_2 capture	Suitable geographical location
Cryogenic	High	High	Low	High for Scope 1 and 2 but low for Scope 3	Can be used in combined with existing heat or/and power generation at various scales to capture CO_2
Adsorption (e.g. amine scrubbing)	High	High	Low	High for Scope 1 and 2 but low for Scope 3	
Absorption	High	High	Low	High for Scope 1 and 2 but low for Scope 3	
Advanced combustion (e.g. chemical looping and oxyfuel combustion)	Medium	Medium-High	Medium	High for Scope 1 and 2 but low for Scope 3	
Membrane	Medium	Low-Medium	Medium -High	High for Scope 1 and 2 but low for Scope 3	
Direct air capture (DAL)	Low	Medium-High	High	High for Scopes 1-3	Not limited to geographical locations

Nature based Solutions	Technology Readiness Level	Emission reduction per hectare	Cost of CO_2e saved	Permanence	Scalability on airport land holding	Scalability through twinning
Woodland planting	High	High	Low	Medium-High	Low	High
Low density agroforestry (30-50 trees ha^{-1})	High	Medium	Low	Medium	Low	Medium
Plant hedges around fields	High	Medium	Low	Medium	Low	Medium
Wetland restoration	High	High	Medium	Medium	Low	High
Increase soil carbon	High	Medium	Medium	Medium	Low	Medium
Reduce N fertiliser use	High	Medium	Low	Medium	Low	High
Biochar addition to grassland	Medium	Medium	Medium	High	Medium	Medium
Rock weathering (20 t ha^{-1})	Medium	Medium	Medium	Medium	Low	Medium
Bioenergy with Carbon Capture and Storage (BECCS)	Low	Variable	High	Potentially high	Low	Medium-high
Use of timber in buildings*	Medium-High	High	Low	High	Medium	Not applicable
Green infrastructure including roofs and walls	Medium	Low	High	Medium	Medium	Not applicable

*: Use of timber incorporated in new, already planned, buildings

Table C also summarises the potential of different nature-based solutions for emissions mitigation. In general, the technology readiness level of most solutions is high, and many have a moderate cost.

Some approaches can be combined, potentially bringing additive benefits even when deployed across only a limited area of available open ground at an airport, potentially mitigating a substantial proportion of Scope 1 emissions (for example up to 50% of ABZ's Scope 1 emissions through woodland planting, wetland creation, and biochar application). With UK aviation targeting an overall 15% reduction in net emissions relative to 2019 by 2030, such approaches may have significant potential. Combining a suite of solutions into a single toolkit may represent one possible pathway for monetisation and promoting adoption.

Nature-based solutions can also bring substantial co-benefits. For example, woodland planting can result in improvements in air quality and enhance biodiversity. Wetland restoration (and the creation of new wetlands) can also increase biodiversity but also provide protection against flooding. Depending on design, constructed wetlands may also be used for wastewater treatment. Heathrow Airport, for instance, use a constructed wetland system (subsurface flow reedbed with a gravel substrate) to treat run-off. Similar systems can also be used for processing sewage waste, often with lower CO_2e emissions than conventional sewage treatment works.

Extensive nature-based solutions for emissions mitigation do, however, face potential scalability issues within airport land holdings. For example, wetland restoration may reduce operational effectiveness (e.g. by increasing bird numbers) unless applied to a much smaller area of land or combined with additional measures (e.g. reducing access for birds or nesting). For all techniques. however, scalability is substantially greater through opportunities for twinning, where an airport enters into a twinning arrangement with another organisation, often locationally linked to the airport, to sequester carbon.

The outputs of this research implicated some opportunities for CCUS at airport. The nature-based solution's TRL is relatively high, and a large co-benefit is expected. However, the potential land scalability could be an issue.

The TRL of DAC is yet low but, it brings the innovative strategic approach for achieving the true net zero target. For example, it could be integrating Hydrogen production generated by renewable energy or low carbon power (Green Hydrogen), SAF production and DAC at airport.

Cooperation with the local government and residents is key for both nature-based and engineering solutions. Furthermore, a large investment and long term policy with strong leadership are required, which can be operated together with the hydrogen generation or green fuel to supply aircraft power.

CCUS at airports should be considered part of the carbon offset scheme and projects. The carbon credit could be awarded like the Clean Development Mechanism (CDM) and Joint Implementation (JI) under the UNFCCC.

It incentivises the airport and local government and can facilitate the investment and finance to cover the abatement cost by establishing the financial system. Of course, it might depend on the geographical location. However, some airports could be the power stations to fuel the air transport operation with CCUS in the long run.

The industry and governments expect the hydrogen or electrified aircraft in a commercial by 2030-35. The CCUS strategy should be investigated and planned along with the aforementioned revolutionary technology for the air transport operation. As a result, a drastic change in the airport infrastructure and operation is anticipated. The comprehensive system approach is imperative to tackle the innovative solutions by accelerating the R&D of new technology.

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Executive summary

List of abbreviations and acronyms

ABZ	Aberdeen International Airport
ACI	Airport Council International
ACRP	Airport Cooperative Research Program
APD	Air Passenger Duty
CaL	Calcium looping
$CaCO_3$	Calcium Carbonate
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CCUS	Carbon Capture Utilisation and Storage
DAC	Direct Air Capture
DEL	Indira Gandhi International Airport
DfT	UK Department for Transport
EC	European Commission
EU ETS	European Union Emissions Trading Scheme
FAA	Federal Aviation Administration
GFGS	Green Fuels, Green Skies
GHG	Greenhouse gas
GSE	Ground Support Equipment
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
JI	Joint Implementation
LTN	London Luton Airport
LPG	Liquefied petroleum gas
MAC	Marginal Abatement Cost
MBM	Market based measures
MEC	Marginal external cost (MEC)
N_2	Nitrogen
OECD	Organisation for Economic and Co-operation and Development
O_2	Oxygen
PV	Photovoltaic
SAF	Sustainable Aviation Fuel
SAGA	Sustainable Aviation Guidance Alliance
SCC	Social cost of carbon
SFO	San Francisco International Airport
TRB	Transportation Research Board
TRL	Technology Readiness Level
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNFCCC	the United Nations Framework Convention on Climate Change

1. Aim and objectives of this study

This project aims to provide a feasibility study of the opportunities for carbon capture and sequestration at airports using innovative new technology at the request of SITA.

Climate change is the greatest challenge of the 21st century. The air transport sector is an intensive carbon emitter and could be the largest greenhouse gas (GHG) contributor in 2050. To achieve the UK Government's net zero target in 2050, four strategic pillars are established for the airline sector: (1) operational efficiency, (2) sustainable aviation fuels (SAF), (3) market-based mechanisms (MBM) (e.g., carbon charge, Air Passenger Duty) and (4) new fuel aircraft technology such as hydrogen and electrified aircraft.

MBM and SAF are practical and existing abatement measures for the short and medium term since electrified or hydrogen-powered aircraft will not be immediately available. The first global carbon offset scheme by ICAO, CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), was implemented in 2021. Substantial SAF production starts shortly in the UK to boost SAF supply. The expectation of these available measures is large. The UK industry currently targets to reduce more than 50% of the absolute CO_2 by MBM and 20% by SAF in 2050. These measures are implemented for reducing the CO_2 emission from aircraft operations. The MBMs for airport emission might be employed in a short time to achieve the net zero target.

Airport operators have also been taking actions to mitigate climate change impacts at the same period as the EU ETS's inclusion aviation. For example, ACI (Airport Council International) started their 'Airport Carbon Accreditation program, which supports airports of all sizes and locations in reducing their impact on the climate, with the support of the UN and ICAO.

Carbon abatement measures have the potential to revolutionise the concept of aerospace sustainability, through carbon capture, sequestration, utilisation, and storage, particularly at airports. Airports could be the best places for green urban infrastructure since they occupy large amounts of space with huge areas of pavement for parking, runways, and storage, which allows the capacity for the facility to process to CCUS. Also, they have many flat-roofed buildings, airports could be a natural choice for green roofs. Many major European airports have a tapestry of green roofs over terminals, concourses, parking buildings, maintenance buildings, and other structures (Cantor, 2008) such as Frankfurt, Ibiza, and Zurich airports.

Technologies to capture, use and store CO_2 (CCUS) can be engineering (i.e. based on an industrial process) or nature based (i.e. applying ecological principles). For example, it is possible to capture CO_2 emissions at source, preventing CO_2 from entering the atmosphere by removing it directly from the air, and storing it deep underground or as useful products. Nature-based approaches include the use of plants and soil to sequester and store CO_2, plus processes such as applying recalcitrant carbon in the form of biochar derived from plant residues, silicate seeding (whereby silicate minerals are applied to the soil surface to absorb carbon dioxide), and novel carbon capture fertilisers. Many start-up firms are looking for the opportunity to develop innovative technology and sequestrate CO_2 and trade in the market as part of carbon offset schemes.

Here, we are investigating the possible commercialisation of carbon sequestration at airports for SITA. We will address the following specific points:

- How is the industry currently addressing carbon management challenges? How can the sector manage and control the emissions produced by their activities?
- What sort of carbon (emissions) abatement measures are currently available? What is the possible next level of options such as the carbon capture, sequestration, utilisation, and storage at airport?
- How effective and mature are these technologies and approaches? How many start-ups are there in this domain?
- Can these approaches be used on the land real-estate of an airport (on and off airfield and on top of airport buildings)? This will include assessments of practical measures required to implement such approaches and whether certain approaches work better in different geographic and climatic zones.
- Will the carbon captured have any meaningful offset to the carbon emissions of an airport?
- What is the market potential of this approach to carbon emission offsetting?

We will address the following five objectives with six tasks.

1. To work with SITA to identify **four contrasting case studies** that have accessible details of the airport estate (e.g. area, land cover).
2. To survey the current **carbon abatement and offset measures and** investigate the differences of impact of measures according to the characteristics of airports (e.g., size, the location, climate).
3. To use existing datasets to estimate the potential **point-source and air-source** carbon/GHG capture technology applications, and identification of integration options and limitations (i.e. heat) for carbon/GHG capture technologies within airports.
4. To identify existing and **innovative approaches** to sequester carbon and reduce GHG emissions on i) the airport estate and ii) neighbouring areas at the selected case studies. To determine, from the literature, the effectiveness and maturity of these approaches, on a non-spatial basis.
5. To investigate the **potential carbon sequestration opportunities**.

2. Inception: The Green Airport

This section provides reviews the current status and trend of airports looking for a sustainable strategy and possible technology and investigates the rationale behind this direction. We consider the definition of a 'green (eco-design) airport' and categorise it according to the cases in the world. The type of practices currently taken and challenges for airport design and operation will be investigated.

Eco-design of airport buildings refers to considerations of green buildings and the environmental and resource-efficient operation and management of the airport building from a life-cycle perspective. Since the airport is a complex hub for various facilities (shops, food outlets, air carrier operations) the eco-design of an airport requires complex collaboration among airport stakeholders, with an overall aim to minimise negative impacts to the natural environment and human health. In addition, airport sustainability needs to involve economic, environmental, and social considerations into planning, design, construction, operations, and maintenance.

The sustainability for airport operation and management can be addressed across areas such as: carbon, water, energy, waste, land and noise. For example these are six areas considered by Christchurch Airport in New Zealand, which has received ACI Carbon Accreditation Level 4+ (**Figure 2.1**).

Figure 2.1. Sustainable Airport concept (Source: Christchurch Airport, 2022)

Carbon, water, energy, waste, land and noise are all used or created during the process of airport operation, in the context of a regional landscape, nature, and community. It is based on their kind of philosophy according to Māori's concept-care, responsibility, and guardianship. The OECD (2022) has defined “responsible business conduct” as "making a positive contribution to economic, environmental and social progress with a view to achieving sustainable development and avoiding and addressing adverse impacts related to an enterprise's direct and indirect operations, products or services". In the end, it can be conducted by caring, taking responsibility and respect and protect the nature, human, wildlife, and the society. As a result, it can lead to the development of business and the society.

This report will focus on GHG emissions with a principle focus on reducing carbon dioxide (CO_2) emissions through carbon capture, sequestration, utilisation, and storage (CCUS).

2.1 Scope of emissions at airports

Industrial initiatives to reduce GHG emissions by promoting emissions management at airports have been taken by the Airports Council International (ACI) (2008, 2009). Establishing emissions inventories is an important step for carbon reduction (Transportation Research Board (TRB), 2009; FAA, 2021). Emissions sources are typically divided into three groups based on the ACI and Airport Cooperative Research Program Guidelines: Scope 1 (direct emissions including airport operator emissions), Scope 2 (indirect emissions including emissions relating to purchased electricity) and Scope 3 (indirect and operational emissions including tenant emissions and emissions from airport surface access including access by employees).

