CIRCULÉIRE

CIRCULÉIRE'S CIRCULAR AVIATION GOOD PRACTICE SECTORAL GUIDE

IRISH MANUFACTURING RESEARCH

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Purpose of this Guide

CIRCULÉIRE's Circular Aviation Good Practice Sectoral Guide is intended for those involved in the aviation industry, from aircraft manufacturers to airport operators, as well as policy makers. It aims to provide industry stakeholders with an overview of industry-led circular innovations that are shaping the aviation sector in other parts of the world, and to highlight the sectoral opportunities to circularise the sector here in Ireland. For policymakers, it should help draw attention to some of the key policy strategies which are helping to advance circular economy in the Aviation sector in other jurisdictions.

It is part of a series of reports produced by Ireland's National Platform for Circular Manufacturing targeted at Irish industry players in sectors deemed strategically important to supporting Ireland's transition to a circular economy.

About CIRCULÉIRE

CIRCULÉIRE, the National Platform for Circular Manufacturing seeks to accelerate Ireland's transition towards a net-zero carbon circular economy. A key objective of the programme is to demystify, de-risk and deliver circular business model innovation for Irish industry.

Want to learn more about CIRCULÉIRE? Visit our website at www.circuleire.ie or contact circuleire@imr.ie

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Acronyms

CE	Circular Economy
CFRP	Carbon Fibre Reinforce Polymers
DECC	Department of Environment, Climate and Communications
ECO-COMPASS	Ecological and Multifunctional Composites for Application in Aircraft Interior and Secondary Structures
EPA	Environmental Protection Agency
EU	European Union
FRP	Fiber Reinforced Polymer
GDP	Gross Domestic Product
GHG	Greenhouse gas emissions
HELACS	Holistic processes for the cost-effective and sustainable management of End of Life of Aircraft Composite Structures
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LCA	Life Cycle Assessment
IMR	Irish Manufacturing Research
NLR	Netherlands Aerospace Centre
MRO	Maintenance, Repair, and Overhaul
OEM	Original Equipment Manufacturer
PAMELA	Process for Advanced Management of End of Life of Aircraft
RFID	Radio Frequency Identification
SAF	Sustainable Aviation Fuel(s)
TRL	Technology Readiness Level
WWF	Worldwide Fund for Nature
YVR	Vancouver International Airport

Section 1: Overview of Ireland's Aviation Sector

As an island nation, the aviation and air transport sector play a key role in supporting Ireland's economy. The sector plays a vital role through the jobs and spending generated by airlines and their supply chain, and the flows of goods and trade, tourism and investment resulting from users of all airlines serving the country (IATA, 2019).

> **"In terms of GHG emissions, aviation sector of Ireland contributes 20.7% to overall transport sector emission" (Department of Transport, 2021)**

It is estimated that the Irish air transport will grow by 55% in the next 20 years, which will result in additional 9.6 million passengers by 2037 (IATA, 2019).

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Importance of Aviation to Ireland's economy

The strategic importance of the Irish air transport sector to the Irish economy cannot be understated. The sector supports 143,000 jobs with more than 27% jobs are directly associated within the sector (IATA, 2019). The sector also plays an important role in enabling connectivity and supporting tourism for Ireland's island state economy. 193 international destinations involving 44 different airlines are covered by the Irish aviation sector. A total of 17.4 m passengers were catered to in Ireland in 2013, which increased to 38.1 m passengers in 2019. As a result of these operations, 6.8% of the GDP is supported by air transport & foreign tourists arriving by air (IATA, 2019).

Air transport is also vital to the flow of goods in and out of Ireland. In 2019, Ireland Aviation Sector handled by Irish airports was 146,000 tonnes, with Dublin airport handling 133,000 tonnes of air freight (or 91.1% of total air freight in Ireland) in this same period. While Air freight accounts for only a small share by weight of all freight exported or imported from Ireland, importantly this includes high-value merchandise such as pharmaceuticals (Department of Transport, 2021).

The global pandemic caused severe disruption to the Irish transport sector in the early 2020s. Nonetheless, it is expected that Irish air transport sector will continue to grow in the years ahead - by 2037 the sector is forecast to contribute $32 billion to GDP, cater to 28.3 million passengers and will support 171,000 jobs by 2037. However, if the sector is to play a role in building back better, and in supporting sustainable development and climate action – then the sector must urgently come to terms with circular economy (a concept that has up to now, been remained marginal in the sector (ICAO - Environment, 2019).

Why Ireland needs to shift away from a linear Aviation sector?

A radically different approach to our currently linear 'take-make-dispose' economic model is needed if we are to future-proof Ireland's Aviation sector against linear risks, while securing the sector's role in enabling Ireland's transition towards a circular, sustainable net-zero economy. Several points underline this need to rethink current business-as-usual approaches within the sector:

- The aviation sector is quite intensive in terms of emissions and resource consumption (IATA, 2019). According to the WWF, aviation is one of the fastest-growing sources of the greenhouse gas emissions driving global climate change (WWF, 2022). In Ireland, it generates more than 20% of the overall transport sector emissions (Department of Transport, 2021).
- If global aviation were a country, it would rank in the top 10 emitters. Before the COVID-19 crisis, the International Civil Aviation Organization (ICAO) forecasted that by 2050 international aviation emissions could triple compared with 2015 (EU Climate Action, 2021)
- In terms of sharing (i.e., a full flight is operated) the effective emissions from per passenger kilometer is almost double of a car shared by 4 people driven equivalent kilometers (calculation based on Eco-invent dataset version 3.7 for carbon emissions per passenger kilometer for different modes of transportation) (Ruiz et al., 2020).
- Current trends suggest that aviation companies are looking beyond carbon offsetting schemes alone to how they can make direct emissions and waste reductions in their own operations and wider supply chains. For instance, in 2022 EasyJet has committed to cutting its emissions by 78% by 2050 while simultaneously scrapping the carbon offsetting scheme (Reuters, 2022).
- Of the more than 27,000 commercial aircraft in service globally, over a fifth 20 years or older and likely to be decommissioned in the coming decade, while an additional 20,000 commercial aircraft are expected to be retired over the next 20 years (Elsayed et al., 2019). Consideration will thus need to be given to ensuring that future aircrafts are designed with circularity in mind, and to

improve circularity outcomes for existing aircrafts once they reach their end-of-life.

- By 2050, the aviation sector is expected to generate about 500,000 tonnes of accumulated carbon fibre reinforced plastic waste from the production and end-of-life phase (Meng et al., 2020).

Looking at the growth pattern of aviation sector, it is vital to focus on circular business and operational solutions to make the sector more sustainable. Indeed, for the reasons outlined above, aviation sector players in Ireland have already set ambitious targets to decarbonise the sector and reduce its resource efficiency:

- Dublin airport authority has set targets to achieve net zero carbon emissions by 2050 and few of the close targets are boost uptake of Sustainable Aviation Fuels (SAF) by 2% in 2025 and 5% in 2030 (Dublin Airport, 2022).
- The Irish Aviation Authority has outlined plans to i) become net carbon neutral by 2025 (excluding operational contingency and resilience requirements), and ii) Reduce waste generation by 50% per employee by 2025. Eliminate single use plastics in favour of reusable items. Recycle 90% of paper, cardboard, metal and glass generated in the IAA operations. (Read more about the IAA's sustainability goals in the Appendix here).

Decarbonising the sector, and meeting Ireland's waste and resource reduction and environmental objectives requires both circular economy innovation and transformative policies. A key aim of this guide is to highlight how although still an emergent concept in the Sector, Circular Aviation innovation can help decouple economic growth from the consumption of finite resources, to lessen the sector's current environmental footprint while opening up new commercial opportunities.

What do we mean by Circular Aviation?

The circular aviation definition used in this guide is adapted from the Joint Research Initiative of Netherlands Aerospace Centre (Future Sky, 2020). It defines Circular Aviation as "an approach to implement circular economy principles in aviation sector". The aviation sector is much broader than commercial aircrafts, cargo planes, and airports. It includes other more emergent industry activities, such as Unmanned Aircraft Systems (UAS) or drones, civil and military airspace use, navigations services, air traffic control, and private aircraft operations, which are not covered in this guide.

Instead, for the purposes of this Guide, we focus Circular Aviation innovation along three thematic areas where industry activity is well-established in Ireland:

1. **DESIGNING AND PRODUCING THE CIRCULAR AIRCRAFT –** Here the guide highlights some of the main aspects of design and production under the headings of circular design solutions, different choice of materials available, recovery and recycling of materials and components, and circular production/manufacturing.

2. **CIRCULAR FLIGHTS** – Here the guide covers circular economy opportunities related to flight operations such as in-flight service, packaging and waste, recycling activities, ground operations, maintenance, repair, and overhaul (MRO), and sustainable fuels are discussed separately.
3. **AIRPORTS AND AIRLINES AS CIRCULARITY AMBASSADORS** - Finally, the Guide highlights some of the circular economy opportunities identified for airports.

