CLEAN AVIATION

Co-funded by
the European Union

STRATEGIC
RESEARCH
AND
INNOVATION
AGENDA

2024

# Towards Disruptive Technologies for new Generation Aircraft by 2035

This document is the **2nd revision of the Strategic Research and Innovation Agenda (SRIA) of the Clean Aviation Joint Undertaking**. It was prepared by the Founding and Associated members of the Clean Aviation Joint Undertaking to update the vision and the overall ambition to the programme's objectives as set out in the Council Regulation (EU) 2021/2085[1].

This version of the SRIA defines the aircraft concepts vision serving as references to mature and integrate aircraft innovative technologies with the aim to deliver impact as defined in the article 57.2 of the council regulation. It incorporates changes to align with the budget allocation and availability of €1.7 billion in EU funding while maintaining the ambition unchanged, to revise the strategic planning to align with the effective date of launch of the programme's operations in 2021 and to revise its strategic content with activities launched through the open calls in the 1st phase of the programme.

This revision was developed between January and June 2024, in preparation for the 2nd phase (2025-2030) of the programme, departing from the 2nd version of the SRIA published in December 2021. It is built on the preparatory work performed within the Technical Committee of the Clean Aviation Joint Undertaking, in which all Members are directly represented, and was approved by the Governing Board on July 2024 after consultation of the different consultative bodies (States representative group and Scientific Advisory Body).

---

1. Council Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe

# Our Mission

The Clean Aviation Joint Undertaking shall have the objectives:

- **to integrate and demonstrate disruptive aircraft technological innovations to decrease net emissions of greenhouse gases by no less than 30 %** compared to 2020 state-of-the-art technology to support the European Green Deal and climate neutrality by 2050.
- **to ensure that the technological and the potential industrial readiness of innovations can support the launch of disruptive new products and services for an entry-into-service by 2035,** enabling 75% of the world's civil aviation fleet to be replaced by 2050 in support of the European Green Deal.

The aircraft developed will enable net $CO_2$ reductions of **up to 90%** when combined with the effect of Sustainable Aviation Fuels, or zero $CO_2$ emissions in flight when using hydrogen as energy source.

# Our Vision

Clean Aviation's aeronautics-related research and innovation activities, focusing on breakthrough technology initiatives, will contribute to the global sustainable competitiveness of the European aviation industry.

Our efforts will ensure that aviation remains a safe and secure, reliable, cost-effective and efficient means of passenger and freight transportation while successfully transitioning to climate neutrality.

European aviation research and innovation capacity will be strengthened through the partnership, enabling new and ambitious global standards to be set.

# Foreword

**The Clean Aviation Joint Undertaking is the European Union's leading aviation research and innovation programme aimed at transforming the sector towards a sustainable and climate neutral future, in line with the European Green Deal.**

Aviation is a strategic industrial sector for Europe with a pivotal role in job creation and in economic activity, supporting 4.4% of the European Gross Domestic Product (GDP). European aviation has the power to lead the way toward a climate-neutral system and set new standards for global aviation. **Accelerating this transformation is crucial** as air travel demand has rebounded following the COVID-19 pandemic (2020-2022) and is projected to double by 2050. This strongly amplifies the urgency to tackle aviation's emissions and their impact on our environment and climate.

> *European aviation has the power to lead the decarbonization journey of the sector and set new global standards.*

The European aviation industry is committed to transforming the sector, through the support of the Clean Aviation Joint Undertaking as well as other notable European Union's initiatives and policies such as (but not limited to) the European Alliance for Zero Emission Aviation (2022), ReFuelEU (2023) and the Net Zero Industry Act (2023). These efforts, complemented by important private investments, are contributing to **maintaining European aviation competitiveness** at global level.

Since its establishment in November 2021, the Joint Undertaking has launched large-size, industry-led projects that are developing **novel concepts for the next-generation of low-emissions commercial aircraft**; investigating various **disruptive aircraft technological innovations** options powered either by Sustainable Aviation Fuels (SAF) or hydrogen, combined with electric hybridization; and performing **trade studies** to assess various aircraft configurations incorporating the most promising technology options aiming at **reducing greenhouse gas (GHG) emissions by no less than 30%** at aircraft level, compared to 2020 state-of-the-art, while enabling **zero CO2 emissions in flight when using hydrogen as energy source,** or **up to 90% net-$CO_2$-emission reduction** when being combined with the effect of Sustainable Aviation Fuels.

As part of the programme's Phase 1 (2022-2026), these projects are supported by more than €800 million in European Union funding through Horizon Europe. This public-side support is complemented and leveraged by a declared private-side in-kind contributions amounting to a total research effort of €2 billion, confirming a strong commitment by the European aviation ecosystem (industry, supply chain research organization, academia and SMEs) through their membership and participation to the Joint Undertaking to achieving the programme objectives and contributing to transforming European aviation towards a sustainable and more competitive system.

> *The European aviation eco-system is strongly committed to delivering disruptive solutions for the next generation of aircraft by 2035.*

Building on this momentum, between January and June of 2024, as part of the preparation of the programme's Phase 2 (2025-2030), the Clean Aviation Joint Undertaking's members[2] prepared this revised version of the SRIA to ensure that the programme's vision and overall ambition remain aligned to the programme's objectives as set out in the Council Regulation (EU) 2021/2085 with the availability of 1.7 billion € in EU funding.

---

[2] https://clean-aviation.eu/members

The primary scope of this SRIA revision is to define the programme's Phase 2 agenda (2025-2030) to integrate and demonstrate disruptive technological innovations around four targeted European aircraft concepts and one scalable demonstration concept. These concepts serve as reference aircraft concepts targeting **the expected impact as defined in the article 57.2 of the Council Regulation** for the integration and demonstration of impactful technological innovations within Clean Aviation, as well as for relevant innovations supported by other EU, national, and regional programmes.

> *This SRIA revision identifies aircraft concepts targeting a reduction of 30% of $CO_2$ emissions by 2035 (up to 86% with SAF).*

Establishing regulations that ensure the safety, functionality, and affordability of new aircraft is essential to accelerate the progress of Clean Aviation's technological innovations aimed at reducing net-greenhouse gas emissions. This aspect is being addressed as part of the programme through a close **collaboration with the European Union Aviation Safety Agency (EASA),** which plays a crucial role in defining future safety standards and certification requirements for Clean Aviation' disruptive innovations to accelerate route to market.

Finally, the SRIA was refined to align with the resources allocated under the Council Regulation and the **synergies that are being established with relevant programmes at European, national and regional level**.

# Disclaimer

As European Union research and innovation programme for sustainable aeronautics, the Clean Aviation Joint Undertaking supports the maturation and demonstration of aircraft technological innovations and aircraft concepts through European Union's funding, complemented by contributions in-kind from the private-side members of the Joint Undertaking.

However, the Clean Aviation Joint Undertaking is not supporting, nor influencing, any specific industry-led (or member-led) product design, development, or deployment initiative. The members of the Joint Undertaking, and the programme's beneficiaries in general, are the players solely responsible for product design strategy, including product-launch decision, departing from potential outcomes of the programme.

Finally, the allocation of European Union's funding to activities described in this document is based on open, transparent and competitive Calls for Proposals, with evaluations supported by independent experts, in line with the Horizon Europe and the Joint Undertaking regulations.

# Table of contents

Our Mission 1
Our Vision 1
Foreword 2
Disclaimer 4
List of Acronyms 6

1. INTRODUCTION 7

1.1. The global context 8
1.2. The challenge of transforming aviation 11
1.3. The necessity for a European Partnership for Clean Aviation 12
1.4. The Clean Aviation's Strategic Innovation and Research Agenda 13

2. VISION, IMPACT AND COMMITMENT 14

2.1. The vision for a Clean Aviation Programme 15
2.2. Plotting an ambitious trajectory to achieve climate-neutral aviation 16
2.3. Coordinated, flexible and impact-driven research agenda 18
2.4. Approach and targeted aircraft performance gains 20
2.5. Impact of a Clean Aviation Programme 23
2.6. The commitment towards a Clean Aviation Joint Undertaking 26
2.7. Instruments 28
2.8. Policies, standards, rules, infrastructures and industrialisation 29
2.9. Maximising impact through synergies 31

3. AIRCRAFT CONCEPTS 35

3.1. Ultra-Efficient Regional aircraft 39
3.2. Ultra-Efficient Short and Medium Range Aircraft 41
3.3. Hydrogen-Powered Aircraft 43

4. DISRUPTIVE TECHNOLOGIES FOR ULTRA-EFFICIENT REGIONAL AIRCRAFT 45

4.1. Introduction 46
4.2. Key technologies and their contribution to the Clean Aviation ambition 50
4.3. Demonstration strategy, key objectives of large-scale demonstration 60
4.4. Scalability, cross-cutting synergies, and exploitation potential 66

5. DISRUPTIVE TECHNOLOGIES FOR ULTRA-EFFICIENT SHORT/MEDIUM-RANGE AIRCRAFT 67

5.1. Introduction 68
5.2. Key technologies and their contribution to the Clean Aviation ambition 71
5.3. Demonstrator strategy, key objectives of large-scale demonstration 79
5.4. Scalability of technologies and demonstrator results 84

6. DISRUPTIVE TECHNOLOGIES TO ENABLE HYDROGEN-POWERED AIRCRAFT (HPA) 85

6.1. Introduction 86
6.2. Key technologies and their contribution to the Clean Aviation ambition 88
6.3. Demonstrator strategy, key objectives of large-scale demonstration 95

# List of Acronyms

| | |
|---|---|
| **APU** | Auxiliary power unit |
| **ASK** | Available Seat Kilometer |
| **ATA** | Air Transport Association |
| **ATAG** | Air Transport Action Group |
| **ATM** | Air Traffic Management |
| **AZEA** | Alliance for Zero Emission Aviation |
| **BoP** | Balance-of-Plant |
| **CAGR** | Compound Annual Growth Rate |
| **CEF** | Connecting Europe Facility |
| **CRL** | Certification Readiness Level |
| **CS** | Certification Specification |
| **EASA** | European Union Aviation Safety Agency |
| **ECS** | Environment Control System |
| **EIB** | European Investment Bank |
| **EIC** | European Innovation Council |
| **EIS** | Entry into Service |
| **EMI** | Electro-Magnetic Interference |
| **ERC** | European Research Council |
| **ERDF** | European Regional Development Fund |
| **ERDF** | European Regional Development Fund |
| **ETS** | Emission Trading System |
| **EU MFF** | European Union Multiannual Financial Framework |
| **EUROCAE** | European Organization for Civil Aviation Equipment |
| **FC** | Fuel Cell |
| **FCPS** | Fuel Cell Propulsion System |
| **FMS** | Flight Management System |
| **GHG** | Greenhouse Gas |
| **H2C** | Hydrogen Direct Combustion |
| **HAR** | High Aspect Ratio |
| **HEA** | Hybrid-Electric Aircraft |
| **HERA** | Hybrid-Electric Regional Architecture |
| **HPA** | Hydrogen-Powered Aircraft |
| **HyFC** | Hybrid Electric Fuel Cell |
| **ICAO** | International Civil Aviation Organization |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IPCEI** | Important Projects of Common European Interest |
| **KPIs** | Key Performance Indicators |
| **LH2** | Liquid Hydrogen |
| **MAWP** | Multi-Annual Work Programme |
| **MoC** | Means of Compliance |
| **MOC** | Memorandum of Cooperation |
| **MoU** | Memorandum of Understanding |
| **MRO** | Maintenance Repair and Overhaul |
| **MW** | Mega Watt |
| **MWh** | Mega Watt-hour |
| **NRRPs** | National Recovery and Resilience Plans |
| **NZIA** | Net-Zero Industry Act |
| **R&D** | Research and Development |
| **R&I** | Research and Innovation |
| **R&T** | Research and Technology |
| **REG** | Regional |
| **RIS3** | Relevant Smart Specialization Strategies |
| **RTOs** | Research and Technology Organisation |
| **S3** | Smart Specialization Strategies |
| **SAB** | Scientific Advisory Body |
| **SAF** | Sustainable Aviation Fuel |
| **SLD** | Supercooled Large Droplets |
| **SME** | Small-Medium Enterprises |
| **SMR** | Short Medium Range |
| **SRG** | States Representatives' Group |
| **SRIA** | Strategic Research and Innovation Agenda |
| **TRL** | Technology Readiness Level |
| **UHBR** | Ultra-High Bypass Ratio |
| **V&V** | Validation & Verification Approach |

# 1. Introduction

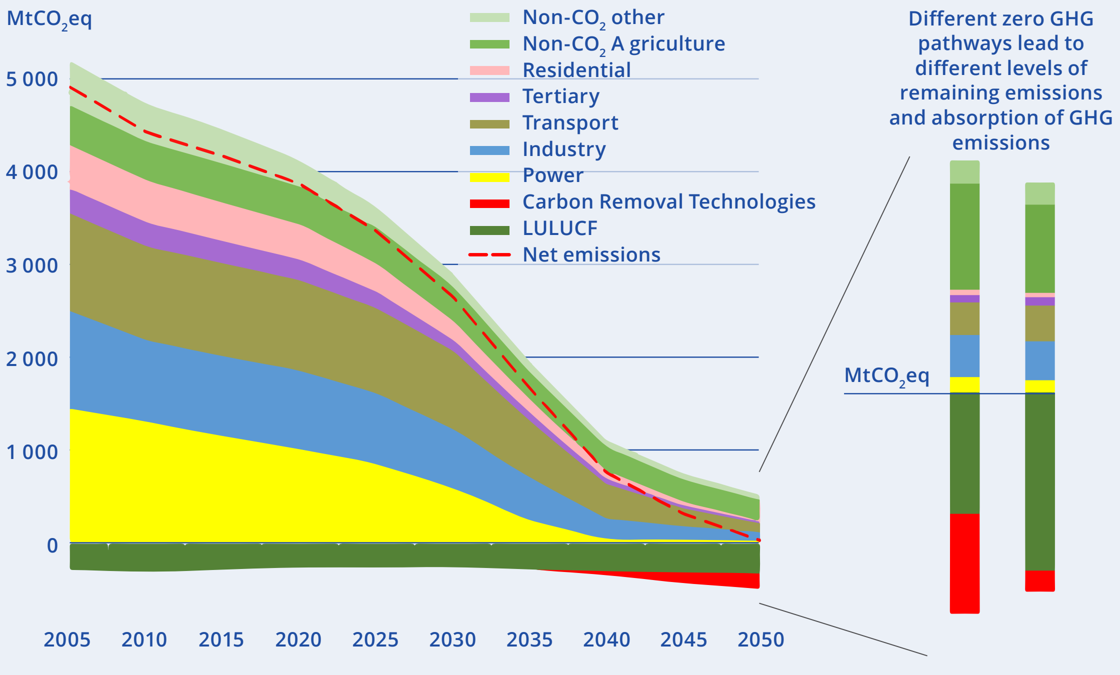
# 1.1. The global context

**The Intergovernmental Panel on Climate Change (IPCC)[3] issued a Special Report in October 2018, on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways.**

In response, the European Commission issued A Clean Planet for all,[4] a communication outlining a strategic long-term vision that underscored the pressing need for deep decarbonisation. The communication indicated the scale of the contributions from various sectors, including transport, towards the required level of decarbonisation in the EU by 2050 (Figure 1-1). The document notably singled out the severity of the challenge for aviation, and the need to tackle emissions using advanced technologies and fuels.

As part of the Sixth Assessment Climate Change 2023 Synthesis Report,[5] the IPCC highlighted the unequivocal impact that emissions of greenhouse gases have had on global warming, with the global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. The report also confirmed the trajectory of the 1.5°C scenario part of the A Clean Planet for all communication.

**Figure 1.1: Europe's GHG emissions trajectory in a 1.5°C scenario**



*Source: A Clean Planet for all*

---

3. IPCC Special Report Global Warming of 1.5°C (2018).
4. A Clean Planet for all, COM (2018) 773.
5. IPCC Sixth Assessment Climate Change 2023 Synthesis Report.

The aviation industry's contribution to economic growth, societal development and cohesion is well recognised. ***Aviation is a strategic industrial and economic sector for Europe, playing*** a key role in job creation, supporting 13.5 million jobs in Europe and one trillion euro in European economic activity – corresponding to 3.6% of all employment in Europe and 4.4% of the European GDP, respectively.[6] Moreover, aviation is key to keeping highly qualified competences and jobs in Europe, which is crucial for European research and engineering capabilities.

While the socio-economic benefits of aviation are significant, and this sector is already subject to intense and increasing global competition, there is an urgent need to address its contribution to the developing climate emergency.[7] The air transport sector accounts for an estimated 2.5%[8] of global $CO_2$ emissions. Although aviation accounts for a relatively small share of global emissions, it is one of the most challenging sectors to decarbonise. If no action is taken, aviation emissions are expected to increase further, based on the forecast of ever-increasing air-travel demand.

To avoid jeopardising the global aviation industry's role and depriving citizens of aviation's benefits, the aviation industry *pledged to reach net zero $CO_2$ emissions by 2050* and to promote global cooperation on the way to achieving this objective.[9] With the European Union's support, **European aviation has the power to lead the way towards a climate-neutral system and to set new global standards in aviation**.[10]

The **European Green Deal**[11] includes the first European Climate Law to enshrine the 2050 climate neutrality objective in legislation. It aims to *'transform the EU into a fair and prosperous society, with a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use*." At the same time, in May 2021, the EU Commission launched the **Industrial Strategy for Europe.**[12] This laid out the importance of industrial leadership when making the transformation to a low-carbon and digital Europe fit for the future. The strategy states for instance that "*there should be a special focus on sustainable and smart mobility industries. These have both the responsibility and the potential to drive the twin transitions towards climate neutrality and digital leadership, to support Europe's industrial competitiveness and improve connectivity.*" This is notably the case for the automotive, **aerospace**, rail, and shipbuilding industries, as well as for alternative fuels and smart and connected mobility. The EU Commission is pushing hard to maintain European leadership by boosting the deployment of net-zero technologies across industries, thanks to more recent initiatives such as the Net-Zero Industry Act (NZIA, March 2023)[13] and the Antwerp Declaration for a European Industrial Deal (2024).[14]

Air traffic growth has proven to be remarkably resilient[15] and rebounded following several earlier economic and political shocks (e.g. the oil crisis in the 70s, the Iran-Iraq war in the 80s, the Gulf crises in the 90s and the 9/11 terrorist attack, the 2002–2004 outbreak of SARS and the financial crisis early this century). Air traffic doubled every 15 years between 1988 and 2018. However, air travel was brought to an abrupt halt in 2020, due to the Covid-19 pandemic. In 2020, the aviation industry suffered "the worst year in history for air travel demand".[16] In the aftermath of the Covid-19 pandemic, Europe took specific measures (example: the EU recovery plan[17]) that have proven instrumental in reviving the industry. In 2023, there were 10.2 million flights within Europe (i.e., +10% compared to 2022), and air traffic is expected to reach pre-pandemic levels of 11.1 million flights within Europe by 2025, as predicted by Eurocontrol.[18]

---

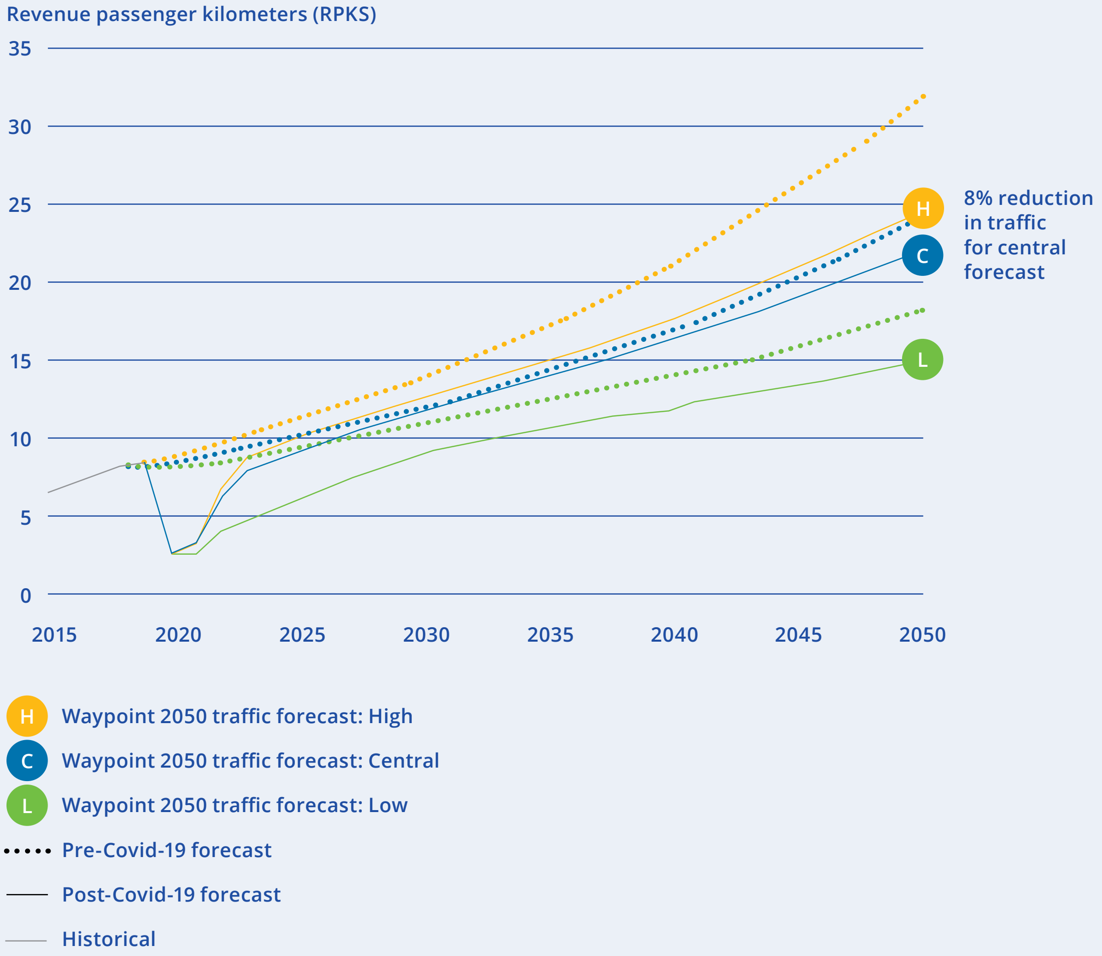
6. Waypoint 2050 (Air Transport Action Group Report, 2021).
7. European Parliament Declaration, 25 November 2019.
8. Hannah Ritchie (2020) – 'Climate change and flying: what share of global $CO_2$ emissions come from aviation?'.
9. In 2022, ICAO member states adopted a long-term global aspirational goal (LTAG) to achieve net-zero carbon emissions from international aviation by 2050. The agreement aims to reduce emissions within the sector itself (i.e. directly from aviation activity). Beyond LTAG, the industry, airlines and Air Navigation Service Providers (ANSPs) are defining their way to translate their vision into concrete actions.
10. The Brussels Effect: How the European Union Rules the World, Prof. Anu Bradford, Columbia Law School ISBN 978-01-9008-838-3.
11. The European Green Deal, COM (2019) 640.
12. A New Industrial Strategy for Europe, COM(2020) 102 final.
13. Net-Zero Industry Act, COM (2023) 161.
14. The Antwerp Declaration for a European Industrial Deal (2024).
15. Airbus Global Market Forecast [GMF] 2019 – 2038.
16. World Economic Forum – Aviation industry suffers 'worst year in history' as COVID-19 grounds international travel (2021).
17. Europe took specific measures – NextGenerationEU (NGEU) – in the form of large stimulus packages that have proven instrumental in reviving the industry (https://commission.europa.eu/strategy-and-policy/recovery-plan-europe_en).
18. Eurocontrol, European Aviation Overview (2024).

**Global air-travel demand is expected to at least double by 2050**. This forecast is based on the central scenario issued by the Air Transport Action Group (ATAG) in the report Waypoint 2050[4] (Figure 1-2). This is a promising outlook for aviation, its users, and the prosperity of the global aviation industry. However, it also represents a growing challenge in terms of airport and airspace capacity, and strongly amplifies the **urgency to tackle aviation's emissions and their impact on our environment and climate**.

Achieving a climate-neutral aviation system by 2050 requires a collaborative effort with the European Union, leveraging the Clean Aviation Joint Undertaking to drive transformative Research and Innovation (R&I) and ensure long-term industrial commitments for sustainable growth and innovation.

**Figure 1.2: Global Air Passenger Traffic Forecast Comparison: Pre- and Post-Covid-19**

Comparison between the traffic forecast used before Covid-19 hit those used in Waypoint 2050 report: the deep impact of Covid-19 on passenger traffic, as well as the long recovery will mean an 8% reduction in traffic in the central scenario in 2050.



*Source: Waypoint 2050*

## 1.2. The challenge of transforming aviation

**The aviation sector faces several key challenges in this and the next decades. Firstly, to develop and introduce safe, reliable, and affordable low- to zero-emission air transport for citizens. Secondly, to also ensure that Europe's industrial leadership is maintained and strengthened throughout the transition to a climate-neutral Europe.**

Transforming aviation towards climate neutrality requires an integrated approach that spans technology providers and innovators, manufacturers and operators, public sector authorities and travellers. It involves re-inventing the innovation, product development and fleet replacement cycles needed to introduce a new breed of aircraft, with decisive gains in performance and efficiency, much more swiftly than 'business as usual'. The transformation also requires significant investment in new infrastructure, to make new fuels and energy sources available.

The EU has started to develop regulations and initiatives that support and enable the required transformations. **ReFuelEU Aviation** initiative,[19] which came into force in October 2023, aims to increase both demand for and supply of Sustainable Aviation Fuels (SAF). Set up in 2022, the **Renewable and Low-Carbon Fuels Value Chain Industrial Alliance**[20] contributes to accelerating both the production and supply of renewable and low-carbon fuels in aviation. The innovative public policies and regulations that have been implemented must encourage and enforce modernization of operating networks and operations. Transforming from kerosene, today's entirely fossil fuel-powered system, to such a future aviation system – with multiple energy carriers and architectures – will be **a massive and systemic challenge**.

> *EU Institutions and Member States' support in the transformation is essential to ensure the trajectory is succesful.*

In June 2022, the European Commission launched the **Alliance for Zero-Emission Aviation (AZEA)**,[21] as a voluntary initiative of private and public partners in line with the Toulouse Declaration on future sustainability and decarbonisation of aviation. The Alliance's objective is to prepare the market for the entry into service of zero-emission aircraft, as well as to identify and prioritise the challenges posed by zero-emission aircraft (operations, fuel demand, airport infrastructures). Aircraft are highly complex and safety-critical capital equipment. Introducing new technologies requires disciplined systems integration, so that the improvement of one system does not adversely affect the performance of other systems or of the aircraft as a whole. So the overall research and innovation (R&I) agenda must be organised to address the complexities, risks, and vigour of an aircraft development programme. European aviation R&I therefore needs an integrative approach, one that enables stable and long-term collaboration across the full innovation chain. A coordinated programmatic approach is needed to handle the strong interdependencies between technologies, the integration challenges at an overall aircraft design level, plus the timescales and risks involved.

The European aeronautics community is convinced the trajectory towards climate-neutral aviation is achievable, despite the high level of complexity and interdependency. However, this progress will depend on:

- An **exceptional research and technology effort** to reduce energy needs and fuel consumption, while ensuring safety and competitiveness in the spirit of a public-private partnership and with shared investments and commitments.
- Fast-tracked research, development, and deployment of **Sustainable Aviation Fuels (SAF)** by the relevant actors and proactive policies for wide-scale and economically viable use within the next decade, enabled by the **ReFuelEU Aviation Initiative,** to increase the uptake of sustainable fuels by aircraft to reduce their environmental footprint.
- **Optimised green air operations and networks** to fully exploit new aircraft and systems capability, with combined efforts from SESAR3 Joint Undertaking and AZEA (Alliance for Zero-Emission Aviation).
- A suitable **global aviation regulatory framework** creating the conditions for a transition.

---

19. ReFuelEU Aviation initiative (October 2023).
20. Renewable and Low-Carbon Fuels Value Chain Industrial Alliance: https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/renewable-and-low-carbon-fuels-value-chain-industrial-alliance_en
21. Alliance for Zero-Emission Aviation (AZEA): https://defence-industry-space.ec.europa.eu/eu-aeronautics-industry/alliance-zero-emission-aviation_en

## 1.3. The necessity for a European Partnership for Clean Aviation

**The journey to a climate-neutral aviation system is well beyond the capability and investment capacity of the private sector alone. No single country in Europe has the financial, technological, and industrial capability to implement the transformation. However, Europe clearly has the necessary added value to undertake this journey. The institutionalised European Partnership for Clean Aviation (i.e., The Clean Aviation Joint Undertaking) under Horizon Europe is the only approach that can pull together the required resources and commitments, and adequately reduce the industrial risk for transformative Research and Innovation (R&I).**

This approach secures the long-term industrial commitments needed for long innovation cycles. It ensures that the research activities of industry are aligned with the Union's policy priorities. It contributes to building Europe's leadership in innovation and technology and to delivering jobs and economic growth throughout the transition to a climate-neutral Europe by 2050. The approach can offer future generations the promise of continued, affordable, and equal access to air travel, with all of its social and economic benefits, and contribute to the UN's Sustainable Development Goals.

The institutionalised partnership with the European Union, aligning R&I efforts together with the sector, is a powerful platform for integrating elements from other EU-level R&I, Member States' national research programmes and regional specialisation strategies. This partnership ensures continual lose alignment with the Commission's policy leadership. This is instrumental in creating the regulatory/legislative and economic conditions for a successful deployment in the aviation system of globally competitive new aircraft with disruptive performance gains, to have the necessary impact by 2050.

Achieving an early and meaningful impact in aviation is critical considering the 'climate emergency', as this emergency is being seen and felt by Europe's citizens, is recognised by the European Parliament and was highlighted in the Commission's agenda for the Green Deal. This impact will be key to developing new processes, methodologies and technologies to accelerate disruptive technology introductions, whilst offering the potential to upgrade existing aircraft. To accelerate this process, Europe must develop relevant regulations and infrastructures to ensure that new aircraft are safe, operable, and affordable.

> *A private-public collaboration is required to drive transformative Research and Innovation for climate-neutral aviation by 2050.*

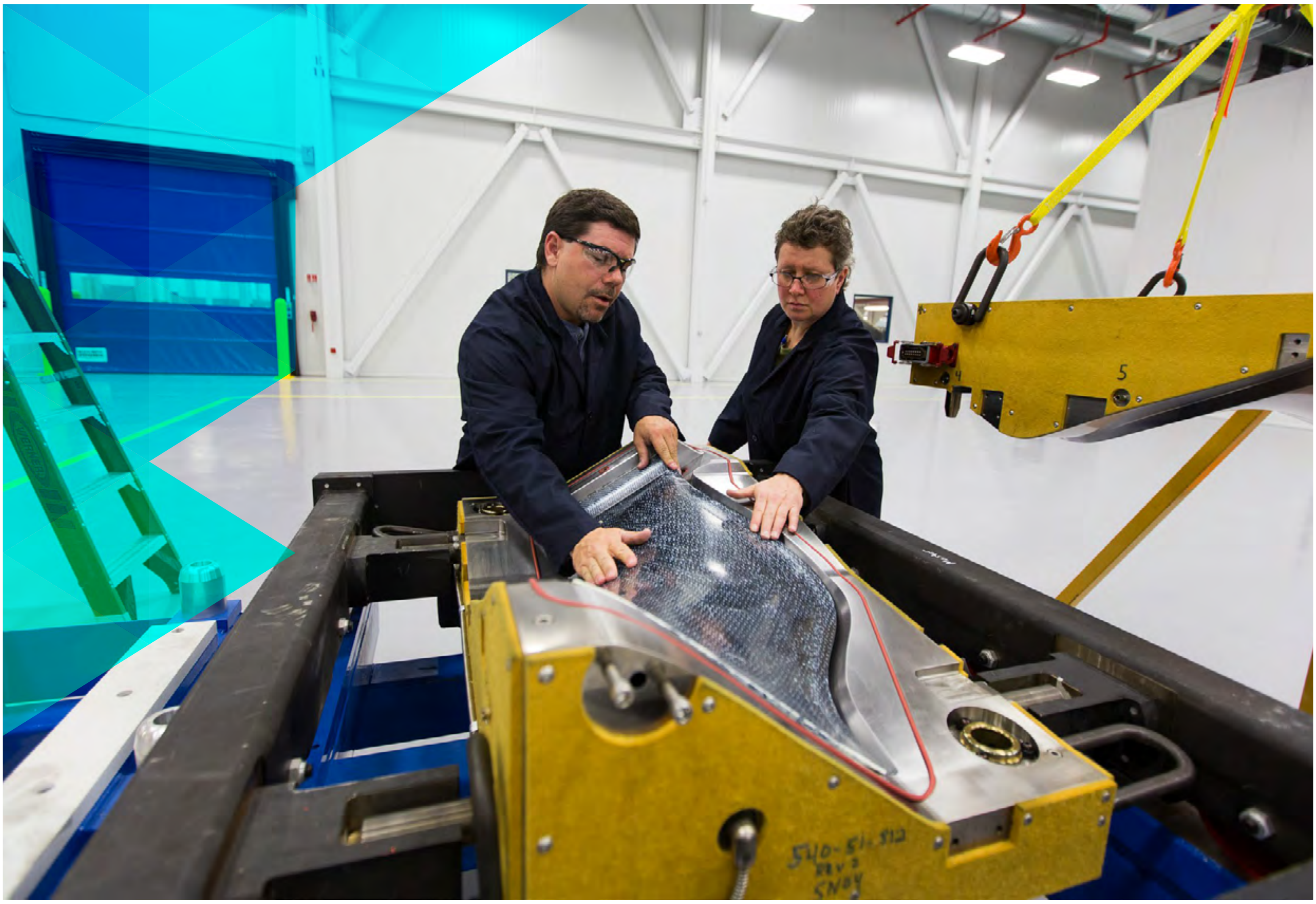
All this development calls for close harmonisation with future safety standards and certification requirements, working with the European Union Aviation Safety Agency (EASA) as part of the governing bodies and participants in projects. This can significantly reduce development time, costs, and ensure that disruptive new technologies will meet the highest levels of safety and reliability. The process is complemented by a collaborative approach within AZEA: the Clean Aviation Joint Undertaking is a member of this Alliance, to foster development of the entire ecosystem required for a successful market up-take of future Clean Aviation aircraft technological innovations. In addition, a close alignment with SESAR 3 Joint Undertaking ensures an effective coordination of efforts, to make the new disruptive technologies compatible with their insertion into the air traffic management system to foster the launch of disruptive new products and services and their entry into service by 2035.