The main emissions at airports, however, belong to Scope 3, and are outside the direct control of the airports. Emissions from passenger surface access are the second largest emission source after aircraft emissions. Although this is not straightforward, the ACI has stated that it is possible that some emissions falling within Scope 3 might be influenced by airports, and they play an important role in reducing emissions. In addition, the boundary of the emission source is another issue, as an airport is a highly complex environment.

Table 2.1 Scope 1, 2 and 3 emissions at airports (Source, FAA 2021)

Category	Type of emissions
Scope 1	Emissions from airport-owned or controlled sources. Examples include airport-owned power plants that burn fossil fuel, conventional vehicles that use gasoline, or conventional GSE that use diesel fuel.
Scope 2	Indirect emissions from the consumption of purchased energy (electricity, heat, etc.)
Scope 3	Indirect emissions that the airport does not control but can influence. Examples include tenant emissions, on-airport aircraft emissions (typically, after an aircraft is parked on the apron), emissions from passenger vehicles arriving or departing the airport, and emissions from waste disposal and processing.

2.2 Tools and guidelines to control emissions at airport

There are several tools and guidelines to control and reduce the emissions at airports. Two representative schemes are explained below. Firstly, examples by the Airport Cooperative Research Program (ACRP) and the ACI's Airport Carbon Accreditation programme are presented.

2.2.1 Airport Cooperative Research Program (ACRP)

Airport Cooperative Research Program (ACRP) Report 11: Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories (2009)

This is one of the first studies to assess controls over GHG emissions at airport. It provides a framework for identifying and quantifying specific components of airport contributions to GHG emissions. This guidebook can be used by airport operators and others to prepare an airport-specific inventory of GHG emissions. It identifies calculation methods that can be applied consistently, improving comparability among airports and enhancing understanding of relative contributions of GHGs in local environments.

ACRP Synthesis 21: Airport Energy Efficiency and Cost Reduction (2010)

This report explores energy efficiency improvements being implemented at airports across the country that are low cost and short payback. The focus of this synthesis is on identifying and listing ways to reduce energy costs at small airports through energy efficiency.

ACRP 141 Renewable Energy as an Airport Revenue Source (2015)

This report provides an overview of renewable energy in an airport setting; offers guidance for identifying, evaluating, and selecting financially beneficial renewable energy projects given an airport's unique characteristics; and gives the steps needed for implementing and operating a renewable energy project.

The guidebook also includes detailed financial information on the cost and performance. To accomplish this, airports are now exploring non- traditional revenue sources and cost-saving measures. At the same time, utility service providers have recently begun looking for opportunities to purchase energy generated from renewable sources to meet state, regional, and federal environmental and energy goals. Since airports often have available property and facilities to host and generate clean and renewable energy sources, there may be opportunities for them to generate revenue and achieve cost savings. Nevertheless, the use of renewable energy as a revenue source is a complex issue, requiring an understanding of emerging technologies, financing mechanisms, regulatory frameworks, and operational factors of projects that have been implemented by airports.

ACRP 151 Developing a Business Case for Renewable Energy at Airports (2016)

This report provides airports with instruction and tools to help them develop a business case that maximises the benefits of renewable energy opportunities. It presents the business case as a comprehensive planning exercise supporting a specific objective (e.g., energy stability, reliability) and integrates it into the airport's typical decision-making process. A decision-making matrix is included that contains criteria used to evaluate a renewable energy project with a system for weighting each factor based on an air- port's particular objectives. Examples of renewable energy business cases from both aviation and non-aviation organisations to high- light lessons learned.

ACRP Airport Sustainability Practices (2016)
This report presents the information about airport sustainability practices with 10 case study examples. The Sustainable Aviation Guidance Alliance (SAGA) website (www.airportsustainability.org) established in 2008 has been promoted and enhanced its utility via this report. This report was originally intended to prepare for the sustainability specialist; however, it aims rather, the data complied through the report provides a high-level overview of the practices in align with other practices already documented on the SAGA website by expanding the wider scope and audience.

2.2.2 Airport Carbon Accreditation

ACI 'Airport Carbon Accreditation' was launched in Europe in 2009. It is the only institutionally-endorsed, carbon management certification standard for airports. It independently assesses and recognises the efforts of airports to manage and reduce their carbon emissions through 6 levels of certification: 'Mapping', 'Reduction', 'Optimisation', 'Neutrality', 'Transformation' and 'Transition'.

Airport Carbon Accreditation is owned and governed by ACI EUROPE in close cooperation with four ACI regions (Asia-Pacific, North America, Africa, Latin America & Caribbean) and with support of ACI World. The programme is administered by WSP (https://www.wsp.com/en-GB).

ACI Airport Carbon Accreditation covers all ACI regions (74 countries), and 333 airports obtained the class in 2021 in total. It supports in reducing its carbon footprint which produced for airport operation. In 2021, 113 airports are now accredited at Level 1 (Mapping), 94 at Level 2 (Reduction), 62 at Level 3 (Optimisation), 61 at Level 3+ (Neutrality), 1 at Level 4 (Transformation) and 2 at Level 4+ (Transition) according to the ACI report (2021a)

Figure 2.2 and Table 2.2 present ACI's Carbon Accreditation category and each requirement.

Source: San Francisco International Airport (2022)

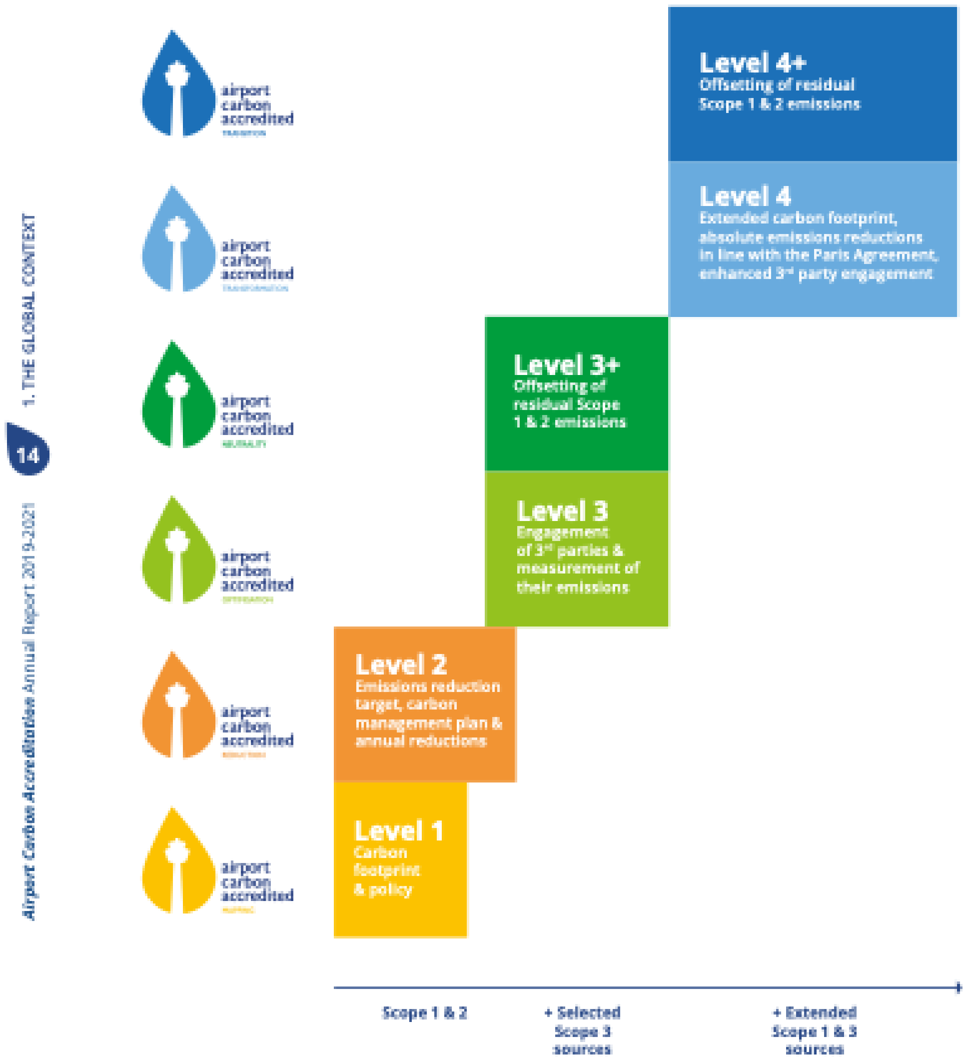

Figure 2.2. ACI Carbon Accreditation Category and main requirements in 2021 (Source: ACI, 2021)

Table 2.2 Airport Carbon Accreditation Category and main requirements in 2021

Main requirements			Scope	Europe	NA	LA	AP	AF
Total number of airports obtained accreditation				164	48	45	59	12
Level 1	Mapping	A policy commitment to emissions reduction endorsed by top management and the development of a carbon footprint for emissions	1 & 2	57	16	26	7	12
Level 2	Reduction	Formulation of a carbon emissions reduction target Development of a Carbon Management Plan achieve the target and annual reduction of emissions under the airport's control versus the three-year rolling average.	1 & 2	40	11	16	19	
Level 3	Optimisation	Development of a more extensive carbon footprint to include specific Scope 3 emissions Formulation of a Stakeholder Engagement Plan to promote wider airport-based emissions' reductions	1,2, 3	16	19	1	25	
Level 3+	Neutrality	Level 3 plus offset their residual emission	1,2,3	51	1	2	6	
Level 4	Transformation	Policy commitment to absolute emissions reductions Development of a more extensive carbon footprint Formulation of an absolute long-term emissions reduction target Development of a Carbon Management Plan (setting out the trajectory, interim milestones and the measures required to achieve the target) Development of a Stakeholder Partnership Plan to address third party emissions.	1,2, 3, Others		1		1	
Level 4+	Transition	Level 4 plus offset their residual emission	1,2, 3, Others				1	

Note: NA refers to the North America, LA for Latin America, AP for Asia Pacific, and AF for Africa.

3. Controlling emissions at airports

This section summarises the current carbon abatement measures, policy and regulation, the positive and negative impact of these measures including the market-based mechanism such as the EU ETS and CORSIA. How these measures effect on the airline and airport operation and management will be investigated. Trends and differences amongst airport type will be discussed.

3.1 The current abatement measures, policy, and regulation

The regulatory framework and drivers clearly started to reduce GHG emissions at the United Nations Conference on Environment and Development (UNCED), the Rio De Janeiro Earth Summit in 1992. It was an agreement on the Climate Change Convention which led to the Kyoto Protocol in 1997, and The Doha COP18 amendment contributed to more international involvement, which was taken over in the Paris Agreement in 2015. The United Nations Framework Convention on Climate Change was formed to establish the international framework for tackling the human's interaction to climate change at the Earth Summit.

In response to the Kyoto Protocol in 1997. Each government started their national policy, for example, the U.K. government (Department for Transport, 2004, 2007) set goals for reducing CO_2 and other GHG emissions from transport by aiming to shift people's mode of transport from road and air transport to rail or other forms of public transport.

The rationale behind this direction is to reduce total CO_2 emissions by using electric powered transport rather than fossil energy-generated modes such as cars and planes (Miyoshi and Givoni, 2013). The Kyoto Protocol categorised signatories: (1) Annex 1 countries-the industrialised countries and economy in transition (e.g. US, EU, Russia), and (2) Annex 2 countries-developed countries which pay for costs of developing countries, and developing countries (e.g. China). Each country in each annex has their own and different responsibilities according to its category under the Kyoto Protocol.

For the aviation industry, in 2009 the International Air Transport Association (IATA) established the carbon neutral growth strategy from 2020 on-wards and to reduce emissions in 2050 by 50% relative to the 2005 level (IATA, 2009) by setting a four pillars strategy: (1) fuel efficiency aircraft, (2) operational measures such as improving load factor, efficient network, (3) navigational improvement, and (4) market based mechanism (e.g. air passenger duty (APD), European Union Emission Trading Scheme (EU ETS)). These strategies to abate the emissions have been implemented widely, particularly since the announcement of EU ETS' inclusion of the aviation activity in 2008 (European Commission, 2006).

Aviation became part of the EU ETS in 2012 (European Commission, 2006), with free emissions allowances being allocated to each airline. According to the European Commission (2011), it was anticipated that over 176 million tonnes of carbon dioxide (CO_2) emissions are expected to be traded by 2020. In practice,1.53 billion tonne of CO_2 was traded in 2019, which were much larger than expected. When the aviation inclusion in EU ETS was announced in 2006, the industry started its preparation and concerned since the impact of EU ETS was unknown, and the externality (CO_2 emissions) is internalised which is now the additional cost for them.

The EU ETS is one of several market-based measures (MBMs) the European Union introduced aimed at reducing emissions and meeting the targets specified under the Kyoto Protocol. As such, it was the first international ETS in the world. The first phase was carried out between January 2005 and December 2007; the second phase ran from January 2008 to December 2012; the third phase started in January 2013 and planned to end in December 2020. The ultimate aim of this scheme was to create an environment where a scarcity of allowances will eventually lead to an upward trend in prices.

