Strategic research and innovation agenda

The proposed European Partnership for Clean Aviation

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Courtesy of DLR

Foreword

Substantial amounts of information contained within this document originate from before the coronavirus crisis

Information and figures, data and forecasts included in this document originate from before the coronavirus-related crisis. It is much too early to understand the full impact of the coronavirus-related crisis on short and mid-term traffic. However, it is clear that this crisis calls for even more action from the European Union institutions on green innovation and in support of the aviation sector's transformation than there has been to date.

- The need and challenge of tackling climate change is an unrelenting priority.
- Connectivity and mobility are essential to humanity. While we believe the long-term need for connectivity and mobility will remain strong, and demand for aviation will recover, the short- to medium-term will be significantly impacted.
- The capability of the sector to self-finance is rapidly eroding due to the severity of the economic and financial emergency that is propelling the aviation and aeronautics industries into an unprecedented crisis.
- For Europe to maintain a leading role in aviation its industry needs a level playing field. On the worldwide stage other economic powers such as the US and China are heavily supporting their sectors with R&I. The US has recently announced a significant stimulus package for the aeronautics industry going well beyond previous levels of R&I support and tax breaks. China's capacity to invest is comparable. There is a significant risk of losing jobs, intellectual property and activity if Europe does not invest proportionately and protect its sovereign capability.
- For the EU political agenda, the success of the Green Deal in aviation depends on the European aeronautics industry's ability to keep its rank on the worldwide stage through its capacity to export its aircraft and European technologies.

Making smart use of the recovery programmes being prepared in terms of accelerating the technology transition to a new, sustainable aviation system with green aircraft, engines and systems can position the European aviation and aeronautics sectors to take a commanding leadership role in a globally strategic value chain, ensure critical capabilities and set new global standards in sustainability.

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1. Introduction

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1.1. The global context

The Intergovernmental Panel on Climate Change (IPCC) issued a Special Report[1] 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 the report: A Clean Planet for All[2]. This report highlights the pressing need for deep decarbonisation. It shows the scale of the contributions from various sectors, including transport, towards the required level of decarbonisation in the EU by 2050 (**Figure 1-1**). Poignantly, the report singles out the severity of the challenge for aviation, and the need to tackle emissions using advanced technologies and fuels.

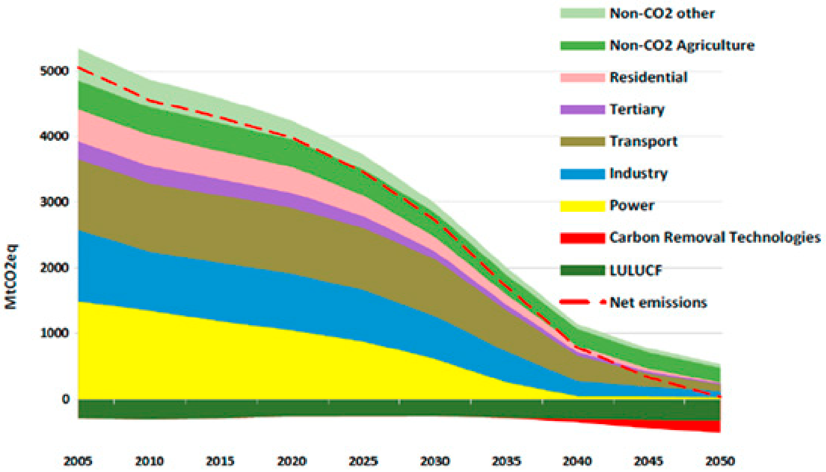

Figure 1-1: Europe's GHG emissions trajectory in a 1.5°C scenario.

The aviation industry's contribution to economic growth, societal development and cohesion is well recognised. While already subject to intense and increasing global competition, there is now an urgent need to address the developing climate emergency[3]. To avoid jeopardising its role and foregoing the benefits to citizens, the aviation sector has a duty to act. With the European Union's support, European aviation has the power to lead the way toward a climate-neutral system and set new global standards[4] in aviation.

The **European Green Deal**[5] will include 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, the newly launched **Industrial Strategy for Europe**[6] lays out the importance of industrial leadership in making the transformation to a green and digital Europe fit for the future. It states *inter alia* 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 ship building industries, as well as for alternative fuels and smart and connected mobility'.*

Air traffic growth has proven to be remarkably resilient[7] and has rebounded in several earlier cases after economic and political shocks (**Figure 1-2**). Global aviation demand is expected to quadruple between 2020 and 2050. This constitutes a promising outlook for the aviation sector and its users, and for new aircraft production. At the same time, it presents an increased challenge related to airport and airspace capacity, and strongly amplifies the issue of aviation's emissions and its impact on the environment and climate.

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[1] Intergovernmental Panel on Climate Change (IPCC) Special Report Summary for Policymakers (SPM) ISBN 978-92-9169-151-7

[2] A Clean Planet for All COM (2018) 773.

[3] European Parliament Declaration 25 November 2019

[4] The Brussels Effect: How the European Union Rules the World, Prof Anu Bradford, Columbia Law School ISBN 978-01-9008-838-3

[5] The European Green Deal, COM(2019) 640

[6] A New Industrial Strategy for Europe COM(2020) 102 final

[7] Airbus Global Market Forecast [GMF] 2019 – 2038

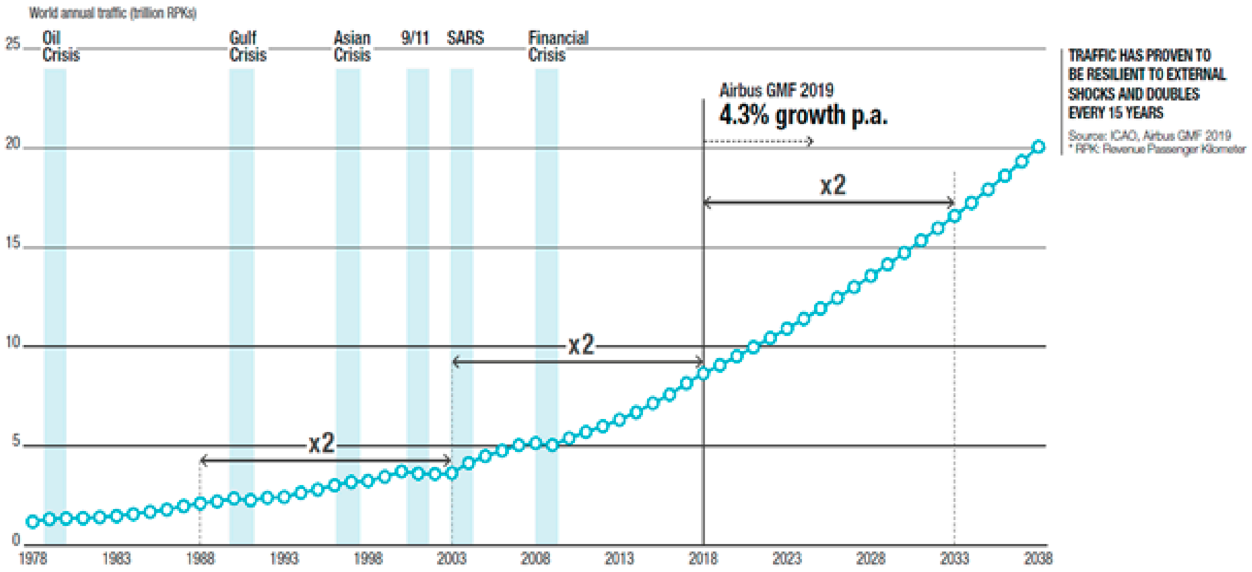

Figure 1-2: World Annual Traffic Forecast 2019 – 2038. (Source: Airbus)

The energy efficiency of aircraft has improved in leaps and bounds in the past decades: today's aircraft are 75% more fuel (and CO_2) efficient than aircraft from the early jet age. However, the growth of air transport has consistently outstripped these improvements. EU aviation CO_2 emissions increased from 88 to 171 million tonnes (+95%) between 1990 and 2016[8]. Worldwide, aviation CO_2 emissions more than doubled in this period. The growth rates currently forecast and the historical rate of technological improvements would lead to aviation's global CO_2 emissions tripling by 2050. If all other sectors achieve the emission reduction targets envisaged, aviation would constitute the overriding majority of humankind's carbon budget by mid-century.

Research indicates that of aviation's emissions, CO_2 and NO_x form the sector's main contributors to global warming, even if other emissions species contribute as well. Due to the extremely long latency of CO_2 emitted at common flight levels, addressing CO_2 emissions as the primary driver of global warming impact and steering policies and measures based on CO_2-equivalent emissions is justified, as this can ensure other emissions are appropriately factored in. As such, the primary challenge facing the aviation and aeronautics sectors in the coming decades is achieving *net zero emissions*. Alongside CO_2 reductions, reducing non-CO_2 emissions will require additional and different technical and/or operational solutions. Likewise, the overall life cycle impact of aircraft, their engines and systems from design, manufacturing, operations and disposal perspectives will need continued focus; in particular when implementing new technologies and materials and energy carriers.

Developing and maturing game-changing technologies and ensuring their rapid implementation in successful products is the only way to achieve the required impact in terms of a climate-neutral, economically prosperous Europe and a *sustainable European aviation industry*.

1.2. The challenge of transforming aviation

> The key challenge facing the aviation sector in this and the next decades is to develop and introduce safe, reliable, and affordable low- to zero-emission air transport for citizens and to concurrently ensure Europe's industrial leadership is maintained and strengthened throughout the transition to a climate-neutral Europe.

Transforming aviation towards climate neutrality will require an integrated approach spanning technology providers and innovators, manufacturers and operators, public sector authorities and travellers. It will involve

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[8] European Aviation Environmental Report 2019

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'. It will also require significant investment in new infrastructure to make new fuels and energy sources available. Innovative public policies and regulations will need to encourage and enforce renovation in operating networks and operations. Transforming from the current, entirely fossil-based kerosene fuel-powered system to such a future aviation system with multiple energy carriers and architectures constitutes **a massive and systemic challenge**.

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. As such, the overall research and innovation (R&I) agenda must be organised in a manner that addresses the complexities, risks and vigour of an aircraft development programme. European aviation R&I therefore needs an integrative approach that enables stable and long-term collaboration across the full innovation chain. The strong interdependencies between technologies, the integration challenges at an overall aircraft design level, and the timescales and risks involved call for a coordinated programmatic approach.

The European aeronautics community is convinced the trajectory towards climate-neutral aviation is achievable despite the level of complexity and interdependency. However, this will be contingent 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** by the relevant actors and proactive policies for wide-scale and economically viable use within the next decade;
- **optimised green air operations and networks** to fully exploit new aircraft and systems capability;
- a suitable **global aviation regulatory framework** creating the conditions for a transition.

EU institutions' and European Member States' involvement and support in implementing this will be essential in creating the conditions for ensuring this trajectory is successful.

1.3. The necessity for a European Partnership for Clean Aviation

The journey to a climate-neutral aviation system is well beyond the private sector's capability and capacity to invest alone. Equally, no single country in Europe has the financial, technological and industrial capability to affect the transformation, nor the capability to promote and support the required changes to global rules and operative frameworks necessary to implement those solutions. The European additionality is evident. A new, institutionalised European Partnership for Clean Aviation focusing on the most impactful solutions constitutes the most effective approach that can adequately reduce the industrial risk for transformative research and innovation (R&I). This approach will secure the long-term industrial commitments needed for long innovation cycles. It is the best assurance for keeping an effective and vibrant, competitive ecosystem across academia, research organisations, SMEs and industry closely collaborating to achieve the common objectives in line with the societal challenge.

An institutionalised partnership with the public interest as represented by the Commission 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. It can ensure close alignment with the Commission's policy leadership. This will be instrumental in creating the regulatory/legislative and economic conditions for a successful deployment of globally competitive new aircraft with disruptive performance gains into the aviation system, in time for the necessary impact by 2050.

Achieving an early and meaningful impact is critical in light of the 'climate emergency' as seen by Europe's citizens, recognised by the European Parliament and highlighted in the Commission's agenda for the Green Deal. Developing new processes and technologies to accelerate product introductions and in parallel provide the potential to upgrade existing aircraft will be key. Accelerating this requires the development of relevant regulations and infrastructures that can ensure new vehicles are safe, operable and affordable. This will entail close harmonisation with future safety standards and certification requirements, thus involving the European Union Aviation Safety Agency (EASA) early in the research phase. This can help in significantly reducing development time and cost, and ensuring that disruptive new technologies meet the highest levels of safety and reliability.

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 bring a decisive contribution towards 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.

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2. Vision, impact and commitment

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2.1. The vision for a Clean Aviation Programme

Clean Aviation will contribute to the delivery of Europe's climate neutrality by 2050 by pioneering new solutions in the aeronautics disciplines, addressing the relevant EU policy priorities (e.g. the Green Deal) and supporting the sector-wide ***European Sustainable Aviation Roadmap***[9]. It will trigger a technology revolution that will target climate-neutral aviation in Europe by 2050. Ambitious zero- and low-emission technologies will drive the transformation. These include hybrid-electric solutions for regional and short-range flights and ultra-efficient aircraft designs utilising thermal engines suited for the adoption of sustainable aviation fuels (SAF) covering the larger and more energy intense medium and long-range sectors.

Clean Aviation low- and zero-emission technologies will allow fuel efficiency gains of one-third to one-half in 2050, compared to today's fleet. In addition, the partnership will enable aircraft, engines and systems to utilise the full potential of low- or zero-carbon fuels, including potential disruptive innovations such as hydrogen. Together these outcomes will accelerate the transition towards climate-neutrality.

Together with the large scale deployment and use of new, net-zero or fully decarbonised sustainable aviation fuels such as power-to-liquid synthetic fuels, methane and/or hydrogen, the operating fleet in 2050 could achieve a 90+% improvement in carbon efficiency compared to today's fleet. The sector can meet the Air Transport Action Group's (ATAG)[10] goal to halve total CO_2 emissions in 2050 compared to 2005 levels, while maintaining its forecast growth. The ATAG commitments are schematically depicted in **Figure 2.1** below, where the European aeronautics sector's approach in terms of contributing change drivers is shown.

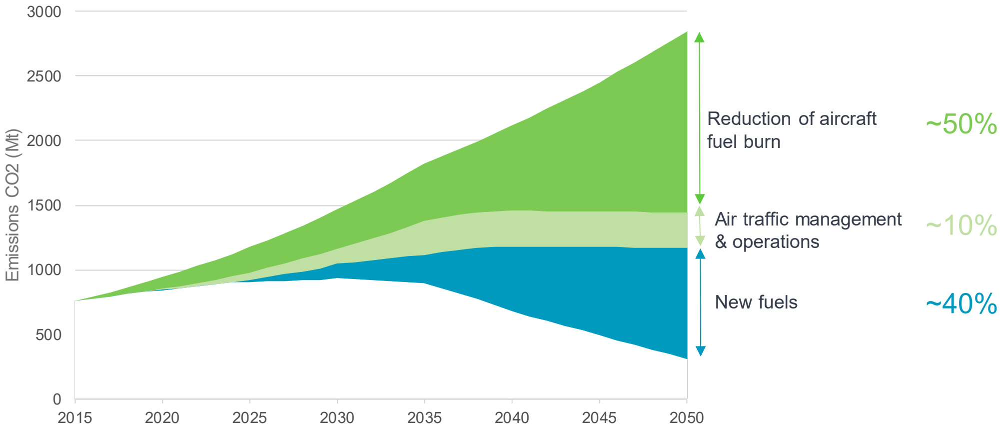

Figure 2.1: Schematic of the ATAG goals and change drivers

The more mature air transport system in the EU has a markedly lower compound annual growth rate (CAGR): global forecasts are roughly 4% CAGR whereas EU internal aviation growth is more likely to be within 1-2% CAGR in the coming decades. This will allow European Aviation to go considerably further and achieve carbon neutrality earlier than in many other global regions.

The ultimate objective is to reach net-zero greenhouse gas emissions, and to enable a *climate-neutral aviation system in Europe* by 2050.

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[9] Publication under preparation, publication foreseen in May 2020

[10] www.ATAG.org

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

To reach the goal of climate neutral aviation, a *new breed of aircraft* with entirely new configurations allowing significantly lower environmental impact will be required. These aircraft will need to start entering the air transport system in the 2030s to have any serious impact by 2050. In addition to these aircraft, innovations will be developed and introduced that can already contribute to emissions reduction by 2030 in line with the European Green Deal.

The ambition of the Clean Aviation Partnership is to ensure that advances in breakthrough technologies will allow new aircraft developments by 2030, enabling maximum progress towards climate-neutral aviation, meeting socio-economic expectations, and providing benefits for European society and businesses.