Specifically, this guide outlines the application of circularity principles such as circular design, eco-efficient manufacturing, sustainable aviation fuel, sustainable services in the sector (including zero waste food and packaging industry), predictive maintenance, extension of life cycle, sustainable end-of-life scenarios, and last but not the least circular ground operations.

A case study-led approach to building the case for Circular Aviation

This guide profiles 12 circular aviation innovations ranging in their stage of maturity and technological readiness level. Most of the projects are of technology readiness level 5 and 6; few of them are mature project for example sustainable aviation fuel (TRL 9) and the aircraft fleet recycling (TRL 9).

Methods

The Guide is based on information gathered using the following methods. An initial two-part scoping desktop review was conducted on:

1. the literature on circular economy in the aviation sector
2. policies and public-sector led initiatives aimed at supporting circular aviation

The findings of the desktop review were used to refine our Sectoral Guide objectives and were used to develop key criteria to select our case studies, using purposeful sampling, and to develop our analytical framework. Key circular economy databases were identified and used to identify a long list of circular innovations in the aviation sector.

In the final stage of our research, we identified and selected case studies according to the following criteria:

Circularity of the project/ initiative	In order to enable comparative analysis of the processes enabling different kinds of innovation, we sought to select projects which explicitly presented themselves as a circular innovation, pursued one or more circular economy strategies, and which illustrated circularity under on or more of the following 'clusters': 1. **DESIGNING AND PRODUCING THE CIRCULAR AIRCRAFT** 2. **CIRCULAR FLIGHTS** 3. **AIRPORTS AND AIRLINES AS CIRCULARITY AMBASSADORS**

Impact of the project/ initiative (proven or high potential)	"Circularity" in and of itself does not guarantee positive social, economic, and environmental performance (i.e., sustainability) (Blum et al., 2020). Case studies were shortlisted on the basis that they overtly self-identified as circular innovations and have demonstrated an effort to create impact(s) against different social, economic and environmental impact indicators. Consideration was given to ensure projects and initiatives profiled demonstrated positive performance (proven or high-potential if scaled) against material waste and carbon emission reductions. While we targeted examples of potential or established good practices, the aim of the case studies was not to evaluate projects or organisations - since even less 'successful' cases can yield important insights about existing barriers to implementing or scaling circular innovations.
Type of innovation and circular economy strategies employed	The case studies have been selected on the basis that they demonstrate a diversity of one or more of the following types of innovation. They are defined as the following: • **Process** innovation is the implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software (Eurostat Statistics Explained, 2022a). • **Technological** innovations comprise new products and processes and significant technological changes of products and processes(OECD, 2013). This may include digitally enabled solutions, such as BIM or Material Passports. • **Product** innovation is the introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. It involves significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics(Eurostat Statistics Explained, 2022b). • **Business model** innovation relates to innovations in a company's value proposition, creation and delivery, and in value generation. Circular business model innovation could involve developing a completely new business model or introducing a business model that is new to the company, even if it is considered fairly common in other companies or sectors (European Environment Agency, 2021). • **System innovation** can be characterised as a horizontal approach to innovation directed at problems that are systemic in nature, such as transitioning towards low-carbon energy systems or low-carbon transport systems, involving longer-term private and public sector actors' engagement and collaboration around the issue.

	Some defining characteristics of system innovation we focus on in this guide include i) a process of co-evolution between the different elements and actors in socio-technical systems. Ii) Transitions or transformations which occur at multiples level (i.e. an 'area' where there is space for radical innovation, experimentation and learning); and iii) Changes in consumer practices and markets (including market building through regional and industry cluster-based approaches) (Adapted from: (OECD, 2016).
Technological Readiness Levels (TRLs) of the Initiative	To gather information on both emergent / cutting-edge innovations and more established, 'market ready' circular aviation innovations, we selected case studies that were judged to range from lower and higher TRLs. This enabled us to gather insights about the opportunities and challenges (such as regulatory, scaling and replication challenges) from circular aviation innovations at different stages of maturity, and involving different sectoral players, such as aircraft manufacturers or airport operators.
Geographic variety	Efforts were made to highlight good practices originating in different market and sectoral conditions (with a particular focus on European regions). However, unlike other sectors, aviation as a sector is identified as being highly reliant on transnational actors and collaboration. This feature of the sector is discussed further in Section 3 of this Guide, and explains that while national efforts can and should be made to advance a Circular Aviation agenda with industry, other transnational and international actions will need to be delivered in tandem, such as market-based measures like the ETS and sustainable fuel mandating initiatives (e.g. through ReFuel EU Aviation, and the Alternative Fuel Infrastructure Regulation which will all include binding targets once adopted)(DECC, 2021).

Importantly, the list of circular aviation case studies selected for this guide is not exhaustive. Instead, they aim to highlight the diversity of opportunities for circular aviation action along the three areas outlined above.

To better understand the mix and variety of best practice collected for the guidance of aviation sector stakeholders, Table 1 below summarizes the case studies profiled in Section 2 of this guide.

Table 1: Overview of Circular Aviation good practices

Cluster	Case study name (include project/website links)	Region covered	What are the top CE Strategies?	What is the TRL of the initiative?
Designing and Producing the Circular Aircraft	**NextGen Aircraft Design** is Key to Aviation Sustainability	Global	Redesign/Circular Design	TRL 5
	HELACS A solution for End-of-life composite materials	Europe	Recover & recycle	TRL 6
	ECO-COMPASS Ecological and Multifunctional Composites for Application in Aircraft Interior and Secondary Structures	China and Europe	Redesign, Reuse and Reduce	TRL 4
	Expleo Eco-Design Centre Recycling of Carbon Fibre Reinforce Polymers (CFRP)	Europe	Redesign & Recycle	TRL 4
	SUSTAINair - circular economy for the aviation and aerospace sectors	Europe	Redesign, Reuse, Repair, Remanufacturing, Recycle	TRL 4
	Rolls Royce TotalCare - transforming traditional MRO services to power-by-the-hour	Global	Repair and Refurbishment	TRL 9
Circular Flights	**OzHarvest** Combating food waste and saving food waste to go to landfill	Oceania	Reduce and Reuse	TRL 6
	Reducing single-use plastic waste inflight	Global	Reduce and Reuse	TRL 7
	Loopworks & Delta Airlines Uniform Recycling Activities	United States	Reuse and Recycle	TRL 5
	KLM Royal Dutch Airline Uniform Recycling Activities	Europe	Reuse and Recycle	TRL 5
	Sustainable Aviation Fuel Flextjet - Biomass (food waste) into Biofuel	Europe & Global	Recycle and Reduce	TRL 9
	Using Recycled Aggregate to Build Circular Runway	Chile	Reuse and Remanufacturing	TRL 5
	Circular Economy in London **Gatwick Airport Operations**	Europe	Reduce and Recycle	TRL 5
Airports And Airlines as Circularity Ambassadors	**Amsterdam Airport Schiphol** Circular Economy	Europe	Renewable Energy, Reduce, Resource Efficiency	TRL 5
	Vancouver International Airport's ambitious waste reduction efforts	Canada	Reduce and Recycle	TRL 5

Structure of the Guide

This Guide is structured as follows:

- Section 2 builds on desk research and summarises Circular Aviation international good practices.
- Section 3 draws on the lessons learnt from the case studies and from the wider literature about what is needed to advance Circular Aviation in practice. It identifies three key barriers currently hindering the sector's transition to circularity. It concludes with two key recommendations about what's needed to advance a circular economy for the aviation sector here in Ireland.

Section 2: Circular Innovations in the Aviation Sector

This section highlights industry case studies which illustrate how circular innovations are shaping the Aviation sector. The selected case studies are categorised around the following three clusters:

- **DESIGNING AND PRODUCING THE CIRCULAR AIRCRAFT**
- **CIRCULAR FLIGHTS**
- **AIRPORTS AND AIRLINES AS CIRCULARITY AMBASSADORS**

In the pages below, we unpack the circular innovation opportunities related to each of these clusters and, using a case study-led approach, highlight examples of industry-led good practices.

A. DESIGNING AND PRODUCING THE CIRCULAR AIRCRAFT

> **"The most effective way to incorporate circularity is to implement circular principles at the conceptual design phase of an aircraft. This is because both design and manufacturing aspects need to incorporate circular economy principles in order to transition to a circular design and manufacturing" (Future Sky, 2020).**

Of the more than 27,000 commercial aircraft in service globally, over a fifth 20 years or older and likely to be decommissioned in the coming decade, while an additional 20,000 commercial aircraft are expected to be retired over the next 20 years (Elsayed et al., 2019).

According to the ICAO, on average, between 85 to 90 per cent of the weight content of retired aircraft is re-used or recycled, reflecting the fact that both re-usable parts and recycled materials represent significant residual value. While an estimated 40 to 50 per cent of the weight of all dismantled aircraft is returned to the parts distribution pipeline (*Ibid).*

The currently relatively high recycling and reuse rates mask a changing trend in the materials used. In recent years, aircraft manufacturers have increasingly shifted towards using carbon fibre material, which has been widely adopted for its low weight and related fuel burn reduction. However, recycling technologies are only now being developed to handle this carbon fibre material – which makes up the largest share of the less than 10 per cent of aircraft materials currently treated as waste (ICAO - Denise Pronk, 2019, p.282).