The first multinational emission trading scheme resulted in many regulatory issues and objections being raised by several countries and airlines concerning its legality under the Chicago Convention. In addition, under the Kyoto Protocol, ratified countries have different responsibilities and roles based on whether they are Annex I or non-Annex I countries, whereby the latter do not have to undertake quantitative emissions reduction targets. But equity issues among airlines and countries cannot be avoided, particularly with regard to global ETS mechanisms.

Consequently, EC took a ‘stop the clock’ action in November 2012 and issued a ‘stop the clock’ Decision (Decision no. 377/2013/E.U. (European Commission, 2013) in April 2013 by requesting progress on global MBMs through International Civil Aviation Organisation (ICAO). The global MBM led by ICAO was finalised in 2016 as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2016) for aiming its implementation for achieving the Paris Agreement’s temperature goal of holding the increase in the global average temperature to well below 2°C above pre-industrial levels. It was taken over for pursuing efforts to limit the temperature increase to 1.5°C. by the Glasgow COP26 in 2021. It recognised the aviation net zero global emission target in 2050 by acknowledging the sustainable global SAF development and ensuring the maximum effectiveness of CORSIA through ICAO.

These measures require the additional cost and investment which can be expressed and assessed by the marginal abatement cost. It is the total cost to reduce the negative outputs such as emissions and noise, which is expressed as unit of cost divided by unit of outputs (e.g., USD / tonne of CO_2). The marginal abatement cost (MAC) curve is widely used for assessing the policy and measures. The sample of MAC curve is shown as below.

Figure 3.1 shows the MAC curve for the year 2050 for the central demand baseline / mid policy case for the UK studied for Department for Transport (DfT) in 2011. Two measures, early fleet retirement and the setting of regulatory CO_2 standards, are substantially more expensive (£1,080 and £1,645/tonne CO_2 respectively). The negative MAC are gained ATM efficiency (-£77 per tonne) and behaviour change (£-5 per tonne). For the industry perspective, when the market price of CO_2 is lower than the MAC curve, these measures are efficiency for the industry. However, this curve and values are simply changed according to the traffic forecast, CO_2 and Fuel price, and investment. Estimation of travel behaviour change rate for the long term and its investment are not straightforward even for the assumptions.

In addition, based on the Pigouvian theory, the efficient level of emissions abatement occurs when the marginal cost of abatement is equal to the marginal benefit of avoided damages, which is approximated by the social cost of carbon (SCC). The SCC is much larger than the market price of CO_2, as aviation emission abatement options are expensive relative to those in other sectors.

The MAC curve analysis and production process are imperative to review and assess the environmental policy and each abatement measures. They should be reviewed time to time by reassessing the available technology and its cost, the regulatory change and its impact, the market (traffic) response (e.g. price elasticity, fuel & CO_2 price), which directly related to demand. For instance, the MAC of biofuel and video conferencing were £25 per tonne and £159 per tonne respectively. The MAC of biofuel is calculated based on life cycle CO_2 reduction (not the absolute CO_2 reduction). The price of SAF is yet uncertain, which is currently more than double- three times higher than Kerosine but might be lower to promote SAF under the policy. The cost of videoconferencing is lower because of the travel restriction by COVID pandemic. Thus, the MAC curve changed largely even in ten years.

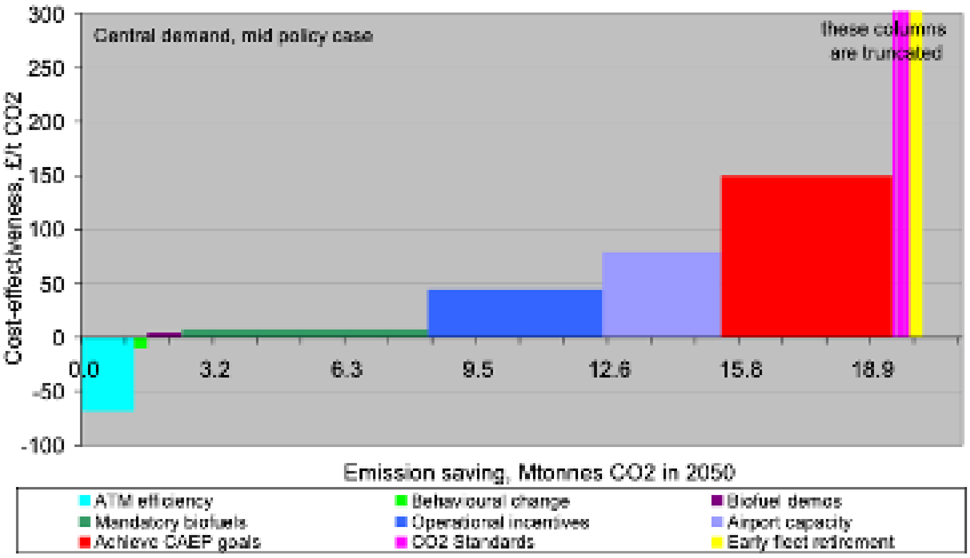

Figure 3.1 An example of UK aviation MAC curve (Source: UK DfT 2011)

3.2 Market based mechanisms

Market-based mechanisms provide one method for addressing environmental problems. It is different from the traditional command and control systems, and uses the price or other economic instruments to provide the incentive for polluters to reduce the negative impact of emissions. It has been widely used as it is said to be achieved in a cost-effective way.

There are several types of market-based mechanism (MBM): pollution charge, subsidies, deposit/refund systems, and pollution permit trading system (Callan, 2010).

According to the OECD (2007), an MBM is defined as seeking to address the market failure of 'externalities' either by incorporating the external cost of production or consumption activities through taxes or charges on processes or products, or by creating property rights and facilitating the establishment of a proxy market for the use of environmental services. Generally, four types of MBMs are below:

(1) Pollution charge

A product charge (a charge to the price of pollution to produce the products) implemented as a tax based on the polluter-pays principle is to make polluters to internalise the externality (e.g., emissions, noise, waste) by considering the marginal external cost. When the pollution charge is conducted by imposing a unit tax on the pollution equal to the Marginal external cost (MEC) at the efficient output level, it is called a Pigouvian Tax. In theory, the Pigouvian tax forces firms to lower production to the efficient level. However, it is difficult to levy in practice because it is not easy to quantify the monetary value of MEC at the efficient level.

Emission charge is a tax levied directly on the pollution (emissions) instead of the product. Generally, the revenue from the charges is stored in the general account in the government which could be used as other financial resources (not limited for emission reduction). The APD (air passenger duty) in the UK is one of these cases.

(2) Subsidies

These are a type of incentive to lower the costs of abatement technology to reduce the pollutions. In theory, they are used to internalise the positive externalities associated with the abatement activities. In practice, these are implemented by grants, low tax, lower interest loan, etc. the ‘Green Fuels, Green Skies’ (GFGS) competition in the UK, and The Sustainable Skies Act in US are examples.

(3) Deposit /refund system

This system is used to prevent the pollution by imposing the upfront payment (deposit). Most common cases are beverage bottles, waste disposal bags, and batteries to encourage the proper disposal among the consumers.

(4) Pollution permit trading system

It is a market instrument that establishes a market for rights to pollute by issuing tradable pollution allowance (or credit). In order to reduce the total amount of pollution (e.g., emissions), the level of emission is restricted (a fixed number of permits) as a baseline. Therefore, it is also called a cap-and-trade system. The EU ETS (Emission Trading Scheme) is one of the noticeable cases.

The market is established by setting the amount of pollution and abatement to be achieved by letting the market determine the price (e.g. carbon price). The challenge is here it is not easy to predict the appropriate price as the government does not know in advance what level of price can achieve a quantity level of reduction target. Therefore, it is required to monitor and observe the market response. If the price of pollution credit is too low (lower than the abatement cost for polluters), the polluters keep purchasing the pollution credit rather than taking abatement actions, for example, the investment on the new technology to reduce the emissions (e.g., new aircraft, new engine) The advantage of pollution permit trading system is the polluters can have a choice how to reduce the pollution. They can buy and sell allowances required, which leads access to abatement technologies and their costs.

Table 3.1 A summary of market based mechanisms

General category	Description	Examples for aviation
Pollution charge	A fee charged to the polluter that varies with the quantity of pollutants released	Air Passenger Duty (APD)
Pollution permit trading scheme	A market for rights to pollute using credits and allowances	EU ETS, UK ETS
Offset	A system to incentivise the actions to reduce pollution or promote the pollution reduction	CORSIA, IATA Offset Scheme

3.3 Selection of case airports and background

Four case airports have been selected to investigate the baseline level of CO_2 emissions across airport types and regions, and the potential of reduction measures for mitigating emissions, and to identify any challenges specific to these airports.

The following selection criteria are established:
(1) Airport traffic size (Traffic size (super large > 50 M passengers per Annum, large >30M, Mid > 5M, Small < 1M)
(2) ACI (Airport Council International) Carbon Accreditation certified airports or airports with established sustainable policy.
(3) Geographical location: UK, Asia, and the USA.

Four airports are selected: (1) Aberdeen Airport (Scotland), (2) London Luton Airport (England), (3) Indira Gandhi International Airport (India), and San Francisco International Airport (USA). The year 2019 is adopted as the baseline for avoiding the significant traffic reduction by the COVID-19 in 2020 and onwards. Table 3.2 presents the summary of key information by airport according to each traffic and carbon emission record in 2019.

As it is explained in the previous chapter 2, Scope 1 emissions are 'emissions on-site, or an associated process, from the combustion of fossil fuels, e.g. natural gas, oil, LPG and company-owned vehicles. Scope 2 emissions are associated with the use of electricity imported from the grid or from a third party supplier of energy in the form of heat or electricity. Scope 3 emissions include aircraft movements, passenger and staff travel to the airport, airside activities, waste disposal, water and business travel. Airport mainly focuses on the reduction of Scopes 1 and 2 emissions as they are directly controllable (manageable) emissions by airport. However, there are yet to be possible to manage the emissions from passengers and airport employees' surface access and business trips by establishing the strategy supported by the regional government and community.

The government policy and strategic actions for decarbonising aviation are indispensable for the airport emission management and control, since the impact of these policies are significant.

Table 3.2 Summary statistics of case airports in 2019

	Aberdeen (ABZ)	Luton (LTN)	Delhi (DEL)	San Francisco (SFO)
No. of passengers in 2019	2.98M	18M	69M	57.6M
Aircraft movement	91,711	63,593	464,000	458,490
Cargo (Metric Tonnes)	7,432	32,693	1M	489,505
Scope 1 (tonne CO_2)	5,513	2,966	4,310	17,456
Scope 2 (tonne CO_2)	0	4,981	59,195	0
Scope 3 (tonne CO_2)	66,436	278,268	1,887,426	1,680,125
ACI Carbon Accreditation		Level 1	Level 4+	Level 3
Scope 1 & 2 (kg CO_2/ pax)	0.54	0.54	0.99	0.43
Scope 3 (kg CO_2/pax)	22	15	27	29

Source: AGS (2020), Luton Airport (2020), GMR (2020), and San Francisco International Airport (2020)

Figure 3.2 shows the different CO_2 kg e/passenger among regions each ACI member airport is located (only Scopes 1 and 2). Lower values of Latin America and the Caribbean are based on their lower grid CO_2 intensity in this region. Average Scope 1 & 2 emissions per passenger at all levels among the ACI member airports in 2019-2021 was 1.63 kg of CO_2 per passenger. All case airports show much lower values (0.43-0.99) in Table 3.2.