An **inclusive, ambitious, and institutionalised (Art. 187) European Partnership for Clean Aviation** under Horizon Europe is the most effective and impactful means through which the aeronautics and air transport sectors can make a decisive contribution to a climate-neutral Europe. Only such a partnership can pull together the resources, develop, and enable the introduction of safe, reliable, efficient, and affordable **climate-neutral air transport.** It will build Europe's leadership in innovation and technology and deliver jobs and economic growth throughout the transition to a climate-neutral Europe by 2050. It can offer future generations the promise of continued, affordable and equal access to air travel and its social and economic benefits and contribute to the UN's Sustainable Development Goals. The European aeronautics community is ready and committed to act now.

## 1.4. The Clean Aviation's Strategic Innovation and Research Agenda

This revised version of the SRIA provides the vision for the 2nd Phase of the programme and outlines aircraft technological innovations proposed around four (4) aircraft concepts for integration and demonstration. These candidate aircraft concepts, addressing the SMR and Regional segments (with some spill over benefits to long range segment), offers the best potential to decrease net-greenhouse gas emissions by no less than 30% at aircraft level and to ensure that the technological industrial readiness of innovations achieved at completion (up to TRL 6 by 2030) can support the launch of disruptive new products and services for an entry into service by 2035.

Chapter 2 of this document outlines the overall Clean Aviation programme vision and ambition. Chapter 3, introduced in this revision, focuses on the targeted European aircraft concepts (and one scalable demonstration concept); these concepts serve as a reference guidance for the integration and demonstration of impactful aircraft technological innovations within the programme. The subsequent chapters, describe the strategic areas of research dedicated to disruptive technologies for ultra-efficient regional aircraft (Chapter 4), disruptive technologies for ultra-efficient short/medium-range aircraft (Chapter 5) and disruptive technologies to enable hydrogen powered aircraft (Chapter 6).



# 2. Vision, impact and commitment

## 2.1. The vision for a Clean Aviation Programme

**Clean Aviation Joint Undertaking (CAJU) will contribute to the delivery of Europe's climate neutrality by 2050 by pioneering new solutions in the aeronautics disciplines, thus addressing the relevant EU policy priorities (e.g. the Green Deal) described in Chapter 1. It will trigger a technology revolution that will target climate-neutral aviation in Europe by 2050.**

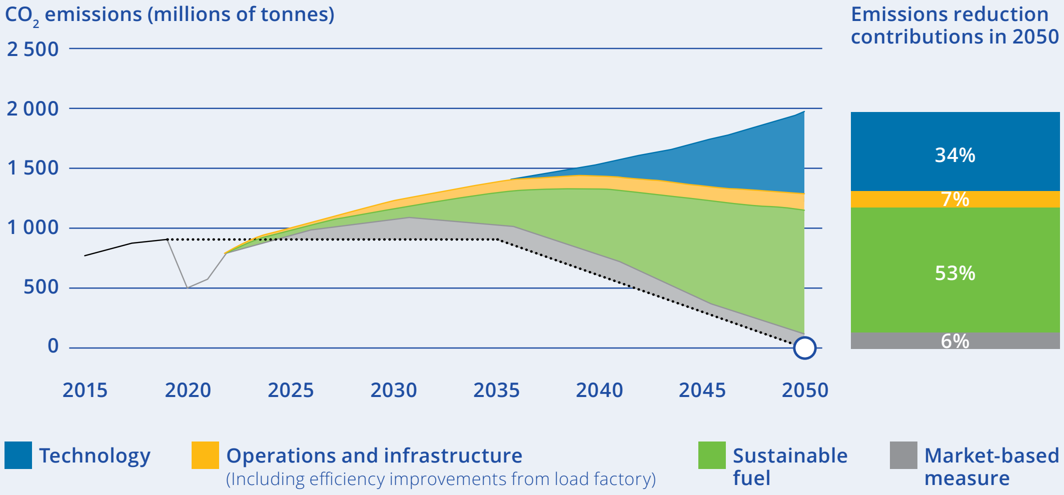
Ambitious zero- and low-carbon emission technologies will drive the transformation. These include hybrid-electric solutions for regional and short-range flights, plus ultra-efficient aircraft designs utilising thermal engines suited for the adoption of sustainable aviation fuels (SAF) that cover the larger and more energy-intense medium and long-range sectors.

Clean Aviation technologies will aim to a greenhouse gases reduction of no less than 30% by 2050, compared to 2020 state-of-the-art aircraft. The partnership will also enable aircraft, engines and systems to utilise the full potential of low- or zero-carbon fuels, including potential disruptive innovations like hydrogen. Together these outcomes will accelerate the transition towards climate neutrality.

> *The ultimate objective is to enable a climate-neutral aviation system in Europe by 2050.*

Together with the large-scale deployment and use of sustainable aviation fuels (such as power-to-liquid synthetic fuels) or hydrogen, the operating fleet in 2050 could achieve a 90+% reduction in net-carbon emissions compared to today's fleet. Under stringent conditions illustrated below, the sector can meet the goal to reach net-zero carbon by 2050,[22] while supporting aviation growth. Forecasts of global compound annual growth rate (CAGR) are roughly 3% CAGR.[23] However, the EU has a more mature air transport system with a markedly lower CAGR that is expected to be ~1% CAGR[24] in the coming decades. The change drivers and resulting impact required to support the sector's growth, while contributing to achieving the targets for climate neutrality by 2050 (European Green Deal), are schematically depicted in Figure 2.1 below:

**Figure 2.1: Schematic of the ATAG Waypoint 2050 Scenario 3 for $CO_2$ emissions[25]: Aspirational and aggressive technology perspective.**



*Source: A Clean Planet for all*

---

[22] ATAG Waypoint 2050 (September 2021) ATAG Waypoint 2050 (September 2021)

[23] IATA Sustainability and Economics, Tourism Economics (March 2023 release)

[24] Eurocontrol Aviation Outlook (April 2022)

[25] Scenario for non-$CO_2$ emissions is not provided, given the scientific uncertainties (refer to §2.4 for details about non-$CO_2$ effects).

## 2.2. Plotting an ambitious trajectory to achieve climate-neutral aviation

**To reach the goal of climate-neutral aviation, a new breed of aircraft will be required. They must support the introduction of disruptive technologies, to ensure a significantly lower environmental impact. These aircraft will need to start entering the air transport system in the 2030s, if they are to have any serious impact by 2050. Besides these new aircraft, innovations will be developed and introduced incrementally on current generation aircraft, and can already contribute to an emissions reduction by 2030, in line with the European Green Deal.**

The ambition of the Clean Aviation Joint Undertaking is to ensure that advances in breakthrough technologies will support the launch of new aircraft developments by 2030. This will enable maximum progress towards climate-neutral aviation, meet socio-economic expectations, and provide benefits for European society and businesses.

The above-mentioned objectives are reflected in Article 57 of the Council Regulation[26] of 19 November 2021 establishing the Joint Undertakings under Horizon Europe:

> **To integrate and demonstrate disruptive aircraft technological innovations** able to decrease net emissions of greenhouse gases by no less than 30% by 2030, compared to 2020 state-of-the-art technology, while paving the ground towards climate-neutral aviation by 2050.

> **To ensure that the technological and the potential industrial readiness of innovations** can support the launch of disruptive new products and services by 2035, with the aim of replacing 75% of the operating fleet by 2050 and developing an innovative, reliable, safe and cost-effective European aviation system that is able to meet the objective of climate neutrality at the latest by 2050.

> **To expand and foster integration of the climate-neutral aviation research and innovations value chains,** including academia, research organisations, industry and SMEs, also by benefiting from exploiting synergies with other national and European related programmes and by supporting the uptake of industry-related skills across the value chain.

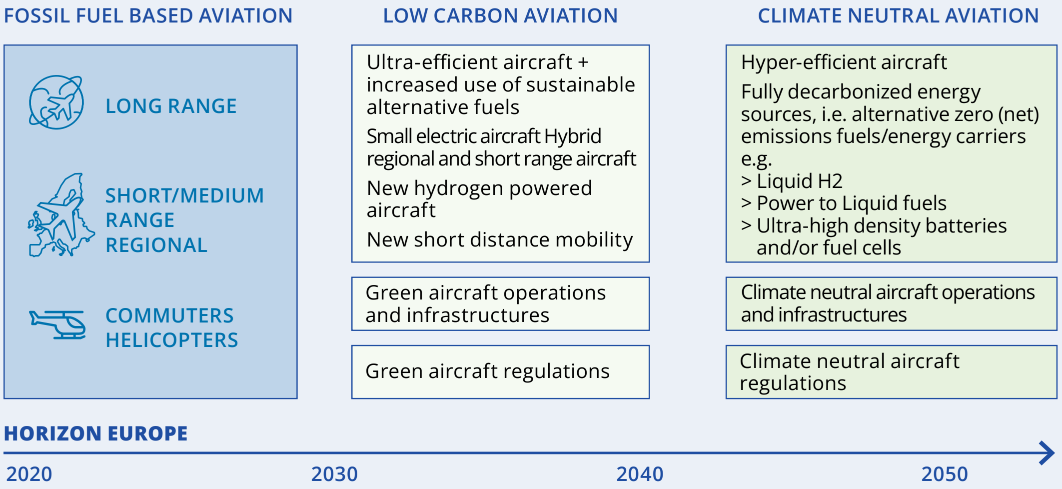
Clean Aviation will build on important earlier research under previous Framework Programme R&I (e.g. under the Clean Sky and Clean Sky 2 Programmes), as well as promising research under the collaborative research programme, and will go well beyond the technological progress made to date. It will accelerate the transition towards a climate-neutral system by enabling all-new aircraft platforms and configurations, and taking a system-wide approach. The Partnership will aim to demonstrate decisive steps in performance by 2030, so new aircraft configurations can be defined at that stage and can be available for airlines by 2035.

The Clean Aviation trajectory matches the **two horizons** towards climate neutrality in the Green Deal legislative proposal (Figure 2.2)

---

[26] (EU) 2021/2085 hereafter 'Council Regulation'.

Figure 2.2: Two horizons in the trajectory towards climate-neutral aviation



Given the scale of the challenge and limited R&I resources, the Clean Aviation Partnership will focus on the most promising technologies. It will pursue a **demonstration strategy to mature these to the highest possible TRL** (Technology Readiness Levels) for their integration into aircraft in those market segments most likely to absorb new clean sheet designs by 2035 and representing a significant share of aviation's climate impact. Technology potential compared to programme and budget constraints, and market readiness, have been considered as well as the need to deliver actual results to the public and private stakeholders of the Partnership. **The Clean Aviation Partnership will aim for decisive steps in new aircraft performance to be demonstrated by 2030 and available by 2035.** It will develop key technologies that will support the transition to climate neutrality by 2050 in parallel to this. It will also bring these technologies to a maturity that can enable appropriate scaling across the full spectrum of aircraft segments and flight operations.

The demonstration efforts in the proposed programme will focus on bringing decisive progress in technology maturity and performance, in order to support the pivotal aircraft concepts foreseen in Chapter 3, by integrating and demonstrating technologies along three main pillars (see for detailed descriptions Chapters 4, 5 and 6): **ultra-efficient short/medium range aircraft, ultra-efficient regional aircraft, and hydrogen-powered aircraft.**

Aircraft in these three categories are expected to be able to bring a crucial step-change in aviation's emissions by 2050 because of the potential for significant, disruptive performance and the market's earlier readiness for disruptive solutions in these aircraft classes. They will deliver major steps in the operating fleet, together with optimised sustainable trajectories and operations, and with accelerated transition to low- or zero-carbon fuels. The maturation of technologies strategy within these efforts will create significant **positive spillover effects to other aircraft categories** and in the exploitation of R&I results. In addition, the architectures demonstrated will not be confined to one or two distinct, narrowly defined aircraft configurations, but can be applied to a more dynamically developing air transport system where new concepts emerge. This will bring additional benefits across a wide selection of aircraft sizes and missions, as shown schematically in Figure 2.2.

Reaching maximum impact will depend on new architectures, effective technology maturation and integration, product development and certification, and deployment in the market. It will also depend on the new aircraft concept's operational suitability and affordability in the aviation system. **Public policies, including certification, will need to evolve to enable the fast adoption of disruptive technologies.** Economic policies will have to spark a rapid transition to new sources of sustainable energy and aviation fuels, as set out in the ReFuelEU regulation: these sources will have to be available within far more aggressive timescales than previously anticipated.

## 2.3. Coordinated, flexible and impact-driven research agenda

**The Strategic Research and Innovation Agenda (SRIA) aims to set out the overall trajectory to achieve the vision. It identifies the key building blocks of R&I needed, with defined gates and timelines, from key upstream enabling technologies, through component and system-level technology maturation.**

It also includes, for example, ground demonstrations through to large-scale, highly integrated high-technology readiness level (TRL) demonstration projects. Technologies and solutions that are cross-sectoral or that are developing in other sectors, but have the potential to be adopted in the aviation environment, are identified for potential synergies. Developing these to suit aviation will require collaboration with other sectors and with other mechanisms in Horizon Europe, whether they are partnerships or other instruments. The SRIA roadmaps also highlight the areas of synergies with national and regional research and innovation. See paragraph 2.9.

Continuous and close research collaborations between the stakeholder community of academia, research centres, small-medium enterprises (SME), and tier-one suppliers and aircraft manufacturers, are essential. Non-aviation sector innovators will play an increasing role. These collaborations will help energise the **upstream 'exploratory' research** required for finding tomorrow's pathways to mature technologies, ready for incorporation into further disruptive innovations.

Agility and flexibility in planning, as well as prioritising research actions, will ensure a strong focus on impact. Regular reviews and dynamic (re-)allocation of effort and resources will ensure the effective use of resources and the maximisation of impact within the timescales set out for the trajectory. The integrated roadmap will aim for the selection of best approaches and solutions for product implementation.

> *The first phase of the Clean Aviation programme will focus on validating concepts and designs.*

The programme scope and duration can enable the full maturation and validation cycle of the aircraft concepts, as described in chapter 3. The first phase of the Clean Aviation programme will focus on validating concepts and designs. This will include trade-offs based on technology maturity, environmental performance, certifiability and affordability, operational feasibility and consequently market readiness. The second phase of the programme will focus on the validation of technologies for their functional use in the new aircraft concepts considered in Chapter 3, through increasingly integrated demonstrations, and include a viable route to certification.

The roadmaps for the second phase of the programme will be based on the technical progress on the technologies developed in the first phase, and their suitability to support the considered aircraft concepts. Each of these future aircraft concepts will have a defined set of top-level project objectives with timelines, and their breakdown into environmental, technical, industrial/economic, certification and operational requirements. The milestones and decision gates needed to monitor technology readiness will be in line with these top-level programme objectives. In parallel, system readiness, market readiness and air transport scenarios will be monitored regularly by involving European aviation stakeholders. The goal is to ensure maximum efficiency in the exploitation of research results and in the programme's impact.

> *The second phase of the programme will focus on the validation of technologies for their functional use in the new aircraft concepts.*

The overall programme approach towards the final demonstrators will allow a broad participation during the maturation of technologies and progressive demonstration phases. This in turn will lead to a modularised and stepped approach, so the potential performance gains and development risks can be closely monitored. This progressive approach, with clear decision gates and down-selection phases, will allow several architectures in the earlier phase of the demonstrator programme to be scaled and adapted for application and exploitation routes around the four European aircraft concepts and the one scalable demonstration concept targeted in Phase 2.

Beyond the 'technology-based' improvements that the programme will develop, the rapid development and **large-scale adoption of new sustainable aviation fuels** is essential. For the aviation sector to achieve ICAO's long-term global aspirational goal of net-zero carbon emissions by 2050 (resolution A41-21) including overall system growth, an overall improvement of about 90% in net-carbon emissions per passenger-kilometre is estimated necessary. This reduction versus the current trend is only possible with new low- or zero-carbon fuels in various forms, ranging from 'drop-in' to more promising 'non-drop-in' options such as liquid hydrogen (LH2)-based energy systems. Investigating these non-drop-in fuel concepts requires significant research into the technical system requirements. Progress towards climate-neutral aviation by 2050 may be feasible via ultra-efficient aircraft using fully decarbonised energy sources on the path. Progressive demonstration through Clean Aviation will lay the foundation for a climate-neutral outcome in the long term.

> *Clean Aviation will engage the research and industrial excellence resources of public and private stakeholders from across Europe, under competitive conditions, to deliver impact.*

Finally, **Clean Aviation will also monitor the conditions for which its solutions will have a smooth and wide impact.** For new, disruptive aircraft (i.e. hybrid-electric and hydrogen-powered) to succeed in terms of market acceptance, an important trade-off will exist between the (global) aviation market's ability to absorb new products or innovations, the infrastructural adaptations needed (e.g. in the case of non-drop-in fuels) – and the performance that new, potentially radical technology options can deliver. The pathway defining future aircraft in the aviation system of 2030-2050 will depend largely on the mix of future propulsion solutions and related energy sources that will be widely available for air transport operations at the estimated date of entry into service of a new aircraft concept. This mix in turn will hinge on the complementary policy measures (rules, tax, incentives, and infrastructures) that will determine the economics of the various fuel and technology options. Market conditions and accelerated market adoption can be redefined, by linking research and technology demonstration with effective public policies. For instance, the ReFuelEU Aviation regulation27 defines a growing share of SAF(including synthetic aviation fuels, or e-fuels) over time (from 2% in 2025 to 70% in 2050), to increase their uptake by airlines and thereby reduce emissions from aviation. It seeks to ensure a level playing field for sustainable air transport.

---

27. ReFuelEU Aviation initiative (October 2023).

## 2.4. Approach and targeted aircraft performance gains

Three key thrusts for the R&I efforts have been identified to drive the energy efficiency and the emissions reductions of future aircraft, in line with the aircraft concepts described in Chapter 3:

- **Ultra-efficient Regional (REG) aircraft architectures –** driving research into novel (hybrid) electrical power architectures and their integration; and maturing technologies towards the demonstration of novel configurations, on-board energy concepts and flight control, and efficiency improvements for a next regional aircraft between 50 and 100 pax.

- **Ultra-efficient Short and Medium-Range (SMR) aircraft architectures –** to address the short-medium range needs with innovative aircraft architectures, making use of highly integrated, ultra-efficient thermal propulsion systems and providing step-change improvements in efficiency. This will be essential for the transition to low- or zero-carbon fuels, which will be more energy-intensive to produce, more expensive, and only available in limited quantities.

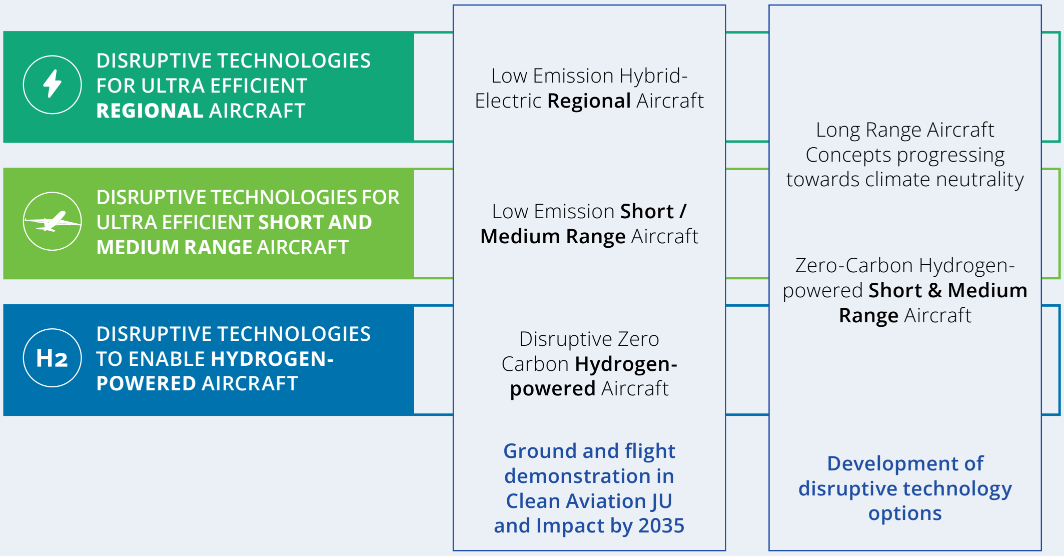
- **Hydrogen-Powered Aircraft (HPA) architectures –** to enable aircraft and engines to exploit the potential of hydrogen as a non-drop-in alternative zero-carbon fuel, in particular liquid hydrogen. The specific constraints and opportunities of hydrogen technologies might lead to new classes of aircraft, with their own specific capabilities, besides the current Regional and SMR market segmentation, as detailed in Chapter 3.

The application of results from these areas in new aircraft will depend on performance requirements for the various aircraft categories, the technological capability, the maturity and the performance gains achievable. The programme set-up will allow for dynamic allocation of efforts and resources, in order to maximise the impact and value that can be delivered.

The thrusts will develop **technologies and enablers,** leverage essential knowledge and capabilities and de-risk the identified research topics where further maturation, validation and demonstration are required to maximise impact. The thrusts will target demonstrations to support the aircraft concepts highlighted in Chapter 3, integrating the key technologies needed for ultra-efficient regional aircraft, ultra-efficient SMR aircraft, and hydrogen-powered aircraft concepts. These demonstrations will enable the integration of technologies that have been matured and demonstrated into new aircraft concepts, and provide a clear understanding of the full aircraft performance achievable at a high maturity and fidelity, as of 2030. These demonstrations will also anticipate the operational and certification issues (CS 25) of future aircraft models, and are relevant for an actual in-service introduction of the disruptive innovations.

The research agenda for Clean Aviation is shown below, with a mapping of the potential applicability of the above-mentioned thrusts to the most relevant aircraft categories (**Figure 2.3**).

Figure 2.3: Mapping of the research thrusts against aircraft categories and concepts



While the primary focus of the demonstration efforts will be on the ultra-efficient regional, ultra-efficient short-medium range, and hydrogen-powered aircraft concepts, the approach will involve a stepwise development and demonstration strategy. This will allow several opportunities for technology spin-off to other aircraft categories: towards commuter and vertical lift applications that can benefit from the hybrid-electric maturation of technology; and from the ultra-efficient SMR architectures towards long-range applications. Similarly, aircraft situated in-between the regional and SMR segments, such as large regional jets, will as well benefit from the technologies developed in these 2 thrusts. This is particularly important, as it will allow both a broad-based participation in the programme, and a much broader and deeper penetration of the overall air transport system with **important additional environmental and climate-related benefits.**

As introduced in chapter 1, aviation's various particles and gas emissions have different effects on the climate. While the effect of $CO_2$ emissions are well understood, there is greater uncertainty around **non-$CO_2$ effects** (particularly contrail cirrus and NOx at high altitudes). Nevertheless, as these emissions generate potentially large effects on climate (according to current scientific understanding), they must be taken into consideration.

Given the very complex and uncertain nature of these non-$CO_2$ effects, the GHG emissions reduction targets defined in Article 57 of the Council Regulation cannot be directly broken down into quantified objectives. The Clean Aviation Joint Undertaking's Scientific and Industrial communities endorsed the implementation of the following approach at aircraft level to deal with the GHG emissions targets:

- **Focus on the $CO_2$ emissions reduction target by no less than 30%** (without SAF effects) for all aircraft categories.

- **Monitor and report key parameters and exhaust emissions linked to non-$CO_2$ effects** (including but not limited to NOx, water, and non-volatile Particulate Matter) to constitute a dataset available to further scientific and climate-impact analysis. These project outputs will be considered in future assessments of compliance with future regulation on non-$CO_2$ aviation effects (Directive (EU) 2023/958). This will support the parallel development of non-$CO_2$ emissions reduction technologies, needed to achieve the ultimate climate-neutrality goals.

The target performance levels across the aircraft categories selected for demonstration in Clean Aviation are shown in Table 2.1.

Table 2.1: Clean Aviation aircraft category targets

| Aircraft Category | Key technologies and architectures to be validated at aircraft level in roadmaps | Entry Into Service Feasibility | $CO_2$ Emissions reduction (technology based)[28] | Net $CO_2$ Emissions reduction (i.e. including SAF effect)[29] | Current share of air transport system emissions |
|---|---|---|---|---|---|
| **Regional** Commercial Aircraft | > Hybrid-electric (SAF + Batteries) coupled with highly efficient aircraft configuration | ~2035 | -30% | -86% | ~5% |
| | > Same with H2-electric power injection (Fuel Cells electric generation) | Beyond 2035 | Up to -50% | Up to -90% | |
| **Short-Medium Range** Commercial Aircraft | Advanced ultra-efficient aircraft configuration and ultra-efficient gas turbine engines | ~2035 | -30% | -86% | ~50% |
| **Hydrogen-Powered** Commercial Aircraft | Full hydrogen-powered aircraft (H2 Fuel Cells or H2-combution) | ~2035 | -100% | N/A | N/A |

Besides the above emissions targets, all aircraft concepts considered in Clean Aviation (described in Chapter 3) will have to comply with more stringent ICAO noise regulations expected by 2035.

On top of the above aircraft categories selected as primary focus, Clean Aviation technologies will also impact other aircraft segments, via the scaling and transfer of technologies, as shown in Table 2.2.

Table 2.2: Clean Aviation potential scaling and transfer benefits for other aircraft categories

| Aircraft Category | Key technologies and architectures transferred from Clean Aviation | Entry Into Service Feasibility | $CO_2$ Emissions reduction (technology based) [28] | Net $CO_2$ Emissions reduction (i.e. including SAF effect) [28] | Current share of air transport system emissions |
|---|---|---|---|---|---|
| **Long Range** Commercial Aircraft & **Business Aviation** | Advanced ultra-efficient aircraft configuration, ultra-efficient propulsion using drop-in SAF with optimised airframe integration, hybrid auxiliary power unit [APU] | ~2040 | -30% | -86% | ~45% |
| **General Aviation Commuter & Rotorcraft** | > Hybrid-electric and bi-fuel concepts<br>> Full electric concepts utilising hydrogen fuel cell-based propulsion (augmented with advanced battery technology energy storage) | ~2030+ | N/A- | -87 to 100% | ~1% |

---

28. Improvement targets are defined as CO2 reduction compared to 2020 state-of-the-art aircraft available for order/delivery.
29. Assumes full use of SAF at a state-of-the-art level of net 80% carbon footprint reduction (and where applicable, zero-carbon electric energy for batteries charging and green hydrogen production).

# 2.5. Impact of a Clean Aviation Programme

**The Clean Aviation Partnership's approach will target impact against the two horizons linked to the European Union's Green Deal legislative package and the high-level objectives of the Council Regulation and geared towards climate neutrality by 2050 (Table 2.3).**

The overall European aviation system forecast progress, and the Clean Aviation contribution, is shown below:

**Table 2.3: Forecast progress towards the Green Deal objectives in 2030 and 2050**

| Year | European aviation's forecast progress towards the Green Deal objectives |
|---|---|
| **2030** | **Efficiency and emissions of the European aviation fleet** in operation have improved, as the benefit of accelerated fleet replacement with the current state-of-the-art aircraft will exceed growth in intra-EU travel volumes.<br>**Technologies from the Clean Sky and Clean Sky 2 programmes** suitable for retrofitting in the existing fleet or 'forward fitting' in product enhancements will bring additional efficiency gains and related impact.<br>**Optimised flight trajectories and 'smart' redesign** of flight operations (speed, cruise altitude, routing, and potentially utilising operational concepts such as flying in formation, or contrails avoidance) developed in close collaboration with SESAR JU will allow further efficiency improvements of 5 to 10% and partial mitigation of non-$CO_2$ effects.<br>**The ramp-up of low-carbon sustainable aviation fuels** will bring further gains of at least 5% based on ReFuelEU targets and potentially more ambitious voluntary schemes.<br>**The technologies matured in Clean Aviation will be exploited** on the emerging next generation of regional and short/medium range aircraft offering 30% lower $CO_2$ emissions (not including SAF effect) compared to 2020, and 100% SAF compatibility, foreseen to be introduced in the market by 2035.<br>The technologies supporting a first generation of hydrogen-powered aircraft will emerge from the Clean Aviation programme, for potential introduction in the market by 2035. |
| **2050** | **Aircraft exploiting the research demonstrated in Clean Aviation** will continue replacing the legacy airline fleets from 2035 onwards and progressively infiltrate the (global) operating fleet, with the ambition to replace ~75% of the fleet by 2050.<br>**Technologies matured through Clean Aviation will become available** across the majority of aircraft classes, and the majority of 2050 operating aircraft will emit one-third less $CO_2$ than today's fleet and will be 100% SAF compatible. Hydrogen-powered aircraft with no $CO_2$ emissions represent a growing proportion of the fleet.<br>**The continued acceleration of the use of sustainable fuels** (supported by ReFuelEU mandate) and optimised 'green' operations will deliver progressively lower net emissions compared to 2030.<br>**European airport, and energy production improvements will be synchronised** in support of the introduction of the new aircraft and fuels/energy systems.<br>**Further breakthrough technologies developed and matured** beyond Clean Aviation, coupled with full deployment of sustainable aviation fuels and alternative energy carriers, will ultimately contribute to climate-neutral aviation in Europe. |

The Clean Aviation Partnership will cultivate an ecosystem approach that allows the aviation sector to introduce disruptive technologies in a timely and economically prudent manner, in close coordination with airlines, operators, service providers and authorities. Regular assessments including life cycle aspects will support the selection of technology routes and ensure a close monitoring of progress and tracking of potential benefits. This will create the pathway to a climate-neutral aviation system that helps the EU Member States to meet the Paris Agreement, and the International Civil Aviation Organization (ICAO) environmental goals (long-term aspirational goals of net-zero carbon emissions), and meets EU mobility targets. Clean Aviation will contribute to all dimensions of Horizon Europe. See (Table 2.4).

Table 2.4: Impact dimensions of Clean Aviation

| Impact Dimension | Clean Aviation contributions |
|---|---|
| **Scientific impact:** to create and disseminate high-quality new knowledge, skills, technologies and solutions | **Increase scientific knowledge of climate impact** and atmospheric effects and so enable optimised interventions in the aviation system;<br>**Accelerate development of know-how** and knowledge transfer for key new technologies;<br>**Create new high-value skills and new engineering capacities** for future generations of the European workforce;<br>**Create models and metrics** for new and different life-cycle assessment of disruptive solutions. |
| **Societal impact:** to strengthen the impact of R&I in developing, supporting and implementing EU policies, and to support the uptake of innovative solutions in industry and society to address global challenges such as climate change and environmental protection | **Deliver solutions to reduce the environmental impact** of aviation by cutting emissions and ensuring better air quality and lower noise, in particular around airports;<br>**Contribute to increased safety and security levels,** in cooperation with the European Union Aviation Safety Agency (EASA) by deeply transforming present operations with the help of innovation;<br>**Fulfil customer and general public expectations** of a globally competitive European industry;<br>Offer innovative solutions that improve the mobility and connectivity of European citizens with safe, reliable, affordable and resilient air travel options;<br>Utilise life cycle ‘eco-design’ approaches that will develop a strong circular economy dimension for aviation. |
| **Economic impact:** to foster breakthrough innovations, and strengthen Europe’s intellectual property, sovereign capability, design and manufacturing base, and the market deployment of innovative solutions towards a dynamic and prosperous EU economy | **Permit new sustainable business models** for innovative aircraft technology for future aircraft and fleet retrofits, exploiting next-generation digitalisation/automation technologies;<br>**Enable valuable spin-off opportunities** that will benefit European citizens through exploitation in critical areas such as disaster response, emergency interventions, space and security;<br>**Facilitate new safe and efficient airborne** transport modes that have the potential to reduce traffic congestion in highly populated areas, and connect remote regions;<br>**Encourage strategic partnerships** with non-aviation sectors to make use of emerging technologies (e.g. drop-in and non-drop-in fuels, fuel cells, batteries, electrical power distribution, artificial intelligence, electronics, materials);<br>Support the European Commission where appropriate regarding input for policies, including international coordination and extracting benefits for Europe. |

The Council Regulation has assigned a key task to the Clean Aviation Joint Undertaking, i.e. to monitor and assess the technological progress towards the achievement of its objectives, in line with the Strategic Research and Innovation Agenda (SRIA) and focused on the three thrusts.

**Three monitoring levels are foreseen** and coordination and exchange of data between these three levels is required. These are:

**The monitoring and assessment of the Clean Aviation Work Programme activities,** that will implement the Strategic Research and Innovation Agenda, towards achieving the general and specific objectives of Clean Aviation. The CAJU has the oversight of this task.

**The impact monitoring of aviation research and innovation,** which aims to integrate the potential impact of technological, operational, market-based measures and sustainable aviation fuels. It will contribute to the definition and impact assessments of future EU aviation policies, support the EU position at ICAO and communicate the impact of EU aviation research and relevant policies. The European Commission (RTD, MOVE, ENV, CLIMA and DEFIS) has the oversight of this task.

The monitoring and evaluation of all Horizon Europe Partnerships (including CAJU). Within this process, the evaluation aims to assess the **most effective policy intervention** mode for any future action, as well as the possible renewal of the CAJU Partnership within the overall European Partnerships landscape. The European Commission has the oversight of this task.

The CAJU will follow the first task on the Work Programme activities. The Executive Director of the CAJU will ensure the programme's monitoring and assessment of the progress, compared to relevant impact indicators and the Joint Undertaking's specific objectives, under the supervision of the Governing Board and in coordination with advisory bodies where relevant, and in accordance with monitoring and evaluation principles set out in the Council Regulation.

The **aircraft integrators,** supported by the propulsion and system suppliers and their participants in projects (RTOs, academia, and SMEs), are responsible for providing **performance predictions,** including the environmental impact at aircraft level. They will integrate all the results stemming from different projects contributing to an aircraft concept (one report) and provide visualisations of the cumulated programme impacts as compared to the objectives set out in the SRIA, including interdependencies between technical, operational, and environmental dimensions. The reports will also consolidate the expected impact from SRIA-relevant projects that arise from other relevant European Partnerships. Expected impact from synergies with other EU, national or regional initiatives (including Horizon Europe missions) should be explored.

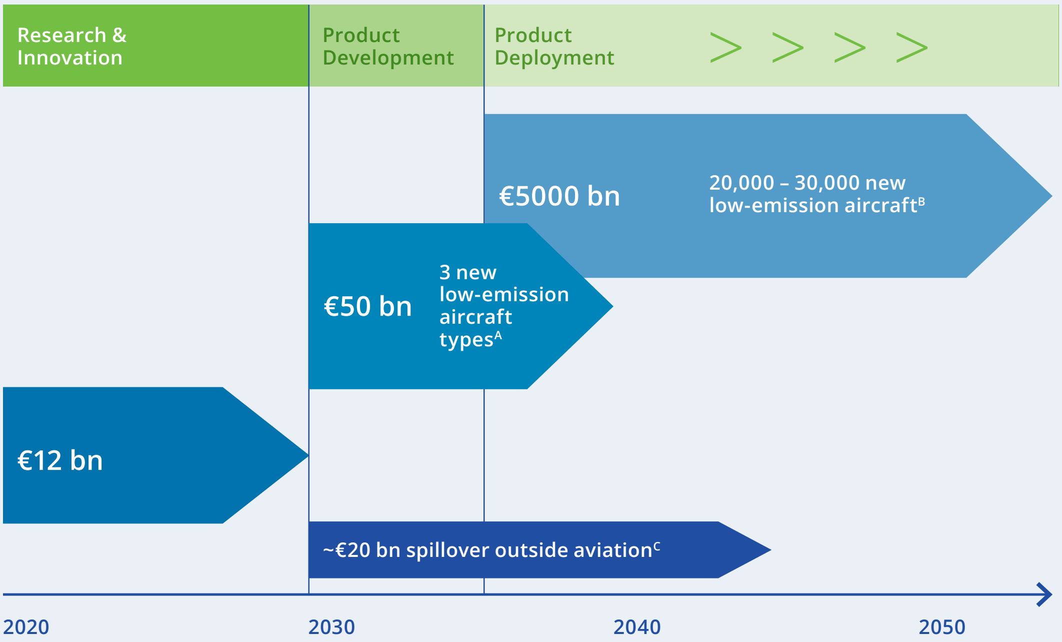
The impact monitoring report(s) will be submitted to the Technical Committee in order to propose, for deliberation and final decision by the Governing Board, either revisions or optimisation of the technical scope of the programme. The aim is to align the Work Programme and the objectives of the Clean Aviation Joint Undertaking with the overall Horizon Europe and other European Partnerships' related Work Programmes.