> **“By 2050, the aviation sector is expected to generate about 500,000 tonnes of accumulated carbon fiber reinforced plastic waste from the production and end-of-life phase”**(Meng et al., 2020).

The remaining aircraft waste materials are comprised of cabin interior components such as: insulation blankets, carpets, seat cushions, sidewalls, and ceiling panels, all of which contain embedded flame retardants, which are precluded from recycling due to safety regulations (ICAO - Denise Pronk, 2019, p.282).

It is widely recognised that it is better to incorporate and implement the circularity principles at the design phase of a product's development, where up to 80% of the product environmental impacts can be determined (European Parliament, 2022). As shown in Figure 1 below, integration of circularity thinking at the design stage affords product producers a greater degree of freedom/flexibility to explore repair / reuse / refurbishment / remanufacturing and even recycling outcomes at end-of-life. Such opportunities are significantly reduced where circularity thinking has been overlooked and as the product life cycle moves towards production, use and end-of-life. Meanwhile, integrating circular design into the production of aircrafts will also have a bearing on the design, selection of materials, recyclability (and other circularity outcomes), and manufacturing / production processes.

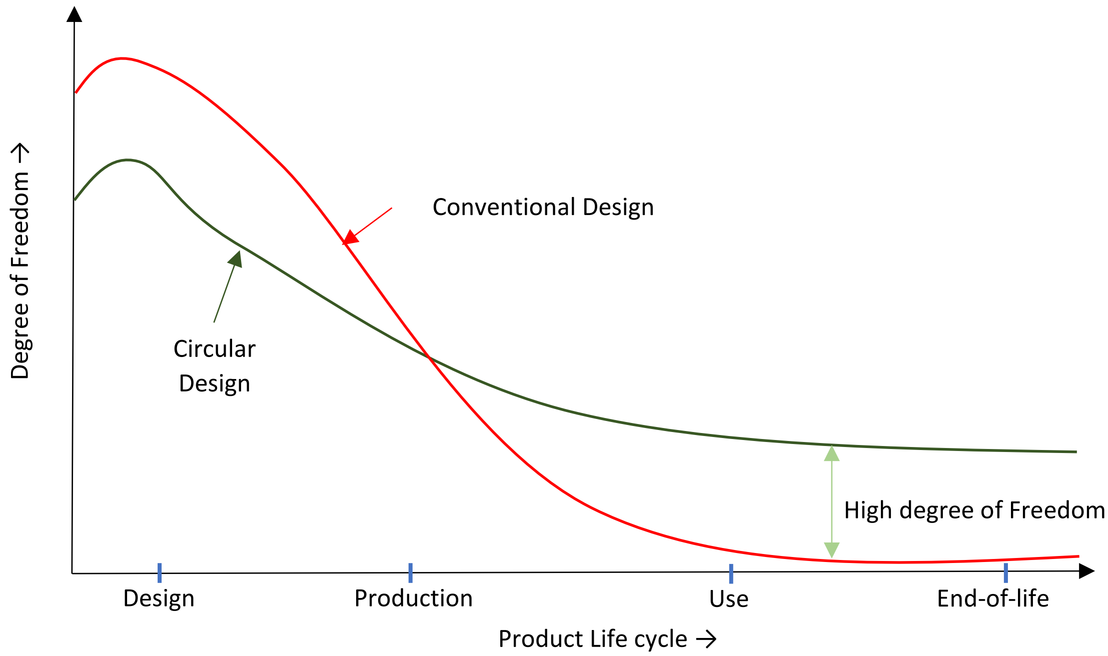

Figure 1: Diagrammatic representation of impacts of circular design outcomes over a product's lifecycle (Source: Own Artefact)

Hence, both design and manufacturing aspects need to cover in terms of circular economy principles. The following key aspects of circular aviation are identified regarding aviation industry:

1. Circular design solutions

Circular design solutions should have key focus on longevity, design for disassembly, reuse of components, eco-design, repairability and recyclability. To make viable circular design solutions, best design practices, useful tools, and frameworks need to develop and implemented for applications in the aviation sector (Future Sky, 2020).

Next generation of Aircrafts

NASA in collaboration with Boeing and TRI models is working next generation aircraft design with a key focus on environment, efficiency, and electrification and circular economy. NASA's X-57 Maxwell all-electric propulsion-based aircraft reduces dependencies on fossil fuel-based propulsion and improve operational circularity of aircrafts (NASA, 2018).

Beside electrification, the future aircraft design will also focus on 'Small Core Gas Turbine', 'TTBW - Transonic Truss-Braced Wing', and 'High-Rate Composites'.

(Image Source: NASA X-57 Maxwell | NASA)

2. On the reuse of aircraft components, recyclability of raw materials & components

Transforming the dismantling process of the aircrafts of the future

Running between 2021 and 2023, the EU-funded HELACS project is targeting the 40,000 tonnes of end-of-life composite material waste in landfills generated by difficult-to-recycle composite and thermoset components used in the aircrafts. It is doing this through the development of novel robotics to support the recycling and recovery of these materials. The project is expected to support several key impacts (Helacs -aitiip.com), including:

- Increasing the recycling capacity of aircraft components by 40% and, therefore, reducing the CO_2 emissions in aviation.
- Optimization of recycling technological processes through the use of intelligent technologies, such as smart robotics

Presently the project is still in the development pre-commercial phase and is estimated to be at a TRL 6-7 (HELACS, 2022).

3. Choice of Materials

Resources and raw materials selection plays a key role when embarking on the circular economy journey for aviation sector. During the selection of raw materials environmental impacts of should be accounted for, and methods to be developed to assess the product life cycle assessment at the design stage. The use of secondary/recycled materials & bio-based materials should be promoted, and critical materials harvesting minimized as far as is possible. For effective implementation of circular economy, attention should be given to the potential of industrial symbiosis opportunities for by-products / waste from raw materials and alternative raw materials.

Using Eco-Composites to improve circular outcomes for aircraft interior and secondary structures

ECO-COMPASS was a collaborative project involving industrial actors (e.g. Airbus), SMEs, research organisations, and universities in China and Europe, to develop and assess different eco-composites for use in the aviation sector. Eco-composites are bio-based and recyclable, which substitute traditional synthetic and difficult to recycle composite constituents.

Running between 2016 – 2019, the project successfully manufactured generic demonstrator parts for interior and secondary structure using eco-composites, including the successful blend of partly bio-based epoxy resin and traditional carbon fibres to produce an empennage side panel along with a lightning strike protection.

The project undertook an LCA of developed eco-composites in comparison the state-of-the-art materials. This showed that partly bio-based epoxy resin systems have strong potential for uptake in aviation applications and perform well when compared with the fully petrol-based epoxy resins used today (EU Climate Action, 2021).

The project helped increased the technology readiness levels (TRL) of the different approaches, concepts and technologies that were under investigation in ECO-COMPASS (EU Climate Action, 2021). For eco-composites, the project reached generally the TRL 3-4. An example is the hybrid combination of flax fibres with recycled carbon fibres in a hybrid nonwoven with TRL 3, whereas partly rosin-based epoxy resins and another component that was manufactured (a Green Honeycomb sandwich core) have achieved a TRL 4 (*Ibid.*).

4. **Sourcing recovered/recycled materials**

Many of the materials used in aircraft components, particularly the fuselage, are made from sophisticated alloys requiring a costly manufacturing process, often using more difficult-to-come-by elements (Aviation Benefits, 2022a). Components and materials play an important role in supporting circular aviation and should be targeted to recover materials and aircraft fleet. In 2019, practices of aircraft weight recycling and reuse rate of retired aircraft are between 85 to 90% (Elsayed et al., 2019). However, recycling and reuse rate of aircrafts components made from composite materials remain comparatively low, and limited use of the same represents the lack of viable recycling methods and uncertainties about the qualification and safety of such materials.

Meanwhile, reducing the sector's reliance on virgin mining will require that recycled or secondary materials can be resourced for circular aeronautical applications (NLR, 2020). While access to such feedstock remains a challenge, efforts are underway to improve advanced recycling technologies within the sector. Meanwhile, there are opportunities to address current challenges by embedding urban mining practices in airports and aircraft boneyards (*Ibid.)*

Recycling of Carbon Fibre Reinforce Polymers (CFRP)

Recycling fibre-reinforced plastic components used in aircrafts is a difficult process, and the recovery rate is low. Expleo is an engineering, consulting and technology firm which partners with different organizations across the globe to support their journeys of business transformation. The Expleo Eco-design centre is targeting an all-new process to make previously unrecyclable aircraft materials more sustainable while decreasing plastic waste. The CFRP project of Expleo Eco-design centre in collaboration with Université Toulouse III (Paul Sabatier) has two key aims: 1) develop a new recycling process to make it possible to recycle CFRPs with 90% of the mechanical properties of virgin carbon fibres maintained, and 2) using Green chemistry to develop a new bio-based resins to replace virgin raw materials in the manufacture of future composites.