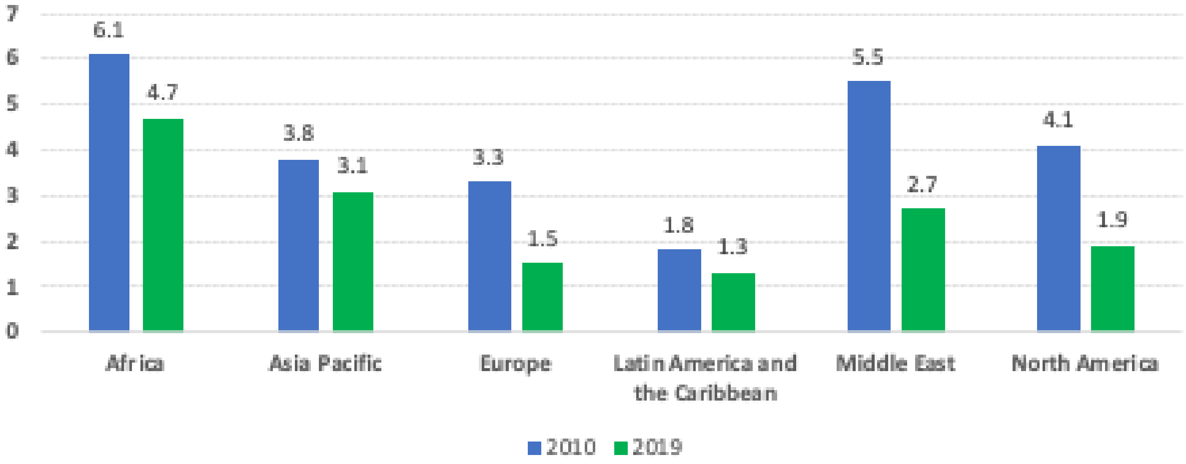

Figure 3.2 CO_2e (kg) per passenger by regions in 2010 and 2019 Source: ACI (2021)

Natural gas remains the largest energy source in Scope 1 at the airport. However, like SFO, the airport is investigating the possible an all-electric, zero-emission central utilities plant in line with the government policy (e.g., City and County of San Francisco's new all-electric building requirement). Indeed, the government electricity generation mix policy contributes to the Scope 2 indicator largely. For instance, the U.K. government grid policy change has pushed up the low carbon electricity share significantly since 2006 by investing and facilitating renewable energy. As a result, Aberdeen Airport purchased all renewable electricity, resulting in zero emission in Scope 2 (see Table 3.2).

How to power automobile vehicles used at the airport is another key agenda. It can be achieved by electrification, hydrogen or biofuel for heavy duty vehicles, which requires a large investment, including the infrastructure. The airport can plan and control their own vehicles. However, sometimes it is not straightforward to manage their tenants' vehicles (e.g., ground handling, airlines, catering companies, hotels), of which emissions belong to Scope 3.

The government energy policy can significantly affect the airport's carbon performance in any scope. Of course, the lower carbon intensity with a low price is crucial, but the government fully establishes how to generate the electricity and its direction. Particularly, the policy and strategy for green next generation energy such as hydrogen should be planned in advance including the investment and incentive and how to finance them.

4. Carbon Capture, Utilisation and Storage Technologies

The capture of process emissions from industrial and power generation sources is well commercialised and an understood technology. It is therefore conceivable that if a particular process/generation system is present at an airport then CCUS technologies could be applied. A range of technologies including amine scrubbing, zeolite adsorption, calcium looping will be considered for their integration potential, and an indication of costs and performance will be presented. An evaluation of wider GHG capture technologies will also be presented which could include offsetting emissions from aviation activities via non-point source capture technologies. A state-of-the-art summary of CCUS will be presented as part of this deliverable.

In this section, a state-of-the-art summary of CCUS has been presented and evaluated for the possibility of integrating the CCUS technology within an airport which was followed by the analysis of challenges and opportunities. A recommendation for future CCUS technology development to decarbonise airports has been suggested.

4.1 CCUS technologies

CCUS is broken into several steps: capture, compression, purification, transportation, and storage or utilisation. Within this section we break down these stages of CCUS and identify the options available at each step.

4.2 CO_2 capture options

There are a range of CO_2 capture technologies that have been used for CO_2 removal from industrial and power generation including cryogenic separation, advanced combustion process (chemical looping process and oxyfuel combustion), adsorption process (e.g. amine scrubbing), absorption, membrane, direct air capture. The typical process and examples of these technologies are detailed below.

(1) **Cryogenic separation**: This method of CO_2 separation harnesses the different boiling points of CO_2 compared to other gases. CO_2 has a boiling point above N_2 and O_2 meaning it will liquify/solidify at a higher temperature whilst N_2 and O_2 will remain in the gaseous phase. A simplified schematic is presented in Figure 4.1 The technology has been commercialised such as CryoCap commercialised by Air Liquide.

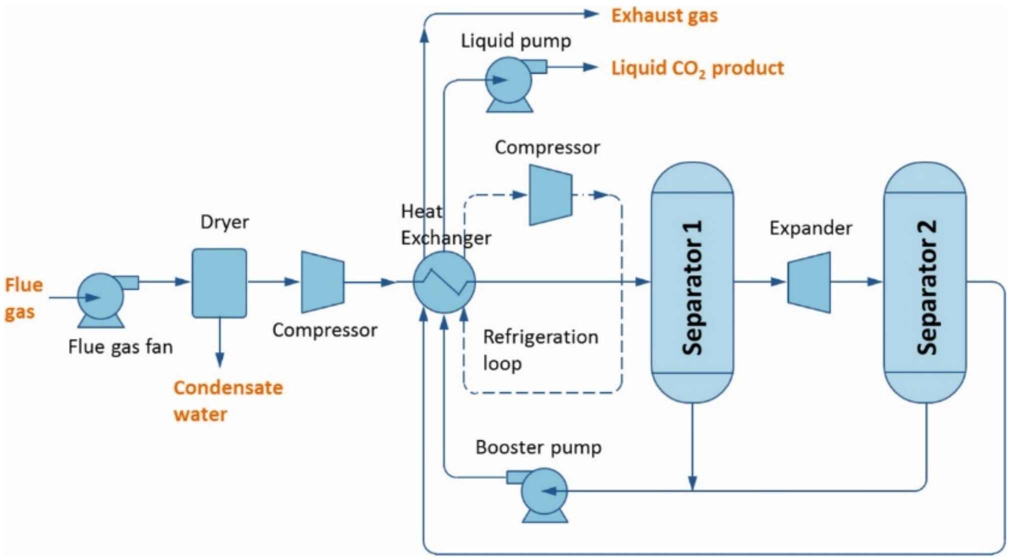

Figure 4.1. Schematic of cryogenic CO2 separation (Song et al., 2019)

(2) **Calcium looping (CaL) Combustion:** In the CaL process the flue gas from fuel combustion in air, which usually contains between 4%vol and 15%vol CO_2 depending on the primary fuel used, is fed to the carbonator. Under such conditions, CO_2 reacts chemically with CaO through an exothermic solid-gas reaction. CO_2 is removed from the flue gas in the form of solid $CaCO_3$ at a reasonably fast rate. $CaCO_3$ is transferred to another fluidised-bed reactor, the so-called calciner, in which it is calcined and CO_2 is reclaimed (Blamey et al, 2010). To produce a CO_2 stream of high purity, which can be directly transported for safe storage or use after the purification and compression stages, combustion takes place in an O_2/CO_2 environment. Figure 4.2 shows a typical fluidised bed CaL process, which has been demonstrated at the pilot-plant scale.

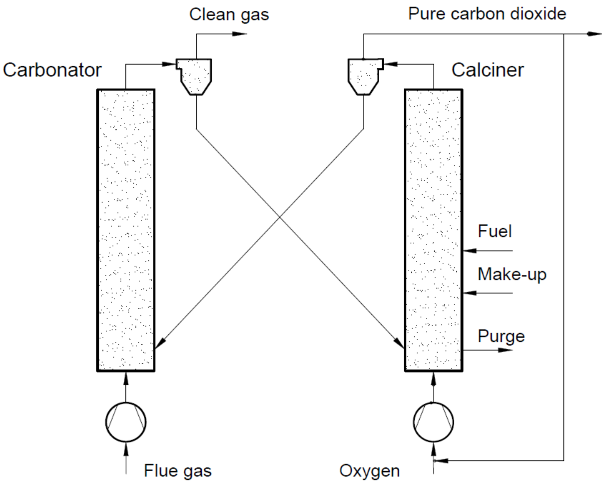

Figure 4.2. Conceptual scheme of CaL process system for CO2 capture

Oxyfuel combustion: Oxyfuel combustion is similar to conventional combustion using air, but the air is swapped for a gas containing O_2 and CO_2. This method of CCS works on the principle that it is easier to remove the N_2 from the air before combustion than from the product gas after. Figure 4. 3 presents a simplified overview of the oxyfuel process. As can be seen, the main difference of this process is the addition of an air separation unit, this is also the main reason for the increased operating cost. CO_2 is recycled into the oxygen feed gas to absorb some of the heat from the combustion process thus preventing too much heat from being generated within boiler. Oxyfuel combustion does result in a simple gas compression and purification train post combustion before the CO_2 is transported away.

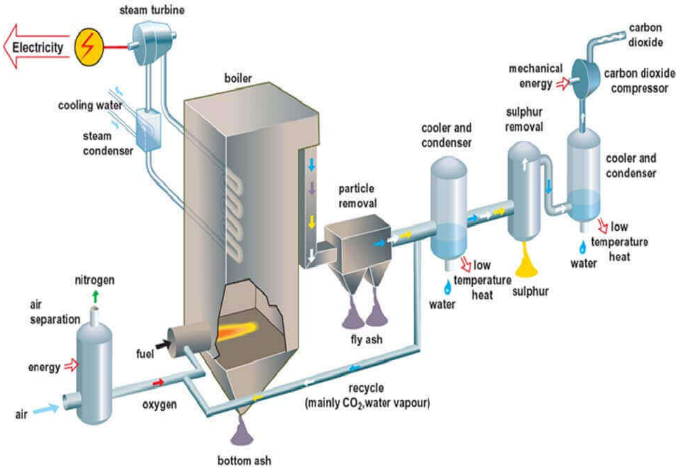

Figure 4.3. Schematic overview of the oxyfuel process (https://www.oresomeresources.com/resources/oxyfuel-combustion-fact-sheet/)

(3) Adsorption – solvent-based absorption is a cyclic process in which CO_2 is scrubbed from flue gas on contact with the lean solvent that takes place in the packing absorber and is reclaimed from the rich solvent on heating in the regenerator. Some well-known adsorbents are amine and zeolite sorbents. **Figure 4.4.4** shows the process of ammine scrubbing for CO_2 adsorption. It has been identified that the most efficient manner to provide the heat requirement for solvent regeneration is to extract part of the low-pressure steam from the primary steam cycle and it is operated at commercial scale for CO_2 capture.

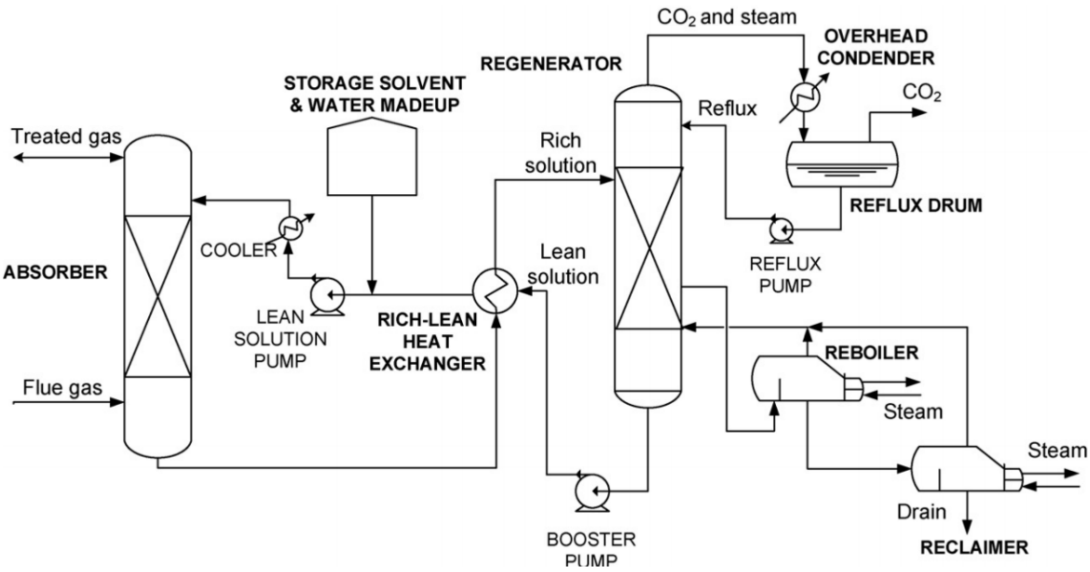

Figure 4.4 Typical configuration of solvent-based adsorption CO_2 capture process (Thitakamol, B., Veawab, A., Aroonwilas, A, 2007)

(4) Absorption: Similar to chemical adsorption such as amine scrubbing, physical absorption is another way of capturing CO_2. There are a few physical adsorption process such as Selexol and Purisol methods (Smith, Nicholas, Stevens, 2016). One of the examples is the potassium carbonate looping process involves cycling an aqueous solution of K_2CO_3 which the CO_2 is physically absorbed into forming a bicarbonate. Potassium carbonate scrubbing has a similar regeneration temperature (~120 °C) to amine scrubbing but has slower kinetics meaning larger reactors. This process will also remove acid/sulphurous gases from the flue gas as well.