Clean Aviation will build on important earlier research under previous Framework Programme R&I (such as 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**):

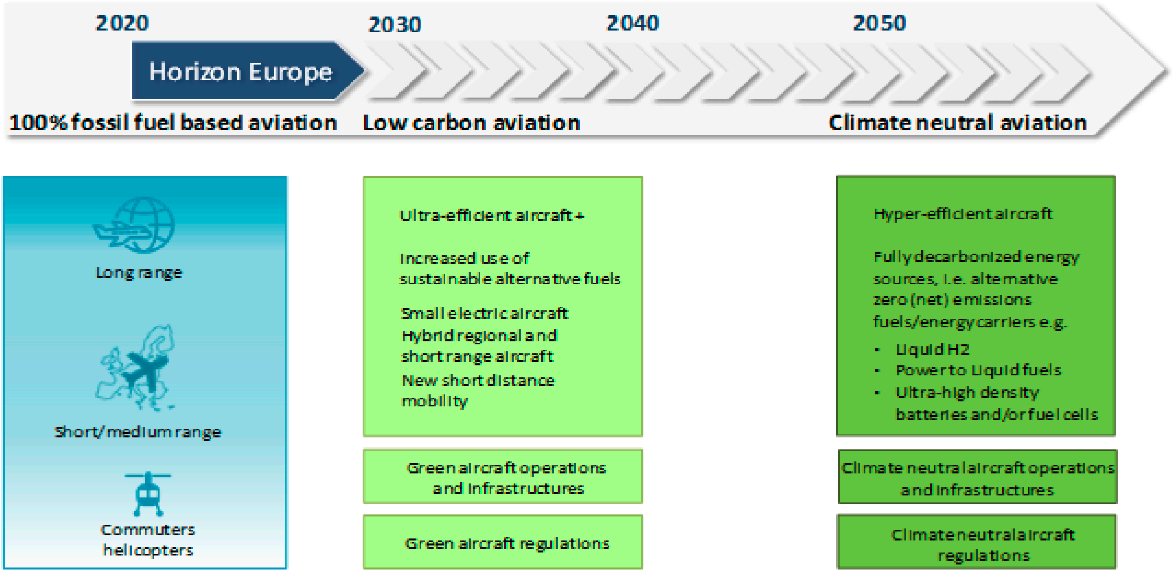


Figure 2.2: Two horizons in the trajectory towards climate neutral aviation

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 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 full climate neutrality by 2050 in parallel to this and bring these to a maturity that can allow appropriate scaling across the full spectrum of aircraft segments and flight operations, including long-haul travel.

The demonstration efforts in the proposed programme will focus on bringing decisive progress in technology maturity and performance to two pivotal aircraft concepts (see for detailed descriptions Chapters 3 and 4): ultra-efficient short/medium range aircraft and hybrid electrical regional and short-range aircraft. Aircraft in these (broad) performance 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 green trajectories and operations, and with accelerated transition to low- or zero-carbon fuels. The technology development strategy within these efforts will create significant positive spillover effects towards 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, deployment in the market, and 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 need to spark the rapid transition to new sources of sustainable energy and aviation fuels, which will have to be available within far more aggressive timescales than anticipated to date.

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 development and, for example ground demonstrations, to large-scale, highly integrated high technology readiness level (TRL) demonstration projects. Technolo- gies 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), 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 and 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 programme scope and duration can enable the full maturation and validation cycle of two 'clean sheet' new aircraft concepts as described in chapters 3 and 4. 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, certificability 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 new aircraft programmes through increasingly integrated demonstrations, and include a viable route to certification. The detailed roadmaps for the second phase of the programme will be based on the configuration decisions in the first phase. 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 involving European aviation stakeholders, in order to ensure maximum efficiency in the exploitation of research results and in the programme's impact.

The overall programme approach towards the final demonstrators will allow a broad participation during the technology development and progressive demonstration phases. Transferring disruptive technologies from development into the demonstration phase will require a staged validation of concepts and architectures. 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 a broader array of applications and exploitation routes than the two target demonstrator aircraft of the programme, thus additionally leveraging the economic return of the R&I efforts.

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 the commitment that it made in 2005 to halve its CO_2 emissions in 2050 compared to 2005 levels – including overall system growth – and transforming aviation towards climate neutrality, an overall improvement of at least 90% in net carbon emissions per passenger-kilometre is considered 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 (LH_2) based energy systems. Investigating these non-drop-in fuel concepts necessitates significant research into the technical system requirements. Progress beyond the ATAG goals towards climate neutral aviation by 2050 would be feasible via hyper-efficient aircraft using fully decarbonised energy sources on the path. Progressive demonstration through Clean Aviation will lay the foundation for a zero-emissions long-term outcome.

Finally, Clean Aviation will also monitor the conditions for which its solutions will have a smooth and wide impact. For new, disruptive aircraft to succeed in terms of market acceptance, an important trade-off exists 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 upon 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 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. Linking research and technology demonstration with effective public policies will redefine market conditions and accelerate market adoption.

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

2.4. Approach and targeted aircraft performance gains

Three key *thrusts* for the R&I efforts have been identified that will drive the energy efficiency and the emissions reductions of future aircraft.

- **Hybrid electric and full electric 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.
- **Ultra-efficient aircraft architectures** – to address the short, medium and long-range needs with innovative aircraft architectures making use of highly integrated, ultra-efficient thermal propulsion systems and providing disruptive improvements in fuel efficiency. This will be essential for the transition to low/zero emission energy sources (synthetic fuels, non-drop in fuels such as hydrogen), which will be more energy intensive to produce, more expensive, and only available in limited quantities.
- **Disruptive technologies to enable hydrogen-powered aircraft** – 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 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 setup 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 is required to maximise impact. The thrusts will chiefly target two pivotal aircraft demonstration programmes (as highlighted in paragraph 2.2): the hybrid electric regional and the ultra-efficient short-medium range aircraft concepts. These aircraft 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. The two aircraft demonstration programmes 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 aforementioned thrusts to the most relevant aircraft categories (**Figure 2.3**).

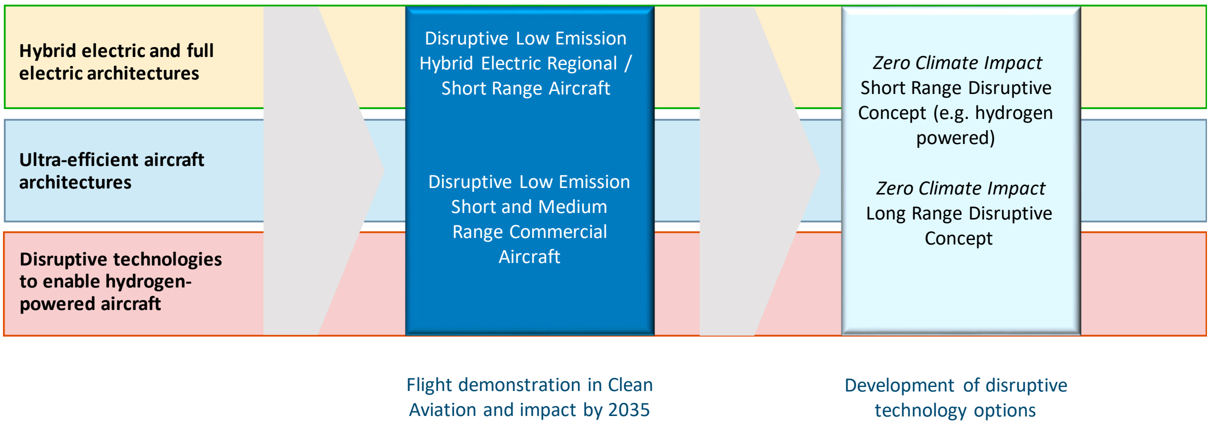


Figure 2.3: Mapping of the research thrusts against aircraft categories and concepts

While the primary focus of the demonstration efforts will be on the hybrid electric regional and the ultra-efficient short-medium range 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: on one hand towards commuter and vertical lift applications that can benefit from the hybrid-electric technology development; on the other hand from the ultra-efficient architectures towards long-range applications. 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.**

The figure highlights the priority areas for research, which can lead to early adoption, i.e. where high technology readiness level (TRL) outcomes will result. The target performance levels across the aircraft categories selected for demonstration in Clean Aviation are below in **Table 2.1.**

Aircraft Class	Key technologies and architectures to be validated at aircraft level in roadmaps	Earliest EIS Feasibility	Fuel burn reduction (technology based) [1]	Emissions reduction (net – i.e. including fuel effect) [2]	Current share of air transport system emissions
Regional Aircraft	Hybrid-electric, distributed propulsion coupled with highly efficient aircraft configuration	~2035	-50%	-90%	~5%
Short-Medium Range Commercial Aircraft	Advanced ultra-efficient aircraft configuration and ultra-efficient gas turbine engines, ultra-high bypass (possibly open rotor)	~2035	-30%	-86%	~50%

Table 2.1: Clean Aviation aircraft category targets

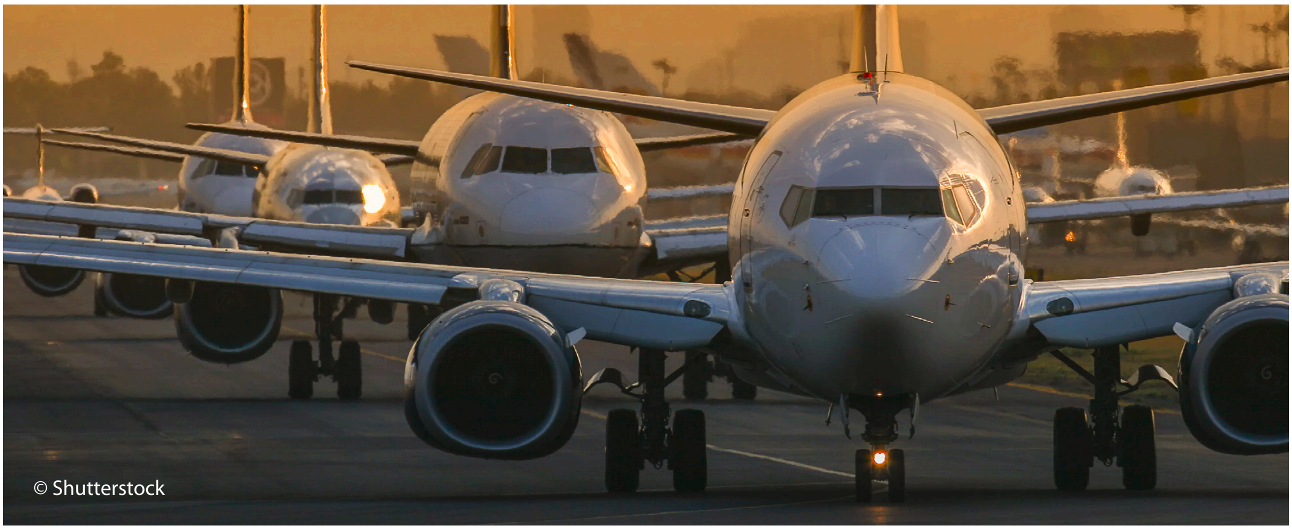
The impact of Clean Aviation technologies on other aircraft segments via the scaling and transfer of technology referred to is as follows (**Table 2.2)**

Aircraft Class	Key technologies and architectures to be validated at aircraft level in roadmaps	Earliest EIS Feasibility	Fuel burn reduction (technology based) [1]	Emissions reduction (net – i.e. including fuel effect) [2]	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 Full electric concepts utilising hydrogen fuel cell based propulsion (augmented with advanced battery technology energy storage)	~2030+	N/A	-87 to 100%	~1%

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

[1] Improvement targets are defined as fuel burn reduction compared to 2020 state-of-the-art aircraft available for order/delivery

[2] Assumes full use of SAF at a state-of-the-art level of net 80% carbon footprint, (or where applicable zero-carbon electric energy)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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 geared towards climate neutrality by 2050 (**Table 2.3**). The overall European aviation system forecast progress, and the Clean Aviation contribution is shown here below:

Year	European Aviation's forecast progress towards the Green Deal objectives
2030	• Efficiency and emissions in the European aviation fleet in operation have improved, as the benefit of fleet replacement (roughly 2% improvement per annum) will exceed growth in intra-EU travel volumes (currently around 1% per annum). • Technologies from the Clean Sky and Clean Sky 2 programmes suitable for retrofitting in the existing fleet or 'forward fitting' in product enhancements will allow additional efficiency gains and related impact. • Optimised flight trajectories and 'smart' redesign of flight operations (speed, cruise altitude, routing, and potentially utilising operational concepts such as flying in formation) developed in close collaboration with SESAR JU will allow further improvements of at least 5%. • The ramp up of low carbon sustainable aviation fuels (in first instance sustainable bio-fuels) up to around 15% usage by 2030 will bring further gains of up to 10%. • The next generation of disruptive aircraft offering 30 to 50% lower fuel burn and emissions compared to 2020 will emerge from the Clean Aviation research and demonstration phase at a high R&I technology readiness level (TRL). • Regional and SMR aircraft **will be defined by 2030 so they can be available for airlines 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 ~75% of the fleet replaced by 2050. • Technologies matured through Clean Aviation will become available across the majority of aircraft classes, the 2050 operating fleet will be one-third to one-half more fuel-efficient than today's fleet. • The continued acceleration of the use of sustainable fuels and optimised 'green' operations will deliver progressively lower net emissions compared to 2030. • European airport, ATC and energy production improvements will be synchronised in support of the introduction of the new aircraft and fuels/energy systems. • Further breakthrough technologies developed and matured beyond Clean Aviation, coupled with full deployment of sustainable aviation fuels and alternative energy carriers will lead to fully climate-neutral aviation in Europe.

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

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, reaches or surpasses International Civil Aviation Organisation (ICAO) environmental goals (on global emissions, local air quality and noise) and meets EU mobility targets. Clean Aviation will contribute to all dimensions of Horizon Europe. See (**Table 2.4**).

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; • Accelerate development of know-how and knowledge transfer for key new technologies and 'differentiators'; • Create new high-value skills and new engineering capacities for future generations of the European workforce; • Create models and metrics for new and different lifecycle 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; • 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; • Fulfil customer and general public expectations of a globally competitive European industry; • Offer innovative solutions that improve the mobility and connectivity of European citizens with safe, reliable, affordable and resilient air travel options; • Utilise lifecycle '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; • Enable valuable spin-off opportunities that will benefit European citizens through exploitation in critical areas such as disaster response, emergency interventions, space and security; • Facilitate new safe and efficient airborne transport modes that have the potential to reduce traffic congestion in highly populated areas, and connect remote regions; • 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, artificial intelligence, electronics, materials); • Support the European Commission where appropriate regarding input for policies including international coordination and extracting benefits for Europe

Table 2.4: Impact dimensions of Clean Aviation

The partnership will set up an **Impact Monitor** to serve private and public stakeholder needs to monitor the progress of their joint efforts in the Clean Aviation Programme. Its outputs can help to accelerate the trajectory towards climate neutral aviation. The benefit of an integrated Impact Monitor being part of the programme stems from the close collaboration of all stakeholders on the implementation; and the accessibility to key data and results needed. The Impact Monitor will build on the project efforts and their achievements, their progress against objectives and their contributions to overall impact. It can support strategic decisions in the optimisation of the programme's resource allocation and direction of efforts. It will establish effective mechanisms across all relevant R&I efforts to collect and assimilate research results and their potential benefits, from integration studies up to large-scale demonstrations, to weigh and deliver valuable impact information. The goal of this new instrument will be to summarise and visualise the cumulated programme impacts versus the aviation sector's trajectory towards climate neutrality, including interdependencies between technical, operational, and environmental dimensions. The Impact Monitor will provide data collection, modelling, and simulation-based assessments in order to assess progress towards the ultimate goal of climate-neutral aviation. The regular reporting of the outcomes will provide valuable information to the private and public stakeholders to support their dialogue with internal and external counterparts regarding environmental facets, life-cycle aspects, climate impact, policies, required infrastructures and critical success factors for the transition to climate-neutral aviation. Where needed, it can support the definition of research topics that are needed to form the required level of understanding in terms of impact, and provide an input to the decision on where and how to commission such research projects.

The configuration and overall set-up of the Impact Monitor and its links to the partnership's technical programme as well as interfaces with other research initiatives within Horizon Europe and beyond will be subject to elaboration in the preparation of the partnership's first bi-annual work plan.

2.6. The commitment towards a Clean Aviation partnership

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 can finally lead to an overall private investment in product deployment of more than €5 000 billion by 2050, see **Figure 2.4** below.

In close collaboration with the Commission as public partner, the partnership can play a central role within a European **'innovation architecture'**, ensuring shared roadmaps and synergies with EU collaborative research, other relevant European Partnerships and EU research programmes; national research and innovation programmes, and European structural investment funds and financial instruments (see paragraph 2.9). Within this architecture, the Clean Aviation Partnership should mobilise impact-orientated research representing a relevant and significant share of the total estimated R&I effort needed. Further EU level collaborative research dedicated to aeronautics would need to address the wider agenda, e.g. upstream exploratory research towards future breakthrough technologies.