For reference, a Boeing 787 Dreamliner is 50% CFRP by weight which currently would be destroyed at the end of its 15–20-year lifecycle. Having validated Expleo's process in a lab setting has demonstrated that much of that material can now be reused either in the manufacture of new aircraft or other products. The project expects to industrialize its process at the end of 2023 (Expleo, 2022).

5. Circular Manufacturing

While much of the negative environmental impact of aircrafts come from operational phase, compared to manufacturing and end-of-life, the raw materials, energy and other resources required to manufacture are significant.

Circular manufacturing approaches can extend an aircraft or its component's lifespan (e.g. by supporting design for disassembly or repair) and allow for improved recovery of residual value from reused parts and recycled materials at end-of-life.

Circular manufacturing processes are often assisted by the adoption of advanced technologies to reduce the scrap rate, reduce waste, and to reduce requirements for component testing (NLR, 2020). Here digitalisation can also play a role in improving material efficiency and quality of manufacturing processes – such as through the adoption of virtual testing and digital twin frameworks. The Circular Aviation White Paper also acknowledges the important role of advanced manufacturing techniques can play, such as additive manufacturing and 3D printing.

Using Circular Manufacturing processes to develop lightweight, multifunctional and intelligent airframe and engine parts

Running between 2021 and 2024, SUSTAINair is an EU-funded Circular Aviation project involving manufacturers, research centres and universities from across Europe. One of the EU's priorities is to advance the design, production and field operation of multifunctional and intelligent airframe and engine parts (ECb, 2021). While new technologies and manufacturing processes are being developed with support from EU R&I funding, key obstacles must be overcome to address issues across the entire aircraft component value chain. Tackling these challenges, the SUSTAINair project aims to address each stage of the component value chain by developing and introducing novel concepts and techniques that will shape design, manufacturing, maintenance, repair, overhaul and recycling processes for lightweight, multifunctional and intelligent airframe and engine parts(SustainAir, 2021). Specifically the project will involve:

1. Developing an online process monitoring of induction and conduction welding of thermoplastic composite structures.
2. Advanced near-net shape manufacturing (additive manufacturing) of nano-eutectic aluminium alloys providing repairable, laser-welded structural assemblies, and
3. Design combined nano- and macro-structures for joint interfaces of dissimilar materials

The project expects to improve circularity outcomes for aircraft and engine parts. Additionally, the following project impacts are expected:

- Cost reductions of c. 75% to repair (replacement parts)
- 5-10% cost reduction due to zero waste assembly of thermoplastic parts
- A 3 factor increase in the value of thermoset and thermoplastic parts at their end-of-life
- 100% recyclability of current aviation thermoset and thermoplastic FRPs

6. Maintenance, repair, and overhaul (MRO)

Repair, reuse, refurbishment, and retrofitting are key aspects of the maintenance, repair, and overhaul of aircraft industry. These strategies match exactly the principles of circular economy. An aircraft is designed to provide a long service life (>20 years) and principles of maintenance repair and overhaul support these goals to be achieved in a timely manner. It is better to design the product with consideration of 'design to repair and reuse'. Alongside total productive maintenance: new solutions to be developed using total predictive maintenance and prescriptive maintenance. Also, active use of structural health monitoring systems, retrofit based repair methods, and non-destructive inspections are key. Data monitoring and analysis are also key for predicting an aircraft's life span and improving maintenance strategies.

Rolls Royce's TotalCare- transforming traditional MRO services to power-by-the-hour long term service agreements for airlines

While sharing economy models based on leasing rather than outright purchasing are well established within the aviation industry, Rolls Royce's propulsion-as-a-service, 'TotalCare' demonstrates how circular economy business models can help rethink traditional MRO services. In an interesting flip on traditional linear repair services, TotalCare is charged to airline customers on a fixed $ per flying hour basis. As a result, Rolls Royce is only rewarded for engines that perform. This helps ensure greater alignment between the OEM and the customer, both of whom have a shared interest in seeing operational disruptions minimised.

ICT and digital technologies play a key role in enabling the TotalCare service.

Rolls Royce can access flight related data history, apply predictive maintenance, and ultimately assists with product life extension and reuse. Assisted by smart technologies and data insights, the platform also supports(Smith-Gillespie et al., 2019):

- **Engine health monitoring and associated technology and data insights.** The data and insights provided from engine health monitoring are fundamental to providing TotalCare. This enables efficiency and effectiveness of MRO services; it feeds back into product design; and enables a suite of value-added services provided to customers to help improve their operations.
- **Parts and materials management.** Data and IT helps Rolls-Royce avoid over-production of parts and ensure their efficient deployment around the world.
- **Repair innovations.** Novel technologies (such as 'snake probes' and 3D/additive manufacturing techniques) are enabling higher material efficiency and eliminating waste in repair operations;

B. CIRCULAR FLIGHTS

Current projections indicate that as of 2024, air passenger numbers in Europe are set to exceed 2019 figures (IATA, 2022). With the continued recovery and growth of the industry, airlines' negative impacts are only set to rise (Salesa et al., 2022). Embedding circularity in the flight experience is thus a strategic and important opportunity to demonstrate to customers the sector's commitments to tackling the climate crisis, and to transitioning to a net-zero carbon economy.

> **"The flight experience and the connected operations are the most visible aspects of aviation to society, and, consequently feed the societal perception that the majority of the GHG and of other pollutants emissions related to aviation are connected to its operations"** (Future Sky, 2020).

Research undertaken by (Salesa et al., 2022) has found that circular adoption amongst airline is still low, and that where adopted, circularity strategies do not seem to follow specific patterns. That said, the research found airlines are starting to look at how they can develop novel business models aimed at improving their sustainability, and in particular to stem the negative impacts associated with airline flights. Importantly, in-cabin waste is the most common waste for airlines worldwide, with an estimated 70% being generated by passengers (Abdullah et al., 2016). Airline companies are consequently devising new strategies to increase their awareness of material management and waste produced during flights (Salesa et al., 2022) , while shifting over to alternative and low-carbon aviation fuels. Below we present a selection of initiatives which illustrate how this in happening in practice:

a. In-flight Food and packaging waste reduction

Combating food waste and saving food waste to go to landfill.
To tackle its high-level of surplus food waste generated during flights, Australian airlines, Qantas and Virgin Australia set up a partnership with food rescue organisation, OzHarvest and Gate Gourmet. As a result of the partnership, over 1 million meals have been saved and distributed to vulnerable children across Australia since the initiative started in 2015. This is equivalent to 333 tonnes of food.
Every month, 8000 kg (or 16,000 meals worth) of quality surplus food items like sandwiches, wraps, muffins, bars, etc., donated from Virgin Australia are directed to schools in vulnerable communities around the country. OzHarvest delivers this food through the help of 76 schools and a network of 1300 charity partners (Ozharvest, 2018) .

b. Airline Recycling activities

Several airlines are now taking actives steps to tackle the issue of operational waste by recycling or reducing it. These initiatives are oriented towards providing more circular/sustainable onboard experience to the consumers/flyers. These initiatives include transitioning to biodegradable alternatives to reduce single-use plastic waste, or recycling textiles waste (such as from cabin crew uniforms) to repurpose them into aircraft interiors. Some illustrative initiatives are listed below.

Air New Zealand pilots eco-serviceware to reduce in-flight single-use plastic waste

Air New Zealand has implemented several pilots to reduce single use plastics and made a commitment to remove close to 55 million plastics items. It has also removed single use plastic bottles from its business and premium economy cabins, which is expected to reduce 460,000 bottles from landfill annually. The airline also removed sauce packs from business premier cabins in its North America and Hong Kong services. Along with this, the airline is also looking to replace single use plastic- cups with biodegradable plant-based cups across its domestic and international services. Since 2018, the airline has also transitioned 55 million single-use plastic items to lower-impact alternatives, or removed them entirely, across its global network and ground locations (Air New Zealand, 2021).

Reducing textiles waste by implementing cabin crew uniform recycling initiatives

The textile industry is often described as one of the most polluting and resource-intensive industries in the world and is recognised as a major global emitter of greenhouse gases.[1] Currently, just about 1% of all clothing is recycled to a high standard. The rest is downcycled, burned, or landfilled, resulting in an annual material loss of circa $500 billion (EMF, 2021). A growing number of airline companies are starting to explore how they can reduce their operational waste and emissions by implementing uniform recycling initiatives:

i. **Delta Air Lines Inc. implements the 'largest textile diversion scheme' ever by a single US-based corporation**

In 2018, following a multi-billion dollar companywide makeover, Delta Air Lines Inc. updated its 64,000 employees in new uniforms. As a result, nearly one million pieces of uniform were due to be "retired" (i.e. discarded or sent to landfill). Instead, Delta implemented a textile diversion scheme, partnering with Looptworks, to find a creative way to give the old uniforms a new life. With the help of 900 refugees, people with disabilities and veterans, these uniforms were then redesigned into upcycled products such as laptop bags. A total of 158 tonnes of uniforms were re-directed from landfill, in what is claimed to be one of the largest textile diversion schemes by a single US-based corporation. Delta airline also donates yearly used uniforms to non-profit organizations, which then converts them into rugs, cushions, etc. (Edie - Looptworks, 2018).