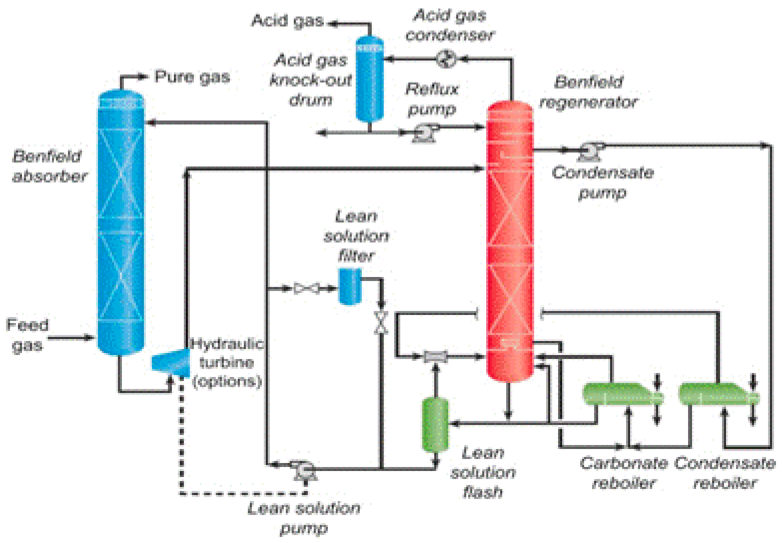

Figure 4.5. Schematic of the Potassium Carbonate looping process (Smith, Nicholas, Stevens, 2016)

(5) **Membrane separation** – Although gas separation using membranes has been already performed in other industries, such as air separation (technical grade nitrogen or O_2 enriched air) or H_2 separation (refineries and petrochemical industry) (Yampolskii, 2012), the development of this technology for CCS application is still in its preliminary stage of development. Yet, membranes are regarded as a promising technology for post-combustion CO_2 capture and are expected to offer lower efficiency penalties compared to the mature chemical solvent scrubbing technologies (Kenarsari et al., 2013). It has been stated that although membranes are capable of achieving CO_2 capture rates higher than 90% for CO_2 concentrations in flue gas of $10\%_{vol}$, such system would be highly energy-intensive (Favre, 2007). This is mainly associated with the need for flue gas compression to improve the separation driving force in the membrane (Favre, 2007; Kenarsari et al., 2013; Zhao et al., 2010). Therefore, this CO_2 separation technology has a potential to provide better performance compared to the mature solvent adsorption processes for the CO_2 concentrations higher than $20\%_{vol}$ (Favre, 2007).

(6) **Direct air capture -** Direct removal of CO_2 from ambient air, referred to as direct air capture (DAC), has recently gained significant attention among researchers, because it could minimise the problems associated with transporting large volumes of CO_2 from point-source emitters to sites suitable for geological sequestration. Furthermore, DAC systems can be widely distriuted and don't require the use of existing assets. In addition, unlike conventional capture processes that target only large-point sources and can, at best, slow the rate of increase in the atmospheric CO_2 concentration, DAC, if widely adopted, can reduce atmospheric CO_2 levels. Ambient air passes through a chemical media, typically an aqueous alkaline solvent or solid sorbents, which will capture CO_2 from air. These chemicals are subsequently stripped of CO_2 through the application of energy (namely heat), resulting in a CO_2 stream that can undergo dehydration and compression, while simultaneously regenerating the chemical media for reuse (Erans, et al, 2022). The primary industrial developers of DAC today are Carbon Engineering (Canada), Climeworks (Switzerland), and Global Thermostat (USA). According to the IEA, as of 2019 there are 15 operational DAC plants worldwide. In the US alone, there are plants in advanced development (construction planned to begin in 2022) with the potential to capture up to 1 Mt CO_2 yr^{-1} (Erans et al, 2022).

Table 4.1. Compares different capture technologies

CO_2 capture technologies	Merits	Obstacles (Cost of CO_2 captured) (USD (t CO_2e)$^{-1}$)
Cryogenic	(1) Matured technology at TRL of 9, (2) no need for CO_2 compression as in liquid state CO_2 capture, thus easy transportation; (3) Suitable for high CO_2 composition gases	High energy penalty for cryogenic condition (USD39-105/t-CO_2) (Tuinier, Hamers, Annaland, 2011)
Adsorption (e.g. amine scrubbing)	(1) Matured technology TRL of 9; (2) CO_2 capture efficiency is high	Solvent challenges related to efficiency, stability and process optimisation (USD26-52/t-CO_2) (Tuinier, Hamers, Annaland, 2011)
Absorption	(1) Matured technology TRL of 9; (2) CO_2 capture efficiency is high	Very low selectivity of CO_2 absorption (USD26-52/t-CO_2) (Tuinier, Hamers, Annaland, 2011)
Advanced combustion (e.g. chemical looping and oxyfuel combustion)	Suitable for power plant applications, TRL of 4-6	Currently limited to <100 MWth plants due to solids loops, Oxyfuel is limited to high cost associated with air separation and compression (USD66-98/t-CO_2) (Alalwan, and Alminshid, 2021)
Membrane	Does not require any chemicals and suitable for small scale application, TRL of 4-6	High cost with membranes (USD197-393/t-CO_2) (Tuinier, Hamers, Annaland, 2011)
Direct air capture	Not limited to point source of CO2 emissions, TRL of 3-5	High cost due to very low CO2 concentration in air (USD655-1,046 /t-CO2) (Erans, et al, 2022)

Note 1: TRL refers to Technology Readiness Level. A TRL rating is based on the technology progress.

Note 2: Exchange rate: 1 GBP = USD 1.31

4.1.2 CO_2 transportation options

The captured CO_2 must be moved to a storage or utilisation site, this will involve either transportation by pipe, ship, or road/rail tankers. The transportation of CO_2 is already common practise and is no more dangerous than hydrocarbon transportation. A summary of the different transportation options is presented in Table 2.

Table 4.2. A summary of CO_2 transportation options, adapted from (Baroudi et al., 2021).

Transportation method	Conditions	Phase	Capacity	Remarks
Pipeline	4.8-20 MPa 283-307 K (Ozaki, et al., 2013)	Vapour dense phase	~100 Mt CO_2/year (Svensson, et al., 2004), 6500 km of pipeline transport in operation (Roussanaly, et al.,2017)	• Higher capital costs, lower operating costs • A low-pressure pipeline system is 20% more expensive than dense phase transmission • Well-established technology for EOR use
Ship	0.7-4.5 MPa 221-283 K (IPPC, 2005, Wang, S., 2005) (IPPC, 2005, Wang, S., 2005) [Ref]	Liquid	>70 Mt CO_2/year (Svensson, et al., 2004)	• Higher operating costs, lower capital costs • Currently applied in food and brewery industry for smaller quantities and different conditions • Enhanced sink-source matching
Road	1.7-2 MPa 243-253 K (IPPC, 2005, Wang, S., 2005)	Liquid	>1 Mt CO_2/year (Svensson, et al., 2004)	• 2-30 tonnes per batch • Not economical for large-scale CCUS projects • Boil-off gas emitted 10% of the load (Wang, S., 2005)
Railway	0.7-2.6 MPa 223-253 K (IPPC, 2005, Wang, S., 2005)	Liquid	>3 Mt CO_2/year (Svensson, et al., 2004)	• No large-scale systems in place • Loading/unloading and storage infrastructure required • More advantageous over medium and long distances

4.1.3 CO_2 Storage and utilisation options

Once CO_2 has already been captured, conditioned and transported to the storage location, its long-term and safe storage must be assured to mitigate adverse effects or risks to the environment and human health. Geological storage is at present considered as the most feasible option for CO_2 storage (Leung, Caramanna and Maroto-Valer, 2014). Yet, other storage techniques, such as ocean storage, mineral carbonation and terrestrial carbonation could also contribute towards storing around

410–1670 $GtCO_2$ between 2000–2100, depending on the end of century CO_2 atmospheric concentration (Dooley, 2013; Maroto-Valer, 2010).

Having been already proven at a commercial scale (Maroto-Valer, 2010), geological storage involves CO_2 injection into a wide range of geological formations such as underground oil, gas or water reservoirs, deep un-minable coal seams having potential for enhanced coal-bed methane recovery, as well as deep saline geologic formations for a safe, long-term storage. These formations are typically located one to three kilometres under the ground, which allows CO_2 to remain in the liquid or supercritical phase, and have the effective and practical capacity to store 13500 and 3900 Gt of CO_2 globally (Dooley, 2013).

The capacity of the geological formation to store CO_2 is determined by two trapping mechanisms. The first trapping mechanism, physical trapping, corresponds to the physical characteristics of the geological formation that should include the impermeable shale or clay rock layer that prevent upward migration of CO_2 and, eventually, its leakage to the environment. The second tapping mechanism, geochemical trapping, involves a chemical reaction of CO_2 with the host rock to produce carbonates that minimises the probability of CO_2 leakage and allows for a long-term, safe storage. Importantly, when injected into oil and gas reservoirs, CO_2 can be simultaneously stored and utilised to enhance the production of oil and gas, bringing an economic benefits to the oil and gas industry, as well as providing an additional financial incentive for CCS in power sector (Spliethoff, 2010). Such techniques for enhanced oil recovery have been already practiced commercially since early 1970s, especially in North America. Also, enhanced gas recovery via injection of CO_2 into the depleted gas reservoirs has been demonstrated.

Ocean storage is another potential storage option for storing CO_2, although it is perceived more negatively by the public compared to the geological storage (Metz et al., 2005). Yet, it has been estimated that for the atmospheric CO_2 concentration of 350–1000 ppm_v, about 2300–10700 Gt of anthropogenic CO_2 will be eventually stored in the ocean due to the equilibrium between the atmosphere and the ocean (Metz et al., 2005). The ocean storage relies on limited mixing of the deep ocean and surface water at depths below 800–1000 m, resulting in the surface water layer acting as an insulation from the atmosphere (Spliethoff, 2010). Importantly, below at the depths below 2600 m, the water temperature drops to 2°C and CO_2 is denser than water (Spliethoff, 2010). As a result, the upward movement of CO_2 is restricted and so-called CO_2 lake is created. In addition, CO_2 interacts with water to form hydrates, and thus is stored for a long periods of time.

Mineral carbonation is seen as a potential storage technique, in which CO_2 is fixed through carbonation of naturally abundant magnesium, iron and calcium oxides or silicates (Maroto-Valer, 2010), especially in locations where geological storage capacity is limited or not viable (Sanna et al., 2014). It has been estimated that the mineral requirement of this process is 1.6–3.7 tonne per tonne of CO_2 to be fixed (Metz et al., 2005). Although this process is exothermic and has a theoretical potential for energy recovery, the kinetics of the natural mineral carbonation is slow and thus an energy-intensive thermal pre-treatment is required to enhance the carbonation reaction rate (Metz et al., 2005). It has been estimated that the energy requirement for the mineral carbonation would reduce the net power output of the power plant by 30–50% (Spliethoff, 2010), what makes this process not economically feasible at this moment (Sanna et al., 2014).

Terrestrial ecosystems can be used to fix CO_2 emitted from anthropogenic sources, and thus they do not require CO_2 to be captured and transported. Such terrestrial carbon sequestration techniques involve tree planting, wetlands restoration, grass and grazing land management, forest preservation and fire management. This aims at removing CO_2 directly from the atmosphere through biological, chemical and geological processes taking place in the soil and plants, as well as preventing of the net CO_2 atmospheric emission from the terrestrial ecosystems (Maroto-Valer, 2010). These processes are described in more detail in Section 5.

4.2 Challenges and opportunities associated with CCUS at airports

After the discussion with the four airports surveyed and analysis of their CO_2 emissions from three scopes from different airports, a number of opportunities and a few challenges have been identified. It has been found that some mitigation measures have been taken by airports to reduce CO_2 emissions while there are some challenges to remove CO_2 in certain areas. Airports can reduce their impact on climate change by addressing emissions in ground transportation, energy use in buildings and other related infrastructure as well as addressing the associated indirect emissions present at the airport. For example, Aberdeen and SFO airports purchased energy from renewable energy sources to support energy use in airport operation (Scope 2 CO_2 emission is completely mitigated). Delhi airport started to use PV system to provide energy for airport to reduce CO_2 emission. All the three airports reduced their energy consumption with more efficient monitoring of heating, ventilation, and cooling systems. All the airports have considered the acquisition of low or zero emission vehicles and ground service equipment (GSE). The use of electric powered vehicles which are environmentally more favourable as they reduce vehicle emissions at an airport.

The challenges with the CO_2 capture from Scope 1 and 3 emissions are evident, particularly the capture of CO_2 directly emitted from the combustion of jet engines and fuels for central energy use such as diesel engine which is widely used in Delhi airport. The current CO_2 capture technologies as mentioned above can be applied to the stationary power and heat generation but not possible to abate CO_2 emission from aircraft.

Some countries have government regulations and incentives to support CO_2 reduction at airport. For example, in the US, there are state and Federal incentives for certain energy efficiency measures. Tax exempt leases, renewable energy cooperatives, power purchase agreements, and other arrangements are low-risk, low-cost options to simultaneously reduce GHG emissions and energy costs. The Federal Aviation Administration provides also provides grant funding for certain airport emissions reduction projects. This is the reason why SFO airport have achieved significant CO_2 emission reduction. UK government and Department of Transport also provide fundings to support CO_2 capture and conversion to green jet fuels such as recent “Green Fuels, Green Skies” funding.