## 2.6. The commitment towards a Clean Aviation Joint Undertaking

**To reach sufficient technology readiness within the Horizon Europe timeframe, ambitious resourcing is essential. The EU institutions' and European Member States' support will be essential in creating the conditions needed for impact, and ensuring the trajectory is successful. The research needed to meet this challenge within the Horizon Europe timeframe is likely to exceed ~ €12 billion in effort.**

This effort can stimulate a product development in this sector worth over €50 billion. This stimulus could finally lead to an overall private investment in product deployment of more than €5,000 billion by 2050, see Figure 2.4 below.

Figure 2.4: Impact dimensions of Clean Aviation



A. Based on aircraft development €15bn per type.

B. Estimated regional and short-medium range new aircraft deliveries between 2035 and 2050 on the basis of Clean Sky 2 Technology Evaluator report (2024) https://www.clean-aviation.eu/technology-evaluator.

C. Estimate based on €12bn investment in aviation R&I over 10 yrs. Value at 2020 NPV.

In close collaboration with the Commission as public partner, the Clean Aviation Joint Undertaking can play a central role within a European **'innovation architecture'**, ensuring shared roadmaps and synergies with EU collaborative research, other relevant European Partnerships, EU research programmes, national and regional research and innovation programmes, and Cohesion Policy funds such as the European Regional Development Fund (ERDF) and financial instruments (see paragraph 2.9). Within this architecture, the Clean Aviation Joint Undertaking should mobilise impact-oriented research and innovation that represent a relevant and significant share of the total estimated R&I effort needed. Further EU-level collaborative research on aeronautics would need to address the wider agenda, e.g. upstream exploratory research of future breakthrough technologies.

> The approach proposed in this SRIA is supported by a research effort of at least €4.1 billion as a key component of the overall €12 billion effort. It is supported by an EU funding level of €1.7 billion, complemented by at least €2.4 billion of in-kind contributions from the Clean Aviation Joint Undertaking's private-side members.

The content proposed in this document might exceed the above-mentioned research effort[30], which is currently reflected in the Council Regulation, due to the level of uncertainty inherent i) in technical challenges of such an ambitious R&I programme, and ii) in a predefined articulation of activities with relevant programmes, particularly at national and regional levels.

**The overall success of the programme will be dependent on the level of public support at EU, national and regional levels,** and will be contingent on the implementation of a coordinated approach to mobilise investments across Europe through an integrated architecture, ensuring an inclusive participation from contributing nations and regions (see Section 2.9).

The overall leverage effect in the Joint Undertaking of EU funding to private investment in the research phase alone (i.e. not including the development beyond the research phase) is expected to be ~ 150%, and other non-EU public investment (e.g. from Member States) will further increase the EU's leverage significantly beyond this. This estimate is based on the current estimates of project costs and funding rates that would be representative of the nature of the research in terms of risk, long development cycles and highly uncertain payback periods. The funding level includes an estimate of non-profit entities' participation and requisite funding rates and conditions.

As EU research and innovation programme for sustainable aeronautics, the Clean Aviation Joint Undertaking will support the maturation and demonstration of aircraft technological innovations and aircraft concepts through EU's funding, complemented by contributions in-kind from the private-side members. The effort undertaken through Clean Aviation will be a significant contribution to the overall €12 billion effort required in research and innovation over the Horizon Europe timeframe (figure 2.4). However, the Clean Aviation Joint Undertaking will be not supporting, nor influencing, any specific industry-led (or member-led) product design, development, or deployment initiative. The private-side members, and the programme's beneficiaries in general, will be the players solely responsible for product design strategy, including product-launch decision, departing from potential outcomes of the programme.

Spillover effects are positive contributions to the broader economy. Aerospace technology requirements are among the most extreme of any industry. Because of this, the industry is often an innovator across many fields, including e.g. materials, design, manufacturing, sensing, data capture and analytics, and even business models. Once aerospace has proven that an innovation works, this innovation can often find other commercial uses, thus generating further economic benefit in other industries. For example, composite materials first developed to reduce the weight of aircraft are now commonplace in many products.

---

[30] This volume of EU funding will be complemented by contributions deriving from the association agreement to Horizon Europe with the UK.

## 2.7. Instruments

**The Clean Aviation Partnership will have an open and transparent governance and management structure. A lean and effective regulatory framework will allow the Partnership to operate smoothly and be able to meet its objectives. The Partnership functions via open and competitive calls. These are open to all interested stakeholders willing to commit, contribute and collaborate in the Partnership, including the demonstration of new ambitious technology solutions and climate-neutral aircraft concepts.**

The Partnership will identify those solutions with the highest impact in terms of climate, combined with the best chance of evolving into sustainable product and service innovations. This would enable a realistic and fast uptake by the market, thereby introducing sustainable aviation operations and delivering expected benefits for citizens.

The selection and allocation of all European Union funding will be based on open, transparent and competitive calls for proposals, with evaluations supported by independent experts, in line with the Horizon Europe and the Joint Undertaking regulations.

The Clean Aviation Joint Undertaking will allow for long-term allocation of budget through multi-annual grant agreements in line with the open calls and the JU financial rules on multi-annual commitments. The JU's Multi-Annual Work Programme (MAWP) will identify and govern the calls, topics and related R&I actions.

The JU will design a dedicated type of open call for the large-scale demonstration projects, in cooperation with the Commission. The calls will invite the submission of proposals by industry-led consortia and will set out the requirements needed in the demonstration area, including the key capabilities required in the field of aeronautics as well as from other sectors as appropriate. The call topics will require long-term commitment from the stakeholders to deliver the necessary resources and execute the research activity as defined by the technical roadmap. Conditions may be included to ensure the *commitment to implement the results* in terms of European exploitation, thus warranting the targeted effect in terms of climate impact and European competitiveness. Calls for additional Associated Members may be launched over the life of the programme, in order to ensure the consortia have the appropriate configurations and skillsets needed to maximise results and impact. Complementary Calls for Proposals are foreseen, so as to allow for tailored and time-limited contributions from partners, towards the integration and build-up of demonstrator hardware as well as for analysis, simulation, testing and validation activities.

The JU will ensure an open and transparent process for all open calls and will ensure a broad and wide participation from the stakeholders. The calls should include flexible mechanisms to allow other partners/ contributors to enter the Partnership and contribute to the core activities based on capabilities, as well as programme priorities and possible evolution.

# 2.8. Policies, standards, rules, infrastructures and industrialisation

**The public-private partnership approach is essential to ensure alignment of the research roadmap with public policy, and to secure critical enablers for market adoption, including certification of disruptive technologies. The public partner's policy-setting role will be instrumental in creating the regulatory/legislative and economic conditions for a successful and globally competitive implementation in the aviation system, in time for a successful deployment from 2035 and with an effective impact by 2050.**

## UPFRONT EFFICIENT CERTIFICATION OF DISRUPTIVE TECHNOLOGIES

Clean Aviation Joint Undertaking's ambition to perform decisive impactful steps, in demonstrated disruptive aircraft performance compatible with 2035 EIS, will only be possible if the future regulatory framework is not an impediment to innovation. **Certification will still improve safety while shortening the time to bring new products to market** and into service. This approach will simplify the uptake of innovations on existing products while maintaining European leadership and competitiveness. Because aeronautic product complexity exponentially increases, and certification requirements become increasingly challenging and demanding, the safety regulators (EASA for European products) have launched several initiatives to adapt their processes and methods to keep pace with the digital transformation that the aviation industry is undergoing. It will guarantee the compliance of innovative and disruptive technologies and architectures with certification requirements and a safe integration of these new sustainable concepts. A systemic change in the way the aircraft are developed and certified is needed, making full use of new means of proof and new processes available from digitalisation and AI techniques. A holistic and integrated approach – from breakthrough research to rulemaking on certification, and adopting a new capability framework of research and innovation – is imperative for the "flying machines" primarily but also for all the systems and infrastructures.

**EASA and the Clean Aviation Joint Undertaking signed a Memorandum of Cooperation** in November 2022, to facilitate creation of the pathway towards the certification of new aircraft innovation technologies in line with the European Green Deal and the EU Climate Law.

Examples of disruptive technologies at the core of the programme will need an integrated and close involvement of certification experts in the research phase, including but not limited to active flutter control, hydrogen fuel, and high voltage power distribution. A modularised and stepped transversal approach, with representative proof of concepts and demonstration, should deliver draft certification principles and approach by 2026, as preliminary outcomes of the joint collaboration of the industry with EASA. This will pave the way to the future new certification basis, compatible with the start of aircraft development.

The modularised and stepped transversal approach will encompass two main actions: **the development of a comprehensive set of regulatory inputs/dispositions on certification** and the preliminary **description of methods of compliance,** together with a first status of comprehensive digital framework of formalised collaborative tooled and model/simulation-based processes for certification. The introduction of a brand new dedicated certification assessment scale (similar to the TRL approach) to assess the maturity of new certification specifications and standards, called CRL (Certification Readiness Level) associated with specific KPI, will be enforced as a new assessment tool. The aim is to deliver a brand new set of draft certification specifications at CRL6. It will cover the full set of CS25 airworthiness requirements, targeting the aircraft concepts defined in the next chapter but also applicable to other aircraft segments. This new approach will be facilitated through digital solutions that can also contribute significantly to reducing the duration and cost of development and validation phases, while maintaining or increasing safety. Maintaining full traceability and digital continuity of all shared information will make the overall product definition life cycle more robust and much faster.

Experiments and demonstrations, aimed at favouring the widespread practice to the three thrusts' identified critical risks for certification, will require a significant investment. A strategy to develop a real life testing environment to assess adequacy of future regulatory changes – including most appropriate MoC (Means of Compliance) demonstrations (ranging from simulations and digital twins, up to ground test benches, sub-scale or full test flights, and including hybrid approaches) – will be set up with EASA. This will also benefit from synergies with other applicable and available test platforms and test rigs.

At the end of the Clean Aviation programme, a **full-fledged certification route with clear milestones** should be elaborated and demonstrated. Safety regulators and experts in industry will have to be convinced that the proposed solutions at integrated level are certifiable and that nearly all of the certification critical risks have been identified and mitigated.

> *The collaboration between EASA and Clean Aviation Joint Undertaking will facilitate creating an efficient pathway towards the certification of new aircraft technologies with EIS by 2035.*

Of key importance too is **outreach to other industries,** other national (and regional) programmes and the connection with standardisation bodies (e.g. European Organisation for Civil Aviation Equipment – EUROCAE) and existing frameworks including infrastructures, in order to ensure a holistic approach.

This outreach objective must involve safety regulator experts, primarily EASA, acting together with industrial and research technical teams for the conception and endorsement of new solutions in all relevant Clean Aviation projects. This initiative, targeting the regional and short and medium-range aircraft, will strive to be federative, easily transposable and scalable to different product lines and aircraft segments, e.g. general aviation, rotorcraft, business jets and commercial medium-long range affecting the complete fleet. It is also seen as a tremendous opportunity to reinforce European leadership and sovereignty, by leveraging Europe's position as the forerunner of new certification frameworks worldwide.

## INFRASTRUCTURES AND INDUSTRIALISATION

The successful entry into service (EIS) by 2035 of the Clean Aviation disruptive technologies would require additional major investments, beyond Clean Aviation funding support and the current SRIA content, to support the launch of new products and to prepare industrialisation and production capabilities, as well as to create the necessary conditions for market uptake.

More specifically, those additional investments are needed in the following key areas to foster and accelerate the market uptake of the Clean Aviation disruptive aircraft technologies by 2035:

> **large Research & Technology infrastructures** to validate and certify future clean technologies and demonstrators (e.g. a new European flight test infrastructure, ground testing facilities for H2-engines), but it should be noted that large-scale demonstrations to progress maturation beyond TRL5+ are very costly;

> **competitive, eco-sustainable industrialisation** over the full production chain (including clean technologies manufacturing, new industry pilot lines for the "Factory of the Future");

> **ground infrastructure** supporting the deployment of new aircraft powered with SAF, batteries, or hydrogen.

# 2.9. Maximising impact through synergies

**Strong collaboration among participants spanning different sectors will be essential to close the gap to climate-neutral aviation. The aeronautics roadmap towards climate-neutral aviation will require strong and proactively managed synergies across a wide array of funding and financing sources, from regional and national authorities and from within the European Union's Multiannual Financial Framework (MFF).**

**Synergies with programmes at European, national and regional level** are an integral part of the Clean Aviation Joint Undertaking's objectives **to fully achieve the ambition of the Clean Aviation Partnership** as presented in this document. At its own initiative, the Clean Aviation Partnership set up an ambitious plan to establish synergies with other programmes/partnerships with significant investment of effort. However, **the impact of this plan is suboptimal, due to the lack of a framework for synergies encompassing the EU MFF, national and regional programmes.**

The programme and its stakeholders would need to leverage resources spanning national and regional efforts, as well as transversal synergies, in order to leverage non-aerospace capabilities towards the programme's activities and objectives. Strategic collaborations would be needed to identify potential solutions based on emerging technologies (including those from other sectors) and consider their implementation on the new aircraft concepts. This would include the assessment, adoption and development of technologies, skills and methods that are unreachable within the term of the Clean Aviation demonstrations, and potentially beyond the traditional boundaries of the pure aviation sector, and contribute to a long-term convergence towards full decarbonisation and climate neutrality.

Leveraging the combined resources and funding would produce a substantial multiplier effect and help reach the objectives. The goal of this Innovation Architecture is **to unite Europe's research and industrial resources and capabilities for setting a new global standard of sustainable and clean aviation**.

Beyond the massive R&I effort, policy instruments and public/public-private financing instruments would also be essential to close the gap from research outcomes towards implementation in the fleet by 2050. Policy measures must include interventions that create a 'level playing field' between a continued (fossil fuel-based) system and a 'net-zero carbon' system by 2050.

## SYNERGIES WITHIN HORIZON EUROPE (PUBLIC-PRIVATE PARTNERSHIPS AND PARTS OF HORIZON EUROPE'S WORK PROGRAMME)

Developing strategic synergies with the European Commission's Collaborative Research programme is mandatory. This is to address specific concept requirements and low-maturity solutions, in order to feed a long-term but stable convergence to full aviation decarbonisation. This process requires a strategic and technical alignment between the collaborative research content dedicated to sustainable aviation and Clean Aviation.

While Clean Aviation would aim at down-selecting and integrating the most promising solutions from the latest matured technologies into low-emission aircraft concepts, the **Collaborative Research Programme** should assist in developing these related synergies by:

- Maturing technologies to be integrated into the next innovative aircraft systems for reducing the environmental impact of aviation.
- Identifying and exploring disruptive future technologies and accelerating their maturation to reduce emissions through progression breakthrough technologies and architectures for an EIS from 2035 to 2050.

Therefore, the targeted synergies would naturally focus on lower TRL research related to technologies and methods that can accelerate the gains towards the targeted aircraft performance.

The Collaborative Research Programme should support the early identification of emerging technologies, so their potential integration into viable flying configurations can be assessed within the framework of Clean Aviation. Two research streams are advised, which complement each other:

- **Breakthrough technologies towards climate neutrality** is a stream that aims at exploring, preparing and maturing all the potential technologies to be integrated into innovative aircraft and propulsion system configurations (next aircraft generation), and exploring disruptive technologies to be integrated into long-term products (EIS beyond 2035).
- **Transverse technology enablers** stream would develop the means to accelerate an affordable decarbonisation by leveraging all the steps of the product life cycle – from the early trade-offs, technology down-selection, and integrated demonstrations on the ground, up to the certified operational aircraft joining the fleet.

## COLLABORATIVE RESEARCH IN AVIATION UNDER CLUSTER 5

Within the Cluster **Climate, Energy and Mobility** in Pillar II of Horizon Europe, synergies with other proposed Partnerships are most notably (but not exclusively) with the **Clean Hydrogen Joint Undertaking** (fuel cells, as well as hydrogen as a potential fuel source) and **BATT4EU Partnership** which is focused on batteries. The Clean Aviation JU has strengthened strategic collaboration on hydrogen-powered aviation in the Clean Hydrogen Joint Undertaking via a **Memorandum of Understanding** (2023), as well as on aviation batteries with the BATT4EU Partnership through a strategic (SRIA level) and technical (Work-Programme call topic level) alignment to Clean Aviation.

As history has shown us repeatedly: the exacting standards needed for aerospace applications seem unnecessary for other sectors; yet once these standards are established, their spin-off to other sectors is substantial. A study in the UK determined that each £1 in aviation R&I delivers over £7 in spin-off value outside the sector. The performance levels of fuel cells and batteries – that can be unlocked through an aeronautics programme linked to Clean Aviation – could allow Europe to leapfrog Asia, rather than just follow or play catch-up. Other synergistic effects are evident with the partnership for **ATM**, i.e. **SESAR 3 Joint Undertaking**, in areas such as (but not limited to) the impact on ATM of the Clean Aviation aircraft concepts powered by disruptive propulsion systems based on SAF, hydrogen and batteries; and flight trajectories for the Clean Aviation aircraft concepts, and the combined benefit of these aircraft and the ATM system developed by SESAR3.

The respective (multi-annual) work programmes of Clean Hydrogen JU, BATT4EU and SESARJU specify which actions (if any) would follow in each of the Partnerships (or other instruments).

While the Clean Aviation Joint Undertaking resides in the Cluster Climate, Energy and Mobility, synergies with elements of other Pillar II programmes and clusters would also be important. The **Digital, Space, Industry** cluster is particularly relevant, as the digital agenda, industrial leadership and competitiveness are key, integral components of a successful transition to a net-zero emissions aviation system. Outside the cluster, more opportunities may exist with **Chips Joint Undertaking**, other research instruments related to digital technologies, the **Made in Europe** partnership, and the recently launched **Advanced Materials** partnership and the Space Initiative.

For the **European Innovation Council (EIC)**: likewise, a collaboration mechanism connecting the Fast Track to Innovation (and Accelerator) mechanisms funded under the EIC to Clean Aviation where relevant could bring significant benefits. The Council Regulation should clearly mention the goal of maximising these horizontal financial leverage effects as needed, to achieve the goals of the Clean Aviation Joint Undertaking.

For Pillar I R&I (e.g. the **European Research Council (ERC)**), the nature of fundamental research must be preserved. Here an effective 'technology watch' mechanism could be envisaged for an early identification of upstream technology efforts with a promising potential, if picked up in the applied technology arena in Clean Aviation.

## SYNERGIES WITH NATIONAL PROGRAMMES IN MEMBER STATES AND TRANSNATIONAL COOPERATION

One important lever to reach the critical mass needed (in funding as well as R&I efforts) is establishing collaboration between Clean Aviation and key national research and innovation programmes through strategic and technical alignments, leveraging on cooperation agreements and joint programming and steering mechanisms, as appropriate.

Key Member States and Associated Countries can jointly provide important funding volumes aligned to climate-neutral aviation. Based on lessons learned in Clean Sky 1 and Clean Sky 2, the Council Regulation establishing the Clean Aviation Joint Undertaking makes clear reference to Member State engagement in order to align and develop synergies, with a strong mandate of the JU and effective mechanism to be developed with the support of the States' Representative Group of the JU.

> *Synergies with relevant programmes at European, national and regional level are required to fully achieve the ambition of the Clean Aviation SRIA.*

The Council Regulation facilitates the close collaboration and synergies with other relevant initiatives at national level: these are key to achieving greater scientific, socio-economic and environmental impact and ensuring uptake of results. Several countries have notable **national programmes for sustainable aeronautics** supported by substantial volumes of funding such as - but not limited to - **LUFO** (in Germany), **CORAC** (in France)**, Aeronautical Technology Programme** (in Spain) and **Luchtvaart in Transitie** (in the Netherlands) and **ATI** (in the UK). The Clean Aviation programme would benefit from these through contributions in-kind by members, as well as through engaging in and strengthening strategic collaborations with these programmes, and by leveraging on **National Recovery and Resilience Plans (NRRPs)**, as well as on association agreements to Horizon Europe with key aeronautic countries such as the UK and Canada.

Collaboration agreements between 'sovereign' innovation programmes and joint steering boards are seen as an effective approach. Beyond bilateral arrangements, connections should in some cases be sought with **Important Projects of Common European Interest** (**IPCEI)**, e.g. in the areas of hydrogen as well as batteries technologies development and industrialisation.

## SYNERGIES WITH REGIONS, THROUGH SMART SPECIALISATION STRATEGIES [S3] AND STRUCTURAL FUNDS

Important benefits would derive from engagements on strategic cooperation on **synergies with the key European Aeronautics Regions**, so as to accelerate the maturation and demonstration of disruptive aircraft technological innovations.

In line with the CAJU's key mission, its ambitious strategic and technical objectives, and the policy aim of strengthening synergies between the EU and regions to maximise and accelerate the impact of the EU R&I funding – the goal must be to extend the current parallel regional funding achieved so far in Clean Sky 2 through 18 Memoranda of Understanding (MoUs) signed with Member States/Regions from €50 m to at least €100+ m and to the top 30+ regions with relevant smart specialisation strategies (RIS3) and ESIF Operational Programmes in place or under preparation for 2021-2028. The Clean Aviation Joint Undertaking is reaching out to additional competences, capabilities and resources available in regional supply chains, in order to connect them to the programme and its objectives.

Synergies with regions are being established and fostered. These are based on three key principles: i) focusing on delivering impact on Clean Aviation objectives and its SRIA; ii) leveraging substantial regional investments from the Operational Programme 2022-2027, e.g. including from **Cohesion Policy funds,** in particular the **European Regional Development Fund (ERDF)** aligned to these objectives; and iii) cooperating on synergies between the relevant Regional Authorities and with the support of the European Commission, CAJU Technical Committee and States Representatives' Group (SRG).

Collaborations with key Aeronautics Regions should be developed on the basis of a strong alignment of regional strategies (e.g. **Smart Specialisation Strategies**) to Clean Aviation, deriving **joint technical roadmaps** for 'Net-Zero Aviation'. **Memoranda of Cooperation** should define the terms of the collaborations, including co-designing of funding instruments at regional/national level and implementation aspects. **The cooperation with Regions based on synergies by design** should enable the alignment of Structural Funds with Horizon Europe funds, and to link Operational Programmes to European Partnerships. Beyond the research phase, regional funding mechanisms can be highly effective means to accelerate industrialisation investments and to widen MS participation (EU13) in the European Partnerships.

## USING OTHER EU FUNDING SOURCES AND INITIATIVES FROM WITHIN THE SCOPE OF THE MULTIANNUAL FINANCIAL FRAMEWORK

The **Connecting Europe Facility** (**CEF**) can serve as a potent enabler in the transformation – particularly where the market uptake and speed of implementation and deployment are strongly dependent on infrastructure development. Examples are the transition to sustainable fuels, or airport-level infrastructure to support a future hydrogen and/or battery powered fleet.

**Just Transition** mechanisms could also help the upstream energy transition needed for new aircraft types relying on electric propulsion to be viable more quickly and enter the market more swiftly.

Finally, the Clean Aviation JU could benefit from being a member of the **Alliance for Zero-Emission Aviation (AZEA),** as it would be able to align on preparing the entry into commercial service of hydrogen-powered and (hybrid) electric aircraft.

## GREEN DEAL AND FINANCING THE TRANSFORMATION

There is a significant potential related to a coordinated use of the **Emission Trading System (ETS)** proceeds, in light of the revision of the ETS Aviation Directive (2003/87/EC). Opportunities should therefore be sought with European instruments, such as the ETS-financed **Innovation Fund**, to accelerate the demonstration and deployment of the Clean Aviation disruptive technologies by 2035.

**European Investment Bank's (EIB)** financing and **InvestEU** can be effective multipliers in areas of the supply chain where access to commercial finance is limited, e.g. SME programme finance. An important option could be 'green finance' for airlines: this could enable earlier and more aggressive rollout of new technology aircraft in their fleets.

# 3. Aircraft concepts

**The second phase of Clean Aviation (2026-2030) will concentrate on integration and demonstration of technologies around aircraft concepts powered either by Sustainable Aviation fuel (SAF) or hydrogen, combined with electric hybridisation. The chapter outlines the most promising technological routes proposed around various aircraft concepts having the potential to reduce $CO_2$ emissions by no less than 30% and to meet a technology readiness level (up to TRL6) to support the launch of new products and services for an Entry into Service (EIS) in 2035 for the next generation of aircraft, in order to hit the emission reduction impact.**

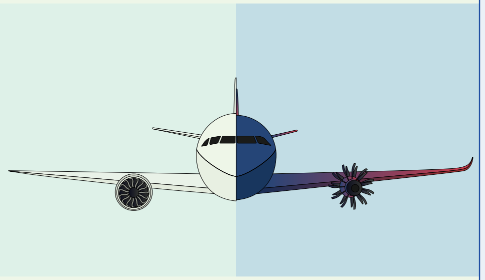
At the same time, additional technologies in which a high level of innovation and promising benefits are expected – but where exploitation is forecast by 2040 – will also be integrated and demonstrated to keep some alternative solutions to reach climate-neutral aviation by 2050.

As practical support for this second phase, four aircraft concepts and one validation platform supporting an aircraft concept have been proposed to match Clean Aviation’s main scope: short and medium range and regional market segments. These aircraft concepts will serve as reference exploitation route guidelines for the innovative technologies being developed in the first phase of Clean Aviation, as well as for technologies that could emerge from synergies with other EU instruments (SESAR, Clean Hydrogen, etc.) or National Programmes.

The technological content and the demonstration strategies, proposed in each of the three thrusts for the second phase of Clean Aviation, will have to refer to one or more of these aircraft concepts. One concept is linked to the ultra-efficient SMR thrust, one concept to the ultra-efficient Regional thrust, and two concepts to the Hydrogen-Powered Aircraft thrust, with the latter benefiting also from a third scalable concept, providing a validation platform to support technology demonstration.

The contribution of each of the aircraft concepts to the Clean Aviation objectives per thrust can be summarised as shown in Figure 3.1.

Figure 3.1: Illustration of possible aircraft concepts across Clean Aviation thrusts

| THRUST | ULTRA-EFFICIENT **REGIONAL** AIRCRAFT | **HYDROGEN** POWERED AIRCRAFT | ULTRA-EFFICIENT **SHORT AND MEDIUM RANGE** AIRCRAFT |
|---|---|---|---|
| AIRCRAFT CONCEPTS |  | <br>Validation Platform<br> |  |
| CO$_2$ Emissions<br>vs 2020 State-of-the-art<br>Non-CO$_2$ effects not yet quantified | -30%<br>excluding SAF effects<br>up to -86%<br>including SAF effects | -100% | -30%<br>excluding SAF effects<br>up to -86%<br>including SAF effects |

These aircraft concepts will serve as 'lighthouse aircraft' to define the demonstration path and to build the technology roadmaps required to reduce emissions currently produced on short-medium range and regional aircraft segments. The aim is to meet TRL6 for most of the contributing technologies between 2028 and 2030.

**These aircraft concepts are proposed on the basis of their potential** to address Chapter 2 objectives, as stated in Article 57 (2) of the Council Regulation.[31] As European Union research and innovation programme for sustainable aeronautics, the Clean Aviation Joint Undertaking will support the maturation and demonstration of aircraft technological innovations and aircraft concepts. However, as highlighted in Chapter 2 - **the Clean Aviation programme will be not supporting, nor influencing, any specific industry-led (or member-led) product design, development, or deployment initiative**. The private-side members, and the programme's beneficiaries in general, will be the players solely responsible for product design strategy, including product-launch decision, departing from technological outcomes of the programme.

The maturity level of aircraft technological innovations envisaged for each of these aircraft concepts, and the associated estimated performance (based on the current level of technology maturation from Phase 1 or other initiatives), are expected to meet the Clean Aviation performance targets for a new breed of aircraft, for which the primary exploitation route would be in Europe for an EIS from 2035.

> *For Regional and SMR market segments, the foreseen aircraft concepts have the potential to reduce $CO_2$ emissions by no less than 30% by 2035.*

These aircraft concepts could significantly reduce the greenhouse gas emissions of the aviation sector, by no less than 30%, and could support the replacement of 75% of the existing fleet by 2050 in each market segment, assuming viable economic conditions to operate them are in place (e.g. infrastructures, fuel price, H2 and SAF availability).

Architectures and supporting technologies for each of the aircraft concepts will have to address the following challenges, as key success criteria:

- **Achievement of a high TRL maturity level (up to TRL6) by 2028-2030,** supported either by ground and/or flight demonstrations, sufficiently representative to demonstrate the achievement of performance objectives, and compatible with the maturity level required to support an EIS by 2035.
- **Identification and anticipation of the certification route,** including adequate means of compliance (demonstrations, testing, modelling, etc.).

**Addressing the industrialisation readiness of technologies** is necessary, in order to enable a short development lead-time (design processes and architecture) and a fast ramp-up (manufacturing techniques) and that is compatible with the fleet replacement objectives. The ramp-up and availability of sustainable fuels for aviation (SAF and H2), and the availability of renewable primary energy to produce them, must be taken into consideration. However, Clean Aviation will only focus on the impact of technological innovations to reduce emissions within the given timeframe and their ability to deliver the best integrated aircraft solutions. As a result, the SAF-based aircraft concepts set out here do not consider the SAF net-effect to reach the -30% $CO_2$ emissions reduction by 2035. This SAF net effect would come on top of the -30% delivered by the technologies proposed for demonstration, bringing the total net-$CO_2$ reduction up to -86% (given full use of SAF with a net 80% carbon reduction footprint).

---

31. (EU) 2021/2085 of 19 November 2021.

## 3.1. Ultra-Efficient Regional aircraft

**The configuration of the Ultra-Efficient Regional aircraft concept proposed in Clean Aviation is expected to remain tube and wing and should target an Entry into Service (EIS) from 2035. Such an aircraft concept should have a capacity of around 50-100 passengers (pax) with a design range up to 500 Nautical Miles (NM), operated on a typical mission of 250NM.**

This new regional aircraft concept targets a 30% $CO_2$ emission reduction from use of technology, not considering an SAF net-effect, on a typical mission. The aircraft should be compatible with 100% Sustainable Aviation Fuel (SAF) and should remain a flexible and versatile aircraft that can operate in the network and use airports typical of regional operations worldwide. It should be a rugged, easy-to-operate aircraft on short and possibly unpaved runways, use airports close to cities, and meet existing and future Air Traffic Management (ATM) rules and local regulations.

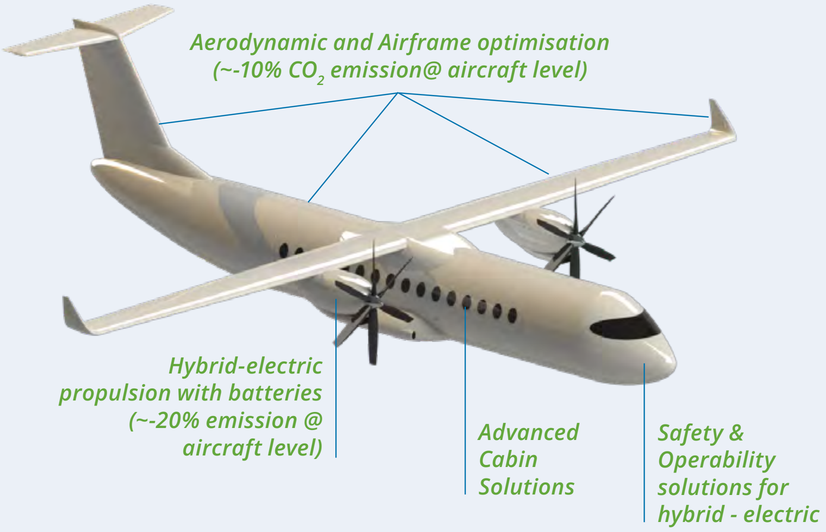
> *The Regional aircraft concept is a hybrid-electric solution.*

This new generation aircraft concept is based on several advanced design features that affect most of the critical systems and major components, plus an innovative powerplant with hybrid-electric capability based on batteries. Batteries will provide both a simpler introduction and operation into regional networks, because recharge and maintenance ground infrastructures will be simpler to exploit in the EIS horizon and they will enable an almost immediate demonstration within the Clean Aviation timeframe – while allowing significant improvements in performance, affordability, and sustainability. Use of a fuel cell beyond 2035 is an alternative or complement to batteries, if a fuel cell can be demonstrated to be affordable for regional operations.

The ultra-efficient regional aircraft concept should incorporate disruptive technologies designed to boost sustainability, circularity, and affordability: these criteria will all be very important for maximising the return for operators.

**This aircraft concept should include technologies meeting by 2028-2030 an industrial readiness level of innovations compatible with an EIS by 2035.** This entails very important enablers such as high production rate, low lead time and low recurring cost production to maximise the market uptake of the various technologies. The phase 2026-2030 broadly corresponds to a time period where the industrial readiness of technologies takes high importance.

Figure 3.2: Ultra-Efficient Regional aircraft



## PROPULSION SYSTEMS

The hybrid propulsion of this concept should include an advanced thermal engine, coupled with an electric motor/generator, for a hybrid solution that will deliver **a reduction** of more than around **20% of $CO_2$ emissions,** at aircraft level. This propulsion system would require a new propeller operating at high efficiency and low noise, to match the severe operative constraints for a regional aircraft. An advanced powerplant like this should achieve a high TRL (up to TRL6) by 2028-2029, including industrial aspects, to support an EIS by 2035. The new propulsion system must include a suitable nacelle and pylon, in order to revise the wing aerodynamics for new loads and flight control effectiveness. The propulsion and related systems must be compatible with existing ground and maintenance infrastructures at airports.

## WING

The wing should be adapted to the effects of the new propulsion system on aerodynamics and flight control surfaces. **Together with fuselage and empennages, the wing would bring a further 10% reduction of $CO_2$ emissions,** thus complementing the propulsion improvement. Further options for future regional aircraft concept to achieve higher emissions reductions include higher aspect ratios for aerodynamic drag reduction, reducing structure weight, and including advanced wing systems. However, these may not be the primary choice, if the goal is to reach the forecasted EIS before 2035. Technology readiness of the wing solutions, together with the propulsion system, should reach high TRL (up to TRL6) by the 2028-2030 timeframe, so as to support an EIS by 2035.