[1] Read more in CIRCULÉIRE's (2021) Circular Fashion and Textiles Good Practice Sectoral Guide.

ii. From KLM uniforms to cabin interior carpet

When KLM Royal Dutch Airlines decided to launch a new uniform in 2010, the switch resulted in a potential of 90,000 kg of textiles waste from the old uniform. To avoid having these uniforms get sent to landfill, the company devised an upcyling pilot with carpet manufacturer Tarkett (formerly known as Desso), to transform the old uniforms into cabin interior carpets. In the aviation sector, carpets must be replaced every 12-20 week due to wear. All the old uniforms were collected, and the old uniforms were converted into new raw materials or yarn. These blue yarns made from uniforms are incorporated into blue details of the interior cabin carpets. The rest of the recycled uniform fabric was used to produce multiple products. At their end-of-life, the carpets were collected in hangars and reprocessed at Tarkett in accordance with the cradle-to-cradle principles. This pilot programme of KLM Royal Dutch Airlines to recycle uniforms into carpets and other products has served as a flagship best practice for how airline companies can save virgin raw materials, reduce emissions, by embedding circularity thinking and practices holistically in their operations (Business Europe, 2019).

c. Ground operations

Airport operations play a key role in the operations of aviation sector and can open up circular innovation opportunities through the use of digital technologies, renewable energy sources, big data to support improved traceability, and establishing industrial symbiosis partnerships. Other aspects for circular airport operations are electrification of airport fleets, zero waste initiatives, use of secondary raw materials for runways & airport development (construction), reduction of packaging waste, and energy harvesting.

i. Using recycled aggregate to build a Circular Runway

Depending upon the number of flights handled by airports and geographical conditions, runways are very prone to damage and need to be repaired frequently. In 2020, Tobalaba airport in Chile constructed a new runway using asphalt recycled from an old runway. This resulted in 70% reduction in virgin raw material consumption and 45% less costs. The government of Chile has started to focus on more such kind of projects to use construction waste in new developments (We Forum, 2021).

ii. Embedding circular principles in an airport's ground operations

London Gatwick airport started its circular and sustainability journey in 2009. For several years the airport has reported that zero untreated waste from the airport operations goes to landfill, while 53% of the airport waste is reused or recycled. The airport remains committed to reducing airport emissions and aircraft and surface access emissions, along with targeting biodiversity, water, zero waste, noise, workplace safety, etc. (London Gatwick Airport, 2021).

d. Sustainable aviation fuel or alternative fuels:

> **Worldwide, flights produced 915 million tonnes of CO_2 in 2019 (12% of CO_2 emissions from all transport sources globally) (ATAG, 2020).**

> **Around 80% of aviation CO_2 emissions are emitted from flight of over 1,500 kilometres, for which there is no practical alternative mode of transport (ATAG, 2020).**

While aircrafts today are much more fuel efficient (c. 80%) than earlier jets from the 1960s (ATAG, 2020), shifting to alternative and sustainable aviation fuels (SAF) is viewed as a key tool in helping the industry to reach its climate targets. According to the Air Transport Action Group, SAF sourced from algae or water-based by-products have been shown to significantly reduce the carbon footprint of aviation fuel by up to 80% over their lifecycle (ATAG, 2020).

Multiple airlines in collaboration with the IATA (International Air Transport Association), research institutes, and companies are working together to develop SAF. Even two of the world's biggest aircraft manufacturers and engine manufacturers are trying to develop more and more efficient aircrafts without compromising on carrying capacity and speed. One of the key examples of adoption of SAF in Ireland is by airline Ryanair. In 2021, Ryanair and Trinity college launched a SAF center with a focus on sustainable aviation fuel, zero carbon aircraft propulsion systems and noise mapping with €1.5 million funding donation from Ryanair (Ryanair, 2022).

As we have highlighted above, electrification is another strategy being pursued by organizations like NASA are trying to develop aircraft running on batteries (X-57 Maxwell all electric experimental plane) – although more work will need to be done to limit the negative impacts of electric batteries (such as their reliance on critical raw materials, and difficulties recycling batteries at their end-of-life).

FlexJet - Transforming biomass (food waste) into biofuel (jet fuel)

Running between 2018 and 2024, EU-funded project, FlexJet, brings together leading researchers, industrial technology providers and airlines and renewable energy experts from across Europe to advance the potential of biomass-derived biofuel. The project will build a pre-commercial demonstration plant for the production of advanced aviation biofuel (jet fuel) from waste vegetable oil and organic solid waste biomass (food waste), to produce a fully equivalent jet fuel (compliant with ASTM D7566 Standards) (Cordis EU Research Results, 2022). To fully exploit the commercial potential of its novel biofuel, the FlexJet project will validate a comprehensive business plan, building on already established end user interest with existing offtake agreements already in place with British Airways. The project plant installed at the source of where the waste arises in BIGA Energie at Hohenstein (Germany) will produce 1,200 tonnes of jet fuel from 3,482 tonnes of dried organic waste and 1,153 tonnes of waste vegetable oil per year (*Ibid.*). A subsequent scale-up first commercial plant will be constructed immediately after the project ends with capacity to produce 25,000 tonnes per year of aviation fuel.

C. AIRPORTS AND AIRLINES AS CIRCULARITY AMBASSADORS

Besides the ground operations and flight experience, passengers taking air travel go through a series of steps and experiences, which are managed by the airports and representatives of airlines at the airports. For this reason, airports are recognised as playing a key connector role in enabling 'integrated zero-emissions transportation networks for passengers and freight' (NLR, 2020).

Below some examples of Circular Airport initiatives are outlined:

i. Circular Economy at Amsterdam Airport Schiphol

The Royal Schiphol group have an ambition to develop the most circular and sustainable airports in the world. They do this by focusing on four priority themes: 1) supporting communities, 2) sustainable aviation, 3) energy positive, and 4) circular economy. In the circular economy pillar, special focus in given to design, reuse and recycling, and strategic resource management. Schiphol Airport partnered with lighting provider, Philips, to develop a lighting-as-a-service for high-intensity lights for runways. In this model, Philips owns the lamps and fixtures with extended producer responsibility until end-of-life recycling. This small circular solution reduces energy consumption up to 50% with an extended life span of 75% of the fixtures, and finally it reduced critical raw materials consumption, particularly for LEDs (Modarress et al., 2020). Using these principles has enabled the airport to achieve a 50% reduction in energy consumption, a decline in maintenance costs, high reduction in raw materials consumptions, completely reused fitting(Denise Pronk, 2019).

ii. Vancouver International Airport's ambitious waste reduction efforts

In 2015, YVR (Vancouver International Airport) set itself the target to divert 50% of its total terminal waste from landfill by 2020, a target which it achieved in 2016. These diverted materials include bottles, pallets, glass, metal, and plastics.

Another key initiative taken by YVR is to expand the use of OSCAR (a self-sorting bin that uses Artificial intelligence to ensure proper waste handling and sorting (YVR, 2022).

Section 3: What's Needed to Circularise Ireland's Aviation Sector?

Research undertaken for this Sectoral Guide supports the wider research consensus that circular economy is still an emergent immature concept within the aviation sector. However, in light of increasing awareness and understanding of the linear risks and unsustainability of business-as-usual practices, securing Ireland's reputation as a global circular aviation frontrunner, and need to guarantee the sector's continued competitiveness, performance and sustainability, the concept has been gaining ground.

Despite still being a reasonably marginal concept within the wider aviation sector, the case studies profiled within this guide highlight several of the circular strategies and efforts the sector can build upon. For one, an average of between 85 to 90 per cent of the weight content of retired aircraft is re-used or recycled, reflecting the fact that both re-usable parts and recycled materials represent significant residual value (Elsayed et al., 2019). And while still at a low TRL, new technologies are being developed to improve recycling and recovery rates for currently difficult to recycle materials, such as CFRPs, or to develop novel bio-based eco-composites.

If the industry is to leapfrog ahead on its decarbonisation journey, in time to meet its 2030 and 2050 climate targets, a sustained and whole-industry approach will be needed to increase support for and scaleup up these efforts to bring them from the margins to the mainstream. Indeed, thanks to sustained R&I efforts, both at European and national levels, an increasing number of circular innovation pilots and experiments are being initiated in response to several of these and other linear challenges facing the sector.

3.1 Key Enablers/Lessons Learnt from the Case Studies and Wider Literature

As the twelve case studies profiled for this guide demonstrate, the aviation sector has a wide array of opportunities to pursue circular economy strategies. This ranges from transitioning to more sustainable, efficient fuels; better use of catering wastes; end of service recycling of aircrafts and or re-integrating airplane parts into new supply chains.