4.3 Recommended CCUS technology for airport

As mentioned before, the most difficult part is to remove Scope 1 and Scope 3 CO_2 emissions. One of the opportunities for such CO_2 abatement is to capture CO_2 emission at airport using direct air capture and then convert CO_2 to jet fuels or other commercial applications.

The four airports surveyed have CO_2 emissions in the range of less than 1million tonnes CO_2, which is emitted from different sources. This indicates the suitability of direct air capture of CO_2 in the airport. Converting CO_2 to jet fuel using renewable energy has been suggested and tested at pilot scale to demonstrate the economic viability of CO_2 utilisation, which provides a technologically feasible option for airport applications.

Based on the current technology demonstration, it is estimated that 0.4-24.7 km^2 land is required to build the plant to capture 1 Mt CO_2. The land required for the four airport are summarised in Table 4.3 below. Taking Luton airport as an example, which emit approximately 100 kt CO_2 per annum, only a 0.04-2.5 km^2 land size would be required, which is achievable. Even for SFO which has the highest CO_2 emission (1.7 million tonnes), the land required to capture all CO2 only require 0.65-42.18 km^2 land size, which is feasible given the quite large airport area. It is suggested to assess the economic viability and technological feasibility of the technology.

Table 4.3 Area of the land required of the case study airports using DAC technology

	Aberdeen (ABZ)	Luton (LTN)	Delhi (DEL)	San Francisco (SFO)
Scope 1 (tonne CO_2)	5,513	2,966	4,310	17,456
Scope 2 (tonne CO_2)	0	4,981	59,195	0
Scope 3 (tonne CO_2)	66,436	278,268	1,887,426	1,680,125
Total CO_2 (tonnes)	71,749	286,125	1,950,931	1,697,581
Total airport area (ha)	203	325	2066	920
Required area (km^2)	0.027-1.8	0.11-7.15	0.75-48.62	0.65-42.18

It would not be possible to capture the CO_2 produced from aircraft operation directly due to the size and operating conditions of an aircraft and the capture unit. However, owing to recent rapid deployments of solar and wind energy technologies and cost reductions of renewable electricity based water electrolysis, the cost of hydrogen produced from wind, solar and other renewable sources can be very competitive in the future. By integrating renewable hydrogen with the direct air capture, CO_2 can be converted into sustainable aviation fuel.

Figure 4.6 shows the schematic of the direct air capture from airport and conversion of CO_2 to jet fuel using renewable hydrogen using renewable electricity. ABZ and SFO have already purchased renewable electricity to reduce Scope 2 emissions. It is possible to extend the use of renewable electricity to produce sustainable aviation fuel. LTN and DEL are also considering increasing renewable electricity use in their respective airport. Integrating sustainable aviation fuel production into the whole process is an option to consider.

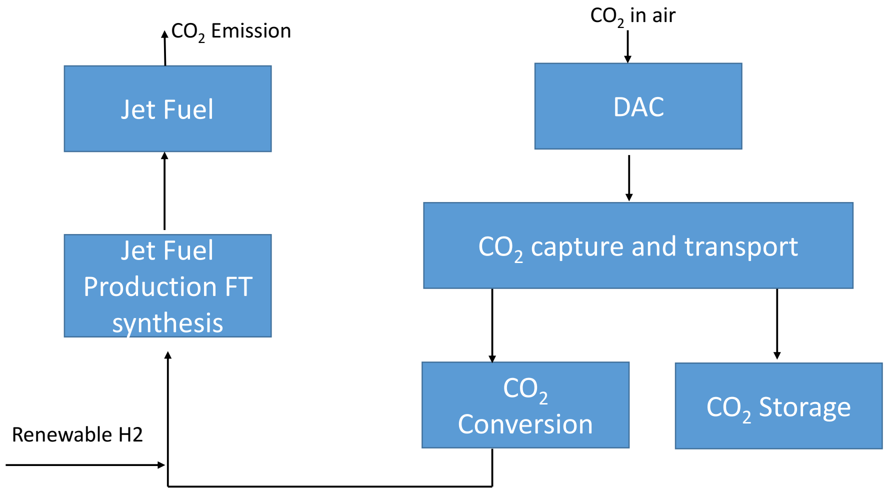

Figure 4.6 Direct air capture and CO_2 conversion for jet fuel production

5. Nature based solutions

Nature-based solutions offer another way to sequester, use and store CO_2 using ecological processes such as photosynthesis and rock weathering. They can often provide additional benefits such as enhancing biodiversity, water quality and an improvement in human well-being. Nature-based solutions are generally not considered to include other sustainability practices that may bring about emissions reduction benefits (for example on-site composting of food waste), or the use of biodegradable material as an alternative to plastics. Although no one measure is likely to offset the full GHG emissions of an airport, they can contribute to a portfolio of approaches.

5.1 Area of airports and GHG emissions per hectare

When examining nature-based solutions, it can be useful to establish the baseline level of carbon stock and net fluxes of GHGs before considering interventions. The four case study airports vary in size from 203 ha at Aberdeen to 2066 ha for Delhi. Excluding the water area, San Francisco airport covers 920 ha (**Table 5.1**). The area of green space across the four airports is more consistent, with a relatively small reported area of green space at Delhi of 51 ha ranging to 110-140 ha for the other three airports. These areas of green space are relatively small and comparable to the size of typical commercial farms in the UK and USA..

The level of Scope 1 and 2 emissions at the four case study airports range from 19-31 t CO_2 ha^{-1} yr^{-1} (**Error! Reference source not found.**). It is assumed that the Scope 2 emissions at Aberdeen and San Francisco are zero because of the use of “green electricity”. By contrast the level of Scope 1, 2 and 3 emissions can be one to two orders of magnitude higher, equivalent to 354 to 1845 t CO_2 ha^{-1} yr^{-1}.

Table 5.1 Area of the land holding of the case study airports, and annual Scope 1, 2, and 3 emissions per hectare.

	Aberdeen (ABZ)	Luton (LTN)	Delhi (DEL)	San Francisco (SFO)
Scope 1 (tonne CO_2)	5,513	2,966	4,310	17,456
Scope 2 (tonne CO_2)	0	4,981	59,195	0
Scope 3 (tonne CO_2)	66,436	278,268	1,887,426	1,680,125
Total CO_2 (tonnes)	71,749	286,125	1,950,931	1,697,581
Total airport area (ha)	203	325	2066	920
Scope 1 and 2 (t CO_2 ha^{-1} yr^{-1})	27	24	31	19
Scope 1, 2 & 3 (t CO_2 ha^{-1} yr^{-1})	354	880	944	1845
Landscape and open space (ha)	110	140[a]	51	136

[a]: Estimated using aerial imagery

5.2 Insetting, twinning and offsetting

Nature-based solutions to carbon sequestration, use and storage require land. The solutions can be directly applied within the airport estate or delivered in the wider landscape. Airports potentially have three options in developing and using nature-based solutions: insetting, off-setting, and twinning.

Insetting refers to the implementation of nature-based solutions within the confines of the existing area of the airport. The opportunities for implementing some nature-based solutions within the airport, such as tree planting, are likely to be constrained by safety concerns such as minimising bird numbers and solid structures close to runways. Such approaches, however, have substantial potential to be supported by airports for implementation at the wider landscape scale (e.g. in neighbouring farmland or urban ecosystems).

Offsetting refers to the purchase of verified reductions in GHG emissions by a third party. The offsets may be a result of avoided emissions or carbon sequestration, where each "offset" of "carbon credit" is usually equivalent to one metric ton of carbon dioxide equivalent (CO_2e).

An alternative intermediate arrangement is where an airport enters into a "twinning" arrangement with another organisation, often locationally linked to the airport, to for example sequester carbon (
Figure 5.1). In addition to carbon sequestration, the process may provide additional local or reginal benefits such as enhanced biodiversity and recreational benefits. For example, it may be possible for Luton Airport to locally offset some of its emissions by working with the local council or landowners in the area.

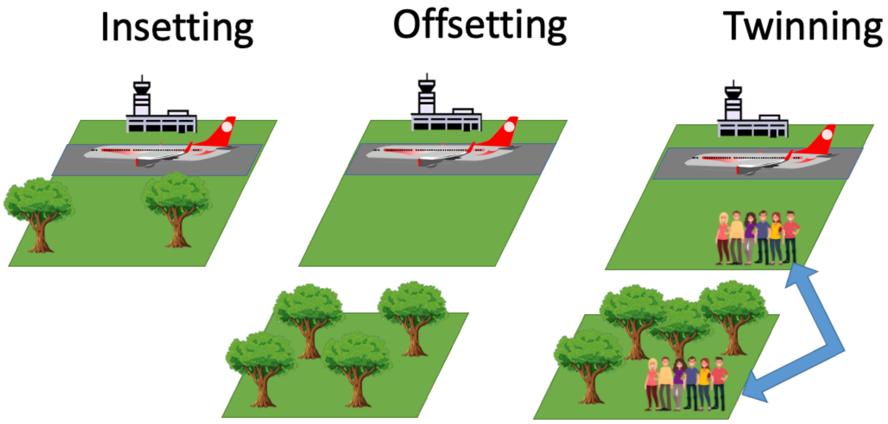

Figure 5.1 Nature-based solutions can be applied within the airport estate (insetting), on totally separate areas of land (offsetting), or through a twinning arrangement involving cultural links between the airport and the area of carbon sequestration

5.3 Nature-based practices

In this section, we review potential plant and soil management practices that the potential to either increase carbon sequestration in the land carbon sink, and/or may result in reduced carbon losses. Increase carbon sequestration (predominantly in agriculture as one of the largest land uses by area but also other ecosystems), and ecosystem restoration, reforestation and afforestation have substantial potential to reduce emissions relative to many other interventions (
Table 5.2).

Table 5.2. Nature-based solutions with indicative values for emissions reduction potential per unit land and indicative costs

Approach	Emission reduction ($t\ CO_2e\ ha^{-1}\ y^{-1}$)	Indicative cost (US$ ($t\ CO_2e)^{-1}$)	Reference
Woodland planting	12.0[a]	15-30	See Section 5.3.1.
Low density agroforestry[b]	3.7	15[c]	Pellerin et al (2017)
Plant hedges around fields	0.7	115[c]	Pellerin et al (2017)
Wetland restoration	0.4-18.0	10-100	Evans et al (2019)
Increase soil carbon	-[d]	3-25	Smith et al (2015)
Reduce N fertiliser use	0.2[e]	-45[c]	Pellerin et al (2017)
Biochar addition to grassland	4.6 - 22.6[f]	18-166	Wolf et al. (2010)
Rock weathering (20 t ha^{-1})	7.0	60-200	Lefebvre et al (2019)
Bioenergy with Carbon Capture and Storage (BECCS)	0-5.8[g]	88-288	Fuss et al (2018) Fajardy and MacDowell (2017)
Use of timber in buildings	300-700[h]	0	Spear et al (2019)
Green roof	13-76	500-3000	Meek et al (2014)

[a]: Indicative value for newly planted broadleaf woodland in the UK over 50 years

[b]: Low density agroforestry with 30 to 50 trees per hectare

[c]: Converted from Euros. 1.08 US$ = 1 Euro

[d]: Emissions reductions and costs depend on ecosystem type and management

[e]: Based on the reduction of 20 kg N ha-1 yr-1.

[f]: Biochar is not an annual application

[g]: European systems

[h]: Wood storage in house expressed per hectare of housing.

The processes outlined are predominantly biological, as they make use of either manipulating vegetation (tree planting or new species mixes in grasslands),or manipulating soils to alter rates of biological transformation processes (e.g. affecting the rate of nitrous oxide production, a potent non-CO_2 GHGs produced in soils following fertiliser applications).

5.3.1 Tree and woodland planting

Mechanisms: Tree and woodland planting encompasses both reforestation (trees being planted in areas that were previously forested but where vegetation was lost, most likely due to human activity) and afforestation (trees planted where previously there were no trees). As trees grow they absorb atmospheric CO_2 which is stored in vegetation and ultimately soils through the accumulation of organic matter (slowly decaying plant material). Once a forest reaches maturity the net uptake of CO_2 slows. The mean level of sequestration for a mixed broadleaf woodland in lowland England over 50 years is about 12 t CO_2 ha^{-1} yr^{-1} (**Figure 5.2**). It can take approximately 10 years for a new woodland to start sequestering high levels of carbon, reaching a peak at 10-40 years, before stabilising at a slowly declining value.