## FUSELAGE, CABIN, CARGO AND EMPENNAGE

One key factor is **weight reduction,** to compensate higher weight resulting from hybrid propulsion. Fuselage, cabin, and cargo are crucial for commercial aircraft operations. With hybrid propulsion, they are significantly affected by the **integration of new energy sources** (batteries or fuel cells in future) and related ancillary systems. But fuselage, cabin, and cargo must also allow simple and rugged operation, in order to be accepted by passengers and operators. Sustainability and circular production will be key to reducing waste and production/end-of-life environmental impacts, while remaining competitive. High TRL (up to TRL6) should be reached by the 2028-2030 timeframe, to support an EIS by 2035.

## SYSTEMS

All on-board systems of this aircraft concept should be updated or fully revised, in the pursuit of **all-electric or more-electric solutions.** These systems will contribute to reductions in the energy required, as well as to further emissions reduction:

- Systems directly affected by the hybrid-electric propulsion features: thermal management, electrical systems, battery storage, and overall energy management among different energy sources.
- Systems to match the new operational constraints and regulations required for fleet penetration, e.g. air traffic management, ground operations, control and monitoring, reductions in pilot workload, and the need to comply with new rules on fire protection or ice protection.

High TRL (up to TRL6) for these systems should be reached by the 2028-2030 timeframe, to support an EIS by 2035.

The challenges, and more details on developing the technologies necessary to produce a regional aircraft concept of this kind, are described in the Ultra-Efficient regional chapter.

# 3.2. Ultra-Efficient Short and Medium Range Aircraft

**To keep pace with the ambitious decarbonisation roadmap in which the aviation industry is engaged, the ultra-efficient short and medium range (SMR) concept aircraft, one that is 100% SAF capable, will have to rely on new technologies for the plane, the production system, digitalisation of the plane and for using data to improve aircraft operations.**

> *The SMR aircraft concept is a 100% SAF solution.*

The configuration of the SMR aircraft concept proposed in Clean Aviation is expected to remain tube and wing and should target an EIS by 2035. Such an aircraft concept should have a capacity of around 200-250 pax with a design range up to 3000NM, operated on a typical mission of 800NM at cruise speed Ma 0.78. Such a configuration would address at least 50% of the $CO_2$ emissions share in 2020.

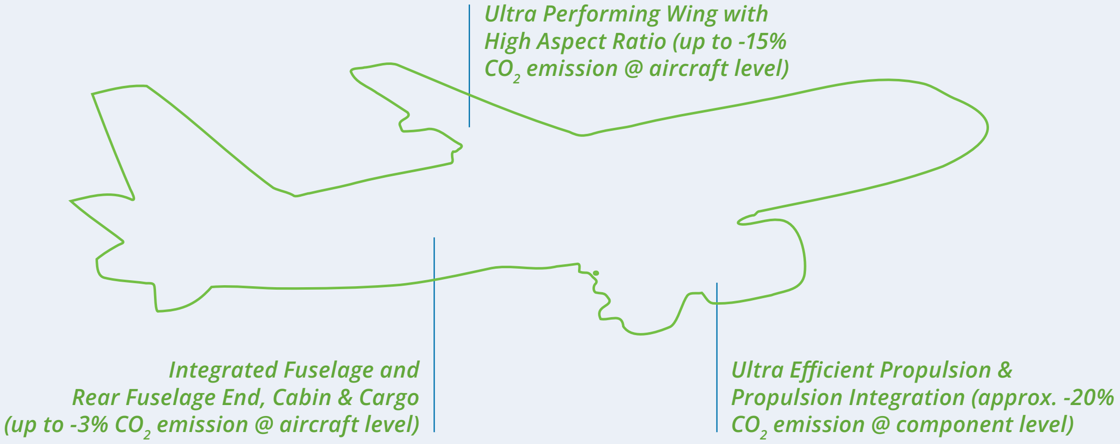
Disruptive technologies related to the airframe will have to be integrated with ultra-efficient propulsion systems, together with multi-dimensional trade-offs, including sustainability and circularity. The resulting ultra-efficient SMR targets a 30% $CO_2$ emission reduction from technology, not taking into consideration the SAF net-effect, on a typical mission.

**The SMR aircraft concept should include technologies meeting by 2028-2030 an industrial readiness level of innovations compatible with an EIS by 2035.** This entails very important enablers such as high production rate, low lead time and low recurring cost production to maximise the market uptake of the various technologies. The phase 2026-2030 broadly corresponds to a time period where the industrial readiness of technologies will be very important.

The most optimised SMR aircraft architecture could integrate disruptive technologies related to different domains, such as propulsion, wing, fuselage, cabin, cargo, empennage, and systems, as well as enabling technologies and capabilities.

The timeframe 2026-2030 should address technology maturation to high maturity levels (up to TRL6 and including industrialisation readiness) and demonstrated by ground tests and/or flight tests integrating the critical aircraft innovation technologies described below. To guarantee impact, the development of associated engineering capabilities through technology maturation will have to be considered. The digital capabilities and digital backbone (critical for the industrial readiness of the various aircraft technological innovations) should offer the right environment and tools to support the launch of new products for an EIS by 2035.

Figure 3.3: Ultra-effcient short and Medium Range aircraft



## PROPULSION SYSTEMS

Two propulsion system architectures (open fan or ducted) are under consideration and they need to reach high TRL (up to TRL6) by 2028-29, including industrial aspects, to support an EIS by 2035. Although specific technologies linked to each configuration must be matured and tested (noise, architecture, integration), some technologies may apply to both types, e.g. advanced systems and electrification/hybridisation.

The position of the engine in the aircraft is key: this position must be optimised to reduce emissions, and it must consider all the constraints, including industrial ones (industrial optimisation and industrial technologies). Consequently, the coupling of the propulsion system onto the aircraft should be done so as to reduce emissions. Furthermore, the technologies and architectures should consider thermal management.

## WING

Besides the propulsion system, the wing is one of the essential levers to improve overall SMR performance and to contribute to the -30% reduction of $CO_2$ emissions.

Any increases in aspect ratios for aerodynamic drag reduction, any reductions in structure weight and any inclusion of advanced systems must remain compatible with the existing aviation and airport infrastructure. Solutions must also focus on integrating a novel powerplant and landing gear technologies onto the overall wing.

Technology readiness of the wing, plus the propulsion system, must reach a high TRL (up to TRL6) by the 2028-2030 timeframe, in order to support an EIS by 2035.

## FUSELAGE, CABIN, CARGO AND EMPENNAGE

Weight reduction is a key contributor to achieving the targeted aircraft performance and matching the 30% $CO_2$ emission reduction. Fuselage, cabin, cargo and empennage components are crucial elements of the functionality and safety for the aircraft architecture as well as for weight reduction. The exploitation of Cabin and Cargo technologies are contingent to the easiness of re-configuration and industrial performance, while technologies linked to the Fuselage and Empennage will have to focus on architecture and installation to enable high production rates and lower time to market to remain compatible with an exploitation by 2035. Sustainable and circular production will be key to reducing waste and production/end-of-life environmental impacts, while remaining competitive.

High TRL (up to TRL6) must be reached by the 2028-2030 timeframe, to support an EIS by 2035.

## SYSTEMS

Development and integration of the system-related technologies must focus on two axis: optimal-non propulsive energy management systems, and avionics.

Challenges linked to develop the technologies for producing an SMR aircraft concept like this are set out in the Ultra-Efficient SMR chapter.

# 3.3. Hydrogen-Powered Aircraft

**The Hydrogen Powered Aircraft (HPA) concepts are expected to enable zero-carbon emissions in operation. As explained in Chapter 2, the use of hydrogen might lead to new classes of aircraft between the Regional and SMR segments.**

All aircraft concepts for the (HPA) share the same boundary conditions, which are related to:

- H2 regulation, standards and certification.
- Decarbonised H2 production and volume availability at airports.
- International H2 ecosystem (services and infrastructure).

All these aspects will have to be addressed outside of Clean Aviation, as they are associated with the general operating and infrastructure environment for aviation.

> *The Hydrogen-Powered Aircraft concepts enable zero-carbon emissions.*

For H2 aircraft, another essential aspect to consider is public acceptance of critical stakeholders (passengers, operators, airports, and EASA). Lastly, it will be key to guarantee that H2 aircraft have a long service life and can function under high-frequency alternating loads.

As a result, two classes of H2 aircraft concepts have been identified to guide technology maturation, integration and testing:

**Figure 3.4: Hydrogen Powered Aircraft (HPA)**

***LH2 storage fuselage integration:** Cryogenic liquid hydrogen management incl. refuelling and boil-off*

***H2 distribution:** Safe, reliable management incl. H2 leakages*

***Fuel cell powertrain:** High power density fuel cell system, high life-time*

***Alternative concept - H2 direct combustion:** Reliable and low NOx emissions*

## 1 - H2 DIRECT COMBUSTION AIRCRAFT CONCEPT

*Favoured design:* tube and wing, flying a typical regional aircraft mission (point-to-point feeder or leisure operations within the current ATM environment and Turn-Around Time).
*Range:* from 100 pax/1000 NM up to 120/150 pax/1,400 NM.
*Installed power:* around 10 megawatts (approximately 14,000 SHP in total).
*H2:* cryogenic liquid H2 storage + pump-fed distribution system architecture.

The main challenges are: optimised turbomachine, fuel system conditioning system enabling high-pressure H2 injection with an accurate range of temperature, metering and an injection system with limited pressure losses with reduced NOx emissions, propulsion system operability, regulation and transient management, and H2 fuel safety.

## 2 - FUEL CELL-BASED POWERTRAIN AIRCRAFT CONCEPT

***Favoured design:*** tube and wing.
***Range:*** average 100 pax/1,000 NM.
***Installed power:*** around 10 megawatts (with minimum 2.5 MW per propulsion system unit).
***H2:*** cryogenic liquid H2 storage + pressure-fed distribution system architecture.

The main challenges are: aircraft and propulsion system architecture, fuel cell propulsion system weight (stack, compressor, inverter, direct current converter, cooling system), high voltage power electronics, and H2 fuel safety.

## 3 - TECHNOLOGY VALIDATION AND DEMONSTRATION AIRCRAFT CONCEPT

Hydrogen-powered aircraft concepts are based on the de-risking of key elements in a representative environment, to allow a thorough understanding of Fuel Cell and H2 Combustion aircraft architecture, certification needs, operability requirements and contrail impact. This de-risking will be key to support a potential industrial decision on launching the operation of H2-based aircraft. More work must be done to fully understand the behaviour and handling of cryogenic fuels for commercial aircraft operation and to translate this knowledge into new concepts and technologies.

Hydrogen-powered aircraft concepts can call on H2 innovative aircraft architectures optimised for H2 technologies. To support the 2035 EIS objective, more conventional aircraft architectures (such as tube and wing associated to wing-mounted engines) may prove to be more effective, as they can benefit from existing airport infrastructures and ATM procedures for an H2 aircraft in-fleet early introduction. If H2 technology is progressing well on the technical and operational learning curves, «innovative H2 aircraft architectures may supplement, and even fully replace in the longer run, more conventional architectures on the path to an optimised H2 operational environment.

A fuel cell-based aircraft concept – envisaging a general aviation platform with technology-migration and power up-scaling potential – could serve as a validation platform to de-risk technologies and certification in the demonstration strategy for the Regional segment, and ideally also for larger aircraft (fuel cell propulsive option). However, technical clarification will be necessary, in order to prove the feasibility of the scaling-up potential to CS-25, for the certification route that the Regional and SMR segments must undergo.

A technology and demonstration platform at this smaller scale could support the Clean Aviation technology maturation, and allow to gain experience on infrastructure and operational issues addressed outside of Clean Aviation:

- Testing the reliability and safety of electrical power trains, to anticipate certification procedures.
- Gaining in operational experience of fuel cell-based technologies (aircraft and airport operating costs).
- Testing the gradual rollout of the necessary hydrogen infrastructures at high-intensity airports, notably H2-related services including refuelling, maintenance, and Turn-Around Time.
- Encouraging the establishment of an EU LH2 supply chain and supporting early customer acceptance of H2 aircraft.

***Range:*** minimum 19 pax /400 NM.
***Installed power:*** 2 megawatts (with 1 MW minimum per propulsion unit).
***H2:*** fuel cell-based.

The challenges linked to developing the technologies necessary to produce the above-mentioned aircraft concepts are described in the HPA chapter.

# 4. Disruptive technologies for Ultra-Efficient Regional aircraft

## 4.1. Introduction

**Greater attention to environmental aspects, along with stringent regulations and higher market demand, are changing regional air mobility – and specifically for typical missions between 500 km and 1000 km. Operators could progressively increase the average capacity of their fleet, to improve unit cost and to meet the increasing traffic demand. However, this could lead to a reduction in the frequency of flights to and from some destinations or less use of the smaller airports that are currently incapable of accommodating higher capacity aircraft due to infrastructure limits, passenger services, etc. Consequently, this would not meet the societal objectives for fast and flexible mobility with a low environmental impact.**

Operators and society expect **regional and inter-urban air mobility to propose innovations** for air vehicles. They also require frameworks that can fulfil expectations for better environmental and operational efficiency, new services, larger networks, optimised frequency, and new business opportunities at a reasonable overall cost. The future propeller ultra-efficient regional aircraft will include the innovations described in Chapter 3 of this SRIA, in order to achieve a significant reduction of emissions. All this while matching customers' expectations, both airlines and passengers, for a more comfortable, safe, affordable aircraft. One that can operate on short routes in future mobility scenarios, and will be competitive against less innovative aircraft and other transport means operating on similar routes.

> *Regional aviation has a relevant role in European and worldwide air mobility, for which low emissions solutions are required.*

Currently, regional aviation plays a major role in air mobility. Thanks to their widespread distribution, both propeller and jet regional aircraft-operated routes and connections now account for over 12% of world ASK (available seat kilometres). **Regional aircraft currently serve roughly 38% of world city pairs** and perform about 40% of the total departures and around 36% of the total flown hours. The innovations sought in this section of the SRIA, potentially combined with solutions from the Hydrogen Powered Aircraft thrust, may open new business scenarios, and improve further connectivity, especially for the 36% of existing airports that now rely exclusively on turboprop-operated services. The ambition for propeller regional aircraft is to replace regional jets, which are more expensive in operations and produce more emissions; in particular on shorter regional or feeder routes, where propeller regional aircraft can maintain a reliable and effective network with only a very small time penalty.

*© Almadesign for HERA project*

## VISION 2030 AND BEYOND

**By the mid-2030s, the mobility of people and goods is expected to undergo a progressive change, especially over distances of less than 500 km** (inter-urban regional connections). Innovations and technologies to improve affordability, match customer expectations, and enable the optimisation of propulsion systems for different fuel types and airframe characteristics, will reach higher levels of maturity and become available for regional air transport. This change will affect Europe, despite the continent's very dense network of surface communications and the relatively short distances to cover. But it will mainly affect the rest of the world – by far the bigger market for the regional segment – where no alternative surface transport network exists, and where population density is lower or geographical constraints make regional aircraft the only reasonable safe and quick mobility transport means.[32]

**The ultra-efficient regional aircraft concept described in Chapter 3, with a capacity of 50 to 100 seats, is the first expected application of hybrid-electric propulsion technologies in the scheduled air transport system.** This concept will come with solutions to reduce the environmental footprint, and provisions to maximise fleet penetration and impact, thus paving the way for affordable sustainable aviation.

Smaller air vehicles, such as commuters and rotorcraft operating on shorter or thinner routes, will also benefit from electric propulsion solutions tested on regional aircraft testbeds. These vehicles will use similar power modules, with different approaches to air vehicle integration.

The ultra-efficient regional aircraft thrust will demonstrate a set of innovative and disruptive technologies. These will enable new aircraft performance levels, as well as new business models that take into account the scalability to other air vehicle applications at both lower and higher scales. Regional air transport therefore offers a first operational deployment of solutions – a laboratory – applicable for other domains in the partnership too. It will address specific constraints such as short-field length capabilities, cockpit workload, simplified operations, quick turn-around times, dense air traffic, and simple airport infrastructures.

## RATIONALE AND GENERAL APPROACH

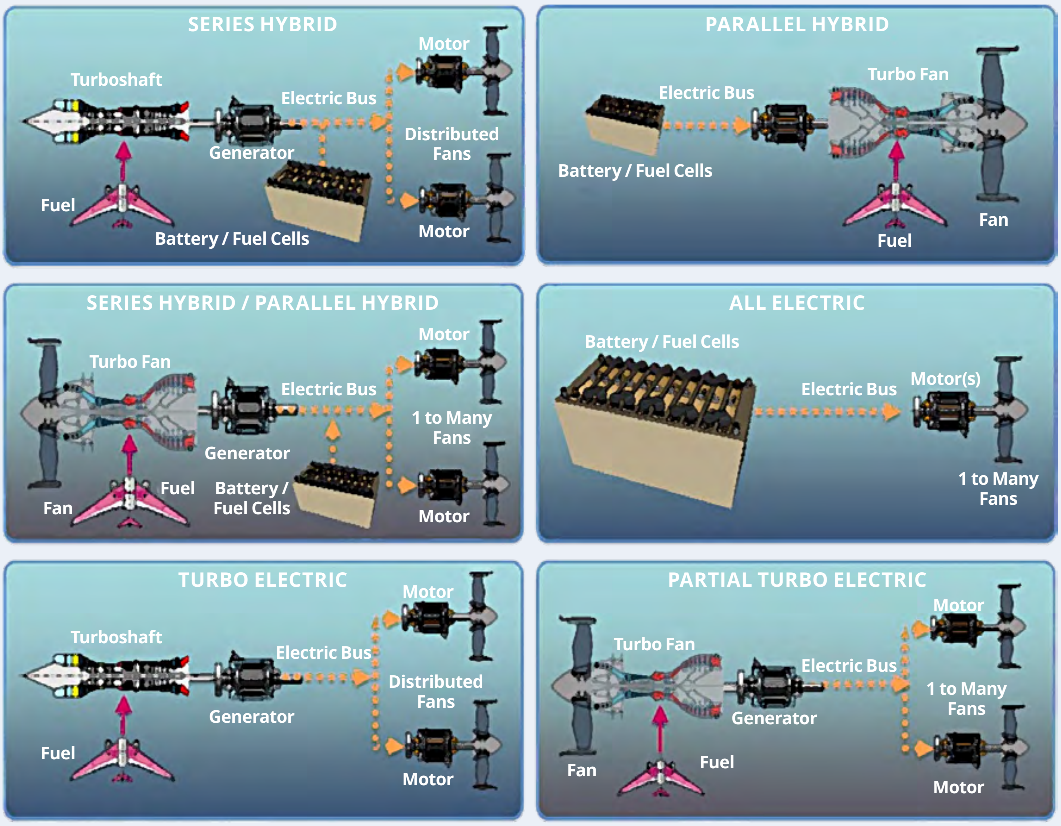
Careful aircraft integration of selected technologies is required to achieve both the sustainability and fleet replacement targets of Clean Aviation.

To identify the most efficient aircraft architecture to achieve lower emissions, various propulsion and aircraft configurations (see figure 4.1 see next page) may be initially assessed in trade-offs. A comparison of various propulsion configurations will be carried out, e.g. distributed propulsion and/or parallel/serial propulsion, including transfer of electric power to the engine shaft. Options from hybrid up to full-electric configurations will be explored, by investigating various levels of hybridisation and different primary energy sources, including a thermal engine, batteries or potentially fuel cells (see the Hydrogen Powered Aircraft chapter). **For an entry into service (EIS) by 2035, hybridisation is likely to be achieved with the simpler integration of batteries, whereas fuel cells can enable higher level of hybridisation for EIS beyond 2035,** depending on the readiness of the regional ecosystem.

---

[32] Mobility Impact Assessment of Innovative Aircraft inside the European Multimodal Transport Network. Conference Paper · August 2021 DOI: 10.2514/6.2021-2952. This paper discusses the potential percentage increase of Population Reached in less than 4 hours (PR4), introducing the 5,000 new routes made possible in Europe by new regional aircraft in the existing inter-modality network.

Figure 4.1: Electric and hybrid propulsion architectures, modified from National Academy of Sciences



In parallel, the complementary technologies and solutions envisaged in Chapter 3, for the ultra-efficient regional aircraft concept, will contribute to short time-to-market, improve customers' satisfaction, and seek to preserve affordability for customers despite more complex on-board systems.

Developing regulations and new infrastructures to support this disruptive aircraft concept will have to be addressed, in order to enable their market potential, as explained in Chapter 2 of this SRIA.

## COMPLEXITY AND DESIGN ACTIVITIES

For the ultra-efficient regional aircraft concept with hybrid-electric propulsion, the integration activities involve several interdependent areas of research, as described in section 4.2 below. As with any radical change in the dominant design of complex systems and the introduction of disruptive technologies, the metrics and associated tools to assess product performance across the life-cycle can radically change: this can lead to the introduction of new parameters not considered before.

In line with the Clean Aviation programme, all activities described in this section are organised in a **first phase** where the building blocks and different integration options will be studied to assess their potential and integration perspectives; this will enable identification of the most promising architectures. A **second phase** will further mature the technologies selected for higher TRL demonstration. This second phase may also mature promising technologies that are not ready for the real-scale demonstrators, but are valuable to maximise aircraft impact and fleet penetration beyond 2035, to a higher TRL.

## KPIS AND TARGETS

The final demonstrations at high TRL will support the ultra-efficient regional aircraft concept described in Chapter 3, with technologies ready for entry into service by 2035. This concept will incorporate product-viable solutions that take into account technology, integration, industrialisation, infrastructure, and certification aspects.

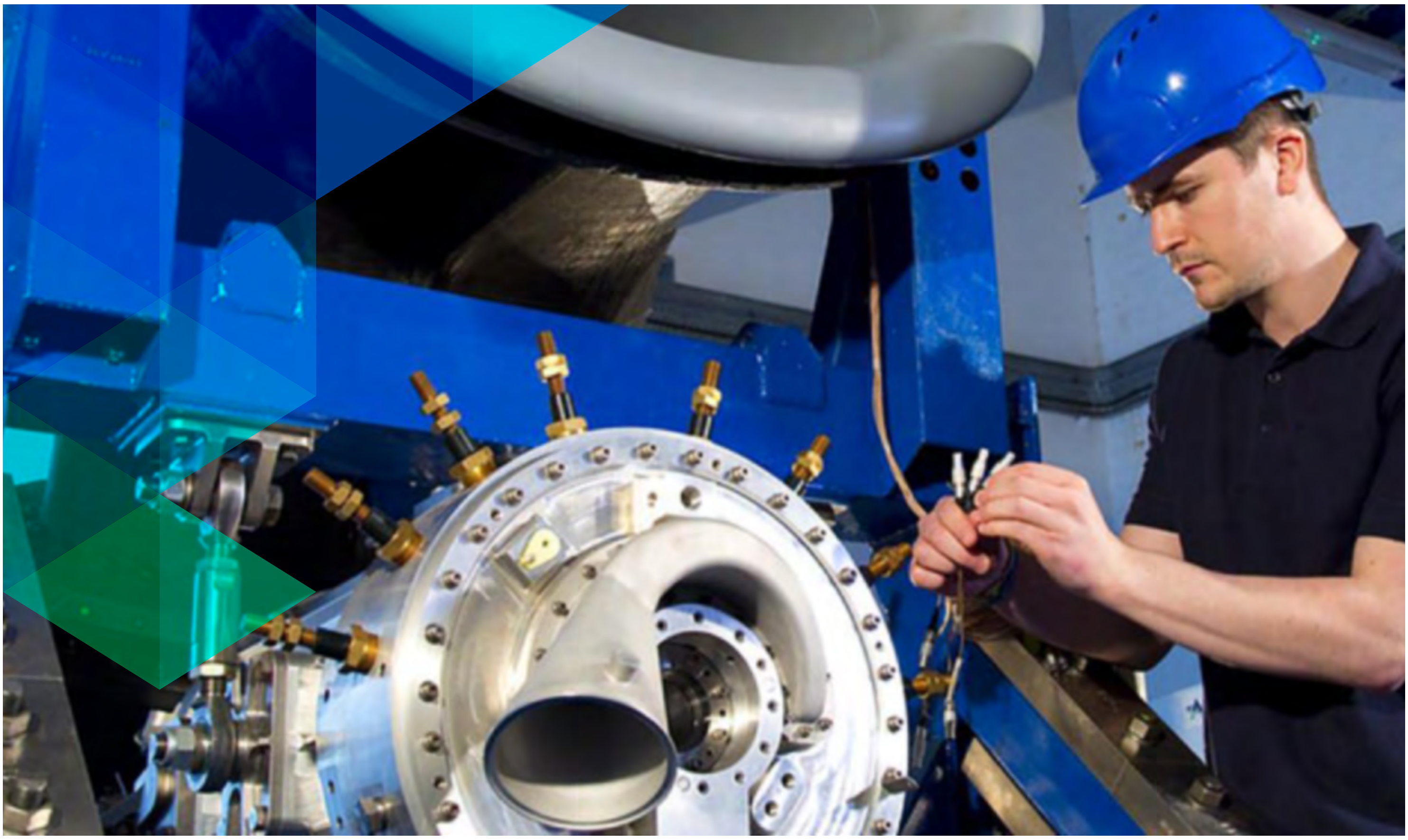
The aircraft will include hybrid-electric propulsion supported by 100% drop-in sustainable fuels for the thermal power source, to reach at least 30% lower $CO_2$ emissions (without SAF net-$CO_2$ contribution) from disruptive technology solutions, while being fully compliant with ICAO noise rules and incorporating solutions to improve impact and fleet penetration. The parameters linked to non-$CO_2$ effects will be monitored and reported, as described in Chapter 2.4.

> *By 2035, ultra-efficient Regional aircraft technologies aim to reduce $CO_2$ emissions by 30% and be 100% SAF compatible.*

The developed technologies will largely support any potential future clean-sheet regional aircraft beyond 2035, using drop-in or non-drop-in sustainable fuels.

The impact of the ultra-efficient regional aircraft, together with results from other thrusts and concept aircraft, will contribute to the Clean Aviation global impact within the wider multimodal, intermodal mobility, and market scenarios foreseen to match the 2050 fleet replacement target.

Meaningful and appropriate KPIs will be selected and identified at technology level and at aircraft level, in order to demonstrate the contribution to the Clean Aviation objectives. All KPIs will be integrated and assessed at aircraft level within the impact monitoring process described in Chapter 2.



# 4.2. Key technologies and their contribution to the Clean Aviation ambition

Figure 4.2 Key technology scheme relevant to ultra-efficient regional aircraft

| KEY TECHNOLOGIES TO REDUCE EMISSIONS<br>see p 52 - 56 | ENABLING TECHNOLOGIES AND METHODS FOR AIRCRAFT INTEGRATION<br>SEE P 56 - 57 | INTEGRATION TECHNOLOGIES AND ROUTES FOR ULTRA-EFFICIENT REGIONAL AIRCRAFT<br>SEE P 57 - 61 |
|---|---|---|
| > Propulsion unit<br>> Propeller and E-propeller<br>> Electric power chain<br>> Power and energy storage<br>> Energy management | > Low emissions<br>> Affordability and sustainability<br>> Life-cycle assessment<br>> Aircraft design and assessment | > New aircraft architecture<br>> Propulsion and on-board energy concept<br>> New propulsion integration<br>> Aerodynamic optimisation<br>> Electric engine, power electronics and management<br>> Power and energy storage<br>> In-flight thermal management<br>> Advanced Systems<br>> New routes to certification |

## KEY TECHNOLOGIES TO REDUCE EMISSIONS

Electric propulsion for aircraft increasingly appears to be feasible given the extraordinary progress envisaged in the high electrical power, high-voltage, and electrical storage technologies. The key aspects to tackle, which differentiate aviation electric propulsion from automotive, are power and energy size of up to many MW and MWh, as well as environmental and operational constraints such as low operative air pressure and temperatures, life-cycle, safety provisions, and power and energy density where weight and volume are paramount factors for aviation. Even though progress in electrical technologies is significant, within the Clean Aviation timeframe (ending in 2030), fully electric propulsion – with electrical stored energy as the only source of propulsion power – appears ready for real applications in commuter and small rotorcraft for short range or flight duration.

**For larger capacity or longer flights involving higher power, as in regional, SMR or larger aircraft, partial electrification of propulsion must include hybridisation.** A mix of electric engines and electrical energy sources with optimised turbo machines appears to be the most likely choice to support an entry into service by 2035, as envisaged in the ultra-efficient regional concept described in Chapter 3.

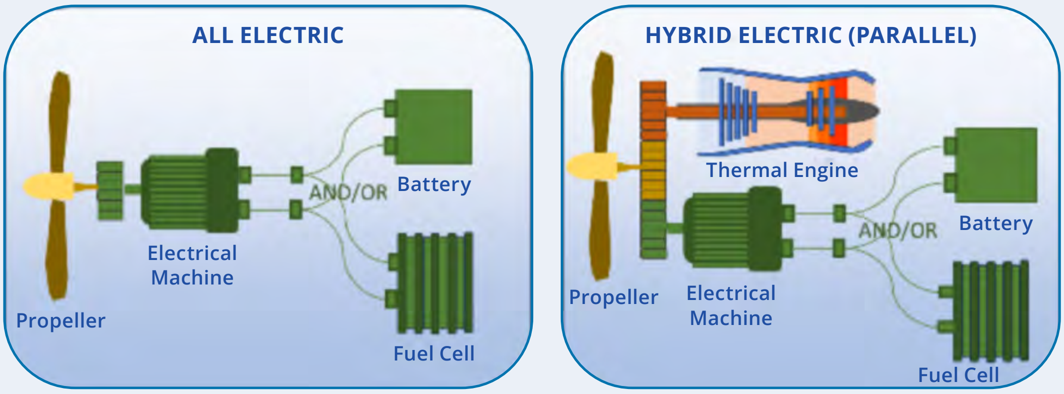
Fuel cells, as covered in the HPA chapter, offer a valid alternative on the path to zero-carbon propulsion for regional aircraft. Full electric and hybrid propulsion can be seen as a continuum at different stages of hybridisation: their technologies, complexity, safety, and integration are evolving at a different pace, depending on the air vehicle application and potential for scalability. Electric propulsion offers additional degrees of freedom for optimising aircraft performance and reducing fuel consumption, while opening a new design space for aircraft configuration, performance, operation and eventually business cases. The ultra-efficient regional aircraft concept appears to be the most suitable candidate for demonstration, in light of technology development status, size, range, and performance. If applied to this market segment, this concept would potentially have an meaningful impact on reducing global emissions.

There is no single predefined solution. The general approach of regional thrust (see fig. 4.4) is that several paths are promising, and the partnership should investigate these in Phase 1, since the community has not yet identified the 'winning configuration' to reach the final objective. Phase 2 will concentrate mainly on demonstrating technologies matured so far, and those from synergies, in integrated demonstrators suitable to the ultra-efficient regional aircraft concept depicted in Chapter 3. The technologies and the architecture must be aligned, in order to optimise aircraft performance and aircraft configuration. The adopted final solutions will likely challenge the existing targeted missions of regional aircraft (their distance range, number of transported passengers, cruise speed, etc.). Two options appear to be most suitable for the ultra-efficient regional aircraft concept (see fig. 4.3):

- **Parallel hybrid-electric architectures:** additional electric energy is used in certain flight phases in times of high-power demand. Bi-directional flow of power would also be possible between the electrical machine and batteries, but not for fuel cells; when the thrust demand is lower, the produced electricity can be stored in batteries.

- Recent developments in high-power fuel cells further mature Multi MW Fuel Cell propulsion systems that are integrally optimised, from liquid hydrogen tank to propeller, for aviation and can be introduced in regional aircraft with **'all electric' propulsion.** This is a potential zero-carbon propulsion system technology for regional applications, to be pursued in the HPA section of this SRIA.

Figure 4.3: Options of all electric and hybrid-electric propulsion pursued in Clean Aviation (the technologies for all-electric solutions based on fuel cells are set out in the HPA thrust – see Chapter 6)



## CONCEPT FOR REDUCING EMISSIONS

**In 2035, the most probable solution for the ultra-efficient regional aircraft concept, described in Chapter 3, is an optimised hybrid-electric propulsion system:** this will be coupled to selected on-board systems that are required to match customer expectations and improve fleet penetration. This solution will make the proposed aircraft competitive and affordable, in the regional mobility scenario in this timeframe.

This effort will include a hybrid turboprop equipped with a 2035 state-of-the-art thermal engine coupled to an electric motor/generator, with batteries that could provide electrical energy, via a MW/kV electrical system. Beyond this date, the propulsion system may even consider fuel cells and/or a distributed propulsion architectures that balance operational constraints, safety, availability, and dispatch reliability with emission reduction. The net-$CO_2$ emission reduction may be drastically improved, by using SAF, or in the most advanced solutions by using hydrogen.

The propulsion effort will be complemented by devices and features designed to improve fleet penetration so as to cope with several aspects, e.g. systems control and monitoring, on-board energy management, passengers' comfort (noise, space), ability of the regional aircraft to operate in the new air traffic control, and simplified maintenance and operation. Hybrid propulsion power management must be developed and connected with the power management required for on-board systems. The system will ensure a split of the power according to flight phase, providing information to the pilot on the power margin and the health of the power sources/electrical distribution, while contributing to overall flight efficiency.

The total on-board power depends on the flying platform and hybridisation ratio. For example, total power, depending on aircraft size and degree of hybridisation, would be in the range of 4 to 8 MW for regional platforms. The single electrical channel, with its specific power management, must comply with safety and certification requirements suitable for an electric propulsive system. The electric architecture may include efficient hybrid turboprops, propellers, electrical storage and all the necessary distribution, protections and interconnection systems needed to implement a high-power and high-voltage channel. The main technologies related to on-board power for the ultra-efficient regional aircraft concept include:

- **An ultra-efficient propulsion unit** designed for a hybrid configuration: a hybrid turbo-propeller capable of delivering both mechanical and electrical power for propulsion that will contribute to the target vision of $CO_2$ emission reduction.
- High-power (up to MW size), ultra-efficient, low noise, integrated **propellers** with dedicated controls.
- Integrated high-power/high-voltage **electric power chain** with lowest possible weight penalty, designed to withstand the relevant environmental and operational conditions.
- High-power and high-energy **battery, or fuel cell,** integrated inside the aircraft.
- Specific and common global **thermal management** for both hybrid propulsion and on-board systems.

> *By 2035 a hybrid-electric architecture based on batteries is foreseen.*

For these technologies, maintainability, reliability, durability must meet the market expectations; certification rules, means of compliance and safety must ensure all the necessary protections for both people and materials.

The high level of modularity and scalability of electric solutions should allow their exploitation in other product classes beyond the Clean Aviation programme, e.g. rotorcraft or commuter airplanes, or even future emerging aerial vehicles. For instance, modules of between 500 kW up to 1 MW power could be applicable to full-electric propulsion for smaller air vehicles, while larger aircraft will potentially use larger modules.