Based on analysis of the wider literature, and supported by our case studies, below we outline some of the key enablers that are supporting industry players to drive circularity in the sector today:

a. Start by reframing how your organisation views its waste – looking at it as a circular innovation opportunity

As many of the case studies in this Guide show, there are considerable benefits and impacts to be achieved by initiating circular economy strategies in the aviation sector. As research by ICAO Secretariat notes of the sector, however, "implementation of a circular economy model remains limited. Many stakeholders have not yet identified the potential scale of aviation-associated waste" (ICAO Secretariat, 2019, p.277).

Circular frontrunners understand the value and innovation potential of looking at theirs and their supply chain partners from a perspective of '*resource'* rather than '*waste*' management. Doing so can help unlock opportunities for co-product valorisation, and for industrial symbiosis. However, a good place to start for aviation players early on in their circularity journey is to start estimating the scale of waste by conducting a systematic waste audit. The Resources and Tools section includes links to useful guides, such as the ICAO's Eco-Airport Toolkit e-collection, which can support this process. A waste audit is a study, which characterises the different types of waste, their origin, and what happens to them at their end-of-life. The audit will show the amount of waste; their possible recycling opportunities; possible reuse; reduction options; and assess how effective the waste management system is over the time. This information is a critical step towards developing more sustainable and circular waste (and resource) management plan. It can also assist in the development of recycling programmes. Exercises like waste audits can help companies visualize the key upstream and downstream activities carried out at key facilities. For airports or airlines, however, undertaking a waste audit requires a different level of skillset, high awareness of relevant rules & regulations, and situations specific to the local airport (dependent on geographical and social constraints) (ICAO, 2020). This takes time. For example, while it exceeded some of its own projected waste reduction targets, London Gatwick Airport started its circular journey almost a decade ago and has now advanced to make zero waste one of its priority areas (London Gatwick Airport, 2021).

b. Technology as an enabler of circular aviation

As many of the case studies profiled in this guide exemplify, transitioning to a circular aviation sector means embedding lifecycle thinking in our production processes. The emissions from an aircraft's production and extractive processes seem lower compared to fuel consumed during used phase. However, this calculus may shift as more breakthrough SAF technologies are scaled and adopted. Overall, it will be impossible to achieve 'Net Zero' carbon emissions without reducing emissions generated from the production and materials used too. In tandem a number of advanced technologies are helping to enable the aviation and aerospace industry's transition to circularity. Here we highlight three key technologies expected to support industry's circularity transition projected to play a leading role - additive manufacturing, advanced recycling, and digital twins are the (Domone et al., 2021).

Additive manufacturing

Additive manufacturing can contribute to circularity by reducing material consumption during the initial production process. As compared to subtractive manufacturing where you remove access materials and it goes to waste, additive manufacturing only deposits the materials required in the part. In many instances additive manufacturing can result in:

- energy savings during production.
- products that are of complex structure and not possible to make using traditional manufacturing methods (Domone et al., 2021).

Alongside additive manufacturing, cold spray technology is also becoming popular in repair or aircraft components that have become distorted due to corrosion, erosion, and wear & tear with time. Cold spray technology gives promising results to repair aircraft components due its characteristics (low process temperature, only plastic deformation, no oxidation, and high repair efficiency) (Tan et al., 2021).

Advanced recycling technologies

Advancing recycling activities and processes requires that design aspects of future generations of aircrafts are considered early in the design phase. These circular design solutions should address the sustainable recycling of aircrafts and their components in the end of their extended lifespan. Also, existing recycling processes need to be designed better to recycle the existing volume of aircrafts retiring every year and were developed more than 20 years ago. Special consideration needs to be given to composite (fibre reinforce plastic composites) materials to recover the value from large number of aircraft parts and components. Technological advancements are needed to enhance the recycling (currently done using heat) rate of composites with a low cost (Domone et al., 2021). However, as discussed above, research and technology advancements (e.g. in projects such as Eco-Compass) are trying to address the issue of composites by developing bio-based composites which will be much easier to solve the recyclability problems in future (Bachmann et al., 2021).

Elsewhere it is envisaged that robotics will assist in the dismantling of aircrafts to reduce human resources cost, improve safety, and increase the rate of dismantling (Domone et al., 2021).

Digital Twins

Meanwhile, digital twins can support the tracking of aircraft components, aiding their traceability across the life cycle. These digital twins can contain information about material compositions, usage information of the components, coatings, material treatments, and other suitable information (*Ibid.*). These details are good enough to select a proper recycling process in the end of these materials/components' life cycle and recover most of it. Most information about the materials and composition can be added to a RFID or Barcode or Laser tagging during the production process, while in-service data (loading, use, repair and performance) can be added during maintenance phase (Domone et al., 2021).

c. Circular business model experimentation is helping aviation sector players decouple economic growth from the consumption of finite resources – unlocking new forms of values

Whether for aircrafts or airports, circularity principles can generate their maximum impact, in terms of environment impact and economic profit, if applied from the earliest stages of the design phases (NLR, 2020). Moreover, if aviation sector players are to seize the new commercial and environmental opportunities of a circular economy, then a mindset of circular business model experimentation must be cultivated (Consultancy.eu, 2019).

For Airports

Some European airports are embracing circular business models of reduce, reuse and recycle. One such example is Schiphol Airport and Philips for high-intensity lights for runways. In this model Philips owns the lamps and fixtures with extended producer responsibility till end-of-life recycling. This small circular solution reduces energy consumption up to 50% with an extended life span of 75% of the fixtures, and finally it reduced critical raw materials consumption, particularly LEDs (Modarress et al., 2020). Successful implementation of circular economy business practices can be seen in London Gatwick airport (as discussed above) to address strategic priorities related to lowering operational emissions, and negative impacts on biodiversity, water, waste, and noise, etc. (London Gatwick Airport, 2021). By integrating circular strategies into its business model, Gatwick Airport has lowered its annual operation cost by $750,000 with more efficient energy and water use, and less processing of waste onsite and disposal resulting in an additional income from recyclables (Modarress et al., 2020).

For Aircraft and Aircraft Component OEMs and Lessors

In a typical linear economy business model, aircraft manufacturers sell the aircraft to airlines or operators. Operators then become responsible for the maintenance of the aircraft, including the decisions on whether to buy spare parts or conduct repairs and finally what to do at the end of the aircraft life (Domone et al., 2021). Consequently, this leads to low incentives for manufacturers extend a product's life. Circular economy business model innovations are already taking place in the aviation sector to unlock greater commercial incentives for keeping resources and assets in the loop and functional.

Oner such example, in are Product-as-Service models like Aircraft-as-a-service. In such scenarios, manufacturers are often best placed to retain, reuse, reduce, design, recover, correct valuation, etc. of aircrafts and their components; and implement circular economy in the value chain. Digital and advanced technologies, such as the ones highlighted above, like digital twins, information about product uses, smart tracking, interchanging parts and components, can help ease implementation of such circular economy strategies for OEMs.

Rolls Royce started leasing engines to airlines instead of selling them. Such service flips can give OEMs greater flexibility to servitize maintenance, repair and ultimately reclaim value from materials and components. Today, Rolls Royce's propulsion-as-a-service, 'TotalCare' is a proven offering. It allows operators to access flight related data history, apply predictive maintenance, and ultimately assists with product life extension and reuse. The utilization of digital technology is key in these kind of business offerings with the use of sensors and real time communications, which bring multiple offering such as minimum downtime and maximum resource efficiency (Fitzgerald L, 2018). The major considerations related to these kind of business models are subscription costs, service offering packages, and the performance of the product (Domone et al., 2021). Such models can be a win-win situation for both manufacturer and operator as no large funding is required to buy the product. Hence, product-service-systems works to decouple the economic growth and consumption of non-renewable and finite resources (Ibid.).

Similarly, Irish aircraft leasing company, AerCap Holdings N.V. (one of the largest aircraft leasing companies in the world) has shifted its operations to become more involved in the whole life of its assets, taking delivery of brand-new aircraft from the OEMs and remaining involved until that aircraft is disassembled and its parts returned into the supply chain to be used once again (AerCap, 2022).

This way companies can recover the value in both upcycling (enhance functionality & high-quality materials) and downcycling (low value materials with reduced functionality) of raw materials and components, which is optimized approach as compared to materials discarded or disposed of.

3.2 Key barriers to advancing a Circular Aviation Industry

Research undertaken by Royal NLR, the Netherlands Aerospace Centre, acknowledges that the transition challenges facing the aviation sector are not unique: “Most of the challenges faced in other sectors during this transition from linear economy to circular economy are similar to the challenges which the aviation industry needs to address in order to successfully implement its own circularity solutions” (NLR, 2020, p. 3). This makes the case from cross-sectoral dialogue to learn from and exchanges with industry leaders and experts in other sectors. Furthermore, Royal NLR also make the case for “inter-industry cooperation, in the true spirit of circular economy” (*Ibid.*).