The approach proposed in this SRIA will require a research effort of around €4.5 billion as a key component of the overall €12 billion effort. This would require a funding level of €2.5 billion over the life of the programme, based on the participation of research organisations as well as industry and on appropriate funding rates and mechanisms.

The overall leverage effect in the partnership of EU funding to private investment in the research phase alone (so not including the development beyond the research phase is expected to be ~ 200%, 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.

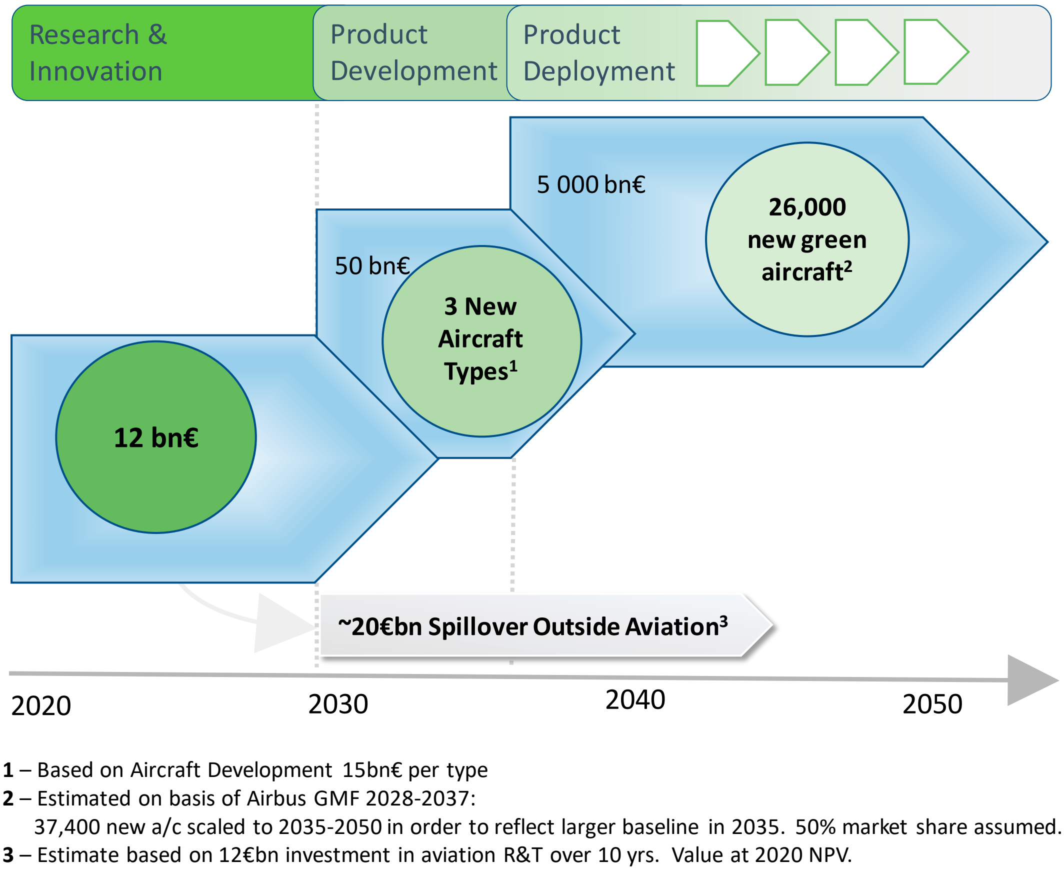

Figure 2.4: Impact dimensions of Clean Aviation

Spillover effects are positive contributions to the broader economy. Aerospace technology requirements are amongst the most extreme of any industry. Because of this, it 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, it often finds other commercial uses, 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.

2.7. Instruments

The 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 Clean Aviation Partnership will function via open and competitive calls. These will be 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 programme 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 will enable a realistic and fast uptake by the market, thereby introducing green aviation operations and delivering expected benefits for citizens.

Open and transparent calls will be the principle for the selection and allocation of all Union funding.

The approach 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 Plan (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 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 in order to allow for tailored and time-limited contributions from partners (in particular from SMEs), 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. In addition, the grant agreement framework should be flexible in terms of duration, budget allocation and composition of its core partnerships.

2.8. Policies, standards, rules and infrastructures

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. 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 sufficient impact by 2050.

As technologies become ever more complex, redesigned methods and processes will be essential to guarantee the compliance of innovative and disruptive technologies with certification requirements. Examples of disruptive technologies, which are at the core of Clean Aviation and will need an integrated and close involvement of certification experts in the research phase, include active control, hydrogen fuel, and very high voltage. Digital solutions can contribute significantly by reducing the duration and cost of development and validation phases while maintaining or increasing safety. The involvement of EASA's experts, acting together with industrial and research teams for their conception and endorsement, is essential to achieve this objective. Maintaining full traceability and digital continuity of all shared information will make the overall product definition life cycle more robust and much faster.

New aircraft configurations in terms of payload/range combinations can improve the sustainability and efficiency of the transport system, e.g. by using small zero- or very low-emission aircraft.

2.9. Maximising impact through Synergies

Strong collaboration among scores of participants spanning different sectors will be essential to close the gap towards 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). These should share commonly agreed objectives, R&I roadmaps and timelines with the Clean Aviation Partnership, as well as agreed rules for involvement and cooperation. The partnership will implement a strategic programming mechanism for all necessary research and innovation activities across Europe and across disciplines. The programme and its stakeholders will make maximum use of resources spanning national and regional efforts as well as transversal synergies to leverage non-aerospace capabilities towards the programme's activities and objectives. Strategic collaborations will help identify potential solutions based on emerging technologies (including those from other sectors) and consider their implementation on the new aircraft concepts. This will include the assessment, adoption and development of technologies, skills and methods 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 will 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.

Synergies with other sectors

The exacting requirements, standards and safety requirements for aerospace applications lead to extremely reliable systems and solutions. History has repeatedly shown that once these are established, the spin-off to other sectors is substantial. UK analysis has shown that the rest of the economy (non-aerospace) receives a return over four times that of the aerospace sector due to aerospace R&D investment. Conversely, in some cases key technologies from outside aviation will have a high potential for leveraging synergies within this SRIA. One example is the space sector, where decades of experience in highly safety-critical applications of hydrogen technologies can serve as an important stepping-stone for the challenges related to this research agenda.

Approach towards the European Partnerships and Horizon Europe instruments

Within Pillar II of Horizon Europe, Clean Aviation will reside within the cluster Climate, Energy and Mobility. The partnership will need to have effective and efficient means to draw key results from a collaborative research programme for aeronautics. It will need to develop and exploit synergies with the Integrated Air Traffic Management [aka SESAR]. Synergies with other proposed Partnerships in that cluster are most notably (but not exclusively) with Clean Hydrogen (fuel cells, as well as hydrogen, as potential fuel sources) and European Battery Research.

Outside the cluster Climate, Energy and Mobility, the Digital, Industry and Space 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. For instance, more opportunities exist within Key Digital Technologies [aka ECSEL] for many subsystems and electronics solutions that can be applied to the aeronautical case. The Made in Europe Initiative, which deals with advanced manufacturing, can bring key enabling technologies to take new disruptive products successfully into production and into service.

Synergies with other EU national and international funding programmes

Another important lever for synergies is the link to national innovation through cooperation agreements and steering mechanisms, which can enable coordinated and/or joint programming. The national innovation schemes across Europe are complementary to aviation R&I and can deliver solutions in support of the Clean Aviation ambitions. Organising this will require a clear, shared, flexible and easy-to-implement framework spanning Member State and Union levels, based on a common vision with respect to the interventions needed to create the future climate-neutral aviation system. In some cases, Important Projects of Common European Interest (IPCEI) can be a relevant mechanism (e.g. for battery technology development and industrialisation). The partnership can play a key role in the creation and leveraging of these synergies through the combined efforts of the Commission and the private members as joint partners.

Smart specialisation strategies (RIS3) and related structural and regional development funds

Collaboration with regions with relevant smart specialisation strategies (RIS3) for aeronautics or related specialisations, and ESIF Operational Programmes in place or under preparation for 2021-2028 can be crucial for building a broad-based commitment and achieving significant synergies. Regional funding mechanisms can be a highly effective means to accelerate industrial investments and to widen Member State participation (EU13). Member States or regions may transfer a share of their financial allocation to augment the budget set for Clean

Aviation and support the execution of the SRIA. This can complement the Union contribution as set for the partnership.

Leveraging other funding sources from within the scope of the multi-year financial framework (MFF)

In line with the stated policy of extracting horizontal synergies and efficiencies beyond Horizon Europe, the other instruments can take the partnership's activities further and strengthen the impact. The Connecting Europe Facility (CEF) can facilitate market uptake where deployment is strongly dependent on infrastructure development. As is currently developing, the link to the European Innovation Council (EIC) can provide significant opportunities for transferring R&I results delivered by SMEs into the next phase of development and market deployment. European Investment Bank (EIB) financing and InvestEU can be effective multipliers in areas of the supply chain where access to commercial finance is limited. An important option could be 'green finance' for airlines: enabling earlier and more aggressive rollout of new aircraft in their fleets. Equally, proposed policy initiatives in the frame of the Green Deal can be of significant relevance. These may include alternative approaches involving the scope and permits of the EU Emissions Trading Scheme (ETS), and measures to accelerate the deployment of low-carbon fuels.


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3. Disruptive technologies for a Hybrid Electric Regional Aircraft

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3.1. Introduction

Greater attention to environmental aspects (even with stringent regulations) and higher market demand are changing the scenario of air mobility in the short range, centred on 500 km and up to 1000 km. On one hand, operators could progressively increase the average capacity of their fleet to sustain unit cost and to face the increasing traffic demand. On the other hand, this could lead to a reduction in the frequency of flights to and from some destinations or a lesser use of the smaller airports which are not organised to accommodate high capacity aircraft (infrastructure limits, passenger services, etc.), thereby not meeting the societal objectives for fast and flexible mobility at low environmental impact.

Operators and society expect regional and inter-urban air mobility to propose innovations for air vehicles and frameworks that are able to match all the above needs and fulfil expectations for better environmental and operative efficiency, new services, larger networks, optimised frequency and new business opportunities at reasonable overall cost.

Currently, regional aviation has a relevant role in the management of that air mobility share: thanks to their widespread diffusion, regional aircraft-operated routes and connections account for over 12% of world ASK (available seat kilometers). Roughly, regional aircraft currently serves 38% of world city pairs and performs about 40% of the total departures and around 36% of the total flown hours. In terms of regional connectivity, 36% of existing airports are relying exclusively on turboprop-operated services. Regional aircraft and other air vehicles such as aircraft commuters and rotorcraft, both traditional and tiltrotor, may further expand and complement air mobility offers below 1000 km. The propulsion innovations studied in this section and globally in Clean Aviation may open up new business scenarios.

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The final demonstration is a regional aircraft with technologies ready for entry into service by 2035, incorporating product-viable solutions for technologies, integration, infrastructure, and certification. The aircraft will include hybrid-electric propulsion supported by 100% drop-in fuels for the thermal power source, to reach up to 90% lower emissions while being fully compliant with ICAO noise rules.

Vision 2030 and following

By mid-2030, the mobility of people and goods is expected to undergo progressive changes, especially over distances of less than 500 km (inter-urban regional connections). Innovations and technologies related to propulsion, optimisation of different fuel types and airframe characteristics will reach higher levels of maturity, becoming available for regional air transport as well as other present and future air vehicles operating in that distance frame.

Air vehicles operating in this range and operational environment (including regional aircraft with a capacity of up to 80 seats) are considered the first application in the scheduled air transport system that will adopt hybrid-electric propulsion technologies for reducing the environmental footprint, toward climate-neutral aviation. Air vehicles operating at smaller distances or on thinner routes will also benefit from electric propulsion solutions tested on regional aircraft testbeds, by sharing the development of power modules and making use of different approaches to air vehicle integration.

Regional air transport is a laboratory for other domains in the partnership. The vision for 2030+ is to demonstrate innovative and disruptive technologies, enabling new aircraft performance levels, and opening up new business models. This approach will consider future societal demands in terms of people and goods transport, as well as environmental and system constraints such as short field length capabilities, cockpit workload, simplified operations, quick turn-around times, dense air traffic, and small airport infrastructures.

Rationale and main issues

In order to identify the most efficient aircraft architecture, different propulsion and aircraft configurations (see **Figure 3.1)** will be initially assessed in trade-offs (i.e. turbo-electric distributed vs. parallel/serial propulsion, or any mix, including, for example, transfer of electrical power onto the engine shaft). These will be explored by investigating different levels of hybridisation and different primary energy sources including options for a thermal engine or potentially a fuel cell as part of the hybrid (or full-electric) configuration. In parallel, technologies and solutions that are able to shorten time-to-market and affordability will be pursued and then used to achieve the climate-neutral aviation target of Clean Aviation. The development of regulations and new infrastructure to support such disruptive aircraft configurations is a key complementary issue to be addressed in order to realise the market potential.

All activities will consider scalability to other air vehicle applications both at low and high end: specific activities and testing will assess this and resolve specific features. Finally, the impact of market measures on air mobility over distances below 500 km as well as up to 1 000 km will be assessed and considered within the wider multi-modal, intermodal mobility scenarios.

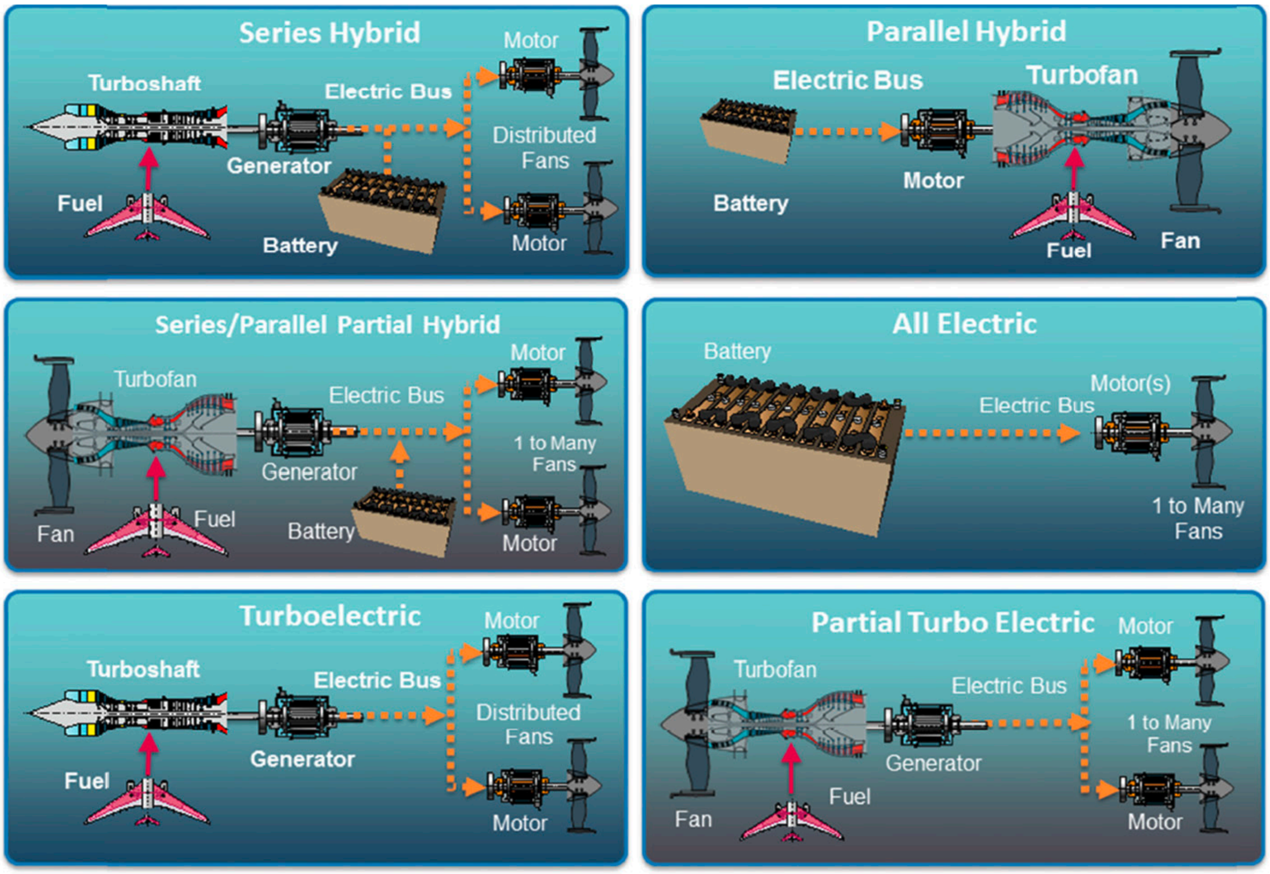

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Figure 3.1: Electric Propulsion architectures.