### PROPULSION UNIT

The propulsion unit, an association of a thermal engine with one or more electric machines, is the essential building block of electric hybrid propulsion. This propulsion unit, as a main source of power, is a breakthrough compared to existing state-of-the-art and it may include readiness for innovative energy sources such as hydrogen or 100% SAF.

The thermal engine will operate in its most economical range, while rotational speeds could be adapted to the electrical drivetrain's optimisation point. This engine will be able to provide electrical power throughout all flight envelopes, to meet all the aircraft's electrical demands for both propulsive and non-propulsive (e.g. ECS) systems. It will be optimised to reduce emissions throughout the mission, while delivering the power/thrust necessary in the whole flight envelope, so as to optimise power sharing. This split will be managed through a distribution/power management system.

Coupled to the thermal engine, a new and very high efficiency electrical machine – starter/booster/generator – and ancillary control systems will be studied. It will be highly integrated into the aircraft and be able to provide both electrical and mechanical power. This new electrical machine will be sized to provide its maximum power for critical phases of the aircraft flight during take-off, or failure cases such as one engine inoperative, etc. The gearbox is a more complex and critical component: the turboprop mechanical shaft transfers its power to the propeller but also drives a reversible electric machine in addition to other potential equipment.

## PROPELLER AND E-PROPELLER

The ultra-efficient regional aircraft must improve thrust efficiency and reduce its noise footprint compared to today's solution. Reducing noise is a fundamental area of improvement for the social acceptance of these aircraft as well as their use of secondary airports, which are often located near urban areas. The propeller design must improve acoustic performance, complying with ICAO Chapter 14 rule evolutions. The propeller must be newly designed to adapt to the thermal engine and electric motor combined contributions, as well as to increase propulsive efficiency and thus reduce the energy required. An advanced propeller may be necessary for high efficiency and low noise at high thrust.

For the distributed propulsion concept, additional requirements and features apply to propellers (E-propeller) and thus require a specific solution:

- It could improve the lift of the aircraft (high-lift propeller) and therefore potentially reduce the wing surface.
- It could reduce the marginal tip vortex (wing tip propeller) combined with the potential controllability of the aircraft by thrust differential
- It could be foldable to reduce aerodynamic drag when not in use in several flight phases.
- It could allow taxiing operations using e-propeller only, leading to zero emissions on the ground.

## ELECTRIC POWER CHAIN (DISTRIBUTION AND INTERCONNECTION SYSTEMS)

This area covers power classes suitable for hybrid-electric applications on regional aircraft but the technology is as well applicable to short and medium-range aircraft (SMR) or even bigger platforms (if the technology potential allows). Today, electrical power system architectures are based on 28Vdc and 115/230Vac voltage levels and they address several hundred kW distribution. Higher power (up to 1.2 MW) is achieved on most modern aircraft using the 270Vdc standard. However, the distribution of power levels representing several MW, as needed for regional aircraft with hybrid propulsion, will require an increase of the network voltage level to keep the system weight and volume increase acceptable.

A key aspect for higher voltage and power usage is the higher cruise altitude, since lower pressure means more partial discharge phenomena. Additional requirements for safety, environmental constraints and integration in low-pressure areas arise. For example, constraints for certification of regional aircraft are driven by CS-25 certification rules, which will have to be applied at higher voltage at an altitude of at least 25,000 ft.

## POWER AND ENERGY STORAGE / FUEL STORAGE SYSTEMS

In hybrid architectures, additional electrical storage components will be embedded, e.g. battery and fuel cells. Batteries and/or fuel cells should be designed to deliver high power in a relatively short period. This will allow for the provision of additional propulsion power to the thermal engine during specific flight phases, i.e. take-off phase and all the propulsion power at the taxiway or at the gate. The common aspects that require study are modularity and the system's capability to adapt to changing propulsion power ranges; and how to interface with aircraft electrical systems (e.g. power quality). Power storage must be combined with scalable power lines. Suitable electrical motor architectures should be inherently designed for redundancy, high efficiency, and the ability to cope with voltage fluctuations.

> *Additional electrical storage components will be embedded such as battery and fuel cells.*

During Phase 1, combinations of batteries and fuel cells will be explored to understand their impact on the aircraft architectures and optimal hybridisation ratio. During Phase 2, the main focus will shift to the battery-based solutions foreseen for an EIS by 2035, as described in Chapter 3 aircraft concept. Moreover, the HPA thrust (see Chapter 6) will further mature the fuel cell technology, which might complement the batteries beyond this date.

### *Batteries*

The development of batteries suited to aeronautical application heavy duty and environmental conditions will be considered in synergy opportunities with BATT4EU Partnership, as envisaged in Chapter 2 of this SRIA. This activity should cover the integration and adaptation of a modular hybrid power pack, e.g. power cellswith high charge/discharge cycle to a full or hybrid electric architecture. This will consider several key aspects, including cell technology and packing from other (EU) initiatives/sectors; energy, power, and volume density; energy storage gauges to accurately show the remaining energy available; charging and recharging cycles to be optimised by suitable battery management systems and efficient power management algorithms; and integration issues such as thermal management and replacement actions. The choice of batteries and their performance must be adapted and harmonised with the other technologies defined above. Batteries with energy densities of up to 500Wh/kg are foreseen as technologically achievable for the 2035 EIS horizon. This battery technology must also take into consideration some specific aircraft issues, e.g. total weight and balance, containment and safety, maintenance, durability, and refurbishment. Designing batteries for peak power delivery means enabling a high discharge current: this discharge rate or C rate is a key differentiator of battery technologies for hybrid aviation compared to other markets. Finally, integration of batteries to fulfil hybrid-electric propulsion architectures – and the aeronautical environment in general – will require their qualification and certification to aeronautical standards, in synergy with other dedicated EU efforts besides Clean Aviation.

### *Fuel cells*

> *Fuel Cells technology is matured in the Hydrogen Powered Aircraft thrust.*

Alternatively, fuel cells are another electrical energy source with potential applications to the ultra-efficient hybrid regional aircraft concept: this will open up opportunities to reach higher hybridisation ratios. Fuel cell usage may lead to a powerplant architecture that is different from hybrid configuration using batteries; however batteries might support fuel cell operations when high peak power is required. Research activities will include investigating the integration and adaptation of fuel cell source, looking at several key aspects such as fuel cell technology options (see the HPA section) and synergies with Clean Hydrogen, effects on aircraft linked to power, thermal energy dissipation and volume density; environmental constraints such as operative pressure and temperature; ancillary systems and devices such as hydrogen tanks and distribution system (see the HPA section of this SRIA). The fuel cell choice and performance will be evaluated and adapted to peculiar aircraft issues, e.g. total weight and balance; containment and safety; maintenance and refurbishment.

### ENERGY MANAGEMENT

The energy management of the propulsive and non-propulsive systems will define the balance and management of power of the different sources between thermal engine and electric motors. The aim is to optimise energy, emissions, noise, and direct maintenance costs as well as control of power supply in normal and abnormal conditions that impact equipment life, efficiency, and system availability. Energy managementwill take into consideration all the different phases of the flight: taxiway, take-off, climb, cruise, descent, landing and taxi, and the associated need for power and constraints.

The energy management at aircraft level will provide the optimal split between thermal and electric energy in order to achieve a given mission target or constraint, i.e. to complete a mission with the lowest emissions, keeping some reserve at the end. The system will work by considering the needs of other aircraft systems, e.g. the Flight Management System or ECS, and the prediction of the aircraft performance over the mission. It will also manage failure cases, to ensure the safety of the aircraft.

## ENABLING TECHNOLOGIES AND METHODS FOR AIRCRAFT INTEGRATION

The complex and challenging pathway to support the ultra-efficient regional aircraft concept, as described in Chapter 3, with hybrid electric propulsion requires specific technology areas to be explored, in order to evaluate their impact on the overall aircraft. These areas relate to the design of essential systems and critical areas, as cornerstones for the potential development and certification of an ultra-efficient regional aircraft concept that will have the expected impact. Furthermore, integration must consider a set of technologies to support the operational and maintenance effects caused by the required emission reduction. This integration must also lead to the envisaged impact and fleet replacement by 2050, allowing smooth operation and acceptance by customers and passengers. Altogether, due to the novelty and complexity of hybrid electric propulsion on the ultra-efficient regional aircraft concept, new heuristics and metrics will be required to correctly evaluate Clean Aviation solutions against environmental impact and sustainability. In other words, to evaluate the impact of the innovative technologies and their actual usage. Understanding those performance effects at aircraft level and on operations is a key difference between a research-oriented demonstration (even if this is at full-scale and high TRL), and a demonstration that supports the impact of realistic solutions and features that a product would need for a successful entry into the market and operations.

- **Low emissions.** Integrating hybrid-electric propulsion demands sophisticated tools to facilitate identification of critical design parameters and to predict performance at aircraft level, as well as to share these with partners and certification authorities. New architectures and performance ranges, which have never been achieved so far in aviation, will be explored. For instance, electric power will be 50 to 100 times higher. These tools include virtual design, integration, Validation & Verification platforms and digital twin platforms to explore and address issues such as managing high levels of electric power, adapting to multiple propellers for distributed propulsion systems, and adjusting the airframe structures in terms of aerodynamics, vibration, noise and thermal dissipation, EMI, etc.

- **Affordability and sustainability.** The shift from state-of-the-art propulsion to hybrid electric propulsion will also necessitate careful consideration of integrating new (and potentially large) components, optimising assembly techniques, and managing maintenance needs to ensure safety, airworthiness, and affordability throughout the aircraft's lifecycle. In parallel, zero-waste manufacturing solutions should ideally be used to better emphasise the goal, which is reducing the environmental impact. To accommodate these new features and possibilities while keeping them affordable for customers, we will need to re-think the process of designing, manufacturing and assembling aircraft. High current return needs and grounding, thermal waste and insulation, or solutions to enhance the flexibility and modularity of electrical propulsion: these are examples of new and critical integration issues to be pursued.

> *Life cycle analysis of hybrid-electric air vehicles is necessary to support technical choices.*

- **Life-cycle assessment.** Carbon-neutral aviation implies a paradigm shift in the metrics and design scope of aircraft. Up to now, aircraft have been designed to reduce life-cycle cost, maximise safety and achieve high operational flexibility. Climate-neutral aviation will require aircraft to release the lowest possible emissions at affordable cost, while maintaining maximum safety; this could lead to reduced flexibility in usage. A different life-cycle analysis of such air vehicle concepts and their potential role in the mobility mix is necessary, to support the technical choices needed. The development of a Life-Cycle Assessment method and tool tailored to include low emissions performances is envisaged within Clean Aviation: this will be the EU contribution to correctly evaluating sustainable technologies that comply with future ICAO frames. Due the lack of new metrics like this and the associated toolset, when 'measured' using current life-cycle heuristics, Clean Aviation may not be able to exploit fully its potential and then reduce its impact by 2050.
- **Aircraft design and assessment.** Existing aircraft-level tools and methods of whole aircraft configuration should include new hybrid propulsion features and performances. For example, distributed propulsion will mean including the effects of multi-propeller and tip propeller. Aerodynamics design and characterisation, aero-elastic analysis, flight control and flight management systems and performance-validated tools must all be updated, in order to include innovative configurations that support the ultra-efficient regional aircraft with hybrid propulsion.

## INTEGRATION TECHNOLOGIES AND ROUTES FOR ULTRA-EFFICIENT REGIONAL AIRCRAFT CONCEPT

From the aircraft perspective, certain building blocks are needed to achieve the vision and define future performance and business viability, e.g. cost and quality/performance thresholds of future aircraft. The actual technologies to be integrated will result from the maturation progress, the integration studies and interaction with rules. A wide range of integration routes could potentially contribute to such goals: the focus will be on a regional aircraft concept to match the impactful demonstrations envisaged by Clean Aviation, even though scalability and applicability to other aircraft segments are being pursued. A non-exhaustive list is proposed below.

### AIRCRAFT ARCHITECTURE

The challenge is to integrate future disruptive technologies in an aircraft concept that can meet the environmental objectives and the market expectations in terms of affordability, flexibility of use and safety. At the same time, the concept must remain competitive with other mobility solutions.

The new propulsive solutions may require the pursuit of innovative aircraft configuration and usage. Trade-offs are expected across different aircraft architectures. These include propulsion architectures, scalable, multi-purpose definition, non-propulsive systems optimisation, and different energy storage solutions that support relevant mission profiles. Internal and external acoustics must be addressed by assessing the impact on citizens.

The aircraft concept and associated configuration must enable the inclusion of technologies to improve the concept's fleet penetration and customer acceptance. Examples of this are systems' control and monitoring, passengers' comfort improvement in terms of noise and space, the ability of the regional aircraft to operate in the new air traffic control environment, maintenance, and simplified operations.

### PROPULSION AND ON-BOARD ENERGY CONCEPT

Based on the aircraft level trade-off, the best propulsion candidates will be studied for their aircraft integration readiness, in order to define the best balance between different energy storage systems and related energy sources as well as the best balance and utilisation strategy for thermal engine and electric motor. The key challenges in such assessments will be high-voltage power distribution, electrical machines with a high ratio of power to weight and volume, power electronics, and having management and control potentially coupled to advanced thermal engines as primary sources of energy using 100% SAF.

## PROPULSION INTEGRATION

> *The integration of hybrid-electric propulsion affects all aircraft major components.*

Integrating new propulsion solutions on aircraft is paramount to delivering a competitive aircraft concept that has an actual impact in terms of emissions reduction. Specific efforts are required to address mechanical and thermal integration combining turbine, gearbox, propeller, electric motor generator and their integration into the aircraft, including complementary systems required to manage and distribute the new energy sources. These integration aspects affect all aircraft major components:

- Nacelle and pylon to cope with different sizes, weights, loads, safety, and functional features of the new power plant.
- Wing design having a shape, size and structural concept to pursue low drag, e.g. high aspect ratio or cantilevered solutions, to match the new powerplant interfaces, and to withstand the new loads derived from new propulsion unit and energy storage moved out of wing into the fuselage, i.e. 'dry wing'.
- Fuselage and empennages to integrate or match new loads and features deriving from new energy sources storage and distribution largely located in the fuselage, associated controls, large electrical devices, and thermal management.
- The new propulsion may also significantly affect other on-board systems. For instance, the flight control system in case of total or partial failures of one energy source (hybrid), or a propulsor (distributed) or electrical system will have more critical failures cases than traditional cases to be considered. New failure cases – related to aircraft control, different actuation systems, new redundancies and functional schemes, new interaction between systems and propulsion – must be assessed with suitable testing and related evidence.
- Noise effects and integration solutions to mitigate them, on each of the major components driven by the new propulsion, must be fully evaluated for their impact on citizens due to the sensitivity of local noise effects.

All those aspects are key enablers of future products. So they require a dedicated maturation path, even if this will be intertwined more closely than before and with a stronger optimisation potential than before.

## AERODYNAMIC OPTIMISATION

Aerodynamic optimisation at aircraft level plays a pivotal role in enabling emissions reduction on the ultra-efficient regional aircraft concept, besides the benefits that come from hybrid-electric powerplant. Complementing the new design of wing and empennages that maximise the effects of new propulsion as described above, this optimisation involves designing more efficient aero shapes, using innovative technologies for control surfaces or material. This has a beneficial impact on the overall aircraft drag. The optimisation must also consider the effects on drag of cooling the airflow inlet and exhaust, which is required by the new, and probably much larger, thermal management system needed for the new hybrid propulsion concept.

## ELECTRIC ENGINE, POWER ELECTRONICS AND MANAGEMENT

The major challenge of an affordable and reliable electric-hybrid propulsion system, as implemented in a regional aircraft concept, is to achieve an integrated power management of the entire system. Key technologies to be matured are electrical machines in the MW class, compact flight-worthy power distribution and power electronics (e.g. Si-C), and dedicated control systems. Modular and scalable solutions must be pursued, in order to cope with different aircraft requirements within a product family as well as to enable aircraft updates following the maturation of new technologies, given the high-speed innovation envisaged in those areas.

## POWER AND ENERGY STORAGE / FUEL STORAGE SYSTEMS

For a hybrid-electric regional aircraft concept using drop-in fuels and/or other energy storage solutions – and depending on aircraft integration constraints, power levels and performance – the optimal degree of hybridisation will result from a trade-off to achieve the maximum benefit from the hybridisation. Developing solutions suitable for the aircraft's operational environment and safety aspects will be a key aspect to pursue, beyond the performance and weight/volume aspects, since they affect aircraft design and configuration. In all cases, the needs and features of ground infrastructure to support the aircraft must be explored in synergy opportunities, e.g. AZEA, Clean Hydrogen or CET to assess operational issues: battery recharging and/or replacement at the ramp, fuel storage on the ground (hydrogen or SAF) and refilling options and interfaces, maintenance and operators' skills and tools.

## IN-FLIGHT THERMAL MANAGEMENT

> *Propulsion and energy system heat generation losses will be significantly higher.*

Propulsion and energy system (e.g. batteries and/or fuel cells) heat generation and high-power electrical distribution losses will be significantly higher than in a state-of-the-art (SoA) equivalent system, up to hundreds of kW in the case of fuel cells. The new thermal management will affect all major aircraft components, including the fuselage, wing, pylon and nacelle, complementary systems and new energy storage devices. The location of heat generation, and the ways that heat may be dissipated, will be very different as well: these will depend on the selected aircraft architecture. Radical thermal management features and architecture must be introduced, enabled thanks to enhanced manufacturing technologies or new materials with very high/low thermal conductivity for insulation and thermal dissipation. This aircraft-level thermal management must manage thermal control solutions at device level (electrical machines, batteries, fuel cells, energy distribution) within an overall system that matches aircraft operational constraints. A close connection and optimisation with an on-board environmental control system is deemed necessary, as well as an assessment of the potential to upscale to other aircraft platforms.

## ADVANCED SYSTEMS

To assure the envisaged high impact and fleet penetration of the ultra-efficient regional aircraft concept with hybrid propulsion, there are two relevant technical streams. They cover the secondary energy for on-board systems, and the ability of the new aircraft concept to successfully operate in the future air traffic environment.

State-of-the-art consists mainly of hydraulic, pneumatic (high-pressure air bleed from thermal engines) and mechanical systems. These tap energy from thermal engines but they require maintenance, decrease engine performance, and have low overall efficiency. Hybrid propulsion with less-powerful thermal engines, or no thermal engine at all in the full electric option, will require innovative systems pursuing 'the more or all electric' systems' concept. However, these must be suitable for the regional scale and they must be able to increase energy efficiency and reduce the spill of energy from the propulsive unit.

On-board systems controls, monitoring and avionics should match the new aircraft capabilities brought in by new hybrid propulsion. They must also correctly interface with and accommodate the aircraft in the future air traffic management environment.

## NEW ROUTES TO CERTIFICATION

New means of compliance, new global certification approaches such as virtual testing and demonstration, or dedicated rules, will be required to certify a new hybrid electrical aircraft concept. Therefore, as extensively described in Chapter 2.8, the ultra-efficient regional aircraft thrust seeks a strong and pro-active cooperation among the airframers (transversal to SRIA thrusts), the engine manufacturers and the certification authorities from the early design phases. Identification of new rules, the evolution of current rules and an EU-wide approach should be brought to the international regulatory and standardisation bodies, with strong support from the EU authorities.

## 4.3. Demonstration strategy, key objectives of large-scale demonstration

**The regional aircraft concept demonstration strategy aims to mature technologies up to TRL6, anticipate certification, and shorten exploitation of new solutions while also increasing their impact, reducing time to market, assessing affordability, and improving customer acceptance. The plan is to implement a smart and balanced use of all available demonstration options, by applying a multi-dimensional and stepped demonstration strategy at different levels of complexity.**

This will allow the assessment of the potential and performance of new technologies in combination with other systems (legacy or new), evaluating their interaction and correlation while controlling risks and cost.

Subject to analysis, capability maturity and relevance, the hybrid-electric propulsion technologies and the other technologies relevant for the ultra-efficient regional aircraft concept described in Chapter 3 may not all fit in a single aircraft demonstrator. This is because they represent significant levels of change that are not fully compatible with the resources and timing of Clean Aviation, as well as the fact that the technologies represented may not fully interact with each other. The selected set of demonstrations depends on:

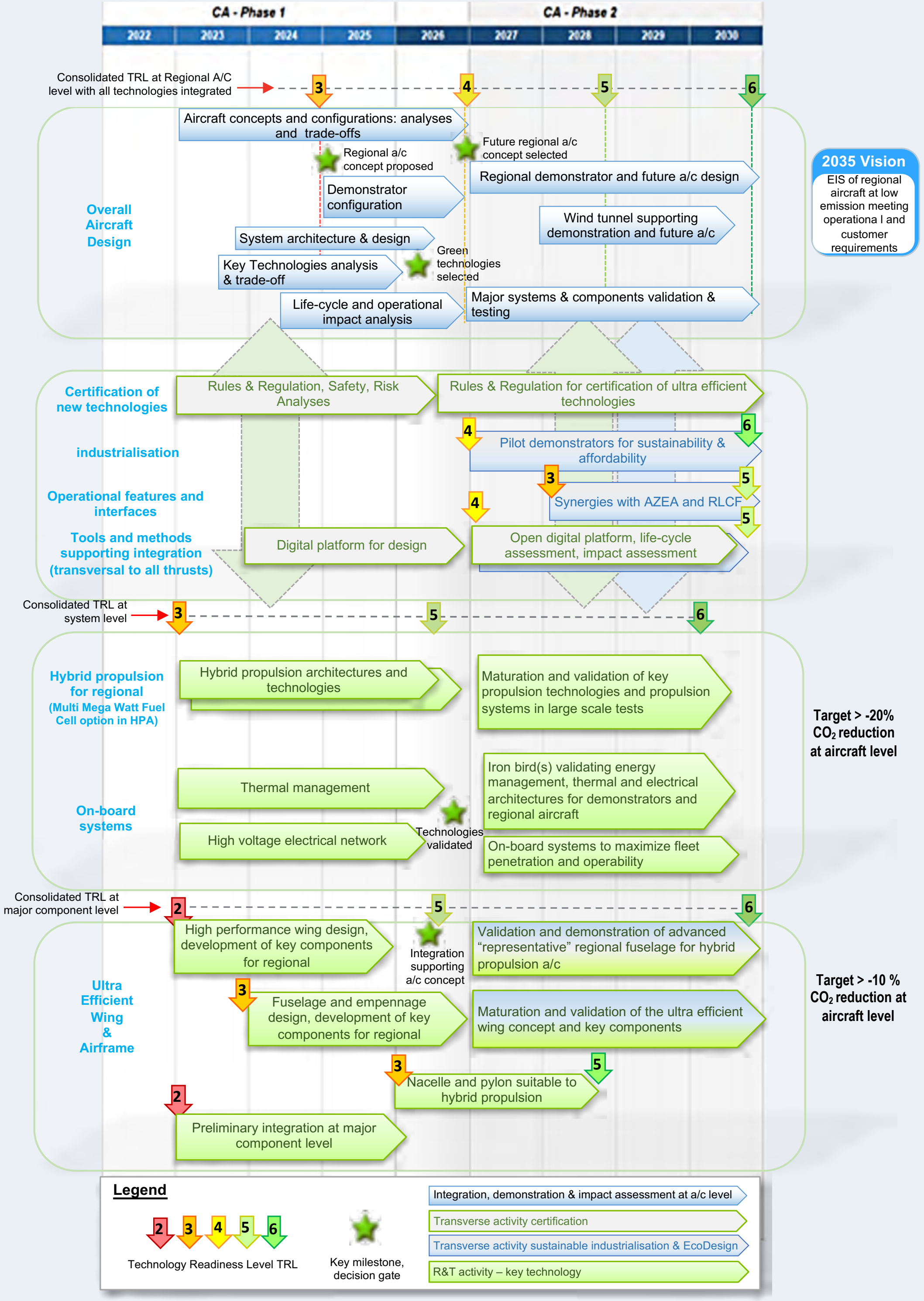
- Nature and range of the figures of merit.
- Type and details of data available for the key items and systems.
- The proximity between those data and data required for the aircraft concept demonstration at real scale.
- Availability of validated scaling methodologies for performances, interfaces and logics.

The selected set of demonstrations will pursue the verification of performance, operational behaviour of solutions, resolve key industrialisation issues, and collect relevant qualification data to obtain 'permit to fly' by authorities for the flight demonstration.

Testing should be complemented by the development, with authorities' support, of certification by simulation tools that are able to extrapolate test data to the real case and scale, thus reducing certification effort and complexity. This 'hybrid' validation, which combines actual testing and simulation, enables a deep reassessment of the qualification process and acceptable means of compliance selection to be accepted by the certification authority.

Figure 4.4 shows the integrated planning for the ultra-efficient regional aircraft and the relevant demonstration strategy, including the three layers discussed in this section, deployed in the Phase 1 and Phase 2 activities.

Figure 4.4: The Ultra-Efficient Regional Aircraft high-level planning



### SUB-SYSTEM DEMONSTRATION

Once specified, **technology bricks could be matured up to TRL4 in isolation** (hybrid turboprop, propeller technologies, power chain, power management, etc.). Single item test rigs and sub-system level rigs will be used for that purpose. Each component and sub-system could be matured in parallel. The following sub-system ground test benches will have to be set up:

- Hybrid turboprop and propellers.
- Electric energy chain component and powertrain technology demonstration.
- Thermal management relevant sub-system.
- Electrical storage installation including electrical interconnection system integration (fuel cell, batteries, or a combination).
- Flight control validating new control laws, logic, links with avionics, and authority suitable to hybrid or distributed propulsion.

### IRON-BIRD/GROUND/WIND TUNNEL DEMONSTRATION

**Ground demonstration aims to combine the different technology building blocks in an integrated strategy up to TRL5 level,** thus de-risking and paving the way for the next flight tests. This work aims also to demonstrate the technology potential and its impact in terms of emissions reduction and fleet penetration. Ground tests will be pursued whenever flight tests are not strictly necessary for technical reasons or to complement and support them. They will also support and validate the new and relevant industrialisation, manufacturing, assembly, and maintenance processes required by such disruptive technologies, so as to ensure they are promptly adopted by industries and support an EIS by 2035. This will require shorter lead-times than traditional for aeronautics. For the ultra-efficient regional aircraft concept, these layer mainly include:

- Testing each type of contributing propulsion technology and key items required for their integration, in order to support performance, and to address qualification and certification issues.
- Testing the complementary systems to enable use of the new energy sources on-board, e.g. electrical distribution of MW class and high voltage, thermal management dissipating new wasted heat, and interfaces to the ground features required to recharge and refill the new energy sources.
- Testing the new energy sources storage on-board to meet the applicable performance, qualification, and safety requirements.

This work would use several test environments, e.g. wind tunnels, test-rigs, pilot cells and iron birds:

- The engine and its integration with relevant components (electric machines, power electronics, batteries, fuel cells if any, propellers, energy storage and distribution, etc.) into the hybrid propulsion system as a mandatory enabler of the entire system. The validation of such a complex system and the related key enabling technologies will be completed and validated through a dedicated powerplant ground demo, before a flight test of the entire system.
- Wind tunnel tests at relevant scale for validation of aerodynamics and performance of new and disruptive aircraft configurations, as well as flight controls authority and aero-elastics aircraft features derived from new propulsion.
- Aircraft-level ground test benches for electrical distribution, thermal management and noise, validating both integration and performance for flight tests and building up the database needed to achieve permit to fly. Other air vehicles might exploit, in parallel, similar campaigns for different use-cases, such as SMR at multi-MW size, or functionalities for rotorcraft or tiltrotor.
- Digital platforms for design, integrating system-level design tools, certification virtual processes as well as a digital platform to control, reconfigure and simulate all lifecycle phases.
- Pilot cells for advanced manufacturing and assembly applied to critical items for a regional aircraft concept.

- Functional verifications and testing of interfaces with typical new ground infrastructures supportive of new energy sources, e.g. recharging and refilling stations, and maintenance features.

### FULL-SCALE DEMONSTRATION

**Full-scale tests** required for an ultra-efficient regional aircraft concept, both ground and in-flight – **up to TRL 6 at aircraft level** – requires appropriate facilities and processes. On ground, they are:

- A ground full-scale test facility able to test the total propulsive power and ancillary systems at applicable environmental conditions relevant to regional aircraft operative conditions. Such a comprehensive full-scale ground test, in line with the real flight-testing conditions, is not currently available in the EU.

- Specific functional and safety tests at specialised facilities related to new energy sources on-board: crashworthiness and fire hazard, recharging and refilling of new energy sources.

- Pilot cells demonstrating key industrialisation aspects relevant to supporting an early adoption of key elements and technologies required by the hybrid propulsion and integration on an ultra-efficient regional aircraft concept.

Flight tests will integrate real-scale solutions, applicable to a regional aircraft concept. They will also include the demonstration that solutions fulfil the basic aviation safety constraints and operative targets, as well as new safety conditions caused by the propulsion. These include partial failure of a propulsion unit, e.g. the failure of one energy source, leading to unprecedented flight conditions to test. Such an effort may include:

- Flight-tests at reduced scale, if tests are relevant and useful to regional size and power scale.

- Flight tests with actual power sources, powertrains and electrical distribution that are compliant with permit to fly constraints, integration rules and principles on a regional aircraft that has been duly modified.

## DEMONSTRATION STRATEGY IN PHASE 2 OF CLEAN AVIATION

The general strategy for demonstrating the ultra-efficient regional aircraft concept with a hybrid propulsion architecture, described in Chapter 3 of the SRIA, must pursue two concurrent objectives:

1. To obtain relevant and consistent experimental data on systems and key items' performances, safety and features supporting the launch of an aircraft incorporating all those solutions.

2. To obtain the set of data necessary to de-risk and support the future certification by authorities of an ultra-efficient regional aircraft concept with hybrid propulsion.

**This demonstration strategy will support the maturation of the needed technologies up to a minimum of TRL5 in the Phase 2 of Clean Aviation, and up to TRL6 where relevant.** A first set of real-scale demonstrations will be done for the ultra-efficient regional aircraft with hybrid propulsion. Those tests will provide data complementing and supporting analyses, drawings and models related to both objectives, but their actual content will depend on test beds constraints – both ground and in flight. Pending the required technology maturation readiness and qualification for flightworthiness is achieved, these tests may also include a flight test. The selection of tests must consider the return value of real-scale tests related to how 'far' the tested solution would be from the real aircraft solution, given any specific adaptation to match test beds' constraints. The key elements are:

- Ground tests of key sub-systems and components, in order to de-risk them for an ultra-efficient regional aircraft concept as per SRIA Chapter 3: i) airframe modifications, e.g. nacelle and pylon, supporting the new propulsion architecture; ii) environmental, key performances and safety tests in compliance with applicable regulations and constraints.

- Ground tests (iron bird type) related to most critical aspects of on-board energy management (high voltage, high current electrical network, thermal systems): new energy source compensation/reconfiguration, partial and total failure cases of one or all energy sources, check of interfaces among systems and propulsion, failure effects on other safety critical on-board systems, full network performance for at least two electrical channels, EMI and electrical transients.

- Wind tunnel tests supporting assessment of flight performance and safety related to the new propulsion and its actual integration.

- Tests, up to flight test, fulfilling relevant technical and implementation conditions of the selected propulsion unit and related ancillary systems to assess performance and to qualify this unit against applicable requirements.

Another set of real scale tests is conceivable in Clean Aviation Phase 2, for aircraft-level demonstration of the ultra-efficient regional aircraft concept. These tests are fully devoted to de-risk and progress towards higher fleet penetration of future regional aircraft concepts, by assessing advanced integration solutions and complementing ongoing studies in Phase 1 of Clean Aviation:

- Real-scale structural test of the high aspect ratio wing studied in Clean Aviation Phase 1 to achieve low drag and more efficient aircraft.

- Real-scale structural test of the fuselage section(s) integrating new energy sources (batteries, fuel cells, liquid hydrogen tanks) and features required to operate them (thermal management solutions, electrical bonding and grounding, access door for maintenance, refill, or recharge interfaces).

- Advanced systems testing enabling further emissions reduction or improving affordability and fleet penetration of the ultra-efficient regional aircraft concept.

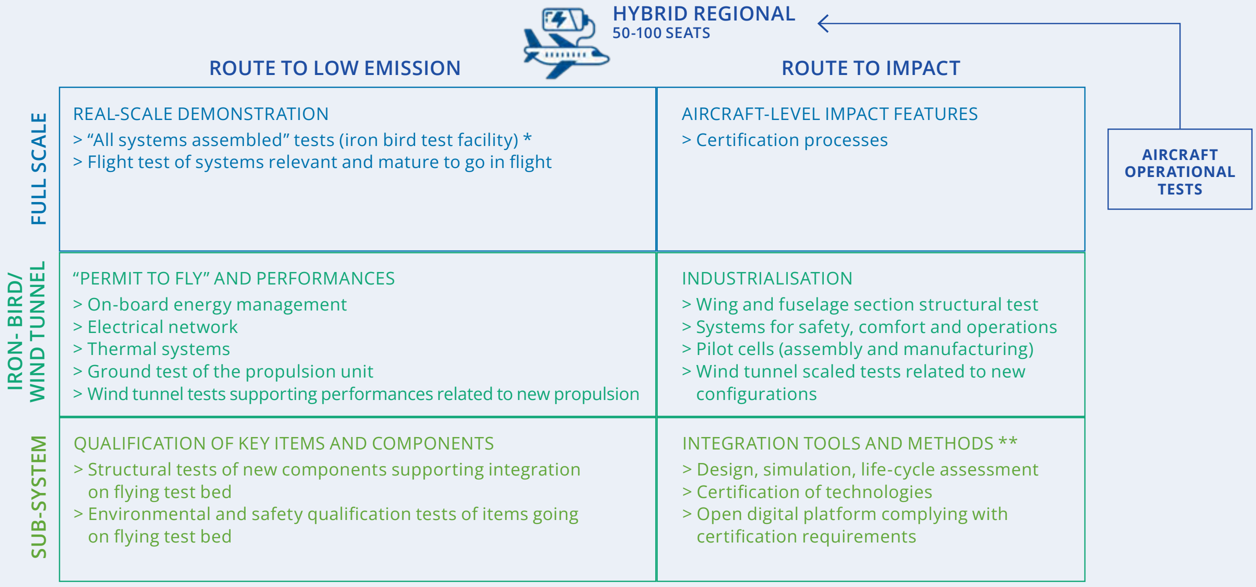
- Pilot cells for assembly of new on-board systems to de-risk and support an early entry into service of the ultra-efficient regional aircraft concept.

- Scaled demonstrator and/or wind tunnel tests related to future more aggressive aircraft configurations.

Finally, as pursued in HPA thrust or in synergy opportunities within AZEA scope, it is very important to perform operational testing and validation at airports that are expected to operate ultra-efficient regional aircraft. Critical questions include approach and departure procedures related to new energy sources, supply and refilling procedures and devices, turnaround tasks, or air and ground emergency procedures.

Figure 4.5 shows graphically the global strategy for Phase 2, with the three contributing elements described above and possible synergies within Clean Aviation and beyond.