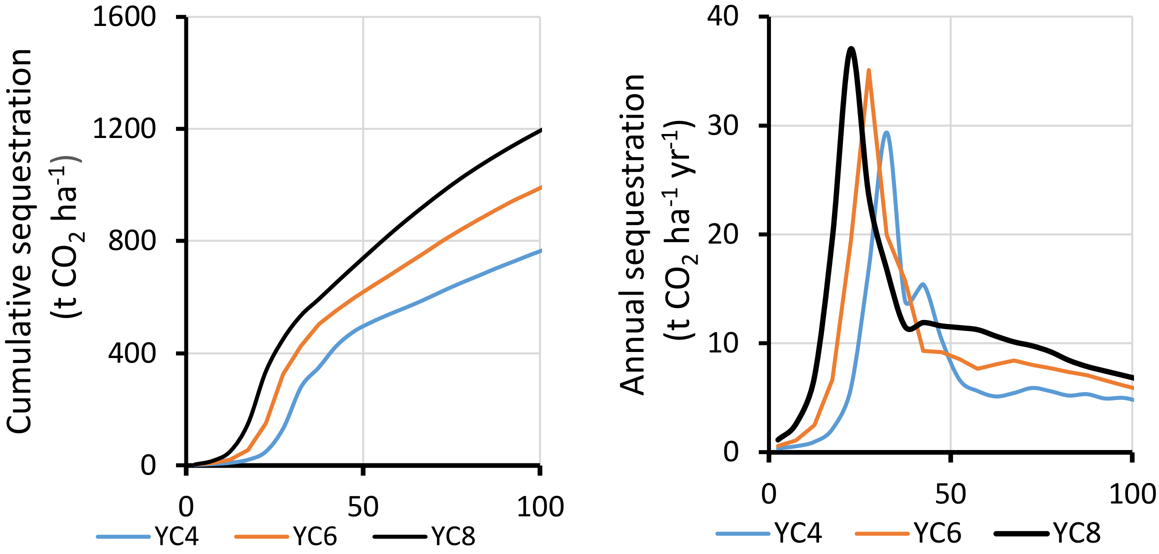

Figure 5.2. Predicted rate of carbon sequestration for beech (standing trees and debris) (unthinned, Yield Class = 4, 6, and 8, initial spacing = 2.5 m) (after Woodland Carbon Code 2020)

The above benefits of carbon sequestration with woodland planting only occur if the change to woodland is permanent and any harvested wood is permanently stored. In the UK, the Woodland Carbon Code is a carbon accreditation programme which includes buffers to ensure the permanence of the carbon storage.

Co-benefits and trade-offs: Tree planting may also bring additional benefits to local environments such as reducing runoff, improving local biodiversity, and moderating the micro-climates. However tree planting in the wrong place, for example peatland areas, can reduce biodiversity and can result in higher carbon emissions than, for example, rewetting the soil.

Potential carbon capture and costs: The methods for planting trees and quantifying the carbon benefits are generally well understood. Establishment costs can be relatively high, but management costs are comparatively low. In the UK there is the potential to sequester 1.2 $GtCO_2$ for under \$30 per tCO_2 and 0.4 $GtCO_2$ per year at less than \$3 per tCO_2. Future cost estimates range from \$15 to \$30 per tCO_2 for the year 2100 (Smith et al., 2015).

5.3.2 Increasing soil carbon by maintaining canopy cover and wet soils

Mechanisms: Increasing the carbon content of soils can be achieved by ensuring that carbon inputs (e.g. from decaying plant residues) is greater than losses (e.g. from soil disturbance). On agricultural land, methods to increase soil carbon include minimising cultivation and ensuring year-long canopy cover. However, in practice, very little land within airports will be cultivated, and grassland areas already maintain year-round canopy cover. In dryland areas, selecting deeper rooting grass species that can maintain photosynthesis for a greater proportion of the year, and thereby sequester more carbon may be an option. Because soil carbon oxidation rates are highest in dry soils, maintaining soil wetness, for example by maintaining a high water table, can also help to maintain or increase soil carbon levels.

Co-benefits and trade-offs: Approaches to increase soil carbon sequestration can be applied to all land (including grasslands airside, and urban soils) without needing to change current land use. Some practices have low energy requirements and can bring cost savings. Adding deep-rooted species may improve biodiversity. However it should be noted that eventually the capacity of the soil to store more carbon will reach a plateau, and hence there is a likely temporal limit to such changes.

Potential carbon capture and costs: Soil carbon sequestration rates are highly variable as they depend on management techniques, soil types (including existing carbon stocks) and climate. The majority of techniques are ready for deployment and have a high technology readiness level. Implementing practices that enhance soil carbon sequestration in agricultural systems and grasslands can cost between \$3 and \$25 per tCO_2 (Smith et al., 2015).

5.3.3 Reducing nitrogen fertiliser use

Mechanisms: mineral fertilisers are often applied to agricultural land in order to replenish the nutrients removed by the harvest of crops. However applying nitrogen mineral fertilizers can contribute to global warming by promoting the release of nitrous oxide, which has a global warming potential over 100 years (GWP_{100}) 273 times greater than CO_2 (IPCC, 2021; Chapter 7 page 125).

Co-benefits and trade-offs: Reduced nitrogen application may increase plant biodiversity and it reduces the emissions associated with fertiliser manufacture and application. Not applying fertilise also may represent a substantial cost saving.

Potential carbon capture and costs: A reduction in fertiliser use of 20 kg N ha^{-1} yr^{-1}, could result in a reduction of emissions equivalent to 0.22 t CO_2e ha^{-1} yr^{-1}. The avoidance of fertilizer costs may result in reduced costs and hence the intervention could pay for itself at a rate of about US\$ 45 (t $CO_2e)^{-1}$ (Pellerin et al. 2017). None of the case study airports reported the use of nitrogen fertilisers and therefore the likely benefits are minimal within airport landholdings. However, such benefits may be achieved through off setting or twinning approaches.

5.3.4 Wetland and peatland management

Mechanisms: Wetlands (including peatlands, mangroves and salt marshes) are generally substantial carbon stores. The oxidation of carbon from unwetted peatland areas can be significant and hence rewetting of peat areas is recommended to minimise carbon losses. Collectively, peatlands and coastal wetlands have been estimated to account for between 44% and 71% of the world’s terrestrial carbon sink. Existing stocks are highly vulnerable to climate change, but also land use (for example drainage for agriculture or urban expansion). Artificial wetland systems can also be created and can provide some carbon sequestration benefits. Moreover, constructed wetland systems may also be used for wastewater treatment, generally with lower emissions than conventional sewage treatment works. The carbon sequestration or GHG mitigation potential of such systems is dependent on design, but evidence suggests overall such systems can have similar mitigation potential across land use climatic zones (Rosli et al., 2017).

Co-benefits and trade-offs: Wetland restoration and improved management can bring substantial co-benefits including improving water quality and water provisioning for local communities, flood protection, and increased biodiversity. Although flooded wetlands can be source of methane, most wetlands are a net carbon sink when restored or in a natural state. Because of the safety requirement to minimise bird strike, wetland management needs to be done in a way that it does not attract large numbers of birds.

Potential carbon capture and costs: The necessary steps for wetland restoration and sustainable management are generally well-understood, and therefore approaches have a high technology readiness level. The long-term potential for carbon capture through wetland restoration is between 0.4 and 18 tCO_2 ha^{-1} yr^{-1}. Evans et al. (2019) reports that a 10 cm rise in the water table of UK lowland peat decreases CO_2 emissions by around 3 t CO_2 ha^{-1} yr^{-1}. Costs for wetland restoration are between $10 and $100 per tCO_2, suggesting high potential for low-cost carbon capture. Wetlands have high potential for the provision of monetizable services, including water provision and flood management, as well as potential tourism opportunities. Estimates of the value provided by wetlands through such services range from $3,000 to $14,800 per ha per year (Worrall et al., 2009).

5.3.5 Biochar

Mechanisms: Biochar is a highly stable, long-lived form of carbon similar to charcoal. It is produced from the thermal decomposition of organic materials in the absence of oxygen (a process known as pyrolysis). Biochar stores the original biomass carbon in a form resistant to decomposition that can remain in soils for extended periods (Weng et al., 2017). Hammond et al (2011) report that of all of the carbon initially in the biochar, 68% would still be present after 100 years. Biochar can generally be applied to existing land without changes in land use.

Co-benefits and trade-offs: Biochar applied to soils can result in improvements in soil fertility and soil health. Biochar can also stabilise heavy metals, reducing their uptake by plants and thereby have a role in site remediation. It can also have some impacts on the production of non-CO_2 gases, particularly nitrous oxide. In addition to soil applications, biochar can also be used as a substitute for fossil fuels for energy production, but this will result in increased CO_2 emissions through combustion. Production also requires some energy use, and land is needed for growing biomass suitable for biochar production.

Potential carbon capture and costs: Biochar is a heavily researched carbon capture technology, at a relatively high readiness level, but is not yet widely applied. In part, this is due to costs, and the availability of suitable pyrolysis facilities. Biochar may be able to remove between 2.1 to 4.8 t CO_2 per tonne of biochar applied to soils (depending on the source material used for its production and application rates). Soil application rates can be as high as 30 to 60 t per ha. Predicted costs for biochar range between $18 and $166 per t CO_2 depending on feedstocks and energy requirements for production (Wolf et al., 2010).

Figure 5.4: Use of biochar in an organic farming system.
Source: Organic Farming (2015)

5.3.6 Enhanced silicate weathering to fix atmospheric CO_2,

Mechanisms: Enhanced weathering has been defined as the "process by which CO_2 is sequestered from the atmosphere through the dissolution of silicate minerals on the land surface" (Renforth, 2012). The process involves both weathering (Equation 1) and carbonation (Equation 2) (Lefebvre et al. 2019).

$$CaSiO_3 + 2CO_2 + 2H_2O \Rightarrow Ca^{2+} + 2HCO_3^{-} + SiO_2 + H_2O \qquad \text{Equation 1}$$

$$Ca^{2+}\ 2HCO_3 \Rightarrow CaCO_{3(\text{in soils})} + CO_2 + H_2O \qquad \text{Equation 2}$$

Co-benefits and trade-offs: the feasibility of using silicate weathering is dependent on a local source of silicate rock, as transport emissions can become significant. The rate of weathering is increased by grinding the rock to a powder, but the fine powder can cause respiration problems (Strefler et al. 2018)

Potential carbon capture and costs: An application of 1 t ha^{-1} of calcium silicate is estimated to sequester 0.125 t CO_2 through carbonation, and 0.225 t CO_2 through weathering (Lefebvre et al. 2019). A potential rate of application may be about 20 t basalt per hectare (Lefebvre et al. 2019). Strefler et al. (2018) estimated a cost of carbon removal around 60 \$ t CO_2^{-1} for dunite and around 200 \$ t CO_2^{-1} for basalt.

5.3.7 Bioenergy with carbon capture and storage (BECCS)

Mechanisms: Although the potential for use on airports is likely to be minimal, there is continued interest in the use of growing crops for bioenergy, capturing the carbon dioxide released from combustion typically using a solvent. The carbon dioxide can then be pressurised or liquefied for transportation before being injected and permanently stored in porous rock formations. Biomass includes both dedicated energy crops such as *Miscanthus* and willow. Detailed analysis of the particular system is necessary to ensure that the overall system results in negative emissions of GHGs, as the results are highly variable (Fajardy and MacDowell, 2017). High biomass yields, low fuel and chemical inputs, and minimising indirect land use change are particularly critical.

Co-benefits and trade-offs: Biomass production and CCS both have different environmental benefits and trade-offs. For biomass production, land use change associated with the dedicated production of energy crops can result in increased emissions. The combustion of biomass can reduce local air quality although CCS technologies can help mitigate some issues. Pollutants produced include sulphur dioxide, particulates, and nitrous oxides (NO_x). Large-scale production of biomass can also affect water availability in dry areas. The time period for growing the biomass also needs to be considered.

Potential carbon capture and costs: Fajardy and MacDowell (2017) estimated that growing willow on grassland in Europe would result in net GHG emissions, but growing willow on marginal land could result in a mean removal of 288 t CO_2 ha^{-1} over 50 years (5.76 t CO_2 ha^{-1} yr^{-1}). Fuss et al (2018) reports that combustion BECCS typically have costs ranging from US$88 to US$288 $(tCO_2)^{-1}$, with the authors considering a cost of US$100–200 $(tCO_2)^{-1}$.

5.3.8 Use of timber in buildings

Mechanisms: Timber, alongside concrete and reinforced steel, is one of the most common building materials. Using timber in buildings is an established way of storing carbon. About 28% of all new houses in the United Kingdom are timber framed (Spear et al 2019).

Co-benefits and trade-offs: Most buildings using timber are less than six storeys high, although taller buildings can use cross-laminated timber (CLT) (Ramage et al., 2017). A critical element in timber building is the strength of timber connections. The strength and stiffness of timber is sensitive to temperature and moisture. The strength at 100°C is only 50% of that at 20°C (Ramage et al., 2017).