Complexity and design activities

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, introducing new parameters not considered in the market before. The integration activities of the hybrid-electric regional platform account involve four interdependent areas of research described in 3.1 below. They also offer solutions that may apply to other aircraft segments and products and enable further benefits to accrue.

All activities described in this section are organised in a **first phase** (up to 2025) where the building blocks and different integration options will be studied back-to-back for their potential and integration perspective to identify the most promising architectures. A **second phase** will further mature the technologies selected for the demonstrator and deliver suitable final solutions ready for integration. This second phase will also mature some technologies not ready for the demonstrator but valuable for actual aircraft integration in 2030.

3.2. Key technologies and their contribution to the clean aviation ambition

3.2.1. Key technologies to reduce greenhouse gas emissions

Electric propulsion for aircraft now appears feasible given the extraordinary progress envisaged in the high electrical power, high voltage and electricity storage technologies. The key synergic aspects to tackle, which do differentiate the aerial electric propulsion from automotive, are power size (up to many MW), environmental constraints (low operative air pressure and temperatures) and power and capacity density (with weight and volume being paramount factors). Even if progress in electrical technologies are significant, fully electric propulsion, with electrical energy storage as the only source of propulsion power, will be reserved to commuter and small rotorcraft at a small range or flight duration. Whenever larger size, higher power or longer flights are necessary, as in regional, SMR or larger aircraft, partial electrification of propulsion through hybridisation, mixing electric engines and electric energy source with optimised turbo machines, will be the choice. Full electric and hybrid propulsion can be considered as a continuum at different stages of hybridisation with related technologies, complexity, safety and integration evolving at a different pace depending on air vehicle application and potential for scalability. Electric propulsion offers additional degrees of freedom for optimising the aircraft performance and reducing fuel consumption, also opening up a new design space for aircraft configuration, performance, operation and eventually business case. Considering size, range and performance, regional aircraft are the most suitable candidates for demonstration under Clean Aviation, as this market segment is able to return a sensible impact on global greenhouse gas emissions.

There is no single, and already predefined, solution. A number of paths are promising, and the partnership should investigate these in the first phase, as long as the community has not yet identified the 'winning configuration' to reach the final objective. The technologies and the architecture must be aligned to optimise the aircraft performance and configuration. It is expected that the final solutions will differ with targeted missions (characterised by distance range, number of transported passengers, cruise speed etc.).

- Hybrid-electric architectures: additional electric energy is used in certain flight phases in times of high power demand, for example for acceleration. Bi-directional flow of power is possible between the generator and battery. When the thrust demand is lower (cruise, descend), the produced electricity can be stored in batteries. Hybrid architecture can be divided into:
    - parallel hybrid: the thrust is mainly provided through a conventional thermal engine, assisted and boosted by an electric motor which provides extra power when needed in critical flight phases such as take-off;
    - series hybrid: electricity is generated by a generator plugged into the main turbo engine. Depending on flight phase, this electricity is stored in a battery or used to power electric motors and propellers.

- Turbo-electric architectures: The turbo machine is used only to generate electricity via a turbo shaft (not used to provide direct thrust). The electricity is then used to drive multiple, distributed fans, driven by electric motors.

Target

In 2035, the most complex yet achievable target is that of a hybrid-electric propulsion system optimised for regional aircraft in a typical mission. This effort will include a hybrid turboprop equipped with reversible electric motor/generators, coupled with batteries or fuel cells which will provide power eventually, via an MV/kV electric chain, several electric fold high lift propellers and electric wing tip propellers.

A new high efficiency 3 000 shp class thermal engine will result in a reduction of at least 20% CO_2 emissions compared to the current state-of-the-art. This impact may drastically improve by using SAF. This thermal engine will be associated with a power gearbox capable of driving a mechanical variable pitch propeller and/or electrical generator(s) in order to supply loads such as electrical motors, batteries and non-propulsive networks. Batteries or fuel cells will allow for the provision of additional propulsion power to the thermal engine during specific phases of flight and all the propulsion power on the taxiway or at the gate.

Hybrid propulsion power management needs to be developed. Connected with the aircraft power management that controls the global power required for all on-board systems and duties, this will ensure a split of the power according to flight phase, providing the power margin indications and the health of the power sources/ electrical distribution to the pilot.

The total on-board power will depend on the flying platform and hybridisation share. For example, total power would be in the range of 1 MW for a large fully electric commuter aircraft and, depending on size and degree of hybridisation, from 2 to 6 MW for regional platforms. The single electrical channel shall address an electric distributed propulsive system with its specific power management to ensure safety to allow certification. The electric architecture will include efficient hybrid turboprops, electrical fold propellers, electrical storage and all the necessary distribution, protections and interconnection systems needed to implement a power channel above 1MW/1kV class. Main goals are to develop:

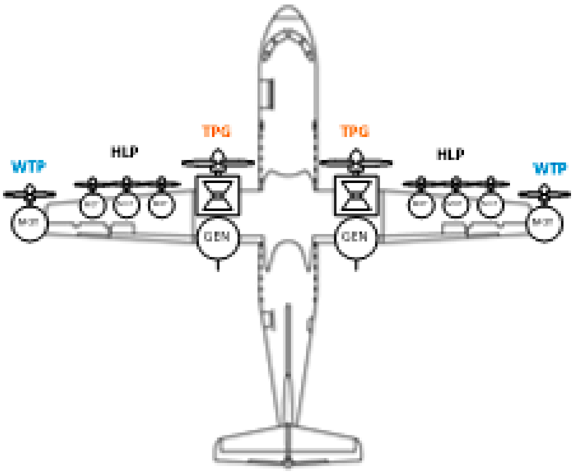
- an efficient turbomachine dedicated to hybrid configuration: either a turbo-generator or a hybrid turbo-propeller with an electrically assisted variable pitch capable of delivering both mechanical and electrical power for propulsion which will contribute to the target vision of CO_2 reduction;
- high power (up to MW size) integrated folding electrical propellers with smart power electronic and thermal management;
- integrated high power / high voltage electric distribution and interconnecting system with lowest possible weight penalty. The electrical system must be designed to resist the different physical phenomena that might jeopardise its integrity;
- high power and high energy battery, or fuel cell, integration inside the aircraft;
- specific and common global thermal management for both turbine and electrical devices;
- maintainability, reliability, durability must conform to the market expectations;
- certification rules, means of compliance and safety: the electric chain shall ensure all the necessary protections for both people and materials.

The high level of modularity and scalability of electric solutions will likely allow their exploitation to other product classes beyond the partnership (e.g. rotorcraft, 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, whilst larger aircraft will potentially use larger modules.

Turbo generator

The turbo generator, an association of a thermal (turbine) engine with one or more electric generators, is one of the essential building blocks of distributed electric hybrid propulsion. The limited power/energy density of the batteries and the absence of any perspective of significant improvement within the 2035 term makes the use of a turbo generator imperative for the propulsion systems of future aircraft. This turbo generator as a main source of power is a breaking point compared to the existing state-of-the-art.

Power density target of the turbo generator in 2035 > 2kW/Kg.



TPG: Hybrid TurboProp
GEN : Generator
HLP: High Lift Propeller
WTP: Wing Type Propeller
MOT: Electrical motor

Figure 3.2: Generic scheme of distributed propulsion engine types

Hybrid turbo propeller (generator and motor)

As a further evolution from the turbo generator to supply power to the overall propulsion system, a new very high efficiency 'Turbo Propeller Gen Engine' will be studied. It will be highly integrated into the aircraft and able to provide both electrical and mechanical power.

This new turboprop generator will be sized to provide the maximum power for critical phases of the aircraft flight (take-off, 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 starter – generator (in addition to other potential equipment).

The thermal engine shall operate in its most economical range, while rotational speeds shall be adapted to the electric motor optimised point. To adapt to these constraints, the propeller will need to have a variable pitch. It will be able to provide electrical power throughout all flight envelopes, to supply all electrical demands of the aircraft for both propulsive (E-propeller) and non-propulsive (ECS) systems. It will be optimised to reduce greenhouse gas emissions along the whole mission while delivering the power/thrust necessary in the whole flight envelope considering an optimised power sharing among all the propellers of the aircraft. This split will be managed through a distribution/power management system.

Thermal (turbine) engine for a class of 3000 shp+: 10kW/kg

Smart reversible motor-generators with integrated power electronic modules:
10kW/kg with an efficiency of 95%.

E-propeller

One of the key technologies is the integrated fold e-propeller. The driving of a propeller by a high power electric motor is a breakthrough in aeronautics and opens new perspectives while bringing constraints in particular in terms of additional mass. The e-propeller could have several functions/benefits:

- improve the lift of the aircraft (high lift propeller) and therefore potentially reduce the wing surface;
- reduce the marginal tip vortex (wing tip propeller) combined with the potential controllability of the aircraft by thrust differential;
- be foldable to reduce aerodynamic drag when not in use in several flight phases; this constraint is specific to hybrid architectures where additional electric motors produce extra power in specific flight phases only. To avoid the oversizing of the electrical motor, specific design features need to be taken into account to address the transitory phases;
- reduce noise: it is also a fundamental area of improvement for societal acceptance and use at secondary airports, which are often located near urban areas. The noise reduction perception can be decreased by 15dB compared to ICAO ch14;
- allow taxiing operations using e-propeller only, leading to zero emissions on the ground.

Smart motors with integrated power electronic modules: 5kW/kg with an efficiency of 95%

500kW to 1,5-2 MW electric engines, generators with integrated power electronics, control command laws and proper liquid cooled thermal management.

Ducted E-propulsor

In the longer term – second phase – and at larger aircraft sizes a ducted e-propulsion architecture may be appropriate for optimum platform capability. This would have a highly integrated MW class electric motor driving via gearbox a multi-blade fan within a nacelle type structure. Whilst there are significant challenges with respect to thermal, electrical and structural design, the functional benefits could include:

- enabling higher aircraft cruise speed;
- noise reduction, due to the propulsor design and also physical separation from the power generator in all phases of flight, but with emphasis during airport operations;
- closer physical and functional integration with aircraft structures, reducing weight and drag.

Electric power chain (distribution and interconnection systems)

This area covers power classes suitable for hybrid-electric applications on regional and short and medium-range aircraft (SMR) or even above (if the technology potential allows). Today, electric architectures are based on 28Vdc and 115/230Vac voltage levels and address several hundred kW distribution. Higher power (up to 1.2 MW) is possible and most modern aircraft use 270Vdc; this would be suitable for commuter and small rotorcraft applications. However, the distribution of power levels representing several MW (as needed for regional aircraft) will require an increase of the network voltage level to keep the system weight and volume increases acceptable.

A key aspect for higher voltage and power needed is the higher cruise altitude (lower pressure in non-pressurised areas means more partial discharge phenomena). Additional requirements for safety, environmental constraints and integration in low-pressure areas could be brought. For example, constraints for certification of regional aircraft and SMR are driven by CS-25 certification rules, which will have to be applied at higher voltage (at least 1 200 Vdc) at an altitude of at least 25 000 ft.

In order to respond to these challenges, a multi-step technology design process will be adapted by proposing several versions of the interconnection system. The activity will start with components that are used today with non-optimised weight, adapting them to new voltage/current requirements. By the end we will propose fully optimised innovative electrical interconnection system components based on innovative design, materials and processes. The propulsive configuration will address hybrid electric distributed propulsive systems with its specific power management to ensure safety and allow certification.

High voltage high current electrical cables, connectors and installations will be tested in a two-phase innovation process:

- modelling and simulation;
- physical integration in a ground demonstration, as part of the global demonstration strategy as detailed in section 3.1.4 on demonstration strategies.

Power and energy storage / fuel storage systems

In hybrid architectures, additional electrical storage components will be embedded such as battery and fuel cells. Batteries (or fuel cells eventually) 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 phases of flight (i.e. take-off phase) and all the propulsion power at the taxiway or at the gate. The common aspects to study are: modularity and the capability of the system to adapt to changing propulsion power ranges; and how to interface with aircraft electrical systems (e.g. power quality). Power storage shall be combined with scalable power lines and suitable electrical motor architectures should be inherently designed for redundancy, high efficiency and the ability to cope with voltage fluctuations.

Batteries

The activity will cover the integration and adaptation of a modular hybrid power pack (energy cells, power cells, high charge/discharge cycle) to a full or hybrid electric architecture. This will take into account several key aspects such as cell technology (from other (EU) initiatives/sectors) and packing; energy, power and volume density; energy storage gauges to accurately show the remaining energy available; charging and recharging cycles; and integration such as thermal management and replacement. The choice of batteries and their performance shall be adapted and made consistent with the technologies defined above. They must also take into consideration some specific aircraft issues such as total weight and balance, containment and safety, maintenance and refurbishment. Designing batteries for peak power delivery means the possibility to enable a high discharge current. This discharge rate (or C rate) is a key differentiator of battery technologies for hybrid aviation compared to other markets.

Power sized to reach a power density of 1.75 kW/kg up to 2.5 kW/kg,
with an energy density of about 410 Wh/kg in 2035 at pack level

Battery discharge rate up to 10

Specific power-sized battery and electrical protection management units of 15kW/kg

Fuel cells

Alternatively, fuel cells are another electrical energy source with potential for aircraft applications. In some specific cases, they are likely to be the best solutions while in others batteries may be the preferred choice. The activities will investigate the integration and adaptation of fuel cell power considering several key aspects such as fuel cell technology options (from the Hydrogen EU initiative); power, energy and volume density; environmental constraints (operative pressure and temperature); ancillary systems and devices. The fuel cell choice and performance will be evaluated and adapted to peculiar aircraft issues such as total weight and balance; containment and safety; maintenance and refurbishment. Finally, investigations will be performed on the water vapour emission effects on climate.

Power management

The power management of the propulsive system will define the level of power of the different sources between turbine and electric motors in order to optimise energy, emissions, noise and direct maintenance costs as well as control of power supply in normal and abnormal conditions. It will take into consideration all the different phases of the flight: taxiway, take-off, climb, top of climb, descent, landing and taxi, and the associated need for power and constraints.

100 KW extraction from electrical machines implies liquid cooling with efficient exchangers

Synergy in thermal management (cooling systems, fluids) between thermal and electric propulsive systems, improved integration

3.2.2. Enabling technologies for aircraft integration

The complex and challenging pathway to achieve hybrid electric propulsion depicted above requires specific technology areas to be explored in order to understand their impact on the overall aircraft. They concern essential cornerstones for the development and certification of an environmentally friendly future regional aircraft in order to have the envisaged impact. The novelty and complexity of hybrid electric propulsion will not allow the use of current tools and methods. Understanding the potential performance effects is a key difference between a research-oriented demonstration at concept level, (even if at full-scale and high TRL), and a demonstration simulating actual solutions and features that a product would need for a successful entry into the market and operations.

- Existing design tools and methods do not include the effects of distributed propulsion on the wing and aerodynamics, or the effects of multi-propeller and tip propeller on manoeuvres, noise and safety. Aerodynamics design and characterisation, aero-elastic analysis, flight control and flight management systems and performance-validated tools need to be applied to innovative configurations.
- Hybrid-electric propulsion represents a significant departure from current state-of-the-art propulsion and its integration. Enabling its use will require an advanced capability to predict design parameters and performance impact at aircraft level, and share these with partners and certification authorities. Virtual design, integration, verification and validation platforms are needed to scale and correlate flight and ground testing, exploiting simulation. "Digital twin" platforms will be required to control, reconfigure and simulate all lifecycle phases.
- New configurations and performance ranges will be explored that have never been achieved so far in aviation. For instance, electric power will be 50 to 100 times higher. Multiple propellers may be installed with effects on aerodynamics, noise, vibration and structures. Validated new design tool-sets will be considered in order to integrate performance towards virtual certification (e.g. power quality, high voltage, EMI, distributed propulsion, noise, cockpit behavior, thermal management, acoustics etc.).

- Integrating hybrid electric propulsion at high power levels will raise several new features relevant to the airframe. High current return needs and grounding, thermal dissipation and insulation as well shall offer a ground to enhance flexibility and modularity of electrical propulsion. All this will require a re-thinking with respect to the airframe and the way to design it, in order to accommodate these new features and possibilities while keeping them affordable for customers.
- New components, with a size and power never before used in aviation, will require a careful back-to-back balance of their performance against assembly and integration constraints, maintenance and repair needs, and assuring safety and continuous airworthiness as well as the time and cost of integration. Advanced assembly and manufacturing solutions are to be pursued to achieve higher quality, reduce the learning process and decrease waste of materials and energy used thus reducing environmental impact and cost of ownership.
- Carbon-neutral aviation implies a paradigm shift in the metrics and design scope of aircraft. Up to now aircraft have been designed to reduce lifecycle cost, maximise safety and achieve high operational flexibility. Carbon-neutral aviation will require aircraft to release the lowest possible emissions at affordable cost while maintaining maximum safety; a reduced flexibility regarding usage may result. A life cycle analysis of new air vehicle concepts and their potential role in the mobility mix is a must, in order to support the technical choices needed.