**Figure 4.5: Ultra-efficient regional aircraft demonstration strategy in Phase 2 of Clean Aviation**



| | ROUTE TO LOW EMISSION | ROUTE TO IMPACT |
|---|---|---|
| FULL SCALE | REAL-SCALE DEMONSTRATION<br>> “All systems assembled” tests (iron bird test facility) *<br>> Flight test of systems relevant and mature to go in flight | AIRCRAFT-LEVEL IMPACT FEATURES<br>> Certification processes |
| IRON- BIRD/ WIND TUNNEL | “PERMIT TO FLY” AND PERFORMANCES<br>> On-board energy management<br>> Electrical network<br>> Thermal systems<br>> Ground test of the propulsion unit<br>> Wind tunnel tests supporting performances related to new propulsion | INDUSTRIALISATION<br>> Wing and fuselage section structural test<br>> Systems for safety, comfort and operations<br>> Pilot cells (assembly and manufacturing)<br>> Wind tunnel scaled tests related to new configurations |
| SUB-SYSTEM | QUALIFICATION OF KEY ITEMS AND COMPONENTS<br>> Structural tests of new components supporting integration on flying test bed<br>> Environmental and safety qualification tests of items going on flying test bed | INTEGRATION TOOLS AND METHODS **<br>> Design, simulation, life-cycle assessment<br>> Certification of technologies<br>> Open digital platform complying with certification requirements |

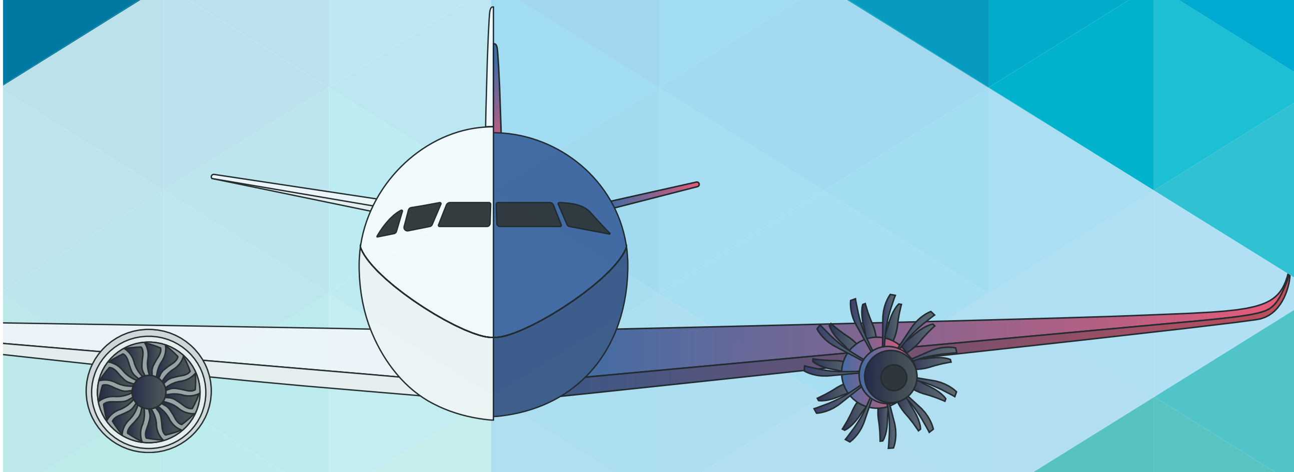
* Facility not available in EU / ** Shared and transversal to other thrusts

# 4.4. Scalability, cross-cutting synergies, and exploitation potential

The key technologies developed within the ultra-efficient regional aircraft section can offer opportunities to several aircraft segments, beyond those tackled in the Clean Aviation programme:

- Market segments with lower energy and power demand such as commuters and light helicopters. Chapter 3 aircraft concepts and validation platforms propose opportunities at similar power useful to regional aircraft if scalability is demonstrated.
- Electric technologies could be scaled up to match full electric requirements, once they demonstrate compliance with certification rules and feasibility in the operational perimeter of commercial aviation.
- Other applications such as large rotorcraft share equivalent power needs, even if specific integration issues need to be addressed.
- Scalable architectures of electrical power management and the related thermal management could match the needs of larger capacity or longer range aircraft like SMR or beyond.
- Regional solutions can provide early insight into certification issues with SMR, since the two segments share the same regulations and certification basis, as well as many aspects of operator demands.
- Regional aircraft present the best opportunity for a scaled flight test of electrical solutions at MW power-level, thus including within Clean Aviation boundaries, at reduced costs and risks, the multi-MW needs of larger aircraft.

# 5. Disruptive technologies for ultra-efficient short/medium-range aircraft

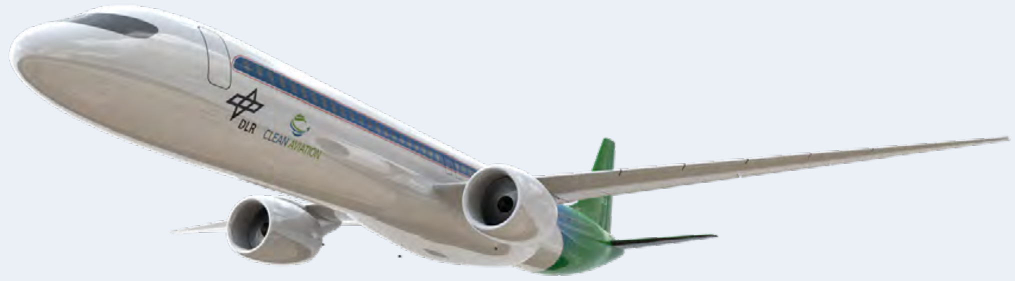


## 5.1. Introduction

**The mid-2030s should see the entry of a new generation of large aircraft platforms aiming towards sustainable climate-neutral flight. While hybrid/electric energy architectures and ultra-efficient aircraft designs will have paved the way towards climate-neutral aviation on <1 000 km routes, aircraft concepts for traditional short and medium-range distances will rely on ultra-efficient thermal energy-based propulsion technologies using sustainable drop-in and non-drop-in fuels to enable climate-neutral flight, for reasons explained in the second chapter of this document.**

The novel aircraft and propulsion concepts will enable low-source noise and low-noise flight procedures. Thanks to a close cooperation with other key stakeholders and actors in the European aeronautical community, the technology developments, and demonstrations of this part of the research programme will yield additional value through direct spin-offs and cross-activities in neighbouring sectors such as business jets and regional aircraft. Some specific developments and limited ground tests will be required to maximise impact here. A next generation of ultra-efficient large and heavy long-range aircraft is expected to have an entry into service timeframe of beyond 2035. The outcomes of the Clean Aviation Programme will open opportunities for a strategy of scaling and applying results to a new generation of climate-neutral heavy long-range aircraft, in a next potential major step of innovation immediately following this programme.

Figure 5.1: Concept aircraft for next generation climate-neutral flight



The research and technology roadmap for the aircraft concept is built on demonstrators addressing all key technologies. Several highly promising technology developments have been started in national or European programmes, such as the EcoPulse and BLADE project, as well as initiatives that are exploiting advanced propulsion concepts such as open rotor and advanced laminar flow, etc. The first phase of the programme will target selecting, maturing, and qualifying 'best athlete' technologies to exploit their full potential and prepare them to be integrated – into future **ultra-low emission single aisle, short/ medium-range (SMR) aircraft.**

The roadmap behind the SMR concept ambition aims to reduce the $CO_2$ emissions of a new generation of short medium-range aircraft by 30%. This should be available by 2035 and will combine disruptive technologies in the airframe with ultra-efficient propulsion systems and their integration. The roadmap also includes an option for the demonstration and validation of an even more disruptive concept using hydrogen as a non-drop-in fuel, subject to a sufficiently mature capability provided by the Clean Aviation hydrogen technology development programme. With the update of the programme in 2024, all activities during Phase 2 associated with hydrogen technologies will be part of the Hydrogen Powered Aircraft (HPA) pillar only; see Chapter 6 of this document.

> *By 2035, Ultra-efficient propulsion systems and their integration into an airframe, combining disruptive technologies, will aim to reduce emissions by 30%.*

Besides the above emissions targets, all aircraft concepts considered in Clean Aviation (described in Chapter 3) will have to be fully compliant with the stringent ICAO noise regulations expected for an EIS in 2035.

The ambition for this demonstration programme goes beyond integrating an improved propulsion concept into 'any' short/medium-range concept aircraft. The programme will result in the possible exploitation of holistic aircraft technological innovations for a future eco-efficient, economically viable and competitive large number of new products for an EIS by 2035: this will enable the creation of momentum and targeted impact at European and global scale. In this context, four pillars are key constituents of the 'Ultra-Efficient Short and -Medium Range Aircraft' development and demonstration roadmap:

> **An overall efficient and optimised aircraft concept design,** with ultra-efficient wing and fuselage, that integrates all key innovative aircraft systems such as cabin platforms, landing gear, and features enabling connectivity to prepare for maximum impact on climate neutrality via a competitive, affordable product.

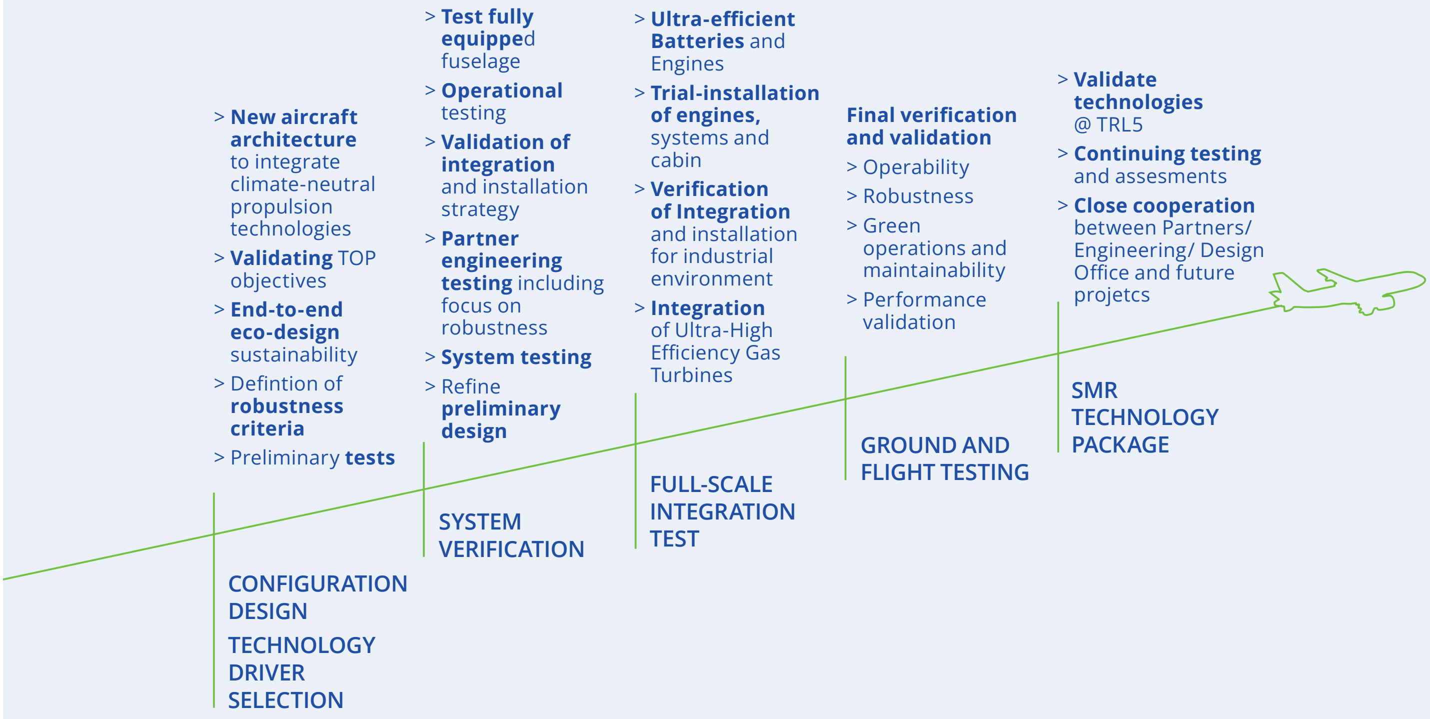
> **The development and integration of the ultra-efficient propulsion system** onto a tailor-made airframe and system architecture.

> **Designing a climate-neutral aircraft concept** capable of sustained highly efficient operations and services designed to ensure maintainability.

> **An eco-sustainable end-to-end, minimum-waste manufacturing and digital design process,** enabling an efficient industrial architecture, will be included to ensure the emergence of impactful climate-neutral aircraft from the programme.

The technical roadmap to develop, mature and demonstrate all needed technologies follows a validation and verification 'V&V' approach, the main elements of which are shown in Figure 5.2.

Figure 5.2: Ambition to demonstrate the climate-neutral short and medium range aircraft concept



CONFIGURATION DESIGN

TECHNOLOGY DRIVER SELECTION

> **New aircraft architecture** to integrate climate-neutral propulsion technologies
> **Validating** TOP objectives
> **End-to-end eco-design** sustainability
> Defintion of **robustness criteria**
> Preliminary **tests**

SYSTEM VERIFICATION

> **Test fully equipped** fuselage
> **Operational** testing
> **Validation of integration** and installation strategy
> **Partner engineering testing** including focus on robustness
> **System testing**
> Refine **preliminary design**

FULL-SCALE INTEGRATION TEST

> **Ultra-efficient Batteries** and Engines
> **Trial-installation of engines,** systems and cabin
> **Verification of Integration** and installation for industrial environment
> **Integration** of Ultra-High Efficiency Gas Turbines

GROUND AND FLIGHT TESTING

**Final verification and validation**
> Operability
> Robustness
> Green operations and maintainability
> Performance validation

SMR TECHNOLOGY PACKAGE

> **Validate technologies** @ TRL5
> **Continuing testing** and assesments
> **Close cooperation** between Partners/ Engineering/ Design Office and future projetcs

The roadmap to develop, mature and demonstrate this concept includes two programme phases:

The **first phase of the programme** will be based on the distinct specification of top-level aircraft requirements that frame the boundaries of a 'technology workspace' for candidate technologies and concepts. This phase will involve finalising the conceptual design and the preliminary design characteristics of the targeted demonstration aircraft, by selecting the best target configuration. This configuration will be based on holistic multidisciplinary numerical simulations, research and development of critical components, materials and processes, technologies, and the associated integrated ground tests, such as high-Reynolds-number (flight condition) wind tunnel tests, functional bench tests (including virtual testing), full-scale sub-component integration tests and flight tests. A digital aircraft platform will be established during Phase 1, and the best combinations of Phase 1 technologies for the target concept aircraft at mission and fleet level will be assessed via a complementary technology and concept aircraft evaluation platform.

The **second phase of the programme** will focus on validating and integrating selected best candidate technologies for a 'best choice' single aircraft concept, which will be the result of the activities in Phase 1 or other synergetic research and technology projects. Key elements of activities in the second phase will be to mature and validate these technologies on the ground in large-scale integrated aircraft component tests, e.g. in structural test rigs, system rigs and wind tunnel tests in combination with virtual testing. Concepts and technologies for sustainable manufacturing and assembly processes of major components will be validated in ground-based demonstrators. This work will be complemented by tools for digital design and manufacturing, to ensure compliance with targeted performance requirements of sustainable industrialisation. Sub-scale or full-scale flight demonstrations will be used where a validation of the performance of technologies at TRL 6 requires the testing in real-world operational conditions.

An important feature for all technologies developed in the Clean Aviation programme, for potential use in a next generation SMR aircraft, is proof that they can deliver the expected exceptional performance at an excellent level of operational availability, robustness, and durability. This performance must at least match the best-in-class 2020 SMR technologies, as a point of reference.

## 5.2. Key technologies and their contribution to the Clean Aviation ambition

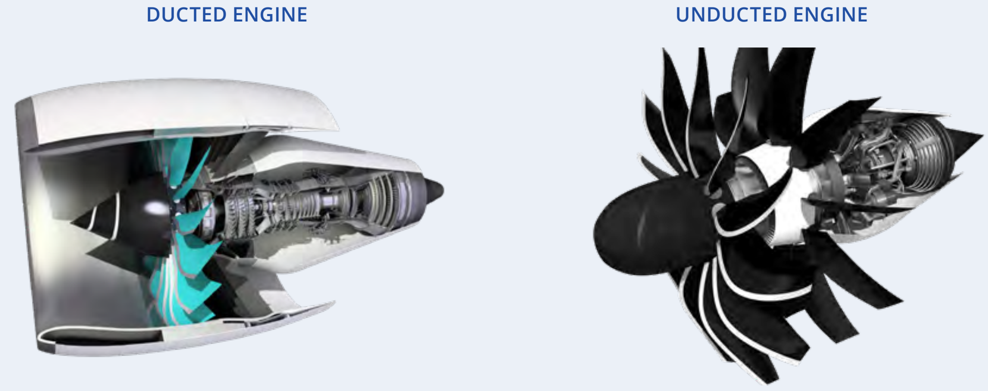
**The key technologies, and their specific ambitions as described in this section, will be steered to ensure their certification and compliance, where appropriate, with the top-level aircraft concept requirements and seamless integration on aircraft level.**

The research and development work plan is laid out to embrace the development of the entire aircraft at R&T concept level, in order to integrate disruptive technologies while maximising operational energy efficiency and substituting conventional fuels with Sustainable Aviation Fuel (SAF). In this context the development, integration, and demonstration of the most effective new engine architecture of ultra-high efficiency propulsors is a key objective of the Clean Aviation programme.

However, to prepare the ground for zero-carbon energy fuels (such as hydrogen) in a new dedicated class of thermal energy-based engines, a corresponding action of integration and large-scale demonstration is included in the Clean Aviation SMR programme as well as during Phase 1, with the development of technologies related to the engine and corresponding systems outlined in Chapter 6. Following the CA programme strategy to prioritise the maturation and validation of technologies in Phase 2 while aligned with the needs of the aircraft concepts – which are associated with each of the three CA pillars, as laid out in Chapter 3 – the integration and large-scale demonstration of the liquid hydrogen option will not be continued in the SMR pillar during Phase 2. Instead, this demonstration will be considered, with a different focus, in the HPA pillar.

**Demonstration of SMR technologies, and the contribution to primary objectives, will be logically arranged throughout the programme until the end of Phase 2.** These may encompass the development and integration of technologies for an ultra-efficient wing, a fuselage and fuselage rear-end and empennage. Furthermore, there are plans for a platform of aircraft systems. This will be designed to be used as a common resource that generates, stores, and distributes, energy and data to all end users, while also enabling new flight and ground operations, and all technologies for a new generation of ultra-efficient propulsion systems. This platform will progress over a range of activities, from rig testing through ground system testing and, where appropriate, integration and assessment in flight tests. The future of propulsion technology and energy is illustrated in Figure 5.3 below.

Figure 5.3: Future of propulsion technology and energy



## ULTRA-EFFICIENT AIRFRAME

Reducing aerodynamic drag, aircraft weight and the energy needs of non-propulsive aircraft systems – together with laminar flow, active flutter control and engine and landing gear integration in the wing – will substantially contribute to the viability of climate-neutral flight.

The physical properties of hydrogen are completely different to those of kerosene: this affects the overall aircraft architecture with respect to storage, distribution, and ground handling of hydrogen. While generic technology developments and tests will be done in the disruptive technologies pillar to enable hydrogen-powered aircraft (HPA), solutions associated with the SMR aircraft-level integration will be part of Phase 1 of this programme, e.g. the definition, safety assurance, testing and validation of efficient and economic operations. Considering the structural optimisations – which include the integration of hydrogen tanks, cabin, and cargo as well as systems, the entire architecture must be reopened to enable an optimised configuration. As the SMR part of the Clean Aviation programme in Phase 2 will be aligned to the priorities of the SMR concept aircraft described in Chapter 3, the integration and demonstration of liquid hydrogen technologies will not be continued in SMR in Phase 2. With a different focus, this will instead be done in the HPA pillar, as described in Chapter 6.

> *A large-scale demonstrator will be developed for flight-testing to mature an ultra-efficient propulsion operating on up to 100% drop-in fuel.*

Existing airworthiness certification regulations and specifications, including means of compliance, must be revised in close cooperation with EASA. This revision must also be done in coordination with other pillars, for an optimised and efficient qualification and certification process that includes virtual means.

The **Ultra-Efficient Airframe** is an essential enabler to reduce fuel consumption. It is largely based on the optimisation of load distribution, the introduction of new and advanced materials, and their efficient use in structural elements such as the fuselage, the wing, cabin, and landing gear. The competitiveness of the new aircraft structures must be ensured and secured by a safe approach of an optimised, sustainable, and efficient industrial manufacturing system, addressing all main components of the airframe, and the integration of systems and sub-systems. They all require the development and implementation of new highly efficient methods and processes for 'buy-to-fly' sustainable manufacturing, assembly, and operational processes. These must call on all opportunities for automation and robotics, with the goal of achieving a very low rate of raw materials used to produce the final part or component. Special attention will be paid to implementing a best cradle-to-grave eco-balance by minimising the use of energy and water, substituting problematic materials, and by minimising waste and emissions throughout all phases of the aircraft life-cycle.

**During the first phase,** generic SMR technologies will be assessed with small-scale and component-level demonstrations. These activities comprise new materials, architecture and design concepts that take into account more radical aircraft configurations, and aspects of airframe-cabin integration, in combination with the integration of hydrogen tanks plus a corresponding non-propulsive energy architecture. A common life-cycle assessment concept, including recycling, will be developed and progressively deployed step by step.

> **The target is to reach TRL 6, and a plan on how to share and synchronise the activities in CA Phase 2 with national-funded projects will be part of the implementation of the projects.**

**In the second phase,** the ultra-efficient airframe technologies will be integrated into overall large-scale airframe-fuselage demonstrators relevant for the selected SAF-based aircraft concept. The results and achievements made on technologies developed in the Clean Sky 2 programme should be used as a basis to develop a large-scale short barrel of a typical fuselage for an ultra-efficient SMR aircraft. The end-to-end industrial system will have to demonstrate the viability for the targeted ecological (energy supply and waste recycling/avoidance), economic (e.g. manufacturing process for high-rate and quick ramp-up), and human operations aspects. Significant improvements are expected in the use of raw materials, recycling and re-manufacturability and these will reduce the environmental impact of manufacturing. The second phase will include hardware ground tests and simulations, and it will address the qualification and certification aspects throughout all development phases. **The target is to reach TRL 6 for a typical fuselage structural concept, with an integration concept for key cabin modules and aircraft systems.** Another element to be matured and developed with technologies emerging from diverse national and EU-funded projects, including Clean Sky 2, is a large-scale fuselage rear-end demonstrator.

Aerodynamic drag directly affects the efficiency of an aircraft. An **Ultra-Performing Wing** with high aspect ratio (HAR) will significantly contribute to reducing emissions. The overall HAR wing and wing movables design, aero-elasticity effects, load, fuel storage capacity and airport operations will be addressed in national funding frames. The exploitation and integration of a high aspect ratio wing – including laminar portion as well as advanced and active technologies (e.g. active flutter control, ice protection systems) with competitive processes and means for production and operation – must be demonstrated for the short and medium-range aircraft concept.

**In the first phase,** the related enabling technologies that cover relevant engineering disciplines of the high-performance wing will be developed and matured. Thanks to multidisciplinary optimisation, the overall wing design will ensure the proper integration of key technologies up to TRL 4-5. A high aspect ratio wing will be developed: it will feature laminar portions in the outer areas, advanced leading-edge solutions integrating smart ice protection systems and optimised integration of the propulsion system. Demonstrations will be conducted via high-fidelity simulations, wind tunnel testing and ground tests for integrated components and functional demonstrations. A preliminary loop of analysis and experiments, for the integration of disruptive technologies on such a wing for future certification purposes, will be performed.

**In the second phase,** main parts of the ultra-efficient wing research activities will be covered in national funding frames. Icing will be a critical topic for the aircraft, so there will be a need to develop design tools and viable means of compliance for the new icing rules, e.g. Supercooled Large Droplets (SLD) and build-up and aggregation of snow and ice crystals. The main areas of the aircraft that are impacted are the wings, tail, engines with engine intakes, propellers, and fans. To appropriately address this issue, new technologies, capabilities, and methodologies must be developed and demonstrated. These will allow the aircraft to be optimised and certified, whilst retaining the high levels of safety achieved today.

## ULTRA-HIGH EFFICIENCY PROPULSIVE SYSTEM DEVELOPMENT AND INTEGRATION

The path towards climate neutrality for short/medium range (SMR) aircraft will necessitate the transition to zero-net carbon emissions energy sources. Unlike smaller aircraft, the payload/range and mission characteristics of these aircraft require energy densities for energy storage and power for the propulsive system (>10 MW power), where weight would prohibit the use of battery storage or fuel cells as the core of the energy and power necessary for the mission. Even aggressive projections of battery energy density or fuel cells' power densities until 2030+ do not foresee that these technologies can take over the role of (liquid) fuels, although they may contribute to the overall propulsive and energy system.

For this reason, thermal propulsion systems combined with the use of SAF should remain the basis of the next (2030+) generations of aircraft in the short/medium and long-range segments. This envisaged future architecture could also include hybrid electric solutions. Hydrogen technologies are addressed in the HPA pillar.

Because the only real 'zero emission fuel' is a fuel which is not burnt, reducing fuel consumption independently of the nature of the fuel burnt is critical to reaching climate neutrality objectives. This is **even more critical when considering new types of fuels, including SAF.** Their availability, cost, as well as the energy intensity for their production, also contribute as parameters to the overall reduction of emissions, under a holistic view of an enhanced energy and fuel economy.

Therefore, next-generation propulsive systems – with an **unprecedented revolution in efficiency** compared to the state-of-the-art and with a targeted Entry into Service (EIS) of 2035 – are **a mandatory element in the path towards climate neutrality.** These systems will contribute not only to emissions reduction in the short term, but will also form **a key and core enabler** for any future product evolution towards hybridisation and non-drop-in fuels.

A best choice of technologies for SMR concept aircraft have been agreed. This will define the target corridor of technologies to be further matured in Clean Aviation Phase 2 in early 2024. For the propulsion technologies and architecture, the priority until 2025-2026 is ultra-efficient propulsion systems operated with SAF, based on an open rotor. This applies particularly with an Open Fan architecture, a promising solution for fuel efficiency. Or with a UHBR engine architecture optimised with complementary technologies, in particular with a hybrid-electric system that is designed mainly to improve the off-design performance, and the WET technology targeting for an additional gain in overall thermodynamic and emission performance. The technologies for integration and demonstration will depend on the technological and potential industrial readiness of innovations compatible with an EIS by 2035. The overall aircraft concept architecture is based on a tube and wing design with a slender, HAR - Ultra Performance wing that will require new concepts for the integration of an engine, as well as for the main landing gear and many other aircraft systems.

This work entails a fundamentally new approach. It will require 'open book' cooperation between airframers and propulsion systems providers, in order to solve the new unknown complexities that arise while searching for extreme efficiency.

Clean Aviation can provide the operational structure to enable this global integration effort. It can do this by teaming the efforts of the required disciplines spread across companies and countries in Europe, which may not be achieved easily through national efforts.

Ultra-efficient thermal engines and novel integration are the most promising technologies for propulsion, with an ambitious target to reduce emissions by 20%, stemming from the architecture of the propulsion system. In combination with other disruptive technologies described further in this chapter, this will lead to an unprecedented 30% reduction in emissions. This corresponds to an improvement in energy efficiency at aircraft level and will lay the foundation for next aircraft generations.

## ULTRA-EFFICIENT PROPULSION DEVELOPMENT AND INTEGRATION ROADMAP

Ultra-efficient propulsion requires system and sub-system level technology developments. Therefore, the programme needs to address the maturation and demonstration of numerous cutting-edge technologies in the following areas:

> **Ultra-efficient thermal Engines:** the next generation of engines will use innovative technologies and a high degree of variable geometry to operate continuously in an optimum condition. Electrical machines within the propulsion system, developed in close coordination with the hybrid electric thrust (Chapter 4), will enable additional efficiency improvements. Together with revolutionary thermodynamic cycles, this will unlock new reductions in fuel burn of up to 20% at propulsion level for a mid-2035s EIS objective and additional reductions for 2040+ EIS. Research topics in this area will include variable pitch multi-blade devices (open fan and ducted propulsive architectures) operating with peak efficiency at multiple flight modes. Transmission systems incorporating electrical machines can enable load transfer during all flight phases. Smaller operable core technologies, working with new low-pressure compression systems, will also support the development of smarter engines.

> **Lighter by Design:** new composite and ceramic materials and additive manufacturing will lead to lighter weight engines and components that have less impact on the aircraft design. This can therefore contribute directly to fuel burn and hence emissions reductions. Reduced size inlets and nacelles, in combination with compact external electrical and mechanical systems, can create new operating limits, e.g. for temperature, within the propulsion system using real-time simulation design tools.

> **Cleaner Emissions:** to unlock all the benefits of new fuel types, new combustion methodologies are required. Additionally, new technologies will manage the by-products of this combustion. As an example, NOx can be reduced through water injection in the combustor, and contrails may be reduced through exhaust particulate removal and water recovery. Research will need to include the following: highly dynamic real-time measurement and control of fuel distribution for constant optimum combustion, heat exchangers, water extraction systems, intercoolers, and their integration into the propulsion system with minimal impact to efficiency and weight. Activities may also consider improved gas-path technologies (Low, Intermediate and High Pressure) to drive fuel burn and $CO_2$ emission reduction as well as low emission combustion technology, and investigate other emissions beyond $CO_2$ reduction to evaluate the overall benefits. Beyond improving air quality, the reduction of non-$CO_2$ emissions will enhance the progress towards climate neutrality, by reducing all greenhouse gases, not just $CO_2$ .

*A combination of revolutionary thermodynamic cycles and hybridization will unlock new reductions in fuel burn of up to 20% at propulsion level.*

The focus of the above-mentioned technologies is EIS in 2035 with -20% emissions reduction. However, consideration may be given to pursuing complementary routes for technologies whose potential may bring further impact beyond 2040, if a clear path to exploitation is identified.

Demonstration activities in these areas will progress through increasing integration levels and towards higher complexity. Design studies and rig tests will explore the technologies under development, their system interactions and the risks associated with their integration into aircraft demonstration. In later phases, testing will progress to ground testing of multiple sub-systems, extending to flight tests, utilising donors, or new-build engines, where operating across flight envelope conditions and integration complexity requires this.

To perform the above-mentioned demonstrations, several steps must take place, in order to reach the targeted and meaningful TRL required to validate the integrated propulsion technologies through:

- Rig and wind tunnel tests (for flight validation and qualification of components).
- Virtual tests (validation) through advanced numerical simulation tools.
- Ground test (including integrated ground testing of all required components and systems for flight test readiness).
- Flight tests (including engine/aircraft integration to prove TRL 6 for the integrated propulsive system architecture).

To support the tests, the appropriate research infrastructures and methods must be available, notably through fast-track research contributions:

- Flight test preparation/post-test analysis methods maturation, e.g. maturing and applying emission measurement technology.
- Aero-acoustic analyses and measurement methods.
- Thrust measurement technology.
- Maturation of advanced wind tunnel technology, wind tunnel model technology and system tests needed for the preparation of flight tests and to support the ‘permit to fly’ process together with activities allowing maturation towards Certification Readiness Level (CRL).

The aim will be to prepare a new generation of propulsive systems in two major steps. These can be integrated where appropriate and necessary into the aircraft level technology, through ground and/or flight demonstrators:

- Phase 1: technology maturation (TRL 4/5).
- Phase 2: full powerplant propulsive system, ground, and flight demo (TRL 6).

### INTEGRATION OF ULTRA-EFFICIENT PROPULSION SYSTEMS ONTO A NEW AIRFRAME

The most promising propulsion concepts and their integration challenges will be investigated, e.g. ducted vs. unducted, with a clear preference for a wing-mount configuration, as is proposed in the SMR aircraft concept that will guide activities in Phase 2. All these multi-disciplinary integration challenges, which are listed below, will have to be tackled in close partnership among engine manufacturers, airframe manufacturers, equipment manufacturers and research institutes. This must be done from the novel conceptual design up to optimised green manufacturing and assembly processes:

- Aerodynamic and aero-acoustic nacelle/pylon design and integration.
- Overall noise characterisation and reduction (external and interior noise).
- Structural nacelle/pylon design and integration.
- Ultra-efficient wing integration, along with its needed actuation system.
- Propulsion system and APU integration plus related power and thermal management (power offtake optimisation, engine operability, micro-hybridisation, engine control functions, etc.).
- Permanent engine performance assessment at aircraft level, including potential impact of any disruptive thermodynamic propulsion cycles.

Propulsion system/airframe integration development is to be pursued, beyond the maturation phase, for both open fan and ducted propulsive architectures, with the inclusion of advanced systems and electrification/hybridisation capability. This could enable the integrated use of propulsive and non-propulsive energy across the aircraft.

### OPTIMISATION AND INDUSTRIALISATION

The goal of Clean Aviation is to prepare all technologies serving the EIS of a future breakthrough aircraft. To this effect, in parallel to the technology demonstration of improved engine and aircraft architectures, reparability, maintainability and industrialisation must be also considered at an early stage in the development. This should be done alongside the design and architecture and should be included in the specifications of all future products.

## A REVOLUTION OF THE AIRCRAFT SYSTEMS

**A revolutionary change of aircraft systems design is necessary, in order to significantly reduce the environmental impact of commercial aviation.** Indeed, aircraft systems will play a major role in the forthcoming steps of the decarbonisation path to 2050 climate-neutral aviation. These systems will lead to drastic modifications of architectures and technologies to cope with new ambitious aircraft configurations. They will also bring a transformation in the management of Non-Propulsive Energy, and will enable a revolution in operations, which will become safer, sustainable, and more efficient.

### TOWARDS AN OPTIMISED SYSTEMS PLATFORM

A revolution in the methodology to specify, define the architectures and design the systems is necessary for a more holistic approach. This approach will enable a step change in the overall aircraft systems optimisation. For example, the ATA-based design should be reviewed to remove duplications of sub-systems and components, while improving the overall integrated systems efficiency and safety. Climate-neutral aviation will require highly optimised architectures and systems to meet top-level aircraft requirements and overall operational efficiency, cost, and environmental performance targets such as range, payload, weight, performance, emission, etc. The Systems Platform for sustainable SMR will be designed to be used as a common resource that generates, stores and distributes energy and data to all end-users. The exploration, validation and verification of such ultra-effective enabling systems will be essential for reaching the overall aircraft design criteria. The technologies and systems described below will have a crucial influence on the overall aircraft design, so they must be part of the climate-neutral aircraft preparation:

- Optimisation of the computing resources to significantly reduce the avionics on-board footprint – e.g. for generalisation of modular avionics, communication networks, computing platforms, and disruptive digital systems for the communication within the aircraft and with the external world.

- Disruptive electrical wiring systems, power and data backbone deployed throughout the aircraft for a much lighter and simplified electrical and digital wiring and more flexible configurations. This should allow substantial improvement in system installation/industrialisation with respect to weight, volume, and complexity.