Potential carbon capture and costs: It is estimated that only 10% of global forests and 30% of global roundwood production is certified. Spear et al. (2019) considered that timbered-framed houses stored 2.0-4.2 t CO_2e more per unit than masonry equivalents. Assuming an internal floor area for a bungalow of about 60 m^2, this represents the storage of 330-700 t CO_2e ha^{-1}. The cost of timber- and masonry buildings are similar (Spear et al. 2019), so the cost of storage is close to zero. Upton et al (2007) report that net GHG emissions associated with wood-based houses (typically 15% rather than 7% wood content) were 20–50% lower than those from comparable houses based on steel or concrete.

5.3.9 Green infrastructure including roofs and walls

Mechanisms: Green roofs are roof surfaces partially or completely covered with a growing medium and vegetation over a waterproofing membrane (Meek et al. 2014). Green roofs and walls can help to mitigate temperature extremes in urban areas due to the evaporative cooling of transpiring plants, thereby reducing the use of energy for air conditioning or heating. However, the extent of the effect does depend on the vegetation type (McConnell et al. 2022). It is estimated that about 14% of newly constructed roofs in Germany are green roofs (Meek et al 2014).

Co-benefits and trade-offs: Green roofs are generally considered to have an aesthetic value, thereby increasing human well-being. This effect can be particularly important in an airport with a high footfall. Green roofs can also reduce air pollution and moderate runoff.

Potential carbon capture and costs: The level of GHG reductions primarily relate to reduced air conditioning costs. Meek et al. (2014) in Australia calculated savings equivalent to between 13 t and 76 t CO_2eq ha^{-1} yr^{-1},. Castleton et al. (2010) estimated that the cost of retrofitting an extensive green roof to an office building would be about 195 US$ m^{-2} (so assuming a roof longevity of 20 years, the cost would be 500 to 3000 US$ (t CO_2eq)$^{-1}$.

Figure 5.5: Green roofs and use of timber in buildings

5.4 Opportunities for Nature-based solutions

Table 5.3 shows the potential for carbon sequestration using available open land for selected techniques. In general, nature-based solutions are likely to make a small but significant contribution to reducing emissions. For example, woodland planting across 20% of the open land at Aberdeen airport, combined with wetland creation on a further 20%, and biochar application across the entire area would potentially reduce emissions by 374-1157 t CO_2e yr^{-1}, equivalent to 7-21% of Scope 1 emissions, or 0.5 -1.6% of total CO_2 emissions. Such an approach would also bring various co-benefits including for biodiversity and flood risk management. The use of off-setting or twinning approaches would potentially result in much greater emissions reduction due to an increase in available land area.

Table 5.3 Indicative levels of carbon sequestration using nature-based solutions, if they could be applied to 20% of the available open land

Approach	Emission reduction ($t\ CO_2e\ ha^{-1}\ y^{-1}$)[b]	Total emissions reduction ($t\ CO_2e\ y^{-1}$)			
		Aberdeen (ABZ) 110 ha	Luton (LTN) 140 ha	Delhi (DEL) 51 ha	San Francisco (SFO) 136 ha
Woodland planting [a]	12.0	264	336	122	326
Low density agroforestry [a]	3.7	81	104	38	101
Plant hedges [a]	0.7	15	20	7	19
Bioenergy carbon capture and storage (BECCS) [a]	0-5.8	0-128	0-162	0-59	0-158
Wetland restoration or creation [a]	0.4-18.0	9-396	11-504	4-184	11-490
Biochar addition[b]	4.6-22.6	101-497	129-632	46-230	125-615
Rock weathering[b]	7.0	154	196	71	190

[a]: Assuming techniques are applied to 20% of available land to minimise impacts on airport operations.

[b]: The assumption is that the application of biochar and rock weathering would not be annual

6. Conclusions

We reviewed the feasible CCUS methods which are suitable for airport operations using four case study airports.

6.1 Feasibility heatmap

Table 6.1 summarises the possible operating cost in the case of 'The DAC (Direct air capture) method. According to the ACI's policy, airports are currently responsible only for Scopes 1 and 2. Airports attempt large efforts to minimise the emissions from their operation by purchasing renewable electricity and electrifying the vehicles to support the airport operations.

Table 6.1 Total operating cost (USD M) and land area required for direct air capture option

	Aberdeen (ABZ)	Luton (LTN)	Delhi (DEL)	San Francisco (SFO)
Scope 1 (CO_2 tonnes)	5,513	2,966	4,310	17,456
Scope 2 (CO_2 tonnes)	0	4,981	59,195	0
Scope 3 (CO_2 tonnes)	66,436	278,268	1,887,426	1,680,125
Total CO_2 (tonnes)	71,749	286,125	1,950,931	1,697,581
Scopes 1 and 2				
Direct Air Capture (required land area for plant) (m^2)	2.2-136	3.2-196	25-1,568	7-431
Total cost (USDM) *	3.7-5.8	5.2-8.4	42-67	11.4-18
Cost (USD) per passenger	1.2-1.9	0.3-0.5	0.6-0.96	0.2-0.3
Total emissions (incl. Scope 3)				
Direct Air Capture (required land area per plant) (km^2)	0.29-17.8	0.11-7.1	0.78-48.2	0.68-42
Total cost (USDM)	47-75	187-300	1,278-2,045	1,112-1,779
Cost (USD) per passenger	16-25	10-17	19-30	19-31

Note: cost refers to the operating cost (excluding the infrastructure investment).
Note 2: exchange rate: 1 GBP= USD1.31

Although the land area required for DAC is relatively small, the initial investment is large. However, when we compute the operating cost to abate CO_2 per passenger, it becomes USD0.2-0.3 for SFO, USD0.3-0.5 for LTN, USD0.6-0.96 for DEL, and USD1.2-1.9 for ABZ in case of Scopes 1 and 2.

Even for the case including Scope 3, the cost per passenger will be USD19-31 for large airports (SFO and DEL), and USD10-17 for LTN and USD16-25. The current EUA (European Allowance) price is €50 per tonne in May 2022, expected to be more than €230 per tonne by 2050.

Many energy production facilities, such as coal, are increasingly equipped with CCUS. For instance, around 80% of coal produced in 2050 applies CCUS in the Net Zero emission scenario (IEA, 2021). Therefore, it could be one of the options to offset all emissions at the airport by applying the net zero policy at the point of emission source via CCUS in the long term.

In addition, the integration of Hydrogen production generated by renewable energy or low carbon power (Green Hydrogen), SAF production and DAC at airport can be the ideal solution for achieving the true net zero target.

A large investment and long term policy with strong leadership are required, which can be operated together with the hydrogen power generation or green fuel to supply aircraft power. As a part of the net zero roadmap by 2050, the CCUS option should be included along with other energy policies for air transport.

Various CO_2 capture technologies for airport operation are summarised as a heatmap in table 6.2. In general, there are a number of commercially ready technologies for capturing CO_2 from the point source. These technologies can be used to capture CO_2 from the combustion of diesel engines for central energy production as widely deployed in DEL. These technologies can also be applied to large scale coal/natural gas-powered plants for CO_2 capture, with the electricity produced being purchased by airport such as practised by SFO and ABZ.

Membrane technology is suitable for small scale point-source CO_2 capture but still requires development to increase efficiency and thus reduce cost. Capturing Scope 1 and 3 emissions is the most challenging faced by all the four airports surveyed. In this case, direct air capture will play a role. Although still in the early stage of development, direct air capture seems to be a feasible option for CO_2 capture for the airport applications, given the flexibility in location and the relatively small total amount of CO_2 emissions (less than 1 million tonnes from Scopes 1 and 3 in all the four airports).

Table 6.3 summarises the potential of different nature-based solutions for emissions mitigation. In general, the technology readiness level of most solutions is high, as are many of the potential emissions reductions that can be achieved. Most solutions are of low to medium cost and can be permanent assuming there is little to no change in current management practices.

Many approaches may be combined, potentially bringing additive benefits even when deployed across only a limited area of available open ground at an airport, potentially mitigating a substantial proportion of Scope 1 emissions (for example 7-21% of Aberdeen's Scope 1 emissions through woodland planting, wetland creation, and biochar application). With UK aviation targeting an overall 15% reduction in net emissions relative to 2019 by 2030, such approaches may have significant potential. Combining a suite of solutions into a single toolkit may represent one possible pathway for monetisation and promoting adoption.

Table 6.2 CO_2 capture technologies heatmap for airport operation

CO_2 capture technologies	TRL	Scalability	Cost	Performance is Scope 1-3 CO_2 capture	Suitable geographical location
Cryogenic	High	High	Low	High for Scope 1 and 2 but low for Scope 3	Can be used in combined with existing heat or/and power generation at various scales to capture CO2
Adsorption (e.g. amine scrubbing)	High	High	Low	High for Scope 1 and 2 but low for Scope 3	
Absorption	High	High	Low	High for Scope 1 and 2 but low for Scope 3	
Advanced combustion (e.g. chemical looping and oxyfuel combustion)	Medium	Medium-High	Medium	High for Scope 1 and 2 but low for Scope 3	
Membrane	Medium	Low-Medium	Medium-High	High for Scope 1 and 2 but low for Scope 3	
Direct air capture (DAL)	Low	Medium-High	High	High for Scopes 1-3	Not limited to the geographical locations

Table 6.3 Nature based solutions heatmap for airport operation

	Technology Readiness Level	Emission reduction per hectare	Cost of CO_2e saved	Permanence	Scalability on airport land holding	Scalability through twinning
Woodland planting	High	High	Low	Medium-High	Low	High
Low density agroforestry (30-50 trees ha^{-1})	High	Medium	Low	Medium	Low	Medium
Plant hedges around fields	High	Medium	Low	Medium	Low	Medium
Wetland restoration	High	High	Medium	Medium	Low	High
Increase soil carbon	High	Medium	Medium	Medium	Low	Medium
Reduce N fertiliser use	High	Medium	Low	Medium	Low	High
Biochar addition to grassland	Medium	Medium	Medium	High	Medium	Medium
Rock weathering (20 t ha^{-1})	Medium	Medium	Medium	Medium	Low	Medium
Bioenergy with Carbon Capture and Storage	Low	Variable	High	Potentially high	Low	Medium-high
Use of timber in buildings*	Medium-High	High	Low	High	Medium	Not applicable
Green infrastructure including roofs and walls	Medium	Low	High	Medium	Medium	Not applicable

*: Use of timber incorporated in new, already planned, buildings

Nature-based solutions can also bring substantial co-benefits. For example, woodland planting can result in improvements in air quality and enhance biodiversity. Wetland restoration (and the creation of new wetlands) can also increase biodiversity but also provide protection against flooding. Depending on design, constructed wetlands may also be used for wastewater treatment. For example, Heathrow Airport use a constructed wetland system (subsurface flow reedbed with a gravel substrate) to treat run-off. Similar systems can also be used for processing sewage waste, often with lower CO_2e emissions than conventional sewage treatment works.

Numerous nature-based solutions for emissions mitigation do, however, face potential scalability issues within airport land holdings. Although the area of open land within most airports is broadly comparable to the average area of a UK farm, not all techniques can be applied equally. For example, wetland restoration may reduce operational effectiveness (e.g. by increasing bird numbers) unless applied to a much smaller area of land or combined with additional measures (e.g. reducing access for birds or nesting). For all techniques. however, scalability is substantially greater through opportunities for twinning, where an airport enters into a twinning arrangement with another organisation, often locationally linked to the airport, to sequester carbon.

6.2 Innovative approach: Airport power train with eco system

The outputs of this research implicated some opportunities for CCUS at airport. The nature based solution's TRL is relatively high, and a large co-benefit is expected. However, the potential land scalability could be an issue.

The TRL of DAC is yet low but brings the innovative strategic approach for achieving the true net zero target. For example, it could be integrating Hydrogen production generated by renewable energy or low carbon power (Green Hydrogen), SAF production and DAC at airport.

Cooperation with the local government and residents is key for both nature-based and engineering solutions. Furthermore, a large investment and long term policy with strong leadership are required, which can be operated together with the hydrogen generation or green fuel to supply aircraft power.
CCUS at airports should be considered part of the carbon offset scheme and projects. The carbon credit could be awarded like the Clean Development Mechanism (CDM) and Joint Implementation (JI) under the UNFCCC.

It incentivises the airport and local government and can facilitate the investment and finance to cover the abatement cost by establishing the financial system. Of course, it might depend on the geographical location. However, some airports could be the power stations to fuel the air transport operation with CCUS in the long run.
The industry and governments expect the hydrogen or electrified aircraft in a commercial by 2030-35. The CCUS strategy should be investigated and planned along with the revolutionary technology for air transport operation. As a result, a drastic change in the airport infrastructure and operation is anticipated. The comprehensive system approach is imperative to tackle the innovative solutions by accelerating the R&D of new technology.

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