3.2.3. Integrated technologies for climate neutral regional aircraft

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

New aircraft architecture

The challenge is to integrate future disruptive technologies in an aircraft that is able to meet the low environmental objectives and the market expectations in terms of affordability, flexibility of use and safety while preserving its competitiveness 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, including distributed propulsion, scalable, multi-purpose definition, non-propulsive systems optimisation and different energy storage solutions supporting relevant mission profiles. Internal and external acoustics have to be addressed considering the impact on citizens.

Propulsion and on-board energy concept

Based on the aircraft trade-off, the best propulsion candidates would be studied for their integration readiness, in order to define the best balance between different energy storage systems (fuel cells or batteries) and related energy sources and the best balance and strategy for thermal engine and electric motor utilisation. The key challenges characterising such assessments will be: high voltage power distribution (up to 1.5 kV or even higher), electrical machines with high ratio of power over weight and volume , power electronics, having management and control potentially coupled to advanced thermal engines as primary sources of energy using 100% SAF.

New propulsion integration

The effect of integrating new propulsion solutions on aircraft is paramount to deliver a competitive aircraft that has an actual impact in terms of reduction of the environmental footprint. Specific efforts are required to address propulsion mechanical and thermal integration (combining turbine, gearbox, propeller, electric motor generator) and its integration into the aircraft (wing design and size, gas-turbine with advanced cycles using SAF, propulsors/propeller, advanced controls, electrical actuators, energy storage systems location and layout). Both aspects are key enablers of the future product and therefore require a dedicated maturation path even if intertwined more closely than before and with an optimisation potential stronger than it has been thus far. Finally, noise effects shall be fully evaluated for their impact on citizens given the sensitivity of local noise effects.

Electric engine, power electronics and management

The major challenge of an affordable and reliable electric-hybrid power plant implemented in a regional aircraft is to achieve an integrated power management of the entire system. Key technologies to be matured are electrical machines (module from 500 kW up to 1-1.5/2 MW), compact flight-worthy power distribution and electronics (e.g. Si-C), and dedicated control systems. Modular and scalable solutions shall be pursued to cope with different aircraft requirements within a product family but also 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

Most likely, from 2035 onwards the entry-into-service scenario will be a hybrid-electric regional aircraft using drop-in fuels and/or other energy storage solutions (e.g. batteries, fuel cells, or non-drop-in) in a not-yet-known mix. The development of safety solutions suitable for the aircraft's operational environment and peculiar safety aspects will be a key aspect to pursue beyond the performance and weight/volume aspects. In all cases, needs and features of ground infrastructure shall be explored to assess operational issues such as battery recharging and/or replacement at the ramp, non-drop-in power storage on the ground, maintenance and operators' skills and tools.

In-flight thermal management

Propulsion system heat generation and high power electrical distribution losses could be significantly higher than a state-of-the-art (SoA) equivalent system, in the order of hundreds of kW. Radical thermal management features should be introduced, enabled by the usage of enhanced manufacturing technologies or new materials with very high/low thermal conductivity for insulation and thermal dissipation. A close connection and optimisation with an on-board environmental control system may be deemed necessary.

New routes to certification

New means of compliance or dedicated rules will be required to certify a new hybrid electrical system, therefore a strong and pro-active cooperation among the airframers, the engine manufacturers and the certification authorities should be activated from the early design phases. Identification of new rules, 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.

3.2.4. Demonstration strategy

The regional aircraft demonstration strategy aims to mature technologies, 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 for the assessment of the potential and performance of new technologies in combination with other systems (legacy or new), evaluating the interaction and correlation with them while controlling risks and cost.

Subject to analysis, capability maturity and relevance, the hybrid and electric propulsion technologies and the technologies for industrial competitiveness and affordability may not all fit in a single aircraft demonstrator. This may be because they represent significant levels of change that are not compatible with resources, timing and risk within the scope of Clean Aviation, as well as the fact that the technologies represented may not fully interact with each other. The demonstration would then be organised in three logical layers. See the planning as shown schematically in **Figure 3.3**.

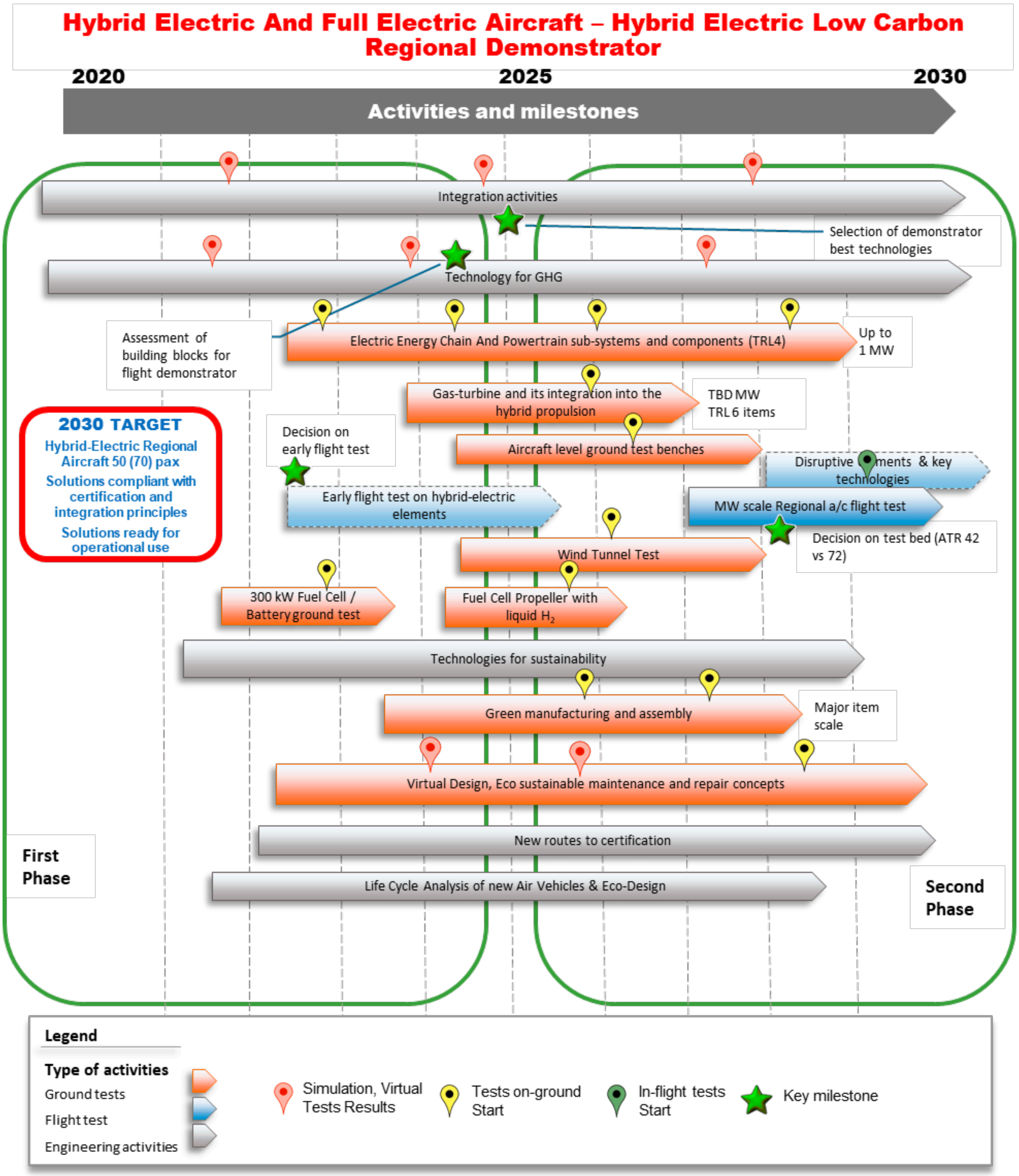


Figure 3.3: Regional Aircraft Integrated Planning

Sub-system demonstration

Once specified, technology bricks can be matured up to TRL4 in isolation (hybrid turboprop, electrical propeller technologies, power chain, power management etc.) but they need to be integrated in a full system at a given point in time so as to be tested in a representative architecture/system. Single item test rigs and subsystem level rigs will be used for that purpose. Each component and subsystem can be matured in parallel. At least three sub-system ground test benches will have to be put in place:

- hybrid turboprop and e-propeller
- electric energy chain and powertrain technology demonstration
- electrical storage installation including electrical interconnection system integration (fuel cell, batteries or a combination).

Iron-bird/ground/wind tunnel demonstration

Ground demonstration aims to combine the different technology building blocks in an integrated architecture that will pave the way for and de-risk the next flight tests or fully demonstrate the technology potential and impact whenever flight tests are not strictly necessary for technical reasons. It would make use of several test environments such as wind tunnels, test-rigs and iron-birds.

- The engine and its integration with electrical components (electric machines, power electronics, batteries etc.) into the hybrid propulsion system as a mandatory enabler of the entire system. The validation of such a subsystem and the related key enabling technologies will be completed and validated through a dedicated power plant demo before a flight test of the entire system.
- Ground test of a scalable fuel cell 300kW module up to the ground test of full electric propeller powered by fuel cell module including on-ground liquid H_2 distribution.
- Aircraft level ground test benches for electrical distribution, thermal management and noise validating both integration and performance for flight tests and building-up the confidence database to achieve permit to fly. Other air vehicles might exploit in parallel similar campaigns for a matter of relevant differences in size (SMR at multi-MW size) or functionalities (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 regional aircraft critical items.
- Wind tunnel test mock-up for validation of aerodynamics and performance of new and disruptive aircraft configurations, especially for distributed propulsion.

Flight demonstration

Flight tests will integrate final, real scale, regional aircraft solutions. They will also fulfil the basic aviation safety constraints and operative targets for a quicker introduction to aircraft products.

- Early flight tests on smaller air vehicles of critical components (electric motors and distribution, power electronics, propellers etc.)
- Flight tests with actual power sources, powertrains and electrical distribution that are compliant with permit to fly constraints, integration rules and principles: in 2028, up (subject to permit to fly) on a regional aircraft duly modified in the largest passenger range allowed by technology readiness.
- Eventual flight tests on an existing full-scale flight test bed of key technologies at higher TRL or on selected more disruptive technologies and items integrated in a single demonstrator.

3.3. KPIs and targets

The hybrid-electric regional aircraft activities will contribute to the overall Clean Aviation objective to offer technological and product-viable solutions ready for entry into service from 2030 at the highest possible maturity level considering the technological, infrastructure, and certification needs.

The aircraft level target of the hybrid-electric regional aircraft is to flight test a regional aircraft in the 50-passenger range (up to 70 depending on the technology maturity) as close as possible to real industrial integration solutions and complying with certification rules spirit and scope. The aim is that the flight test bed – despite flight test instrumentation, features and specific solutions – demonstrates the potential for payload, range, speed and operative features comparable to a realistic revenue service regional air mobility at much lower emissions. The ambition is to achieve 50% less gaseous emission compared to similar aircraft while being fully compliant with ICAO noise rules in 2030.

3.4. Scalability, cross-cutting synergies and exploitation potential

The key technologies and hybrid-electric solutions developed under Clean Aviation can offer opportunities to several aircraft segments beyond those tackled in the partnership's work programme.

- Market segments with lower energy and power demand (such as commuters and light helicopters) may benefit from results obtained in the technology development for the regional aircraft segment.
- Electric technologies could be scaled up to match full electric requirements, if they demonstrate compliance with certification rules and feasibility in the operational perimeter of commercial aviation.
- Other applications such as rotorcraft share power needs with regional aircraft. The technologies developed can find additional routes to market even if specific integration issues need to be addressed.
- Increasing the electrical power managed through scalable architectures could match the needs of larger capacity or increased range aircraft. Towards the short/medium range (SMR) market segment, the regional hybrid-electric solutions can provide early insight into certification issues since these segments share the same regulations and certification base, as well as many aspects of operator demands. Regional aircraft present the best opportunity for a scaled flight test at MW range of electrical solutions, thus including within Clean Aviation boundaries, at reduced costs and risks, the multi-MW needs of larger aircraft.

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4. Disruptive technologies for an ultra-efficient short and medium-range aircraft (SMR)

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4.1. Introduction

The mid-2030s will 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 000km routes, aircraft for classical short and medium-range distances rely on ultra-efficient thermal energy-based propulsion technologies using sustainable drop-in and non-drop-in fuels to enable climate-neutral flight. The novel aircraft and propulsion concepts will enable low source noise and low noise flight procedures. Due to the nature of 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 like business jets and regional aircraft. Some specific developments and limited ground tests will be required to maximise impact. Green large and heavy long-range aircraft are considered to have an entry into service timeframe of beyond 2035. The outcomes of the Clean Aviation Programme will open up opportunities for a strategy of scaling and applying results to a new generation of climate neutral heavy long-range aircraft in a next major step of innovation immediately following this programme.

Figure 4.1: 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 to design and develop the next generation climate neutral aircraft. 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 like open rotor and advanced laminar flow, etc. The first phase of the programme will target to select, mature and qualify 'best athlete' technologies to exploit their full potential and integrate them into an **ultra-low emission single aisle, short/medium range aircraft**.

The roadmap aims to improve the energy efficiency of a new generation of short/medium-range aircraft by 30%. This will be available by 2035 by combining disruptive technologies related to 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 H_2 technology development programme.

The roadmap for this development and demonstration programme goes well beyond the integration of an improved propulsion concept into 'any' short and medium aircraft. It will result in a holistic aircraft suite-solution for a future green, eco-efficient, economically viable and competitive large number serial product that will enable the creation of momentum and targeted impact at European and global scale. Within this context four pillars are key constituents of the 'Green Short/Mid-Range Aircraft' development and demonstration roadmap.

They include the overall efficient and optimised aircraft 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 green product. Another important pillar is the development and integration of the ultra-efficient propulsion system onto a tailor-made airframe and system architecture. An additional aspect when designing climate neutral aircraft capable of sustained highly efficient green operations and services is to be thoughtful with respect to maintainability. An eco-sustainable end-to-end, no-waste manufacturing and digital design process enabling an efficient green industrial architecture will be included in order to ensure the emergence of impactful climate-neutral aircraft from the programme.

The technical roadmap to develop, mature and demonstrate all technologies needed for next generation climate-neutral short- and medium-range aircraft follows a validation and verification 'V&V' approach, the main elements of which are displayed in **Figure 4.2**.

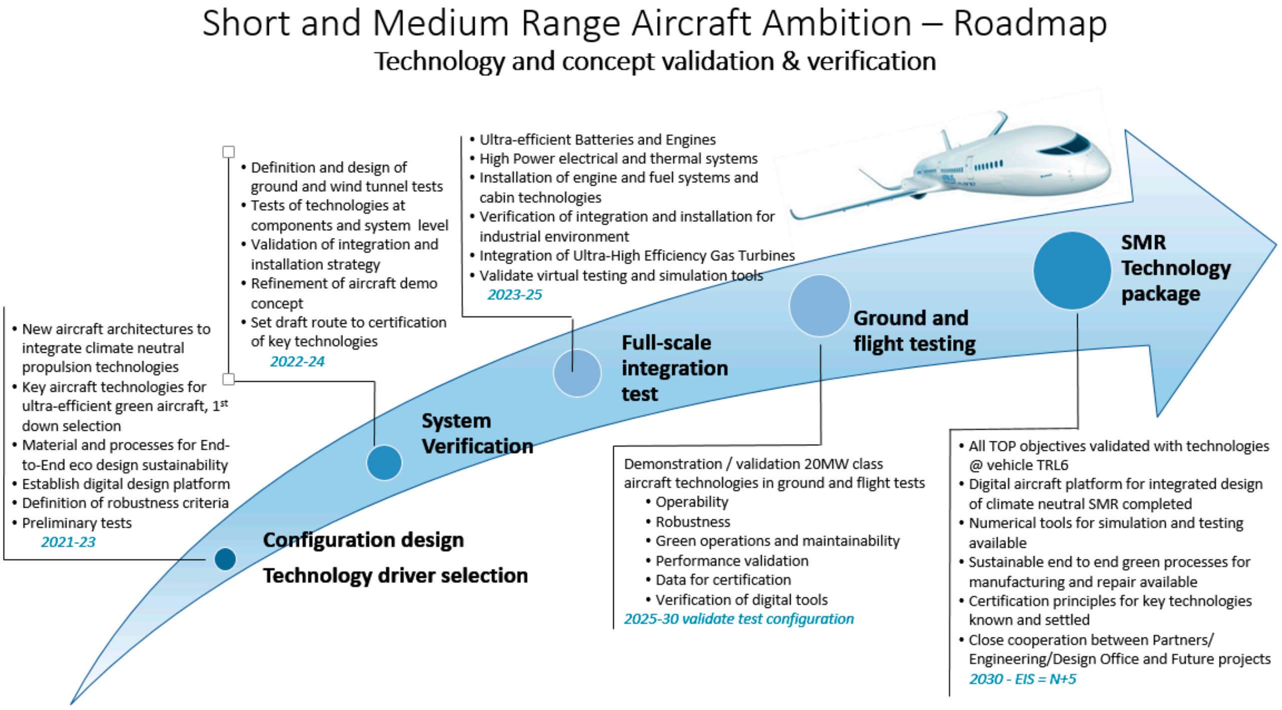

Figure 4.2: Ambition to demonstrate the climate-neutral short and medium range aircraft

The roadmap to develop, mature and demonstrate this vehicle is composed of two programme phases.