Based on analysis of the case studies and wider literature, below some of the key barriers are presented which have been identified as impeding the implementation or scaling of circularity in the aviation sector:

a. Our linear economy does not factor in externalities – which helps make the business case for circular economy

Circular economy practices are gaining importance but not yet in mainstream due to the following challenges of time, mindset, acceptability, production process, technological aspects, etc. To support widespread adoption, it is important to present the development of circular economy best practices and business models (Pronk, 2019). Applying circular economy practices might not have visible short-term benefits, hence, a full life cycle needs to be addressed, where initial cost was high, but the overall benefits become evident over time (as is also shown in section 2 in this guide). Financial controllers are not used to think about pricing externalities in this way.[2] Aviation sectoral players will need to foster circularity thinking and develop these capabilities.

b. Challenges of circular innovation a highly regulated sector

Operational aspects of any industrial sector have its own challenges, especially when the sector is highly regulated, and these regulations are related to human health and safety. Regulation presents a barrier to circular aviation in the following ways:

i. In-flight food waste

[2] To learn more about the circular finance and funding challenges facing Irish industry, please refer to CIRCULÉIRE’s Financing the Irish Circular Economy Thematic Working Group Final Report and Fact Sheet.

One such characteristic of aviation is in flight food and services. The food served need to pass certain rules and check (hygiene, freshness, weight, and packaging), which has made a material like plastic the most attractive solution (Aviation Benefits, 2022b). On the other hand, on board waste, leftover food, drinks, packaging, newspapers, towels, and other plastic waste are related to national waste management controls to limit pollution. Multiple countries have gone further strict with these rules and regulations, particularly catering food from flights and their related animal health concerns (Aviation Benefits, 2022b). For instance, there is a distinction between waste management requirements of Waste category 3 (generated on Community flights – within the European Union) and category 1 waste (generated on non-Community flights) (Zero Cabin Waste, 2022). These rules are there to prevent transfer of diseases between countries. Consequently, much of the arising in-flight food waste goes to incineration or landfill (rather than being reused or recycled). Due to these kind of regulations airlines are limited to use circularity best practices. Industry requires smart waste regulations systems without compromising human and animal health and saving resources.

ii. Aircrafts

Elsewhere, Modarress et al. (2022) acknowledge how various rules and regulations, along with the complexity of aircraft and its software system, ensuring compliance with standards of airworthiness, all pose major challenges for circularity. Indeed, standards of airworthiness and environmental regulations can involve networks of airliners and airports, meaning that implementing circular economy solutions poses considerable demands of multiple players. Nevertheless, there are frontrunners in the sector as well, who are addressing the issue of circularity as well and implementing its best practices (Modarress et al., 2020).

iii. Novel technical processes e.g. additive manufacturing

Additive manufacturing can present a production solution for the aviation sector that facilitates complex designs while using lower resource consumption. However, certification is the major challenge hindering its adoption (Domone et al., 2021). Material qualification information is rarely available for material produced by additive manufacturing. Also, as per the geometry of the part and component, additional qualification of components is required (Ibid.).

iv. Requirements to use toxic, hazardous materials (e.g. in airport terminal buildings)

While transitioning to ‘non-toxic’ and ‘non-hazardous' material cycles is aligned with various circular economy strategies, this is not always possible within the aviation sector due to requirements to use fire retardant and safety materials. When building airport terminal buildings, for instance, there can be strict requirements to use materials which are impregnated with fire retardant. This makes them toxic, meaning reuse is not possible at their end-of-life (Pronk, 2019, p. 296). Industry and regulators will therefore need to find new ways to navigate such scenarios sustainable while not comprising on human safety.

c. Recycling barriers need to be removed

From a circularity perspective, recycling and recovery are the two least preferrable strategies to be selected in a product life cycle (in relation to other 'R' strategies). Recycling should be carried out when no further extension of a product's life span is possible, and recovery should be when other options do not exist. Recovery is used to extract the remaining value from a part/component through remelting or incineration and extracting energy from it. This energy can be used to power anything, from a facility to a plant. "Where lower energy circular strategies are no longer viable recycle and recover strategies can be employed" (Domone et al., 2021).

Nonetheless, recycling can help reduce reliance on virgin raw materials and lesson pressure on natural resources. Considerable waste and emissions reductions are being prevented due to various kinds of barriers to recycling within the Aviation sector. We have already acknowledged above how stringent waste regulations can play a role e.g. for in-flight catering waste.

i. Recycling challenges for airports

Waste signage at airports can pose a challenge and must support the needs of passengers coming from multiple countries with different habits, symbolism, languages, and culture. These signages must be user friendly, independent and the language and should be understood and accepted by all; to ensure proper sorting and segregation of waste in airports (ICAO, 2020).

Along with this, decentralized waste management practices, aircraft waste management, and inspiring occupants to recycle are among key challenges for airports (*Ibid.)*. Airport occupants can arrange their waste management individually, but it is best when all airport waste is managed together. Managing all the waste of the airport together has economic benefits to the airport but also it is beneficial in environmental terms as well (ICAO, 2020). Other benefits include economies of scale, higher efficiencies, better coordination, more waste to be handled, lower handling fees for larger loads, etc.

i. Recycling challenges for aircrafts and components

Specifically for aircraft recycling, it is observed that only a proportion of aircraft is reused or remanufactured and typically only when the aircraft is retired. There could be other reasons for an aircraft to be retired rather than its functional life, it might be economical viability. Another challenge for aviation sector is that most of the recycled material from an aircraft goes to other industries, waste recycling companies or goes to landfill (Domone et al., 2021). If the airlines & airport take the initiative to recycle the waste materials within the industry, then it will lead to more circularity (Ibid.). For example, as discussed above in the report, KLM used old crew uniform to make aircraft carpet is a good example of this (Business Europe, 2019). Another key challenge in aircraft recycling is that it is made of different composite materials mixture (two different kind of polymers, two plastics, plastic – metal joint etc.). Which makes the recycling process more complex and costly. Current metal recycling techniques are not capable of delivering high quality raw material as compared to virgin raw materials. Especially when talked about rare earth metal and precious metals. In those terms manual dismantling can increase the quality of recovery (Suomalainen et al., 2017).

Also, the existence of hazardous raw materials (asbestos, fire extinguishers, smoke detectors, radioactive materials), is a key challenge from a recycling perspective (Domone et al., 2021). As discussed above in the Eco-Compass project, reinforced plastics composite recycling is a complex process and recycling & recovery rates remain low (Bachmann et al., 2021). Thermoset resin composite is recycled using pyrolysis and fibre recovery; these fibres are recovered in form of chopped fibres or short fibres, which are not as strong or stiff as fibre reinforce plastics. With current recycling practices, this results in low value materials (Domone et al., 2021).

3.3 Key recommendations to unlock the circular potential of Circular Aviation

Section one of this guide has already acknowledged how, as a small open island economy on the periphery of Europe, aviation is critical to our national flow of goods and people. Given the highly transnational nature of the aviation sector, many actions are being addressed at EU and international levels to address emissions for this sector, such as market-based measures like the ETS and sustainable fuel mandating initiatives (through ReFuel EU Aviation, Fuel EU Maritime and the Alternative Fuel Infrastructure Regulation which will all include binding targets once adopted)(DECC, 2021). The 2021 Climate Action Plan acknowledges the importance of ongoing international collaboration with key stakeholders, such as the International Civil Aviation Organization, to achieve greater sustainability and preserve a level playing field in these global sectors (*Ibid.*) Nonetheless, several actions can be pursued by key stakeholders at the national level to stimulate circular innovation within the Irish sector – particularly within the thematic areas highlighted in Section 2:

a. Initiate an industry-wide Sectoral Engagement around Circular and Sustainable Aviation Goals and Needs

In the IAA Sustainability Management Plan 2020 – 2025, the public agency states that "the IAA hopes to be industry leaders in embracing the circular economy by forgoing a linear approach to consumption" (IAA - Irish Aviation Authority, 2020). Elsewhere, the plan outlines high-level objectives to support its goals, such as developing "resource efficiency (food, water, waste) strategies to reduce waste generation per capita by 20% across all IAA premises by 2023 and 50% by 2025 (IAA - Irish Aviation Authority, 2020, p.4).

Meanwhile, in its submission for the proposed Budget 2023, Aircraft Leasing Ireland, the Ibec group, noted "By incentivising the development and production of SAF, this Government can help attract what will be a game changing manufacturing sector to Ireland… Ireland now has the potential to be not only a centre of excellence for aircraft leasing but also a centre for aviation sustainability" (IBEC, 2022).