The integration of these systems will therefore require a Systems Platform, allowing validation of the concept with various technology bricks in a common Ground-Based Demonstrator

### A DISRUPTIVE TRANSFORMATION IN THE MANAGEMENT OF NON-PROPULSIVE ENERGY

This Systems Platform must allow optimisation of the SMR Non-Propulsive Energy, to enable low energy-consuming aircraft. Today, most systems use energy from engines, converted into pneumatic, electrical and/or hydraulic energy. The efficiency of using pneumatic/hydraulic energy, as well as the strong constraints weighing on future engines and their challenging objectives of fuel consumption, tend to reduce the use of this form of energy on board. It is therefore necessary to manage the Non-Propulsive Energy of future aircraft in the most optimal manner. Key items to address are:

- **New power generation and electrical systems** that can efficiently support the increasing electrical power demand for aircraft primary functions and in the cabin. There will be a new generation of high-density power electronics, electrical power grids with high-voltage architecture and high-speed electrical generators providing more power and best means for an efficient energy management at a reduced weight and compact size. This will include technologies contributing to engine hybridisation, for which it will be necessary to seek similar technological breakthroughs (high-voltage, battery with new electro chemistries, power electronics, etc.).

- **Review systems using a pneumatic energy source** and consider a transformation: Air Systems, Ice Protection Systems, for which it will be necessary to make them more efficient and optimised through their electrification. Advanced air supply systems and efficient thermal management systems, which have been matured in previous projects, will now need to be integrated and demonstrated into a more global 'More Electrical Aircraft' concept.

The integration of these systems will therefore require a More Electrical Aircraft and High Voltage Ground-Based Demonstrator. Moreover, there is a need for more efficient activation and load logics of all aircraft systems, with a holistic view to reach less energy consumption.

The Systems Platform should also be a strong enabler for transforming flight or ground operations:

- Trajectories or vertical profiles optimisation driven by airline constraints, weather effects ($CO_2$ and non-$CO_2$ effects, including contrail formation), traffic, etc. New operational concepts such as enroute formation flight, or ground operation management to include zero-$CO_2$ push-back and taxiing phases.

- Introduction of automation that may transform the pilot operations and thus require a step change in man-machine interfaces to ensure optimal situational awareness.

- Implementation of individualised and conditioned based maintenance, and assistance to maintenance ground operations through enhanced connectivity, as aircraft availability is a major issue for the competitiveness of air transport.

## SUSTAINABLE LIFE-CYCLE TECHNOLOGIES

### SUSTAINABLE MANUFACTURING AND ASSEMBLY, END-TO-END ECO-DESIGN

Most principal manufacturing and assembly concepts of current serial commercial aircraft have evolved from design features from decades ago. For reasons of commonality, changing production processes results in very long lead times and high costs; and consequently, the certification of aircraft modifications and changes in manufacturing and assembly have typically been evolutionary rather than revolutionary.

In addition to the environmental footprint, the **anticipated further increase in demand for a larger number of aircraft will force the manufacturing process to adapt** as well. As a result, virtual design and digital production technologies will have to be further developed as a means of simplification and cost management, while ensuring full compliance with rules and standards of quality assurance and safety. Sustainable manufacturing, together with an iterative eco-design assessment starting from the design stage, will be an explicit element to be studied during Phase 1. So this can be addressed from the start in Clean Aviation Phase 2, as a baseline for validation and demonstration.

> *The maturation and demonstration of key decarbonization technologies is closely aligned with activities in national funded programs.*

The need for a disruptive, entirely new type of climate-neutral operation of aircraft – in combination with a paradigm change to an eco-sustainable end-to-end industrial process – is a unique chance to combine the latest research and development results of material science, virtual design and manufacturing and digital production technology into a single suite. With the ambition of end-to-end sustainability, Clean Aviation has already initiated the process to define and monitor the environmental footprint of the complete life-cycle, starting with the application of eco-design and circularity principles. More sustainable design, new materials, their future production processes, including recycling and assembly/disassembly techniques are key complementary contributors to Clean Aviation solutions. To manufacture new parts that meet quality standards, on time and at cost, new basic materials and techniques are needed for simplification and streamlining of the production processes: these should be based on the new respective basic materials being used.

New frontiers have opened for aviation, largely thanks to the **introduction of Industry 4.0 concepts and digital solutions** including automation, tolerance management, supply chain optimisation and streamlining, condition-based monitoring and maintenance as well as manufacturing and material techniques such as additive manufacturing, thermoplastics, ceramics, multifunctional and smart materials, advanced joining technologies, and hybrid metal-composites. It is vital to use these technologies from the early definition and design of the next generation disruptive climate-neutral commercial transport aircraft. Doing this will support the launch of disruptive new products for an EIS by 2035. It will also ensure the envisaged impact through a high ramp-up of production and highly competitive manufacturing and assembly processes.

## ENABLING TECHNOLOGIES, CAPABILITIES AND FAST-TRACK ACTIVITIES

It has become increasingly apparent that the existing state-of-the-art simulation tools, prediction methods and other capabilities are inadequate. Put simply, they cannot support the development and maturation of key technologies necessary to achieve the significant emission reductions that the Clean Aviation programme is targeting. To facilitate a fast exploitation and a reduced time to market, enhancements in these capabilities are needed.

This obviously means enhancing numerical capabilities. Fast-track developments, starting from lower TRL in Clean Aviation's second phase, are ideal candidates to address these missing numerical capability needs in parallel.

Activities already conducted in Phase 1 – boosting design and development capabilities – will have to be continued. They should concentrate on enabling technologies, e.g. advanced flight science modelling and verification towards improved optimisation, virtual product approaches, and process automation for production and maintenance.

# 5.3. Demonstrator strategy, key objectives of large-scale demonstration

The strategy of the SMR concept demonstration plan is laid out, in order to enable the validation and demonstration of all key technologies to support the launch of a climate-neutral next generation commercial transport aircraft by the end of the Clean Aviation programme. To be able to achieve this, the research and demonstration roadmap of an SMR aircraft concept is built on a combination of several sub-scale, virtual, ground, rig, wind tunnel tests and large-scale flight demonstration platforms. The detailed setting of the individual tests will be defined with the description of the work programme. This will enable the development, maturation, and validation of all subsequent levels of technology readiness for all key technologies until TRL 6, which is a demonstration under real-world operational conditions at a large representative scale.

Sub-scale, virtual, ground, rig, and wind tunnel tests will be mainly required in the first phase of the programme. Large-scale tests to manufacture, assemble and integrate structures and components, as well as to demonstrate technologies on ground and flight tests, will take place in the second phase. Smaller tests will complement the development plan.

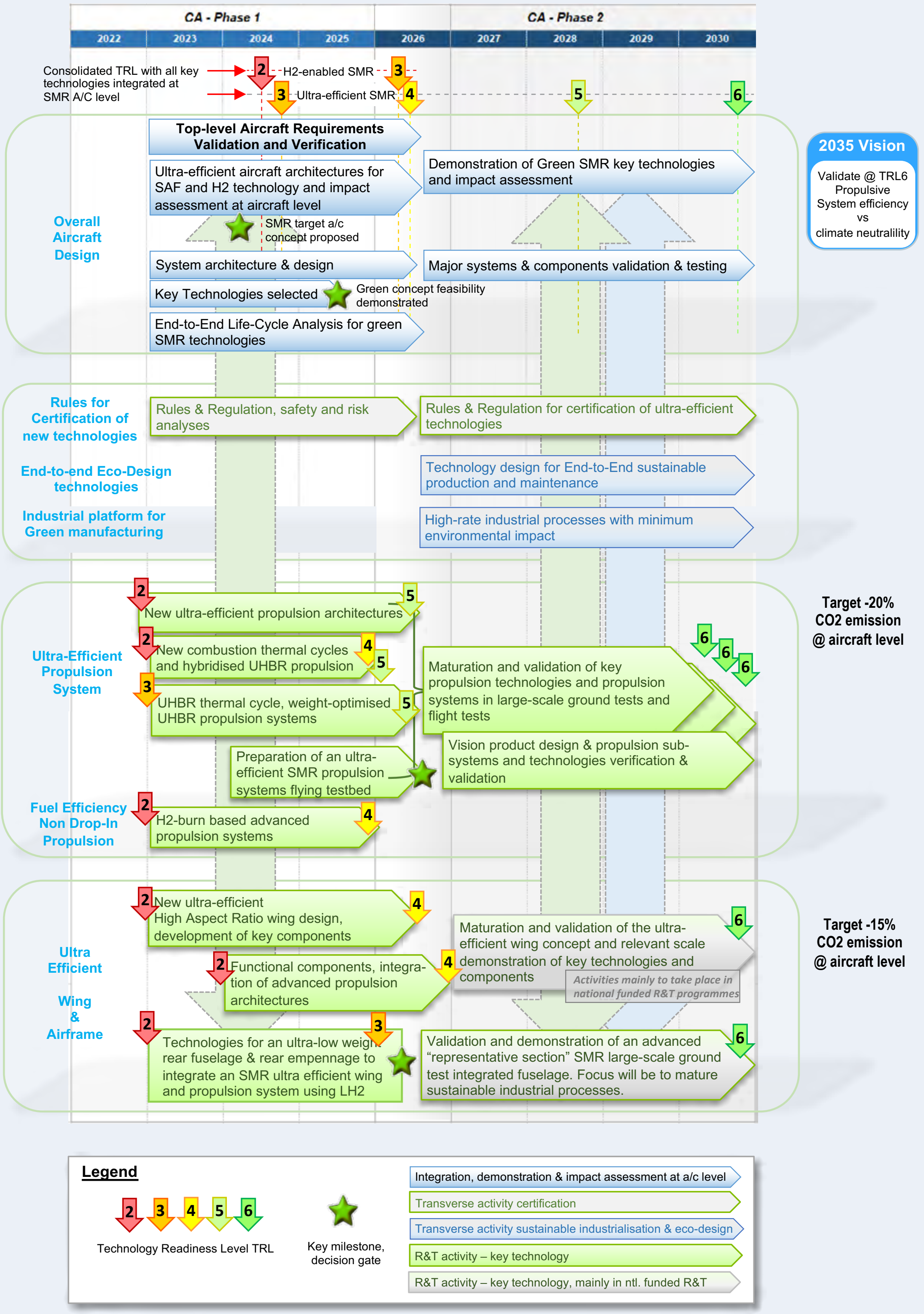
**A single large-scale integrated demonstrator will be developed for flight-testing to mature the ultimate set of technologies, with a layout for an ultra-efficient thermal energy-based propulsion system operating on up to 100% drop-in fuel.** This flight test demonstrator is foreseen to be modified and equipped for the demonstration of ultra-efficient propulsion systems only. The need for large-scale demonstrations for airframe technologies and aircraft systems technologies will emerge with the progress of work and the results of projects established in Phase 1.

In line with the strategy of the Clean Aviation programme to closely harmonise and link activities in other research programmes in Europe to take a maximum of advantages of synergies, the resulting demonstration plan will be effectively built on an alignment with complementary national-funded research activities across Europe.

All on-ground and in-flight demonstrations of propulsion technologies using hydrogen as an energy source are addressed in the HPA pillar. Relevant results of projects achieved in Phase 1 may be matured and demonstrated in the HPA pillar during Phase 2.

As illustrated in the roadmap below (Figure 5.4) and as described in this and the previous sections, the ambition to prepare the technologies for an ultra-low-emission single aisle aircraft requires a dedicated work plan for the overall aircraft architecture. This work plan must tackle and integrate essentially all major components most efficiently. To achieve the targeted TRL 6 for the key contributing elementary technologies, it is critical to have a systematic maturation and demonstration with the right means, scale and level of integration.

Figure 5.4: The Short/Medium-Range Aircraft Technology Roadmap



## SUB-SCALE TESTING, GROUND, AND RIG TESTING

The programme foresees two phases of experimental tests and validation of technologies:

## PHASE 1

### ULTRA-EFFICIENT PROPULSION AND AIRCRAFT TECHNOLOGIES

Studies in Phase 1 will concentrate on the introduction of novel technologies that will support the breadth of operations of the ultra-efficient propulsion and aircraft technology activities, to foster their development, to test and downselect technical options and to answer questions on their feasibility and viability. Several challenges will require attention, in order to deliver the overall impact without adversely affecting other areas, and this will require highly integrated and predictive design tools. Combining the most advanced manufacturing and assembly processes and design methods will be one of the keys to the success of these developments. Technologies will be matured up to TRL 5 through dedicated testing at component, module, and sub-system level.

The development of engine architectures and technologies will initially involve ground and rig tests, followed by full propulsion system tests. Additionally, technologies will be evaluated for their potential for early implementation into service, reducing the time-to-market. Further integration activities include:

- **Technology maturation at propulsion system level,** including the bricks detailed in section Ultra-high efficiency propulsive system development and integration on page 73.

- **Study and sub-scale testing of novel combustion cycle concepts,** with an eye on the longer term, i.e. 2050.

- **SMR hybridisation architectures de-risking and characterisation:**
  - Hybridisation/electrification bricks maturation (energy and thermal management, power generation and distribution, energy storage) – iron bird – 2025;
  - Integrating disruptive/distributed propulsion components (e.g. on wing);
  - Functional integration of propulsion into flight controls, new electrical system integration including fuel cells, integrated wing-propulsion on-ground demonstration – 2025.

- **Integration of ultra-high efficiency propulsive system at aircraft level:**
  - Specifications, detailed design and elaboration of a validation and verification (V&V) plan including systematic assessment of emissions and noise impacts.

## PHASE 2

### ULTRA-EFFICIENT PROPULSION AND AIRCRAFT TECHNOLOGIES

Sub-scale, ground, and rig testing in Phase 2 will be limited to validate or mature specific sub-systems or components for larger tests. Or, if test demonstrations are required to pre-test such components, this testing will be done to prepare or qualify these parts for large-scale integrated ground demonstrators or flight tests.

For propulsion, demonstration activities will also benefit from loops on performance improvements (notably efficiency, weight, and emissions) based on synergies (either from Phase 1 projects or national programme level) as to key engine sub-systems and technologies, including but not limited to Low Pressure spool, advanced gearbox, compact core, advanced/electrical systems. This will support TRL advancement up to TRL 6 by 2030, together with a product vision with 20% fuel burn reduction targeted at 2035 EIS.

For the development of airframe technologies, mainly for the ultra-efficient wing and the low-weight fuselage and rear empennage, substantial parts of the development and demonstration beyond TRL 5 are expected to take place in national-funded R&T programmes linked to the Clean Aviation programme. Pending details of arrangements that will be made with linked programmes, important components and systems remaining in the Clean Aviation programme will be matured and demonstrated: the goal is to achieve or contribute to achieve TRL 5 and 6 at major component or system level with ground or rig tests.

Once specified, part of the enabling aircraft systems detailed in section section «A revolution of the aircraft systems» on page 76 will be at least matured up to TRL 5 at component, module, and sub-system level by 2030 in the Clean Aviation programme. In line with the technical scope of national-funded programmes (where possible), there will be a selection of specific technology bricks that will be further integrated for ground, rig, or flight tests at system level in Clean Aviation for large-scale demonstrators (TRL 6). This integration and testing process will allow for a more comprehensive evaluation of the technologies' performance and compatibility within the overall aircraft concept system:

- Systems Platform allowing the validation of the concept with various technology bricks in a common Ground-Based Demonstrator (e.g. avionics, actuators for primary flight control).
- More electric aircraft, energy management, High Voltage Ground-Based Demonstrators.

**Addressing key questions of sustainable industrialisation will be of high importance in Clean Aviation in Phase 2.** The current assumption is that corresponding activities cannot be tackled in a single major project, but in dedicated parts of individual Phase 2 projects laid out to mature and demonstrate specific technologies. Depending on the arrangement to allocate activities to develop, prepare, test, and demonstrate rigs for advanced automated manufacturing and assembly, parts of these activities will come under the Clean Aviation programme. The detailed set-up of the rigs will be described in the corresponding work programmes.

## LARGE-SCALE INTEGRATED GROUND DEMONSTRATION AND FLIGHT TESTING

The large-scale flight test demonstrator platform, which will be developed and prepared for the maturation and validation of ultra-efficient propulsion technologies, will enable the testing of all major technology components. This will critically depend on a validation of their performance under real flight conditions, in different relevant scenarios, and at size and power levels close to full scale.

The definition, development, and preparation of the test vehicle has started in 2024 of the Clean Aviation programme.

For the development of airframe technologies, mainly the low-weight fuselage and rear empennage, requirements for large-scale ground and flight demonstrations will be defined in the second part of the first phase of the Clean Aviation programme. It is expected that a substantial part of maturation and demonstration activities will take place in national-funded R&T programmes linked to the Clean Aviation programme. With details of arrangements that will be made with linked programmes pending, important components and systems remaining in **the Clean Aviation programme will be matured and demonstrated to achieve or contribute to achieve TRL 5 and 6 with large-scale ground tests or, if required to achieve TRL 6, in flight tests.**

## PHASE 1

### ULTRA-EFFICIENT PROPULSION AND AIRCRAFT TECHNOLOGIES

No large-scale ground test demonstrator is planned for the development of ultra-efficient wing technologies and the low-weight SMR fuselage and rear empennage in Phase 1 of the programme.

Following the results of the key technology maturation, it is anticipated that the first large-scale on-ground tests for the ultra-efficient SMR concept's propulsion systems will be prepared for 2026. These tests will validate the maturity on specific techno-bricks, e.g. the low-pressure systems technologies. In addition to the demonstration of functionality at full-scale, the preparation of the propulsion flight tests will also facilitate engagement with regulatory authorities on the most appropriate methods for compliance of these novel systems and advanced technologies. The intensive integration effort will be common to all activities, experienced jointly with the airframer to maximise the expected benefit at overall system level (engine/aircraft integration).

The preparation of the large-scale flight test demonstrator for the validation of ultra-high efficiency thermal engines, as planned in Phase 2, will take place and will be completed in the second half of Phase 1. No flight test demonstration is planned in Phase 1.

## PHASE 2

### ULTRA-EFFICIENT PROPULSION AND AIRCRAFT TECHNOLOGIES

For the validation of the low-weight fuselage and rear empennage technologies, large-scale ground demonstrations will likely be required in the period from 2026-2030 to accomplish TRL 6. These demonstrations should include a full-size fuselage barrel segment demonstrator, following the results of Clean Sky 2 and including high-rate manufacturing and assembly using a high degree of automation technologies. Additionally, these should include a rear-end demonstrator that also capitalises on the outcomes of recent national and European funded R&T projects. Several maturation and demonstration activities are expected to be carried out under national-funded R&T programmes. These activities should be defined, planned, and carried out in synergy with the Clean Aviation programme. The detailed setting of the plan will be the subject of the work programmes that define the content for topics for projects to be proposed for Phase 2.

For the maturation and demonstration of SMR ultra-efficient propulsion systems, large-scale ground tests and flight tests are foreseen for Phase 2.

Based on Phase 1 results, demonstrations activities will include:

- **Manufacturing, assembly, and delivery of Flight Test Demonstration engines** on the key advanced technologies matured at ground level.
- **Full propulsion system demo** & in-flight validation and data analysis – 2028.
- **Emissions impact via a life-cycle analysis,** noise assessment at aircraft, airport, and fleet level.
- **Other engine concepts, either for longer term EIS capability** or other range applications, will also be integrated in the demonstrations by utilising donors or new-build engines.
- **Aircraft operational assessment,** ground operations, logistics and route to certification.

A further integrated flight test for ultra-efficient propulsion may emerge from opportunities thanks to a portfolio of technologies integrated in Clean Sky 2, and extended in impact under Clean Aviation Phase 1 and exploiting synergies from national programmes. This portfolio of technologies, which is for a power range that includes SMR and extending to higher capacity variants and beyond, is expected to achieve a mix of TRL 4 and 5 at the end of CA Phase 1. If conditions are met to target a full-scale test flight test demonstration to reach TRL 6 within Clean Aviation timescales, additional to SMR impact, this could generate an early spin-off impact of Clean Aviation technologies in the wide-body, high-capacity SMR and/or long-range aircraft segment with EIS opportunities in the range of 2035 to 2040.

# 5.4. Scalability of technologies and demonstrator results

Key challenges for the development of technologies for ultra-efficient propulsion architectures for large aircraft or longer flight ranges are system complexity and specific overall energy density. In many cases, there is a technological challenge due to a low maturity or unavailability of large size or high-power sub-systems. The same is true for the development of new high-power, high-voltage electrical systems and architectures, which are a prerequisite for the introduction of hybridisation and all electric propulsion systems. The thermal management of high-power electrical and mechanical components, in combination of the thermal management of a cabin, is an additional challenge even for the SMR size of aircraft; the opportunity for technology up-scaling will take some time.

> *The scaling of these advanced technologies for airframes will require a significant learning process.*

This will include advanced numerical tools for the design and development of components, manufacturing, testing and industrialisation. The SMR programme in Clean Aviation will stimulate the growth of the applicable technologies in neighbouring aircraft segments from the short to medium-range segments to medium to longer range and wide-body aircraft. The expectation is that this will provide the opportunity to maximise the impact of technologies for additional applications in medium to long-range aircraft in the 2035 to 2040 timeframe. Scalability and spin-offs for other aircraft types, like large business jets, will also be promoted and spread the use of this technology.

Of the SMR technologies planned to be developed and matured in the Clean Aviation programme, ultra-efficient propulsion systems are expected to create the greatest opportunity for high-impact scaling. A number of sub-components and sub-systems for ultra-efficient engines, planned to be developed in Phase 1, have the potential for an upscaling ‘by design’. Hence, for Phase 2, flexibility in approach and scale – for technology maturation and demonstration to high TRL levels – could be relevant. This could create the conditions to generate additional impact beyond the targeted programme goals for Regional and SMR type of aircraft.

A cross-fertilisation of technology development in Clean Aviation is also expected and will be promoted between the SMR and ultra-efficient regional aircraft parts of the programme.

# 6. Disruptive technologies to enable hydrogen-powered aircraft (HPA)

# 6.1. Introduction

**Hydrogen is a promising energy vector for the future, as its usage in a combustion chamber or fuel cell results in zero-carbon emissions.**

Moreover, in transport, hydrogen seems to be a promising zero-carbon option for the electrification of trucks, buses, ships, trains, large cars, and commercial vehicles, where the lower energy density and slow recharging performance of batteries are major disadvantages. Because the transport segment makes up about one-third of all $CO_2$ emissions in the EU, its decarbonisation represents a key element in achieving the energy transition.

If produced with low- or zero-carbon electricity, hydrogen has the potential to strongly reduce the environmental impact of transport systems.

**Hydrogen has several key advantages for aviation application;** it allows for the elimination of $CO_2$ emissions in flight, and along the entire life-cycle if produced by carbon-free energy sources. In terms of non-$CO_2$ emissions, the use of hydrogen in a combustion or fuel cell engine can lead to different emissions. Its usage in fuel cells allows for zero NOx and particulate emission. When hydrogen is burnt in a turbine engine, very low particle emissions can be expected, as well as reduced NOx emissions (provided that the combustion system is optimised). Nevertheless, both hydrogen fuel cell and hydrogen combustion propulsion systems will emit water, which can have an impact in the environment. Particularly, the quantity and the physical aggregated state (water or steam, size of droplets, etc.) of the ejected water could have a significant effect on the risk of contrails formation, and hence needs to be assessed. Consequently, although hydrogen does not result in carbon emissions, a comprehensive global environmental impact assessment is needed to fully characterise the environmental effects of a hydrogen propulsive system.

> *The hydrogen aircraft will completely remove $CO_2$ emissions in flight, with a potential to further reduce non-$CO_2$ emissions.*

To scale up hydrogen-powered aircraft, several technological advancements need to occur for their full potential to be enabled. So, the development of a hydrogen aircraft will require parallel technology developments, in order to increase the maturity of the key technological building blocks. Among these blocks some elements are at very low TRL and will need long-term developments, maturation and demonstration if they are to be ready for integration into future hydrogen-powered aircraft.

While the aerospace industry develops the necessary on-board technologies, **widespread availability of sustainably produced hydrogen and recharging/refuelling infrastructure will be key for the overall success of this aircraft solution.** The maturation of the hydrogen ecosystem – which is needed in parallel to all aircraft technology developments – will lead to extensive operational changes. Using hydrogen technologies will require a full system change, in terms of the energy supply chain and energy integration in airframes and airports. Additionally, their implementation at the level of infrastructure, supplies and logistics will likely be key enabling and/or limiting factors and hence, it must be considered under the Clean Aviation research and demonstration activities. This work can be fostered with joint approaches, like the one already initiated through the Alliance for Zero-Emissions Aviation (AZEA), which includes the participation of stakeholders such as aviation authorities, airports, ground operations partners and airlines.

Incremental improvements – i.e. higher fuel efficiency of aircraft – are not sufficient to achieve the ultimate objective of a zero-carbon emissions aircraft. The emission of greenhouse gases, and especially some non-$CO_2$ emissions and secondary effects (e.g. NOx, SOx, soot) can only be avoided by disruptive propulsion technologies, i.e. ultra-efficient engines using new energy sources. A hydrogen-powered aircraft seems to be a promising candidate to limit climate impact. However, given the challenging fuel properties and impact on the overall aircraft system optimised for conventional fuel, **major research efforts will be required to introduce this technology onto the market.**

## ULTRA-EFFICIENT PROPULSION SYSTEMS OPERATING WITH HYDROGEN

As presented in Chapter 3, these challenges will result in distinct hydrogen-powered aircraft concepts, which will be developed independently from the SAF solutions proposed for the SMR and REG segments. Clean Aviation therefore aims at maturing and demonstrating all relevant elements of liquid hydrogen (LH2) storage systems, hydrogen distribution systems, and hydrogen propulsion systems ready for integration into these future hydrogen-powered aircraft concepts. The aim is to support a potential **entry into service of such aircraft in 2035.** This includes the selection and validation of the most suitable concepts, materials and designs to provide the required performance, lifetime, costs, and safety. The integration of these systems into an aircraft platform requires a deep understanding of operational, maintenance, and certification aspects.

To deliver the impact of a hydrogen-powered aircraft, the high-level requirements of potential platforms will be considered from the beginning. Systems should be scalable for different propulsion architectures (fuel cell or hydrogen combustion) and consider the specific requirements of the different aircraft categories. Impact can thus potentially be accelerated through early scalable demonstrations of hydrogen-powered aircraft, which would improve understanding of hydrogen handling on the ground and in flight.

As introduced in Chapter 3, Clean Aviation will assess hydrogen-powered aircraft concepts that have (i) a hydrogen combustion (H2C) propulsion system, (ii) 100% fuel cell propulsion system (FCPS), and (iii) a (SAF) fuelled propulsion system with electrical hybridisation via a fuel cell (part of the REG thrust). Building on this, radical disruptive hydrogen-powered aircraft are expected to benefit from storage and relevant feed system architectures to exploit hydrogen propulsion systems, paving the way for even longer range applications. So Clean Aviation will lay the foundations for the future clean hydrogen-powered aircraft propulsion architecture.

Due to the specific constraints and opportunities of hydrogen technologies, this work will lead to new classes of aircraft with their own specific capabilities, besides the current REG and SMR market segmentation. So the **tests and demonstrations in the hydrogen-powered aircraft pillar will be dedicated to maturing the understanding and integration aspects** sized for hydrogen-powered aircraft architectures that encompass special requirements for this fuel, technology features of the overall fuel system, fuel storage, heat management system, safety risk mitigation, protection systems and propulsion system elements.

Design constraints and challenges for the overall hydrogen-powered aircraft configuration will be determined on the basis of the outcomes of these tests and demonstrations, in order to complement the overall aircraft and propulsion system requirements.

# 6.2. Key technologies and their contribution to the Clean Aviation ambition

**For aviation, hydrogen will revolutionise aircraft architecture, propulsion systems, and logistics; meaning a significant acceleration of new technologies maturation will be needed. These are the main R&D priorities for Clean Aviation:**

- Assessment of the emissions reduction potential.
- Development of the propulsive system ('from tank to wake'), including engine plus the overall fuel system.
- Aircraft integration.
- Safety aspects and anticipation of future certification requirements.
- Assessment of the industrialisation aspects.

Clean Aviation focuses on those key hydrogen technologies that need to reach the desired technology readiness level (TRL), in order to allow a potential application in line with the disruptive hydrogen-powered aircraft concepts (as introduced in Chapter 3).

**Logistics and the infrastructure of hydrogen at airports are key enablers** for the widespread use of hydrogen in aviation. To enable future hydrogen-powered aircraft, aviation requirements must be taken into account in hydrogen research and development in parallel, to ensure readiness in the 2030s. While mostly supported by energy supply sector or ground infrastructure, the following items are indirectly of particular importance for aeronautical application:

- Production of hydrogen and its liquefaction.
- Liquid hydrogen transport and storage.
- Establishment and harmonisation of airport procedures and regulations.

This overall approach should be shared with several other user and transport domains. Therefore, those activities are not included in Clean Aviation, but are to be executed in synergy with various national and European collaborative frameworks, involving all stakeholders and non-aeronautical applications, i.e. the EU Clean Hydrogen public-private partnership and initiatives like AZEA .

## EMISSIONS ASSESSMENT

As noted above, emissions from hydrogen aircraft are one of the critical elements which needs to be fully characterised. Hydrogen-power aircraft will emit more water vapour than SAF-based aircraft. On the other hand, NOx and emission particulates may strongly be reduced. Therefore, contrails formation, which are suspected to have a substantial impact on global warming through radiative forcing, may be impacted by the different emission characteristics of a hydrogen-powered aircraft.

Assessing the level of this impact is crucial to qualify the full environmental potential of hydrogen-powered aircraft. Scientific understanding of some aspects of emission effects is incomplete and the total effect is still subject to high uncertainties. Non-$CO_2$ impact of hydrogen propulsion (contrails in particular) should be studied in synergy with Clean Aviation, with the same approach as for future SAFs, in order to build a fair comparison based on the same modelling and experimental standards.

The total emissions level from hydrogen-powered aircraft will be investigated under Clean Aviation through measurements (flight test measurements or dedicated test beds) and subsequent modelling activities. Nevertheless, the **climate impact of these non-$CO_2$ emissions** should come through **other research activities,** in parallel with Clean Aviation (i.e. synergies), building on the measurement of propulsion system exhaust measurement activities that will take place in Clean Aviation.

## PROPULSION SYSTEM AND STORAGE/FUEL DISTRIBUTION SYSTEM

**The overall functional propulsive system and its integration into aircraft are key for the development of hydrogen-powered aircraft, based on fuel cell or hydrogen combustion.** As established by the hydrogen-power aircraft concept definition provided in Chapter 3, the high-level characteristics of these systems has been defined. Liquid hydrogen will most likely be stored in dedicated tanks that are integrated into the aircraft fuselage. Hydrogen will be distributed through the aircraft to the propulsion in liquid or gaseous form, and at a predetermined temperature and pressure conditions, depending on the requirements imposed by the propulsion system.

From a propulsion system perspective, the aircraft will require around 10 MW installed power. This can take the form of a propulsion system based on direct hydrogen combustion solution or the use of fuel cells to drive an electric propulsion system (with 2.5 MW minimum per propulsion unit).

All key components for LH2storage systems, hydrogen distribution systems, and hydrogen propulsion systems will be matured as part of this pillar. This will be carried out in synergy with national programmes and Clean Hydrogen, and in coordination with the other Clean Aviation pillars. Work will include:

> **The overall fuel system architecture optimisation** (from tank to engine), especially in terms of heat management and transient operations in order to define the global characteristics of the operational propulsive system.

> **Hydrogen distribution and conditioning** within the aircraft, while assessing the different usages (combustion or fuel cell).

> **Thermal engines capable of burning hydrogen** with low-NOx emissions.

> **Higher efficiency fuel cell systems** including Balance-of-Plant (BoP), thermal management and air supply system optimisation.

Due to hydrogen's relatively poor volumetric energy density, it is likely that hydrogen will need to be in liquid (cryogenic) form for use in aviation, except for specific applications where gaseous may be suitable (i.e. low-range/low-passenger number aircraft). Integrating hydrogen into aircraft requires the development of a 'tank to wake' propulsive system, including the storage system, the fuel distribution system and the engine. Development of the propulsive system will consequently have to study the LH2 storage system, the LH2 fuel distribution and conditioning system, the combustion system for gas turbine and the fuel cell system, as well as the complete powertrain or engine.

> *Delivering a competitive, safe and reliable hydrogen powered aircraft will require a collective effort from the entire industry.*

These studies will entail new material behavioural assessments under hydrogen condition-related new phenomena. They will include research into hydrogen leakage and permeability, metal embrittlement, oxidisation by combustion gases, the compatibility of cryogenic systems with a vibrating environment and the long-term material behaviour in a cryogenic environment. These material behavioural assessments are necessary to answer both safety (design safety) and maintainability (MRO – continued airworthiness) requirements of hydrogen-powered propulsive systems. Activities of this kind can benefit from additional complementary research activities in synergy with Clean Aviation. But they may also call for materials development and certification in parallel with Clean Aviation: the duration of these should not be under-estimated. Failure to characterise the material behaviour, as part of these activities, may lead to no airworthiness certification – with the result that these materials cannot be used.