The **first phase of the programme** will be based on the distinct specification of top-level aircraft requirements that are framing the boundaries of a 'technology work space' 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 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 programme phase** will focus on validating and integrating selected best candidate technologies to form a single aircraft concept, which will be the result of the activities in phase 1. Key elements of the second phase will be large-scale integrated aircraft component tests and a large-scale flying demonstrator platform to validate the performance of key technologies for the targeted aircraft at realistic sizes under operational conditions.

As illustrated in the roadmap below (**Figure 4.3**) and described in more detail in the next sections, the ambition to develop an ultra-low-emission single aisle aircraft requires rethinking the overall aircraft architecture, tackling and integrating essentially all major components most efficiently. The key contributing elementary technologies are described in the following paragraphs.

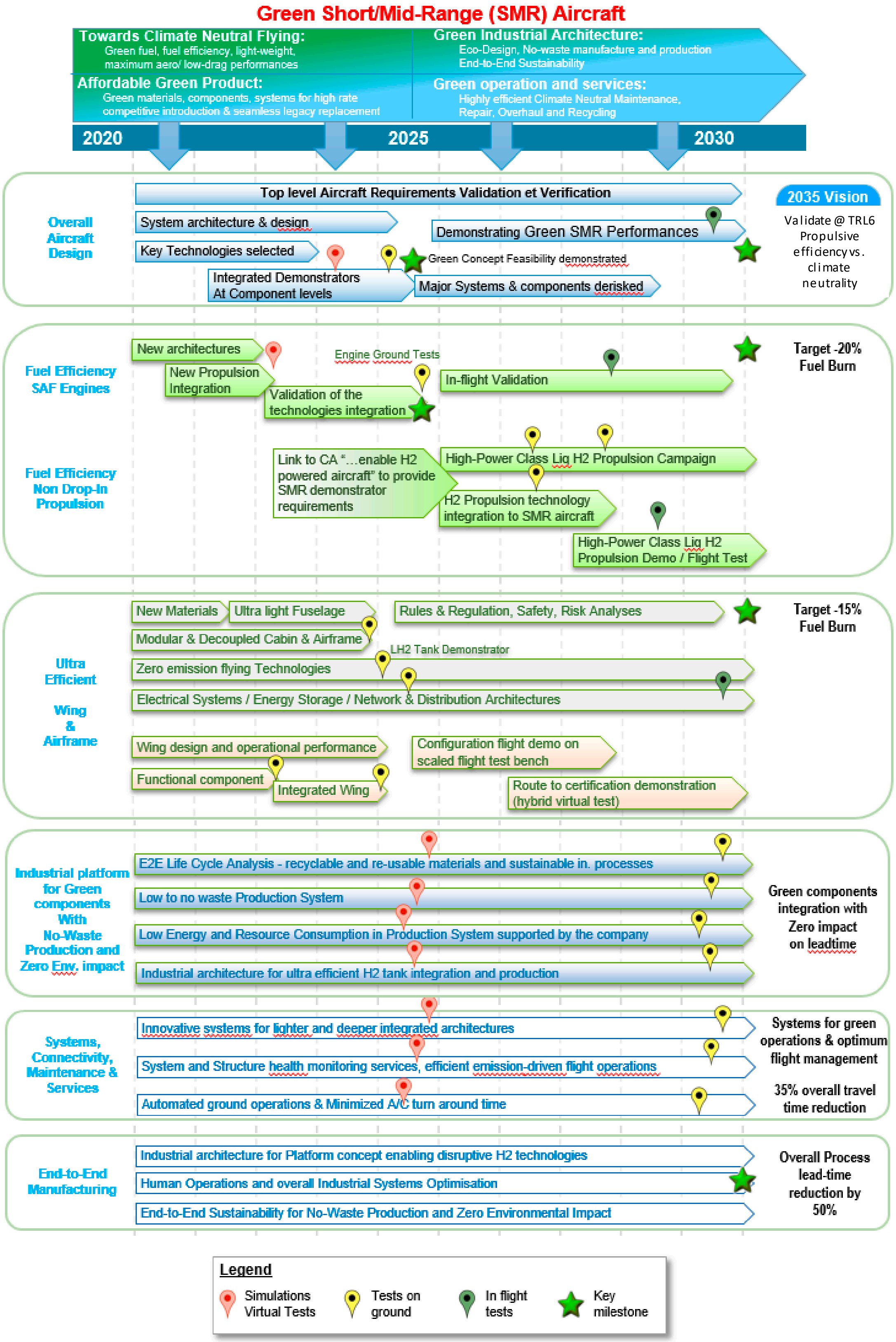

Figure 4.3: The Short Middle Range Aircraft Technology Roadmap

4.2. 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 compliance, where appropriate, with the top-level aircraft requirements and seamless integration on aircraft level.

The research and development work plan is laid out to embrace the development of the entire aircraft in order to integrate disruptive technologies while maximising operational energy frugality and substituting conventional fuels with climate-neutrally-produced drop-in fuels. 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, in order 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. With the development of technologies related to the engine and corresponding systems taking place in the work programme outlined in chapter 5, a close interface to the SMR programme will be made, particularly for the second phase of the Clean Aviation programme, upon accomplishing technology readiness TRL3 or higher.

Demonstration of these technologies and the contribution to primary objectives will be logically arranged throughout the programme. This 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 4.4 below.

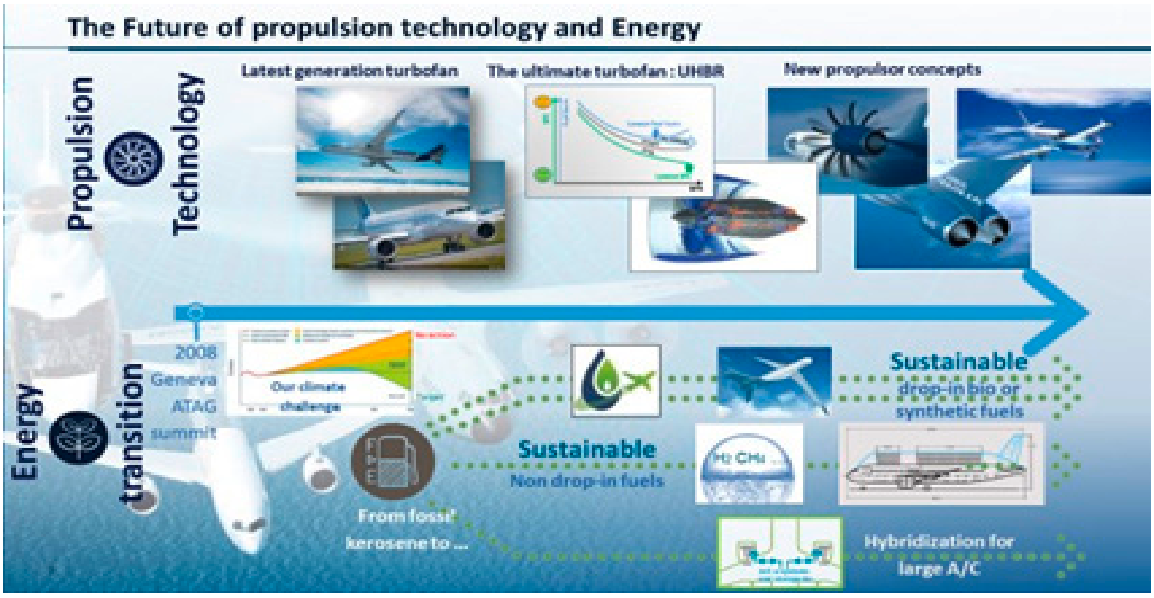

Figure 4.4: Future of propulsion technology and energy

4.2.1. Ultra-efficient airframe

The reduction of aerodynamic drag, aircraft weight and the energy needs of non-propulsive consumers will substantially contribute to the viability of the ambition of climate-neutral flight.

The fluid properties of hydrogen are completely different to kerosene, which affects the overall aircraft architecture with respect to storage, distribution and ground handling. While generic technology developments and tests will be done in the disruptive technologies to enable hydrogen powered aircraft, solutions associated with the SMR aircraft level integration will be part of this programme, for example the definition, testing and validation of green, efficient and economic operations. Considering the structural optimisations including the integration of hydrogen or methane tanks, cabin and cargo as well as systems, the entire architecture – the entire design space has to be reopened to enable an optimised configuration.

Rules and regulations defining the qualification and certification process need to be adapted to the new solutions developed for such future aircraft. Existing rules and regulations need to be revised in close cooperation with EASA for an optimised and efficient qualification and certification process enabling virtual means.

The **Ultra-Efficient Airframe** is an essential enabler to reduce fuel consumption and 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, landing gear. The competitiveness of the new aircraft structures needs to be re-established and secured by an optimised, sustainable and efficient industrial system comprising all components of the airframe, modularised systems, cabin, cargo and functional elements required for an integrated climate neutral aircraft design and development. They all require the development and implementation of new highly efficient manufacturing, assembly and operational processes. Special attention will be devoted to the best implementation of a best cradle-to-grave eco balance by minimising the use of energy, water and problematic material, also to minimise waste and emissions throughout all phases of the aircraft lifecycle.

During the first phase their respective generic technologies will be assessed by smaller scale demonstrations, e.g. on component levels. These activities comprise new materials including life-cycle assessment up to recycling, architecture and design concepts including more radical aircraft configurations, and airframe/cabin/landing gear integration aspects.

Considering the particular complex integration aspects of hydrogen tanks and the future propulsion system as well as non-propulsive energy architecture such as landing gear, **the second phase** will integrate the ultra-efficient airframe technologies into overall airframe/fuselage demonstrators. The end-to-end industrial system will have to demonstrate the ecological (energy supply and waste recycling/avoidance), economic (e.g. ramp up rate), and human operations aspects. It will be conducted by hardware ground tests or simulations and will address the qualification and certification aspects throughout all phases.

Aerodynamic drag directly affects the efficiency of an aircraft. An **Ultra-Performing Wing** with high aspect ratio must significantly contribute to reduce fuel burn. Resulting aero-elasticity, load, fuel storage capacity and airport operations will be addressed. The Clean Sky 2 BLADE flight tests have furthermore proven the potential of natural laminar flow (NLF) to reduce skin friction drag. The exploitation and integration of this technology, including advanced technologies (e.g. active flutter control) with competitive processes and means for production and operation must be secured for the targeted green short and medium range aircraft. As a result, research will focus on the development and demonstration of aerodynamic and structural concepts for an Ultra-Performing Wing including industrial and operational aspects.

In the first wave, the functional technology elements of the high performance wing – which will enable a high aspect ratio wing and tackle active load control aspects – will be developed and matured. To further reduce skin friction drag, natural laminar flow (NLF) will be qualified for local operational application. Demonstrations will be conducted via lab-scale (e.g. wind tunnel testing) and sub-scale flight-testing for integrated components and functional demonstrations. Beyond aerodynamic performance, a step change in industrial efficiency will be based on new high-production-rate-driven integration and assembly methodologies, and on novel design-to-production concepts.

The second phase will target an integrated 'X-Plane' approach as a carrier for disruptive wing technologies. The active adaptive technologies will be further matured, and complemented with new technology bricks. Disruptive propulsion architectures, e.g. distributed on-wing propulsion or a dry wing concept, have to be integrated into the wing design and demonstrated through full-scale functional ground tests including propulsion systems. The flight test bed for fully integrated new components will be scalable to the target applications.

The disruptive industrial demonstrators will cover industrial processes related to new materials, radical build concepts and wing integration, feeding the co-design to production approach.

4.2.2. 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 progress or fuel cells power densities 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 the best option or combination of zero net carbon fuels, will remain the basis of next (2030+) and future generations (by 2050) aircraft in the short/medium and long range segments. This envisaged future architecture could be based on either synthetic fuels or H_2, and can include hybrid electric solutions. The low maturity of a number of key hydrogen technologies required for application on large commercial aircraft is a serious challenge of this programme, but the reward that comes with mastering it due to its inherent potential for a real green future of aviation is in reasonable balance with the risk.

Because the only real "zero emission fuel" is that which is not burnt, reducing fuel consumption independently of the nature of the fuel burnt is critical in order to reach climate neutrality objectives. This is **even more critical when considering new types of fuels**, **including potentially hydrogen**, whose availability, cost (2 to 3 times higher than fossil fuel), as well as energy intensity for their production, will necessitate 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 2030+ are **a mandatory element in the path towards climate neutrality**. These will contribute not only to emission abatement 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.

Such a revolution can only be achieved through global aircraft optimisation, intimately integrating the propulsion system and the aircraft to generate the best possible combination, thus requiring a **novel co-creation approach**: moving away from the current plug and play philosophy towards a disruptive integrated way of working. This can allow for a departure from traditional "tube & wing" and engine placement and shapes, and enable disruptive configurations to be considered. The efficiency in design and operation of the entire platform, i.e. the airframe, thermal engines and other systems is necessary to reduce emissions and deliver the lowest consumption of energy, and simultaneously provide reduced operating costs.

This entails a fundamentally new approach requiring "open book" cooperation between airframers and propulsion systems providers to solve the new unknown complexities arising while searching for extreme efficiency.

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

For short/medium range aircraft, this intimately integrated propulsive system architecture would pave the way towards a future joint development programme, targeting 2030+ EIS.

Ultra-efficient thermal engines and novel integration are the most promising green technologies for propulsion, with an ambitious target to reduce fuel burn by 20%, stemming from the architecture of the propulsion system (high bypass ration (BPR) engine architectures beyond current installation constraints, significant increases in electrical power generation with optimised energy management/control, innovative thermodynamic cycle). In combination with other disruptive technologies described further in this chapter, this will lead to an unprecedented 30% improvement in energy efficiency at aircraft level and lay the foundation for further aircraft generations, for which hybridisation and/or non-drop-in-fuel-based solutions can be enabled by the EIS 2030+ propulsion system and can build momentum towards climate neutrality.

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:

- **Smarter Engines**: The next generation will use smart parts 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 3) will enable additional efficiency improvements. Together with revolutionary thermodynamic cycles this will unlock new reductions in fuel burn of up to 20% for 2030+ EIS and 30% for 2040+ EIS. Research topics in this area will include variable pitch multi-blade devices (ducted or unducted) operating with peak efficiency at multiple flight modes. Artificial Intelligence (AI) based engine control systems can enable learning and adapting, optimising operations in real-time. Transmission systems incorporating electrical machines can enable load transfer during all flight phases. Innovative energy recovery concepts seen in marine/land-based systems that take advantage of new fuels can help achieve efficiencies not possible today in aeronautics.
- **Lighter by Design**: reducing the number of components, eliminating constraints and introducing new multi-functional systems 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 through improvements to both propulsion systems and the aircraft. Research in this domain can include new architectures and electrical components to remove or simplify existing systems. Reduced size inlets and nacelles in combination with compact external electrical and mechanical systems can create new operating limits, e.g. temperature, within the propulsion system using real-time simulation design tools. New composite and ceramics materials and additive manufacturing will enable a reduction in overall system size.
- **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, the ingestion of steam during the combustion process can eliminate the formation of NOx almost completely. Extraction of water from the exhaust gas could reduce contrails. 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. 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.

Delivering the capabilities identified above will require the maturation of technologies that cut across existing areas of responsibility. The challenge of ensuring these are highly integrated and optimised is outside the scope of a single organisation. Addressing this needs to occur in full collaboration with the aircraft platform to ensure an effective solution. Thus, multiple geographically dispersed stakeholders will be required to operate in partnership to create these disruptive solutions and deliver impact at both propulsion and then aircraft level.

Demonstration activities in these areas will progress along 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 subsystems, extending to flight tests, utilising donors or new build engines, where operating across flight envelope conditions and integration complexity require this.