While these and other initiatives led by stakeholders within Ireland's aviation sector indicate interest in circular and sustainable innovation is rising, there is a risk that without a coherent and inclusive dialogue with the wider industry, circular efforts may be ad hoc and piecemeal. Ensuring the Irish Aviation industry successful transformation into circular innovation frontrunners will require that an industry-wider Sectoral Roadmap is devised with clear actions, owners and target dates to identify and build momentum around validated transition pathways. This will require the highest levels of political support and whole-of-Government buy-in and support, such as from the Minister for Transport, DoT, DECC, IAA, and industry leaders. To this end, the IAA, and key stakeholder representing the sector (e.g. representative of all Irish airports, aerospace manufacturers, Ireland-based airlines, key partners, suppliers, service providers) should be supported to devise a Circular Economy Road Map for the Aviation Sector around identified national priorities, barriers and goals for the sector. While not specific to the Aviation Sector, guidance by Finnish innovation agency, Sitra, offers a helpful overview of the key steps involved in developing circular economy sectoral road maps: (SITRA, 2020).

> **"A circular economy road map is a tool for change: it helps define the required steps and compiles key stakeholders' views on the essential changes and actions required for the circular transformation." – (Sitra, 2022)**

b. Spur innovation through inducement prizes and Inno-mission partnerships around identified transition and technology barriers

> **"Research and innovation are key to maintaining Europe's capacities and competitiveness, and it is time to align efforts towards a new long-term vision for this sector." – FlightPath 2050**

Large European R&I programmes, like Horizon Europe and LIFE, have stimulated research and development along circular aviation thematic areas identified in this guide (for instance, through grant funded programmes like SustainAir, Eco-Compass and Zero Waste Cabins, while R&D initiatives to support green and circular airports are supported under Green Deal call area 5: Sustainable and smart mobility). While Irish aviation industry players can and should look to such pan-European R&D opportunities, securing Ireland's reputation as a global circular aviation frontrunner, and guaranteeing its continued competitiveness, performance and sustainability, will require that the Irish Government do more to stimulate circular innovation on-the-ground in response to identified local and national priorities.

Below are just some European and national Government-led initiatives, which can be drawn from when designing national circular and sustainable innovation ecosystem-building initiatives within the sector:

i. Use open innovation approaches to initiate circular and sustainable aviation design prizes and competitions

- **FUTPRINT50's Aircraft Design Challenge 2022 -** FUTPRINT50 is an EU funded collaborative research project set out to identify and develop technologies and configurations that will accelerate the entry-into-service of a commercial hybrid-electric aircraft in a class of up to 50 seats by 2035/40, while supporting the wider decarbonisation and transition from fossil fuel for the industry. In 2022, FUTPRINT50 ran its second Aircraft Design Challenge 2022 which was open to masters students across Europe.
- **Fly Your Ideas** Since 2008, Airbus, in partnership with UNESCO, has led the Fly Your Ideas competition. The initiative encourages students worldwide to propose innovations for the future of aerospace. Circular aviation innovations have featured prominently, such as past winner, Retrolley, a proposal that re-designs cabin trolleys to collect and separate in-flight waste at the same time, thereby improving recycling outcomes.
- **Paris Airports launch global hydrogen development competition –** With support from the French national government, in 2021, Groupe ADP, Air France-KLM, Airbus and the Paris Region launched a global call for expressions of interest to explore the opportunities generated by hydrogen in Paris airports with the aim of decarbonising air transport activities (CAPA, 2022). The competition is part of the French government's energy transition strategy to develop zero emission aircraft by 2035 and is a "key step" to use the technology across the entire hydrogen value chain to create hydrogen hubs in Paris (*Ibid*.). Calls for expressions of interest focused on three key areas:
    - Storage, transport and distribution of hydrogen in airport environments.
    - Diversification of hydrogen use cases in airports and in aeronautics, including ground handling vehicles and equipment, rail transport at airports, energy supply for buildings or aircraft during ground operations.
    - Creating a circular economy around hydrogen, including the recovery of hydrogen dissipated during liquid hydrogen fuelling or recovery of a by-product from a reaction to produce decarbonated hydrogen.

ii. Establish Multi-Sectoral Innovation Mission R&D partnerships and Roadmaps

- **The US SAF Grand Challenge Roadmap** - In recognition of "the critical role that drop-in synthesized hydrocarbon fuel from waste streams, renewable energy sources, or gaseous carbon oxides—or SAF—will play in addressing the climate change crisis, and its role for jobs and the economy" (Energy, 2022), in 2022 the Biden administration launched the Saf Grand Challenge Roadmap. Developed by an cross-government team alongside stakeholders from national labs, universities, nongovernmental organizations, and the aviation, agricultural, and energy industries, the SAF Grand Challenge Roadmap Report roadmap lays out six action areas spanning all activities with the potential to impact the SAF Grand Challenge objectives of (1) expanding SAF supply and end use, (2) reducing the cost of SAF, and (3) enhancing the sustainability of SAF related to a) Feedstock Innovation; b) Conversion Technology Innovation; c) Building Supply Chains; d) Policy and Valuation Analysis; e) Enabling End Use and f)

Communicating Progress and Building Support. The roadmap is expected to help accelerate the research, development, demonstration, and deployment needed for an ambitious government-wide commitment to scale up the production of 3 billion gallons of SAF per year by 2030, and 35 billion gallons per year by 2050 (Energy, 2022).

- **Innomission II - Green Fuels in Transport and Industry (Power-to-X, etc.) MissionGreenFuels** The Danish Government-led 'Innomission II - Green Fuels in Transport and Industry (Power-to-X, etc.) MissionGreenFuels' aims to support Danish, European and global climate goals, specifically 70% reduction by 2030 and net zero by 2050, and to support Danish research, innovation, growth, jobs and export potential within the field of green fuel. MissionGreenFuels aims to become the anchoring framework "for several new partnerships and transversal collaborations with actors from the entire value chain to flourish and thereby accelerate the green transition" (Innovation Fund Denmark, 2022). The initiative involves almost 60 partners among companies, SMEs, universities, knowledge institutions in the mission. The MissionGreenFuels partnership addresses the challenges of green fuels in a focused and coordinated way, using its roadmap to align and guide research and innovation activities, and ensuring knowledge sharing that identifies and builds on synergies whilst avoiding lock-ins (Mission Green Fuels, 2022). The initiative has two tracks – the first track focuses on the commercial scale-up of already known technologies, the realization of large demonstration projects and the construction of new value chains targeted at buyers in the transport sector in the relatively short term. The second track supports research into new business models and forms of financing, behaviour and citizen involvement in the construction of power-to-X facilities (PtX). These are facilities that produce fuels and chemicals from the electrolysis of hydrogen (Innovation Fund Denmark, 2022).

Where next for Circular Aviation in Ireland?

By continuing to develop a better understanding of the scale and diversity of circular aviation innovations already underway, both in Ireland and internationally, we hope to continue raising the ambition of Ireland's aviation sector in transitioning to a net-zero, sustainable and circular economy. In this way, the learnings and insights highlighted by the case studies in this Sectoral Guide are intended to provide encouragement and give confidence to potential first movers who might build upon them and undertake circular aviation innovation pilots. Moreover, it is the authors' hope that the key findings and recommendations put forward in this Guide will feed into government circular economy strategy activities, highlighting potential ways forward for industry stakeholders.

Annex 1. IAA's Sustainability Management Programme - 2020 - 2025[3]

The overall ambition of the Irish Aviation Authority is to aim to achieve net carbon neutrality by 2025. This plan contains the following objectives:

- **Objective 1:** As a minimum, achieve a 50% energy efficiency improvement by 2030. This is a follow-on objective from the 33% by 2020 energy efficiency target – which the IAA is currently ahead of target on.
- **Objective 2:** Measure and offset employee business aviation travel CO2 equivalent - into the Government's Climate Action Fund. This is mandated by Government in the 2019 Climate Action Plan.
- **Objective 3:** Reduce IAA internal business transport energy use and shift to electrified transport where practicable.
- **Objective 4**: Procure renewably sourced electricity in 2020.
- **Objective 5:** Reduce waste generation by 50% per employee by 2025. Eliminate single use plastics in favour of reusable items. Recycle 90% of paper, cardboard, metal and glass generated in the IAA operations. Systematically assess each waste stream and establish a reduction plan for each item including paperless actions.
- **Objective 6**: Define and implement biodiversity management in line with the "Biodiversity for Business" management framework. This will consist of a site-by-site ecological assessment and mitigation plan in addition to education and awareness activities with related incentives for staff.
- **Objective 7:** Strive to be leaders operationally and achieve the targets set down by the EU Single European Sky initiative (supporting reduction of aircraft fuel use).
- **Objective 8:** Fully implement effective green public procurement across all business activities.
- **Objective 9:** Leverage our Sustainability Management Plan and achievements to promote climate action with our stakeholders, key partners, suppliers, contractors, service providers and wider society.
- **Objective 10:** Aim to become net carbon neutral by 2025 (excluding operational contingency and resilience requirements).

[3] Source: https://www.iaa.ie/docs/default-source/misc/sustainability-management-plan-web-version.pdf?sfvrsn=55a716f3_0

Resources and tools

- Eco-Airport Toolkit e-collection (icao.int)
- Waste Management at Airports - ECO AIRPORT TOOLKIT Book 1 (icao.int)
- https://online-learning.tudelft.nl/courses/sustainable-aviation-the-route-to-climate-neutral-aviation/

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