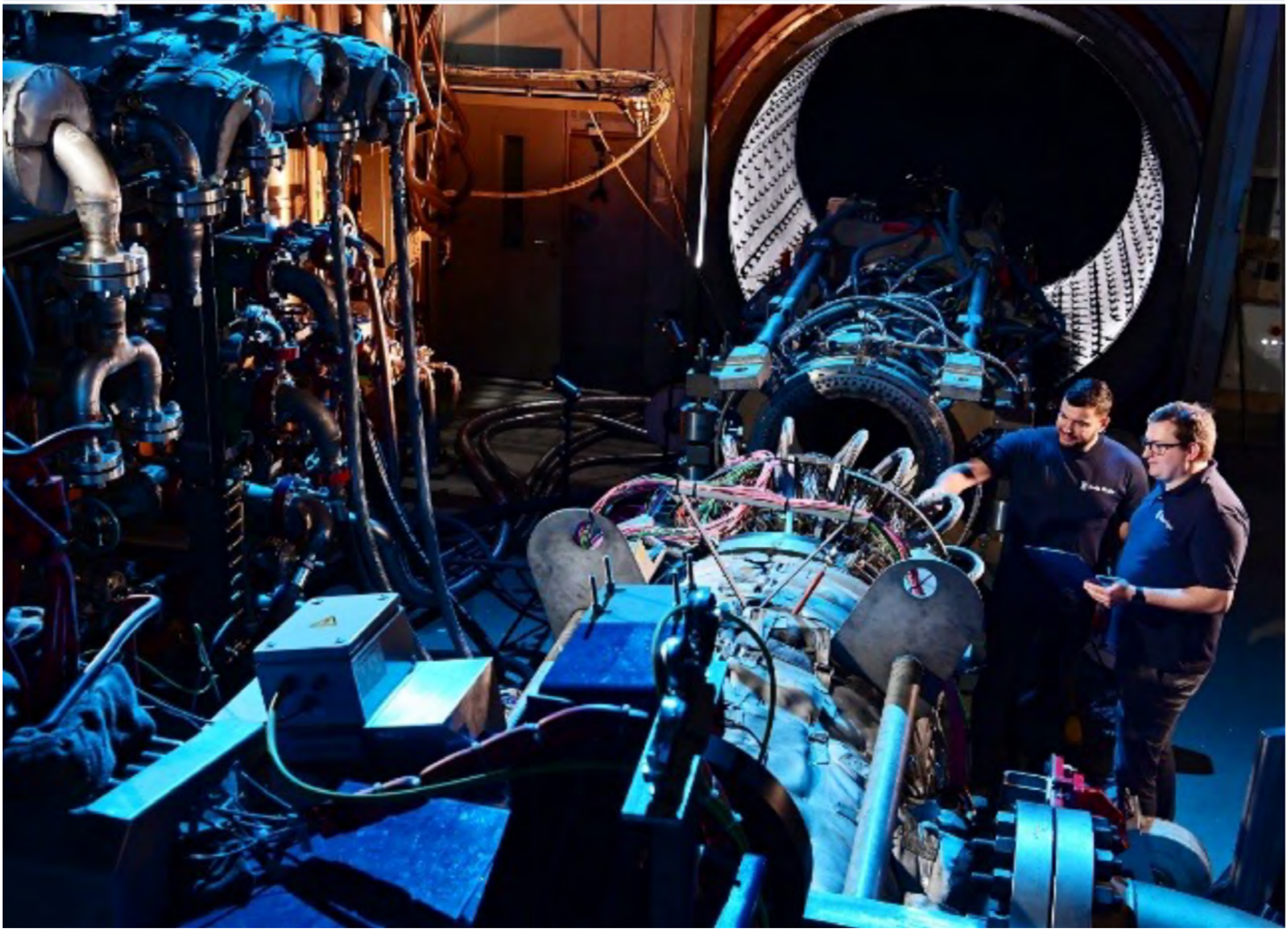
The above-mentioned activities will need to include system qualification activities to address safety issues such as overpressure, leakages, explosion, detonation and fire tolerance of the tanks and fuel systems. In support of these system qualification activities, the corresponding numerical capabilities must be developed to understand the different systems' behaviour. To perform these safety-related activities, system qualification testing will be performed. This will pave the way to further large-scale systems demonstrations or flight demonstrations in Clean Aviation Phase 2.

## HYDROGEN COMBUSTION PROPULSION SYSTEM

The objective of this activity will be to mature hydrogen combustion-based propulsion systems with high combustion efficiency, lower NOx emissions, and a reliable, long-lasting turbine. For high combustion efficiency and lower NOx emissions, the design of the combustion system must be optimised, and lean-fuel injection/mixture technologies applied. The use of cryogenic cooling (enabled by using liquid hydrogen as a fuel) to cool turbine stages and further optimise combustion efficiency could be investigated as parallel research activities, in synergy with Clean Aviation, to accelerate the technology maturation. The hydrogen combustion architecture and the materials used should also be tested and optimised, so as to ensure a long lifetime that is at least competitive with conventional engines.

Finally, the replacement of support functions (e.g. actuators, coolant) will also have to be matured and demonstrated. Maturation of technology building blocks and optimisation of the engine fuel system architecture will also be addressed as part of Clean Aviation. Full validation of such propulsion systems, including pollutant emissions, will have to be done. Engine design modifications, to ensure dual fuel compatibility for both hydrogen and conventional fuel (or SAF), could be studied through research activities in Clean Aviation Phase 1.

**Figure 6.1: Full annular Hydrogen combustion test**



## FUEL CELL SYSTEMS

Fuel cell systems are a possible alternative to hydrogen direct combustion gas turbine propulsion systems at the lower power end (i.e. in MW per unit). Such systems can potentially be the energy source of:

**(a)** A complete electrical propulsion system (either using only fuel cells, or a combination of fuel cells and batteries); and/or

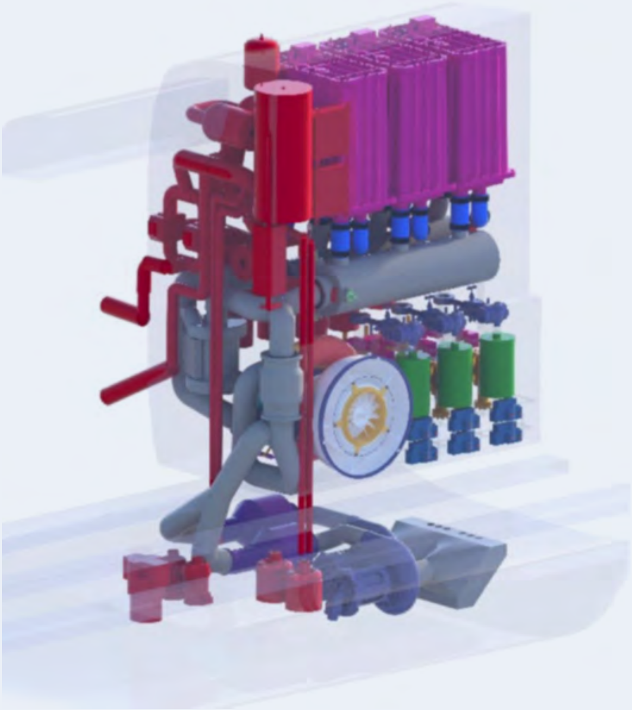
**(b)** The main energy source of a hybridised (i.e. using fuel cells in combination with a thermal engine) propulsion system (which is a solution investigated in Chapter 4, as part of the REG thrust).

Trade-offs must be assessed to determine the feasibility and relevance of each of these potential configurations.

**The use of fuel cells enables the generation of electricity aboard aircraft from hydrogen** (stored in a dedicated tank) and oxygen (air) without any $CO_2$ emissions. The only by-products of this reaction are water and heat. The objective in Clean Aviation is to design an integrated aircraft system of multiple fuel cell stacks with high efficiency and high gravimetric power density, compatible with aeronautical specifications and constraints. The efficiency of this system has to be optimised including Balance-of-Plant (BoP), power electronics and fuel cell stacks for aviation use. During Clean Aviation, phase 1, lab and ground tests will demonstrate concept feasibility and viability for integrated aeronautical propulsion and optimisation for the fuel cell solution. This solution will be further matured through flight demonstrations, as part of Clean Aviation phase 2.

This work will allow the investigation and demonstration of electrical power generation by a fuel cell for hybrid-electric or fully hydrogen-electric propulsion systems and non-propulsive needs (e.g. auxiliary power units). This will include, for the hybrid-electric propulsion, trade-offs between batteries and/or fuel cell systems (or fuel cells in combination with a thermal engine) to assess the most efficient/relevant configuration.

**Figure 6.2: Hydrogen fuel cell propulsive system concept**



## STORAGE AND FUEL DISTRIBUTION SYSTEMS

The storage and fuel distribution system for hydrogen will have to provide several new functionalities, in comparison to current kerosene-based fuel distribution systems, such as:

- **Ability to provide and maintain the storage of hydrogen as a fuel** (either pressurised or in liquid form), as well as to provide and maintain insulation and subsequent boil-off management. This is associated with technology for pressure vessels, materials, pressure valves, lighter tanks, etc., as well as external fuelling systems technologies.
- **Ability to refill and vent/purge hydrogen.** Most of the focus within Clean Aviation will be on reliable hydrogen venting in distress or before periods of non-use of aircraft, control valves valves, redundant valves, passive discharge valves (automatically discharging maximum quantities, while not creating unacceptable hydrogen/oxygen mixture).
- **Technology to provide reliable hydrogen quantity** and out-flow metering (and to detect leakage) in pressurised and liquid hydrogen tanks, addressing sloshing and boil-off in cryogenic tanks, natural leakage, etc. This is analogous to the state-of-charge of a battery (and fuel quantity gauging in conventional applications).
- **Ability to enable auxiliary functions,** making use of the intrinsic presence of high pressure and/or cryogenic temperatures (e.g. the ability to use low temperatures for cooling means for powertrain components, using pressure to power some devices, etc.). Activities aiming to demonstrate the feasibility and the performance of a cryogenic propulsion and electric distribution system will be performed as part of Clean Aviation. Superconducting, while not addressed in Clean Aviation, should be studied in synergy with Clean Aviation as it could potentially be a source of added value at system level.
- **Ability to provide and control hydrogen supply** to the system (whether gas turbine hydrogen combustion or fuel cell based) especially in transient conditions, at the required pressure, temperature and mass flow.
- **Ability to have a holistic performance picture of the system,** including global heat management, system physical and control integration.

> *The shift to hydrogen will lead to radically new challenges in safety, certification, operation, and maintenance of aircraft.*

Activities will focus on the study and maturation of technological building blocks that provide these expected abilities. For example, specific key components will be developed and integrated into fuel systems, e.g. hydrogen heat exchangers, liquid/gaseous hydrogen pumping/discharging/metering systems, hydrogen injection systems and fuel conditioning systems or units. Additionally, due to the close coupling of these systems with the airframe, studies to assess the effect on aircraft integration for these systems should be performed. For all these activities, all necessary modelling tools will have to be developed, as the behaviour of hydrogen (under liquid or gaseous phase) is very different from conventional liquid fuels. Further development of hydrogen fluid models is required, accounting for isomers composition and degradation, as well as development of the fluid systems modelling capabilities that exploit these fluid properties and new models capturing the vibration impacts on liquid hydrogen behaviours.

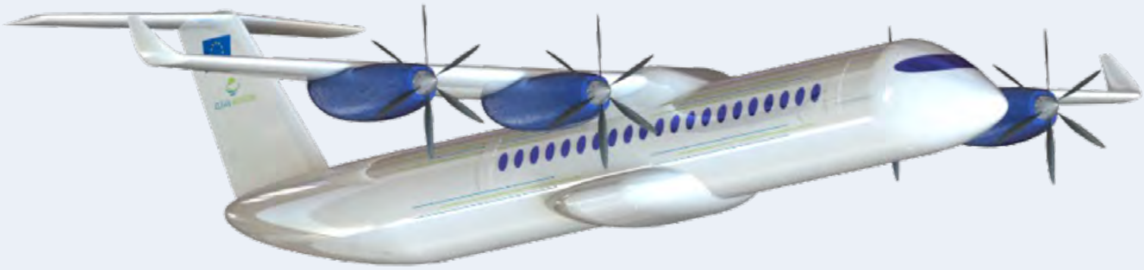
**Fast-track developments starting from lower technology maturity** in Clean Aviation Phase 2 – in parallel to the demonstrations – could concentrate on missing capabilities. Other hydrogen technologies with lower maturity from Clean Aviation Phase 1 should be developed as back-up technologies. They should constitute alternatives to the highest risk hydrogen technologies addressing the expected low tolerance to the flexible and vibrating aircraft environment, as well as long-term material behaviour under cryogenic conditions.

## AIRCRAFT INTEGRATION

**The implementation of non-drop-in fuels such as liquid hydrogen** will require a step change in aircraft configurations, to optimise the tanks and the fuel system integration. A move towards different, more volume-efficient configurations is foreseeable and should be considered. A key challenge for the hydrogen-powered aircraft is integrating all the systems required to store, distribute, and control the LH2 on-board the aircraft, including all means to ensure safe aircraft operations. The demonstration of all the LH2 systems and their integration into airframes, matching the required airport infrastructures, must be conducted through ground demonstrators and flight tests. These demonstrators should be compatible with the operation in today's international commercial air traffic. This would lead to the gathering of data on how infrastructures should improve and evolve to operate future hydrogen-powered aircraft, once the transition phase is over.

Chapter 3 defines some of the hydrogen-powered aircraft concepts resulting from the integration of the different hydrogen sub-systems into an aircraft. To quantify the improvements generated by a hydrogen-powered aircraft architecture for impact monitoring and to fully grasp the specific challenges linked to relying on hydrogen as energy source, a dedicated architecture study comparable to SMR and the REG pillar will be performed as part of Clean Aviation Phase 2.

**Figure 6.3: Hydrogen Fuel Cell powered aircraft concept**



## SAFETY ASPECTS AND CERTIFICATION

Maintaining an equivalent level of safety is key for aviation. The shift to **hydrogen will lead to radically new challenges in terms of safety, procedures,** certification and qualification, operation, and maintenance of aircraft components. This will drive new specific actions covering different technical domains.

The safe and reliable distribution of liquid hydrogen from the LH2 tanks to the hydrogen combustion unit and/or fuel cell must be assured. Since the hydrogen will most likely be stored in liquid form but must be injected into the fuel chamber at high-pressure in gaseous form, the architecture must be designed to handle the pumping and vaporising of liquid hydrogen. To keep the hydrogen as a liquid, lightweight and double-insulated fuel pipes with cryogenic cooling may have to be developed. In addition, boil-off management must be developed in all states of operations including refuelling, parking and maintenance procedures. New types of fire leakages, overpressure and/or explosion which can occur with hydrogen, must be taken into account.

Thus, this architecture has to be designed for inherent safety and must be able to sustain typical static/dynamic loads of CS-25 airplanes, and include as well a leakage detection and venting or ventilation mechanisms. In case of leakages, a venting mechanism and leak detection inside the aircraft, next to LH2 fuel pipes, is also needed. The above-described components and architecture design must consider the maintainability, in order to allow fast learning curves from the start of operations and ensure maintenance costs are kept as low as possible, while fulfilling design and manufacturing safety requirements.

New phenomena such as material compatibility and durability, hydrogen leakage, metal embrittlement, and compatibility of cryogenic systems in an environment with vibrations, shocks and fast-changing outside temperatures also have to be investigated and validated to enable aircraft operations for up to 30 years. Such validation could occur through activities in synergy with Clean Aviation, implemented for instance in national programmes or Horizon Europe.

Last but not least, required certification specifications and associated means of compliance will have to be adapted, or will be newly developed, in order to allow the qualification of such systems and future certification at aircraft level. All relevant stakeholders, including operators and ground segment stakeholders, will have to be included in such activities, which will be taken into account in each phase of Clean Aviation, in close connection with the other pillars.

An important aspect is the collaboration on **defining relevant industrial standards** in the new technical areas, as the primary means to:

- Ensure cross-compatibility and composability of the systems.
- Facilitate qualification and definition of means of compliance
- Significantly reduce the cost of supply chain maturation through standardisation.

These collaboration and standardisation activities should cover liquid hydrogen storage including ground support equipment, hydrogen aircraft installation, fuel cells aircraft integration, high-voltage propulsion buses and their management, and electric/battery-hybrid propulsion.

All actions addressing the key challenges will have to be addressed in a coordinated manner in terms of methods and experiments. This will ensure a controlled progress, with clear milestones towards the certification path.

Finally, the new certification specifications and associated means of compliance will need to be defined, in coordination with EASA, in order to secure the targeted EIS of such technologies as early as 2035.

## INDUSTRIALISATION DURING AIRCRAFT DEVELOPMENT PHASE

The route to a competitive and safe hydrogen-powered aircraft will require aircraft architecture, development of new technologies (e.g. fuel cell-based propulsion, hydrogen storage and distribution), physical design & integration, and safety & certification to be ultimately connected with all dimensions of industrialisation. During Clean Aviation, the foundation will be laid: safety and certification are based on repeatable and reproducible manufacturing processes (among other aspects), achieving the product key performance indicators and expected quality and reliably. Another positive effect of achieving high quality during manufacturing and assembly of a future product is the improved viability of simultaneous serial aircraft manufacturing.

The overall aircraft integration may be de-risked via trials on the shop floor. These trials must show the conceptual feasibility and reduce both overall aircraft development costs and lead time, by starting industrialisation early. Valuable industrial learnings can be directly incorporated in the physical design and integration, in order to reach the figures of merit of a future product and eventual industrial system. Added value could be demonstrated through different approaches; e.g. product modularisation and standardisation, supply chain maturation, end-to-end digitalisation and data-driven development.

These activities will be organised during Clean Aviation Phase 2, in support of the two hydrogen-powered aircraft concepts identified in Chapter 3.

Failure to deliver on time, on specifications or on budget these manufacturing tools may have an impact on certification, with various negative consequences. Therefore, manufacturing readiness must be carefully addressed and demonstrated.

# 6.3. Demonstrator strategy, key objectives of large-scale demonstration

**The development of hydrogen, especially liquid hydrogen, in aviation will require substantial efforts, because most of the needed technologies are currently at low maturity and have never been demonstrated in a representative environment.**

Technologies and hydrogen systems will be developed and tested in synergy with national programmes, and in coordination with Clean Hydrogen, within the HPA pillar and with the other Clean Aviation pillars. The initial strategy is to:

> **Mature key technological bricks:** fuel cells propulsion sub-systems and components, tanks, combustion principles, fuel system components, etc., in synergy with Clean Hydrogen. This will enable potential synergies with other sectors or end-users (stationary applications, other mobility applications) during Clean Aviation Phase 1 up to TRL 4/5.

> **Continue the systems development and maturation** in the HPA pillar, up to a minimum TRL 5 (ground demonstration) in Clean Aviation Phase 2.

> **Study an overall fuel system architecture** (from tank to engine).

> If relevant, **adapt and integrate the systems for a specific aircraft demonstration platform** and demonstrate the systems in a flying testbed configuration up to TRL 6 in Clean Aviation Phase 2.

> **Ensure the operational usability of all HPA integration demonstrators** used during Clean Aviation Phase 2, in a way that can support an EIS in 2035, compatible with the overall Clean Aviation ambition to support 75% of today's fleets by 2050.

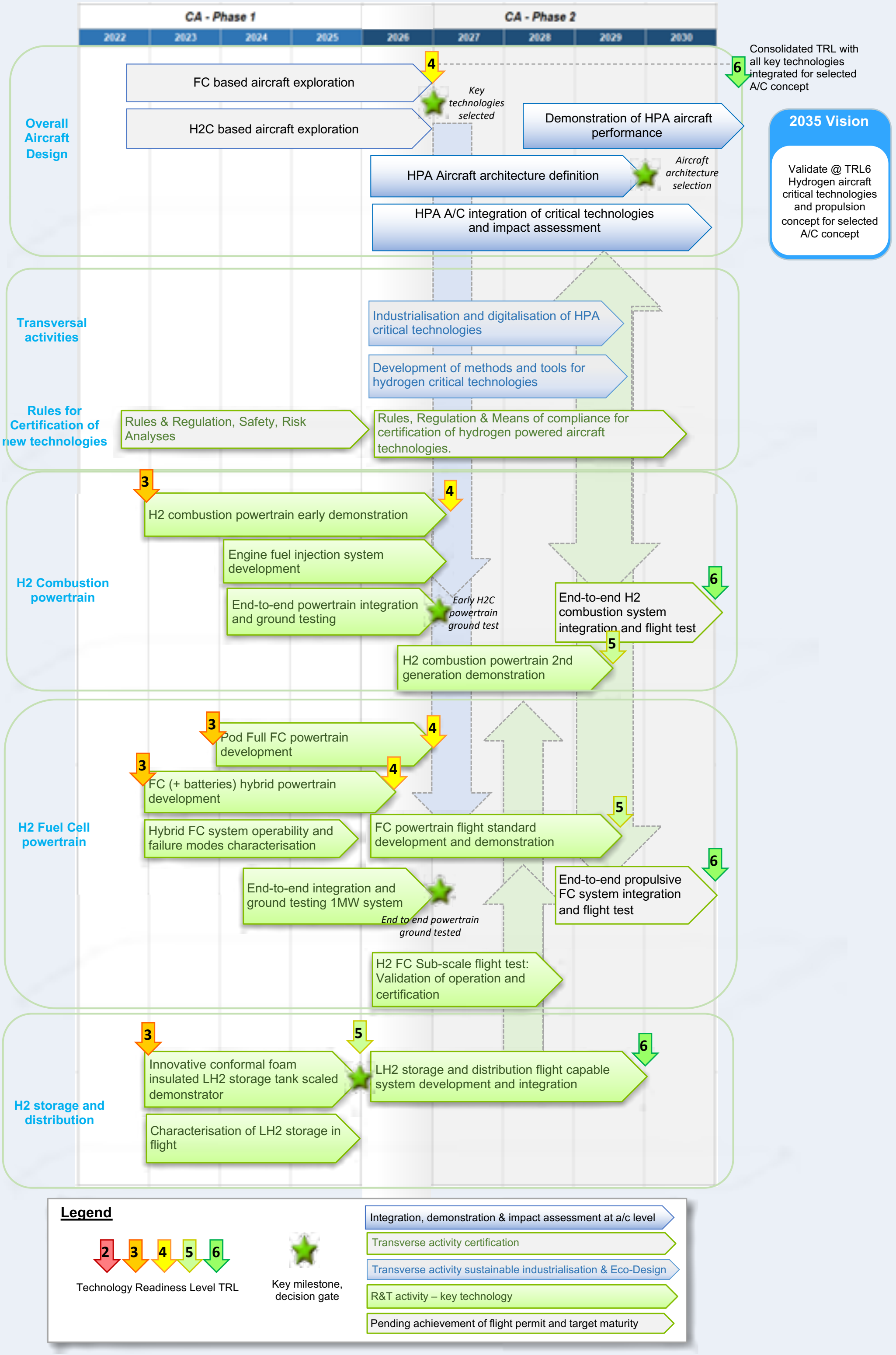
> **Include integration with the interconnected aircraft on-board systems,** including flight controls, thermal management and environmental control systems. Develop and validate the fuselage integration of liquid hydrogen systems and relevant features as part of an integrated demonstration.

The demonstration plan for a zero-carbon, hydrogen-powered, high-power class aircraft (i.e. multi-MW fuel cells or hydrogen combustion) will consequently follow a step-by-step stage-gate approach. Consistently, maturation of technology building blocks and enablers, plus all related safety and certification requirements, will be explored. Validation of these technologies will happen through ground and potentially flight demonstrations that support the qualification of the future hydrogen-powered aircraft, or any other spillover applications for other aircraft classes (e.g. REG).

The HPA pillar will include two types of validation demonstrations. Firstly, **targeted demonstrations will be ground-based** and aim to accelerate the acquisition of knowledge about what 'operating a hydrogen-powered aircraft' means. These will be early demonstrations, based on the assembly of available TRL 4 technologies at the launch of Clean Aviation or made available during Phase 1. Some of these demonstrations may need to be adapted under Clean Aviation, in order to target flight tests as soon as possible.

Secondly, **in-flight flying testbed demonstrations,** where relevant, will use systems better represent targeted aircraft concepts. These demonstrations will serve to validate the TRL 6 maturity of the technologies and associated concepts, during Clean Aviation Phase 2. Carried out at the end of the technological maturation, these demonstrations will be linked to integration activities completed in the SMR and/or REG pillar during Clean Aviation Phase 1, depending on the targeted market segment(s).

Figure 6.4: High-level HPA Gantt Chart



## DEMONSTRATION STRATEGY FOR HYDROGEN-POWERED AIRCRAFT CONCEPTS

For the full hydrogen propulsion technology, a representative hydrogen combustion engine or fuel cell propulsion system will be used for the demonstration, building on the results of Clean Aviation Phase 1, whenever possible and relevant, or on results derived from synergies with national programmes and/or other EU instruments. The size and technology of the system and engine will be selected in order to allow quick and efficient demonstration, while allowing easy scaling up of the global propulsion system. Due to the complexity of hydrogen-related technologies, further technology maturation activities could be considered to support the EIS of the hydrogen-powered aircraft concepts identified in Chapter 3, when relevant, based on the Clean Aviation Phase 1 results.

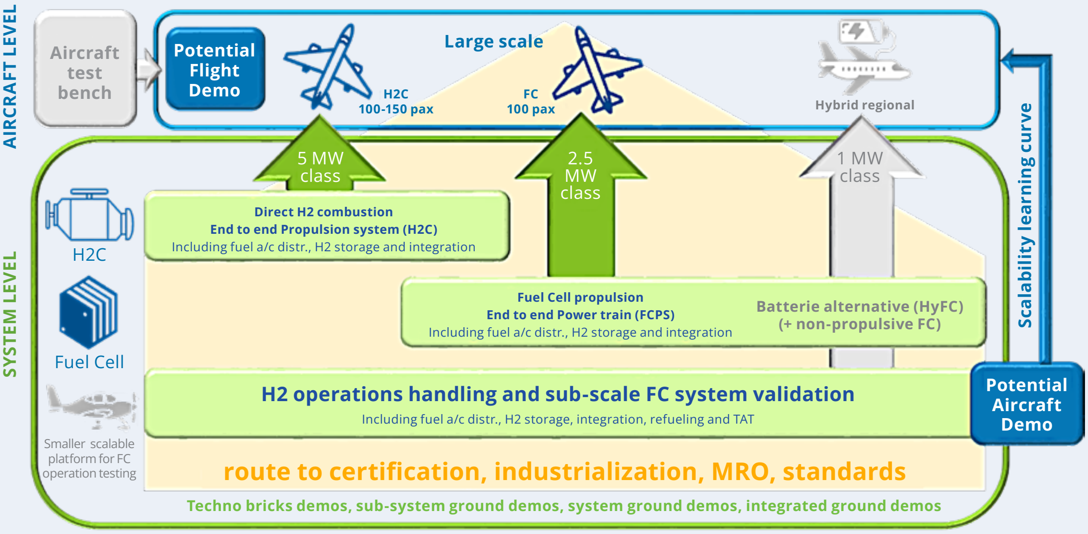
### GOALS OF THE VALIDATION DEMONSTRATIONS

- Become familiar with the use of hydrogen, the associated on-ground and in-flight operational and safety assessment for both hydrogen direct combustion and fuel cell propulsion.
- Explore exhaust gas features and fuel cell emissions: measure exhaust emissions, including high-altitude emissions with regard to contrails formation. Contribute to qualifying and quantifying contrails via measurements and/or simulations.
- Demonstrate viability of hydrogen direct combustion and higher efficiency fuel cell systems, including all Balance-of-Plant (BoP) aspects as zero-carbon propulsion options.
- Identify the enabling conditions for hydrogen technology deployment (e.g. design robustness, supply chain, product representativeness).
- Identify the enabling conditions for hydrogen-based aircraft (e.g. operations, safety, certification, industrialisation, MRO).
- Support the demonstration and the feasibility of integrating liquid hydrogen storage and distribution systems into aircraft.
- Demonstrate ability to supply and manage hydrogen fuel into an engine.

The demonstration strategy will encompass two technological streams that match the aircraft concepts reported in Chapter 3:

- Hydrogen direct combustion (H2C).
- Fuel cell systems as either a propulsion system (FCPS) or contributing to a hybrid-electric architecture (HyFC), as described for the REG pillar.

Figure 6.5: HPA demonstration plan



## VALIDATION DEMONSTRATION

The demonstration strategy will be based on a mix of ground test demonstration and in-flight demonstration, where relevant. Since the hydrogen-related technologies are highly disruptive, the demonstration plan must be flexible enough to build on obtained results. It should be regularly consolidated throughout Clean Aviation and adapted when necessary to match the expected impact.

### GROUND DEMONSTRATION

#### *Hydrogen direct combustion (H2C)*

- Hydrogen-powered thermal engine development and demonstration, with a focus on combustion (e.g. NOx emissions reduction while maintaining an optimal operability) including engine fuel system and related components and system integration and operability.
- Hydrogen engine and aircraft fuel distribution system integration.
- Hydrogen storage systems integration.
- Critical items to support system integration or item qualification for flight tests, including liquid/gaseous hydrogen tanks, valves, pumps and compressors, and heat exchangers.
- Fully functional H2C system including the adjacent ecosystems (i.e. liquid hydrogen (LH2) routing from tank to propulsion system, as well as refuelling technologies from airport to aircraft) with a focus on transient operations (management of LH2 vaporisation, pressure management, global heat management, etc.). Key learnings from Clean Aviation Phase 1 will be implemented and verified, to leverage the full potential of the enabling technology building blocks.
- Assessment of emissions of such a H2C system (including contrail risk assessment).
- Safety and certification: contribute, in collaboration with EASA, to the development of a real-life testing environment to assess the adequacy of future regulatory changes, including most appropriate means of compliance demonstrations.
- Supply chain readiness and industrialisation.

### *Fuel cell systems*

- End-to-end fuel cell propulsion system (FCPS) and fuel cell powertrain demonstration.
- Fuel cell system embedded in a hybrid-electric aircraft architecture (HyFC), with focus on the entire fuel cell system and aircraft efficiency, as well as scalability.
- Updated and optimised fuel cell hydrogen electric or full propulsive sub-systems, complete powertrain and the related key enabling technologies with ground test bench demonstrators targeting a full ground demonstration with hydrogen. Key learnings from Clean Aviation Phase 1 will be implemented and verified, to leverage the full potential of the enabling technology building blocks.
- Liquid hydrogen and gaseous hydrogen storage systems.
- Critical items to support system integration or item qualification for flight tests, including hydrogen tanks, valves, pumps and compressors and heat exchangers.
- Fully functional FCPS and HyFC system including the adjacent ecosystems (i.e. liquid hydrogen (LH2) routing from tank to propulsion system, as well as refuelling technologies from airport to aircraft) with a focus on transient operations (management of LH2 vaporisation, pressure management, global heat management, etc.).
- Assessment of emissions of such a FCPS and HyFC system (including contrail risk assessment).
- Systems impacted by the fuel cell system (e.g. High Power Electrical Network, EWIS, etc.).
- Safety and certification: contribute, in collaboration with EASA, to the development of a real-life testing environment to assess the adequacy of future regulatory changes, including most appropriate means of compliance demonstrations.
- Supply chain readiness and industrialisation.

For both technological streams, ground tests will be executed on qualifying test beds that are representative of aircraft integration constraints. This should allow TRL 5 to be reached at propulsion system level and TRL 6 at sub-system level for ground integration and testing with a focus on operability, and fuel system/engine integration.

In order to support the technological streams that might not be flight tested as part of Clean Aviation, integrated systems optimisation – e.g. fuel systems – should be continued in support of hydrogen technologies that aim at an EIS 2035.

## FLIGHT DEMONSTRATION

According to the results of the ground tests and related developments, the in-flight demonstrations will be based around the first results obtained during Clean Aviation Phase 1. Therefore, upon reaching acceptable system readiness and appropriate TRL maturity at ground test level for envisaging 'permit to fly', the flight tests of the hydrogen-powered aircraft technologies may be considered to serve the hydrogen propulsion technology feasibility and demonstrate TRL6.

A key objective will be to demonstrate the integrated functionality of a hydrogen system from tank to combustion and/or fuel cell system within a representative powerplant system. This must be done safely, in a minimum viable form, on the path to providing support to design and product options that serve the aircraft concepts envisioned in Chapter 3. Flight demonstrations will also address the necessity to measure non-$CO_2$ emissions at exhaust.

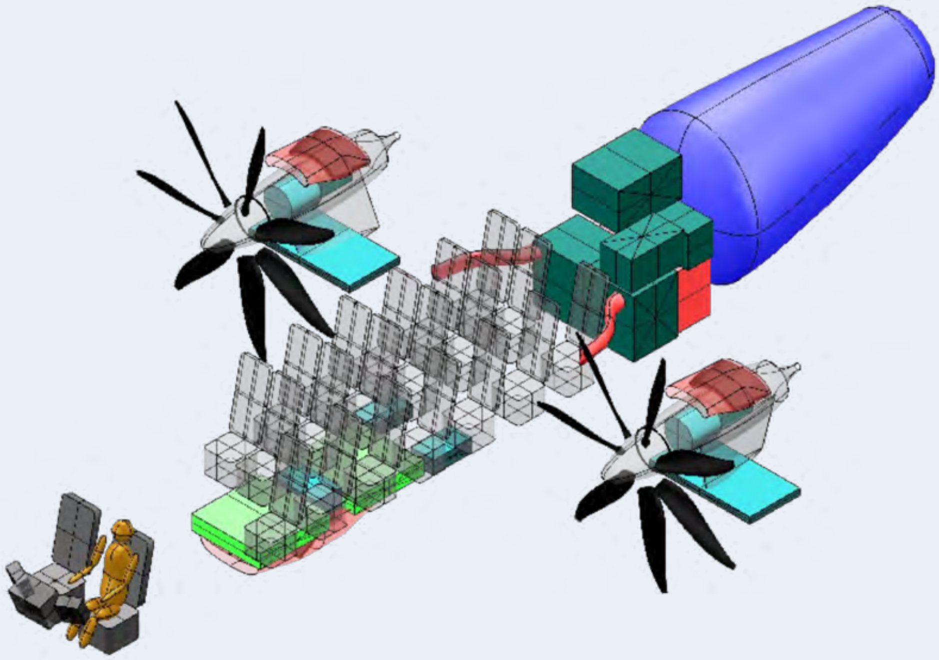
Such activities should also build on the work carried out during Clean Aviation Phase 1 and/or through synergies with e.g. Clean Hydrogen and national programmes. Continuation of the on-ground system demonstration, the consolidation of the supply chain and associated preparation of a 'permit to fly', etc.

Both propulsion concepts (H2C and FCPS) may be developed up to a flight test stage in parallel, because of different market segment targets for a first commercial application. Best test platform candidates will be assessed, in order to select the most relevant ones for demonstration in a further integrated environment. This will depend on the requirements that will be considered in the aircraft architecture studies and on the level of maturity of the technologies themselves.

Flight demonstrations will be carefully assessed, due to the high costs they entail for the demonstration targets. It will be important to assess the relevant technology readiness level and the maturity of the supply chain, as these are necessary to prove the feasability of the technology (H2C and/or FCPS). Because additional market segments could emerge from the possibilities offered by hydrogen technology, H2C and FCPS technological streams will be addressed in parallel, with an expected decision point around 2026: the preferred route for the earliest EIS 2035 application will then be selected. The non-selected route will however need to continue, as the application markets are.

It is expected that TRL 5+ (ground demonstration representative of flight test readiness) and/or TRL 6 (flight tests) will be reached at the propulsion system architecture level. The flying test beds used should be representative of a fully integrated propulsion system in a functional and integrated environment. This should support the granting of a permit to fly, flight test preparation activities, safety assessment, measurement of contrail characteristics at the exhaust position, control of the overall system, and integration of this system with adjacent aircraft systems.

**Figure 6.6: Small Aircraft (19 passengers) Hydrogen FC system integration concept**



Smaller scalable testing platforms (e.g. 19 passenger class aircraft as per Chapter 3) will allow validation of hydrogen-related safe operations, both on ground and in flight. This will result in a clear understanding of hydrogen handling, along with holistic integration of the fuel cell propulsion system with aircraft systems. Both the technical and qualification-related scalability need to be carefully demonstrated. This demonstration should occur early in the Clean Aviation Phase 2, in order to gain sharable experience on obtaining flight clearance. Such a demonstration could also be considered for validating fuel cell integration in the fuselage, in view of hybrid-electric propulsion architecture, as foreseen in the REG pillar. All knowledge derived from this early demonstration should contribute, where relevant, to the described higher end demonstrations.

Published by Clean Aviation Joint Undertaking in September 2024

**www.clean-aviation.eu**