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

- Phase 1: Technology maturation (TRL4/5 and up to TRL6 where needed)
- Phase 2: Full propulsive pack, ground and flight demo (TRL6)

This technology roadmap (**figure 4.5**) is expected to reduce fuel burn and CO_2 emissions in the range of 20% compared to state-of-the-art engines from 2014-2016 and to reduce NOx and noise in line with the ACARE Flight Path 2050 trajectories.

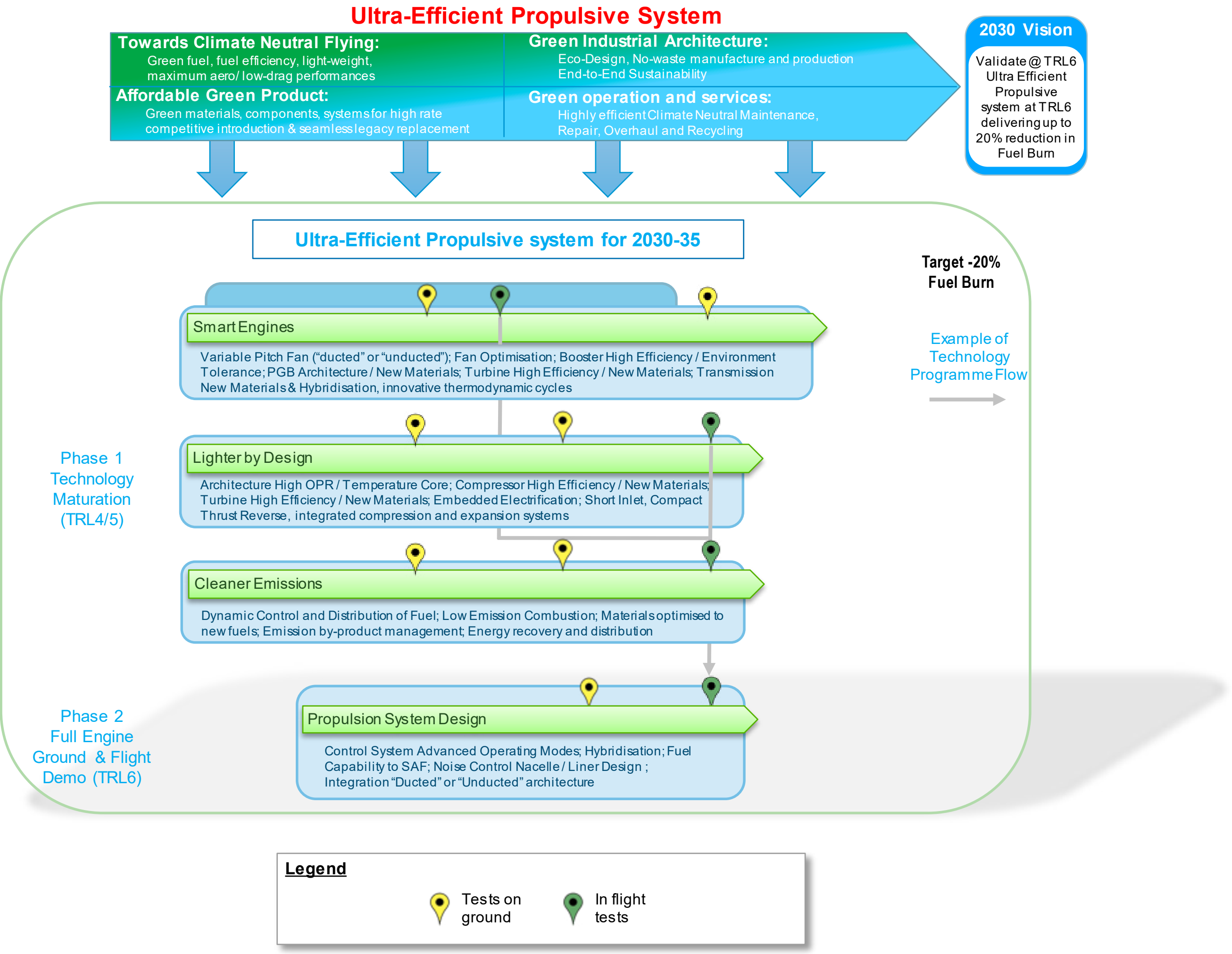

Figure 4.5: Ultra-efficient propulsion roadmap

Ultra efficient propulsion systems operating with non-drop-in alternative fuels

Beyond the drop-in fuel alternatives, more disruptive and potentially far-reaching fuel/energy source options such as hydrogen (H_2) or methane (CH_4) will be targeted for in-flight demonstration. This in-flight demonstration is dedicated to integration aspects sized for short and medium aircraft encompassing special requirements concerning the 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 aircraft configuration will be determined from the outcomes of these tests and demonstrations done in the H_2 technology development programme outlined in chapter 5, which may complement the overall design requirements. It will anticipate a possible early entry into service, operating hydrogen-based flights of up to two hours in duration.

The approach in the SMR programme is to design the demonstrator platform to enable the integrated demonstration of the technologies with minimum changes to key elements of the platform. The close interface with the H_2 technology development programme shall ensure a timely and seamless link of activities in both parts of the Clean Aviation programme. However, it requires a full system change in terms of the energy supply chain and energy integration in the airframe. Additionally, implementation at the level of infrastructure, supplies and logistics will likely be key enabling and/or limiting factors, and as such, to be investigated within the scope of the research and demonstration activities.

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 under wing, fuselage or tail-mounted). All these multi-disciplinary integration challenges are listed below and will have to be tackled in partnership with engine manufacturers and research institutes, namely:

- aerodynamic and aero-acoustic nacelle/pylon design and integration;
- overall noise characterisation and reduction (external and interior noise);
- structural nacelle/pylon design and integration;
- power plant system integration 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.

4.2.3. Aircraft systems for green operation

Systems suite for green short medium range aircraft operations

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, time-to-climb etc. 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 and as such, must be part of the climate-neutral aircraft development. The activities described here below shall be complemented by collaborative upstream research intended to be launched in parallel with the Clean Aviation Programme.

Reduction of the overall on-board energy consumption and weight:

- more efficient activation and load logics of all aircraft systems to reach less energy consumption;
- new power generation and electrical systems able to efficiently support the increasing electrical power demand for aircraft primary functions and in the cabin. A new generation of high-density power electronics, electrical power grids with high-voltage architecture and high-speed electrical generators providing more power at much reduced weight and compact size;
- systems that have less impact on the key aircraft design criteria (weight, specific fuel consumption, drag etc.) and small on-board footprint – for instance, disruptive digital communication systems within the aircraft, with the air traffic control and other aircraft, including permanent, resilient, high throughput, cyber-secured and cost-effective connectivity enabled by active low profile satcom antenna;
- disruptive electrical wiring systems, power bus and optical fibre backbone deployed throughout the aircraft for a much lighter and simplified electrical and digital wiring and more flexible configurations;

Aircraft energy management, which can be further optimised:

- adapted climb-cruise-approach profiles driven by airline constraints, weather effects, traffic etc. The flight management system will integrate new functions for trajectory optimisation, en-route formation flight, or ground operation management to include zero-CO_2 push-back and taxiing phases. In addition, a multi-sensor real-time fusion platform could enable high integrity localisation, remote vision-based navigation, and automatic trajectory management based on detect-and-avoid function. Challenges include sensors based on the fusion of artificial intelligence with new disruptive sensors (e.g. radar, weather, infra-red or camera);
- system health monitoring functions to identify and monitor any source of electrical malfunction enabling better system reliability and optimised maintenance.

Green, lightweight fully integrated cabin service platform

Changing the propulsion and energy concept of an aircraft has a major effect on supplying the cabin with electrical energy, heat, and pressurised air. Another significant effect may be the introduction of fuel or primary energy sources such as liquid hydrogen, as fuel tanks and fuel systems elements will most likely no longer be integrated in the wing but in the fuselage, and so in close proximity to the cabin and cargo space. With this in mind, the cabin, as one of the largest elements of the aircraft, will contribute significantly to the reduction of the environmental footprint and the overall efficiency of the vehicle and its operations.

Future aircraft configuration studies are leading to more radical aircraft and cabin architectures, affecting the fuselage geometry as well as system integration and power source and management options. Enhanced power management will reduce peak loads for new aircraft power sources and smart cabin components will enable modular and flexible cabin systems reducing lead-time and costs. The industrial aspects of cabin integration are essential for an affordable green aircraft.

New materials and design concepts for the environmentally-friendly lightweight cabin will reduce weight and consequently fuel burn. The full material life cycle will be considered, from sustainable and traceable material sourcing, taking full advantage of material properties (hygiene and fire) to achieve a highly efficient, ultra-light, sustainable and 100% recyclable cabin. The life cycle of eco-friendly material will be accessed and verified before the first integrated cabin monuments planned to be demonstrated in 2025. The integration and installation will initially be validated via simulations and mock-ups. Eco-efficient and time-effective automated production systems will be demonstrated via simulation and physical tests targeting industrial concept validation in a "final assembly line" simulation in 2027.

Technologies will be demonstrated and validated for assisted and automated operations for passengers, baggage, and freight via digital data-chains. The integration into an effective aircraft service platform will significantly contribute to a seamless transport system, which will reduce travel time, improve the passenger experience and the overall efficiency of a seamless air transport ecosystem. The end-to end development of these technologies is embedded in the short/medium range (SMR) climate neutral aircraft roadmap.

4.2.4. Green sustainable lifecycle technologies

Green manufacturing and assembly, end-to-end eco design

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

The development of a disruptive, entirely new type of climate-neutral operating 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 will consider the environmental footprint of the complete life cycle. New materials, their future production processes and assembly techniques are key complementary contributors to clean aviation solutions. To manufacture new parts on time and at cost requires new basic materials and techniques for simplification and streamlining of the production processes, 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, on condition maintenance as well as manufacturing and material techniques such as additive manufacturing, thermoplastics, ceramics, multifunctional and smart materials, hybrid metal-composites. Using these technologies from the early definition and design of the disruptive climate-neutral aircraft is an imperative, also with respect to ensuring the envisaged impact through a high ramp-up of production and highly competitive manufacturing and assembly processes.

4.3. Demonstrator strategy, key objectives of large scale demonstration

The strategy of the SMR demonstration plan is laid out to enable the validation and demonstration of all key technologies for a climate-neutral next generation aircraft by the end of the Clean Aviation programme. To be able to achieve this, the research and development roadmap of the SMR programme is built on a combination of a number of sub-scale, ground, rig and wind tunnel tests and a single large-scale demonstration platform. The detailed setting of the individual tests will be defined with the detailed description of the work programme in order to enable the development, maturation and validation of all subsequent levels of technology readiness for all key technologies until TRL6, which is demonstration under real type operational conditions at large representative scale.

While subscale, ground, rig and wind tunnel tests will be predominantly required in the first phase of the programme (roughly the first 5 years), the large-scale integration ground and flight tests will take place in the second phase, with smaller tests complementing 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. The progress and achievements of the prior H_2 activities within Clean Aviation will enable decisions on higher-level demonstration work plan details to be taken in a step-by-step approach. This may then be utilised to offer the capability to integrate and demonstrate hydrogen-based combustion-based propulsion systems of 5MW or larger.

The resulting demonstration plan is effectively building on and complementing industrial and national funded research activities across Europe. It will be composed of a coherent line up of complementary ground rig tests, wind tunnel test, sub-scale ground and flight tests and, essentially in the second phase of the programme, large scale ground and flight tests.

4.3.1. Subscale testing, ground and rig testing

The programme foresees two phases of experimental tests and validation of technologies, as follows.

PHASE 1 (2021-2025)

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 activities, and thus focus on maturation of key technologies. Several challenges will require attention to deliver the overall impact without detriment in other areas, and this will require highly integrated and predictive design tools. The combination of the most advanced manufacturing processes and design methods will be one of the keys to the success of these developments.

Technology will be matured up to TRL5 through dedicated testing at component, module and subsystem level. Implementing this into the engine design will initially involve ground/rig tests, and thereafter full propulsion system tests. Additionally, technologies will also be evaluated for their potential for early implementation into service, reducing the time-to-market. Further integration activity includes:

- technology maturation at propulsion system level, including the bricks detailed in chapter 4.2.2;
- Considering the longer term towards 2050, novel combustion cycles will be studied and concepts sub scale tested when promising. For example, an innovative aero engine concept could apply to all available thrust and range classes, reducing fuel burn and CO_2 emissions by up to 30% compared to 2014 state-of-the-art engines. An example of this is the water-enhanced turbofan (WET).
- 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 merge of propulsion into flight controls, new electrical system integration incl. 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;
  - unconventional propulsion configuration integration studies (e.g. OR integration at rear-end) via simulation, ground tests, wind-tunnel tests.

Propulsion and aircraft technologies for enabling non-drop-in alternative fuels

- First on-ground and in-flight demonstration of low power propulsion systems (~1MW range, seeking to combine with H_2 propulsion technology demonstration). From 2023 to 2025 and aiming towards TRL6, beyond the in-flight data analysis of the powertrain itself, maintenance aspects, safety and certification aspects, future health monitoring and control systems, as well as ground operations will be pursued with the perspective of further development for medium-high power class applications.

PHASE 2 (2026-2030)

Propulsion and aircraft technologies for enabling non-drop-in alternative fuels

- Propulsive system using optimised H_2 on-board storage and combustion for high power class aircraft configurations:

  - overall aircraft integration studies;
  - ground operations and logistics concepts specific to aircraft demands;
  - detailed flight level conceptual assessment of a potential new product, infrastructure and logistic aspects.

4.3.2. Large-scale integrated demonstration and flight testing

The targeted large-scale flight demonstrator shall enable the testing of all major technology components critically depending on a validation of their performance under real flight conditions, in different relevant scenarios, and at size and power levels close to full size scale.

The definition, development and preparation of the test vehicle is planned to start towards the end of the first Clean Aviation programme phase.

In order to enable an early testing of ultra-efficient engine concepts, a first campaign of large-scale tests is planned on "carrier aircraft" in the first programme phase.

PHASE 1 (2021-2025)

Ultra efficient propulsion and aircraft technologies

Following the results of the key technology maturation, it is anticipated that the first flight demonstration could be prepared as early as 2025 to demonstrate maturity on specific techno-bricks, for example, the low- pressure systems technologies. In addition to the demonstration of functionality at full-scale, the flight test activity 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).

- Integration of ultra-high efficiency thermal engines at aircraft level:
    - preparation of the first in-flight demonstration (carrier aircraft, installation challenges and flight clearance), safety and certification aspects – 2021-2025.

PHASE 2 (2026-2030)

Ultra efficient propulsion and aircraft technologies

- Based on phase 1, results from the most promising power plant configuration with drop-in SAF compatibility and including any new engine micro-hybridisation (e.g. 500 kW (integrated generators in low pressure (LP) and high pressure (HP) spools)) in the frame of a more electrical engine will include:
    - aircraft operational assessment, ground operations, logistics and route to certification;
    - other engine concepts, either for longer term EIS capability or other range applications, will also be integrated into flight demonstrations utilising donors or new build engines;
    - in-flight validation and data analysis – 2028;
    - emissions impact via a life cycle analysis, noise assessment at aircraft, airport and fleet levels;
    - for short and medium range, the **engine design**, expected to be finalised by **2026**, will be based on the Clean Sky 2 ground test results. This will include key advanced technologies matured at TRL4/5 during the Phase 1 and an initial flight test demonstration to be performed in 2025. The project will then deliver a new full engine demo, after manufacturing, instrumentation and assembly of all engine parts. The target will be to run a ground test campaign in 2027 and a **flight test campaign in 2028**, to validate the next generation short and medium range benefits and prepare for the product introduction phase, thus reducing the-time-to-market drastically from a 2027 ground demo to a **2030+ EIS.**

Non-drop in fuel propulsion and aircraft technologies

- Propulsive system using optimised H_2 on-board storage and combustion for high power class aircraft configuration:
    - first flight tests by end 2027;
    - flight tests (TRL 6), data analysis (including environmental impacts, emissions, contrails, external noise) and exploitation 2028-2029;
    - emissions impact via life cycle analysis, noise assessment at aircraft, airport and fleet levels.

4.4. Scalability of technologies and demonstrator results

Key challenges for technologies, in particular climate-neutral propulsion technologies for large aircraft and/or longer flight ranges, are system complexity, specific overall energy densities below conventional propulsion systems, and in many cases a low maturity or unavailability of large size or high power systems.

The SMR programme in the Clean Aviation Partnership will seek to stimulate an extension of the applicability of technologies towards neighbouring aircraft segments, here in particular from the short to medium segment towards medium to longer ranges. As similarities of design concepts for the climate-neutral SMR will exist for a family concept, the expectation is that this will provide the opportunity to extend the impact of technologies for additional applications through a wider market in the 2035 to 2040 timeframe to medium to longer-range aircraft. Scalability and spin-offs for other aircraft types like large business jets will promote and spread the operability of this technology to other airports outside of Europe.

A cross feed of technology development in Clean Aviation is also expected and promoted between the hybrid electric regional aircraft and the SMR part of the work plan, for example on the development and integration of hydrogen fuel technology integrated to the aircraft.

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5. Disruptive technologies to enable hydrogen-powered aircraft

© Courtesy of Airbus

5.1. Introduction

Sustainable Aviation Fuels (SAF) are categorised into carbon-neutral drop-in fuels such as synthetic or bio-fuels and non-drop-in fuels such as liquefied natural gas (LNG), low carbon methane or zero-carbon gaseous (H_2) or liquid hydrogen (LH_2). Burning carbon-neutral fuels results in net zero CO_2 emissions whilst burning zero-carbon hydrogen results in CO_2-free emissions.

5.1.1. Energy context

Hydrogen is seen as a promising energetic vector for the future, as it allows the massive storage of energy. Future low- or zero-carbon electricity production (photovoltaic, wind power etc.) will impose a massive adaptation of electrical grid in order to make production and consumption peaks fit. Massive storage systems will be necessary in order to allow this adaptation, and hydrogen seems to be one of the most efficient ones.

Moreover, in transport, hydrogen seems to be a promising greenhouse gas reductions option for trucks, buses, ships, trains, large cars, and commercial vehicles, where the lower energy density (hence lower range), high initial costs, 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.

A comparative assessment of the various potential aviation energy sources (synfuels or biofuels, LNG or methane (CH_4), gaseous (H_2) or liquid hydrogen (LH_2), or batteries and their lifecycle effects) will be performed in order to assess the overall climate impact of these energy chains and their lifecycle effects.

5.1.2. H2 potential for aviation

Hydrogen presents several key advantages when considering aviation application: it allows for the elimination of CO_2 emissions in flight and along the entire life cycle if produced carbon-free. Its usage in fuel cells allows for zero-emission propulsion (including NOx and particles). When 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. Considering also non-CO_2 emissions (high altitude phenomena), the use of hydrogen in a thermal (combustion) engine can lead to different emissions and consequently a change in the global environmental impact, still to be assessed.

Nevertheless, to scale H_2-powered aircraft, several technological unlocks need to happen before delivering the full potential. Non-drop-in-fuel will require parallel technology developments to increase the maturity of the key building blocks. While the aerospace industry is planning to collaborate to develop the necessary on-board technologies, widespread availability of new fuels (e.g. H_2, LNG) and recharging/refueling infrastructure, together with low CO_2 means of production, will be key for the overall success of this approach.

Among these topics, some elements are still at very low TRL level and will need long term developments, maturation and demonstration in order to be ready for integration into future aircraft.

5.2. Ambition and impact

Incremental improvements – i.e. higher fuel efficiency of conventional fuels – are not sufficient to achieve the ultimate objective of a climate-neutral aviation system. The emission of greenhouse gas and especially non-CO_2 emissions and secondary effects (NOx, SOx, soot) can only be avoided by disruptive propulsion technologies, i.e. ultra-efficient engines using alternative fuels. The hydrogen powered aircraft seems to be a promising solution to limit this climate impact. But considering the challenging fluid properties and impact on the overall aircraft system optimised for conventional fuel, high research effort is required to introduce this technology onto the market.

In this light, Clean Aviation aims to mature and demonstrate all relevant systems ready to be integrated into future aircraft. This comprises the selection and validation of the most suitable concepts, materials and designs to provide the required performance, lifetime, costs, and safety. Beyond that, the integration of these systems into the aircraft platform requires a deep understanding of operational, maintenance, and certification aspects.

To ensure the impact of clean hydrogen propulsion, the high level requirements of potential aircraft platforms will be considered from the beginning. Systems will be scalable for different propulsion architectures (fuel cell or H_2 burn) as well as aircraft sizes (commuter, rotorcraft, regional, short/medium/long range). In this light, early impact can be expected through application of the hydrogen fuel cell for hybrid electric regional aircraft in 2035. Building on this, radical short and medium range aircraft will benefit from storage and feed system architectures to exploit hydrogen burn propulsion systems, paving the way for even longer range applications.

Clean Aviation will lay the foundations for the future clean hydrogen aircraft propulsion architecture.

5.3. Key technologies and their contribution to the clean aviation ambition

Applied to aviation, hydrogen would mean a revolution in aircraft architecture, propulsion systems and logistics, meaning new technologies which have to be developed as soon as possible. Four main R&D needs can be emphasised:

- holistic assessment of the environmental potential;
- functional propulsive system development (‘from tank to wake’), including engine but also overall fuel system;
- aircraft integration;
- safety aspects and anticipation of future certification requirements.

Methane (CH_4) will require a new aircraft architecture and logistics, with cryogenic systems. It is therefore proposed to focus on hydrogen developments during the first period. All cryogenic developments made in this period will be capitalised in order to be potentially applicable to methane configurations.

In addition, logistics of hydrogen at airports are key enablers for the widespread use of H_2 in aviation. In order to enable future hydrogen-powered aircraft, it is necessary to ensure that aeronautical aspects are taken into account in hydrogen research and development. This needs to start now if we want to be ready in the 2030s. The following items are of particular importance for aeronautical application:

- production of hydrogen and its liquefaction;
- liquid hydrogen transport and storage;
- establishment and harmonisation of airport regulations.

This overall approach should be shared with several users/transport domains, and as such is not included in the clean aviation activities. It is to be supported in synergy with various national and European collaborative frames such as the EU Clean Hydrogen PPP, involving all stakeholders and non-aeronautical applications.

5.3.1. Climate impact assessment

Aircraft running on hydrogen still emit water vapour and, in the case of hydrogen combustion, also NOx. On the other hand, particles may strongly be reduced. As a consequence, high altitude phenomena, suspected to have a substantial impact on the global impact of aviation on global warming through radiative forcing, may strongly be modified. Assessing the level of this impact is crucial in order to qualify the full environmental potential of H_2 aircraft. The scientific understanding of certain aspects of emission effects is not yet comprehensive and the total effect is still subject to high uncertainties.

The total emissions level of H_2 aircraft and subsequent radiative forcing of these emissions should be investigated in the frame of this programme, through measurements (flight test measurements or dedicated test beds) and subsequent modelling activities.

5.3.2. Propulsion system

The overall functional propulsive system and its integration into aircraft are key for the development of H_2 aircraft, based on fuel cell or H_2 combustion. All key universal components for H_2 storage, distribution and combustion propulsion systems will be developed in this pillar, including:

- lighter tanks;
- liquid hydrogen (LH_2) distribution within the aircraft, and thermal engines capable of burning hydrogen with low-NOx emissions;
- the overall fuel system architecture (from tank to engine) needs to be optimised especially in terms of heat management and transient operations in order to define the global characteristics of the operational propulsive system.

Due to volumetric energy density issues it is likely that hydrogen will need to be in liquid (cryogenic) form for aviation except for specific applications where gaseous may be well suitable (i.e. low-range / low-pax applications). For those specific applications, fuel cells may be suitable as electrical power sources. The fuel cell itself (stacks etc.) and the integrated powertrain for fuel-cell systems will be developed and tested in the hybrid electric pillar.

The propulsive system development will consequently need to study the storage and distribution system and the combustion system.

Storage and fuel distribution systems

This fuel distribution system will have to provide a bunch of new functionalities, such as:

- ability to provide and maintain the storage of hydrogen as a fuel, be it pressurised or liquid, taking into account refrigeration, insulation and subsequent boil-off management. This is associated with cooling source technology for pressure vessels, materials, pressure valves etc. as well as external fuelling systems technologies. Development of lighter tanks (targeting 12 kWh/kg / gravimetric index of 35%);
- ability to refill and vent/purge hydrogen. The majority of the focus is on reliable H_2 venting in distress or before periods of non-use of aircraft, valves, redundant valves, passive discharge valves (automatically discharging maximum quantities, but still not surpassing unacceptable H_2/oxygen mixture). This is a technological challenge, not a specific aircraft challenge;
- ability to provide quantity and out-flow metering. Technology to provide reliable H_2 quantity and out-flow metering (important to detect leakage) in pressurised and liquid H_2 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, of course);
- ability to enable (power) auxiliary functions, because of intrinsic presence of high pressure and/or cryogenic temperature. These could be: ability to use low temperatures for cooling means for powertrain components; using pressure to power some devices, etc.;
- ability to provide hydrogen at the required conditions (pressure, flow) to the system (engine, fuel cell, APU), especially in transient conditions;

- ability to have a global systemic vision of the system, including global heat management, system integration etc.

Activities will focus on the study and maturation of bricks providing these expected abilities. For example, specific key components will be developed and integrated, such as hydrogen heat exchangers, liquid/gaseous hydrogen pumping systems and hydrogen injection systems.

For all these developments, all subsequent modelling tools will have to be developed, as the behaviour of hydrogen (under liquid or gaseous phase) will be strongly different from conventional liquid fuels.

Combustion system

The goal of this work will be to develop H_2 turbines 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 chamber must be adjusted, and lean-fuel injection/mixture technologies applied. The use of cryogenic cooling (enabled by using LH_2 as a fuel) to cool turbine stages and further optimise combustion efficiency should be investigated as well. The new H_2-turbine architecture and the materials used should also be tested and optimised to ensure a long lifetime that is at least competitive with conventional turbines. Finally, the replacement of non-energetic functions of the fuel (actuators, coolant) will also have to be developed and demonstrated. Full validation of such turbines, including pollutant emissions, will have to be done. In addition, engine design modifications will be studied to ensure the dual fuel compatibility for both hydrogen and conventional or SAF fuel.

5.3.3. Aircraft integration

The implementation of non-drop-in fuels such as liquid H_2 will in any case require a step change in aircraft configurations to integrate the cylindrical tanks. A move towards different, more volume-efficient configurations is foreseeable. Besides enlarged and more voluminous fuselages, hybrid and blended wing configurations in particular could finally become the most attractive arrangement, as illustrated below (**figure 5.1**):

Figure 5.1: Airbus MAVERIC Blended Wing Body concept

5.3.4. Safety aspects and certification

Maintaining an optimal level of safety is key for aviation. The shift to hydrogen will imply radically new challenges in terms of safety, procedures, but also certification and qualification of aircraft components. As an example, the safe, reliable transportation of liquid hydrogen from the LH_2 tank to the H_2-combustion unit, fuel cell, or H_2-turbine must be assured. Since the hydrogen is stored in liquid form but must be injected into the fuel chamber in high-pressure, gaseous form, the architecture must be designed to handle the vaporising of the hydrogen. To keep the hydrogen as a liquid, lightweight, double-insulated fuel pipes with cryogenic cooling may have to be developed. Thus, this architecture has to be redundant, and leakage detection and evacuation mechanisms have to be in place. In case of leakages, a venting mechanism inside the aircraft, next to LH_2 fuel pipes, is also needed. The above-described components and architecture design must ensure that maintenance costs are kept as low as possible.

New phenomena such as material compatibility (hydrogen leakage, metal embrittlement, compatibility of cryogenic systems with a vibrating environment) also have to be validated.

Last, but not least, all the certification procedures will have to be adapted and most of them will need to be developed from scratch in order to allow the qualification of such systems. This item has to be taken into account in each development of the programme.

5.4. Demonstrator strategy, key objectives of large scale demonstration

The development of hydrogen, (especially liquid hydrogen), aviation will require substantial efforts, as most of the needed technologies are currently at low TRL and have never been demonstrated.

The demonstration plan for a carbon-neutral H_2 energy based aircraft at a high power class >5MW will consequently follow a step-by step approach, following a stage-gate approach. Consistently, maturation of technology bricks and enablers and all related safety and certification requirements will be explored, and validation of these technologies will happen through ground and potentially flight demonstrations.

5.4.1. Demonstration for higher power class concepts using H_2 burn

Goal of the demonstration:

- become familiar with the use of hydrogen, the associated on-ground and in-flight operational and safety assessment;
- develop an optimised and integrated H_2 power plant system;
- explore exhaust gas features. Characterise in details the exhaust emissions, including high altitude emissions (contrails). Qualify and quantify impact via in-flight contrail measurements;
- build on experimental ground test results to reach flight demonstration.

The work programme will be based on ground test demonstration and in-flight demonstration. Since the H_2 related technologies are disruptive, the demonstration plan needs to be flexible to build on obtained results. It should be regularly consolidated though the Clean Aviation programme lifetime and adapted when necessary to match the impact expectation.

Ground demonstration will involve:

- hydrogen powered thermal engine development and demonstration, with a focus on combustion optimisation (NOx emissions reduction while maintaining an optimal operability);
- development and validation of hydrogen propulsion sub-systems, complete powertrain and the related key enabling technologies with ground test bench demonstrators targeting a full ground demonstration with H_2 by 2027;
- development of storage systems;
- validate the capacity to use a 'dual fuel' strategy (hydrogen/liquid fuels);
- ground tests of critical items to support system integration or item qualification for flight tests including liquid/gaseous hydrogen tank, valves, pumps and compressors, heat exchangers;
- ground demonstration of fully functional system (i.e. from tank to engine) with a focus on transient operations (management of LH_2 vaporisation, pressure management, global heat management, etc.). A representative engine will be used for this work: the size and technology of the engine will be chosen in order to allow quick and efficient demonstration, while allowing to easily scale up the global fuel lines;
- assessment of pollutant emissions of such a system.

All these developments will allow for the definition of a scalable hydrogen architecture, able to be applied on specific flight demos (i.e. SMR or regional). Each of these demos will be managed in dedicated chapters of the current SRIA, including:

- adaptation of H_2 technologies to each specific flight demonstration;
- adaptation of combustion optimisation developed in the current chapter to the specific engine used in each flight demonstration.

Flight demonstration:

According to the results of ground tests / developments, the in-flight demonstration programme will be divided into two parts:

- Phase 1 (2021 – 2025): in-flight demonstration for higher power class concepts using gaseous H_2 burn into existing engines, dedicated to the characterisation of emissions: the work programme will focus on operational aircraft requirements regarding H_2 supply and storage, distribution systems, supplier components, operational security etc. From 2023 to the end of 2025 and after the identification of chasing aircraft for contrail measurements, the flight test campaign will start within the frame of Clean Aviation under typical required flight levels and weather conditions for contrails occurrence.
- Phase 2: Platforms using optimised H_2 on-board storage and combustion for high power class aircraft configuration. This part will study:
  - overall aircraft integration studies;
  - ground operations and logistics concepts;
  - detailed flight level conceptual assessment of a potential new product, infrastructure and logistic aspects;

Flight tests: The exact timing, content and flight tests description (foreseen 2026-2030) will depend on the first results that will be obtained during the early phase of the programme. Best test platform candidates will be assessed to select the most relevant and accurate ones for demonstration. When related to short/medium range aircraft, the integration and demonstration will be performed as described in chapter 4.

6. Annexes

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6.1. Supporting research for breakthrough innovations

The ambitious Clean Aviation concept aircraft taken to demonstration level will only achieve their expected performance by the end of the programme with the right maturity, if a number of key enabling technologies are identified, explored, matured in parallel and are available for take-up.

Aside from Clean Aviation, **strategic synergies** with the European Commission's Collaborative Research programme will be mandatory to address specific concept requirements and low maturity solutions in order to feed a long-term but stable convergence to full aviation decarbonisation. This will require the assessment, adoption and development of technologies, skills and methods that were unreachable during the term of the Clean Aviation demonstrations and that are potentially beyond the traditional boundaries of the pure aviation sector.

6.1.1. A strong link to collaborative research making Europe the source of inspiration and innovation

While Clean Aviation will aim at down-selecting and integrating the most promising solutions from the latest matured technologies into low-emission aircraft concepts, a **Collaborative Research Programme** will have to steer these related strategic synergies and also the associated European Partnerships initiatives in order to support both the short-term and the medium/long-term impacts by:

- Maturing technologies to be integrated into the next innovative aircraft systems for reducing the environmental impact of aviation. The respectively needed technologies will be the outcome of synchronised exchanges of top-down concept requirements and bottom-up solutions between Clean Aviation and the Collaborative Research Programme,
- 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 will naturally focus on low TRL research related to technologies and methods that can accelerate the gains towards the targeted aircraft performance.

Because unconventional and even disruptive aircraft configurations require innovative technologies but also unconventional methods and processes, these synergies will have to address all the different elaboration phases of a new system, integrated demonstrator or aircraft product.

Therefore all dimensions of the product life-cycle generally represented by the classical Vee-Model (see **Figure A.1**) will be source of acceleration to deliver new technology bricks sooner towards unconventional aircraft configurations.

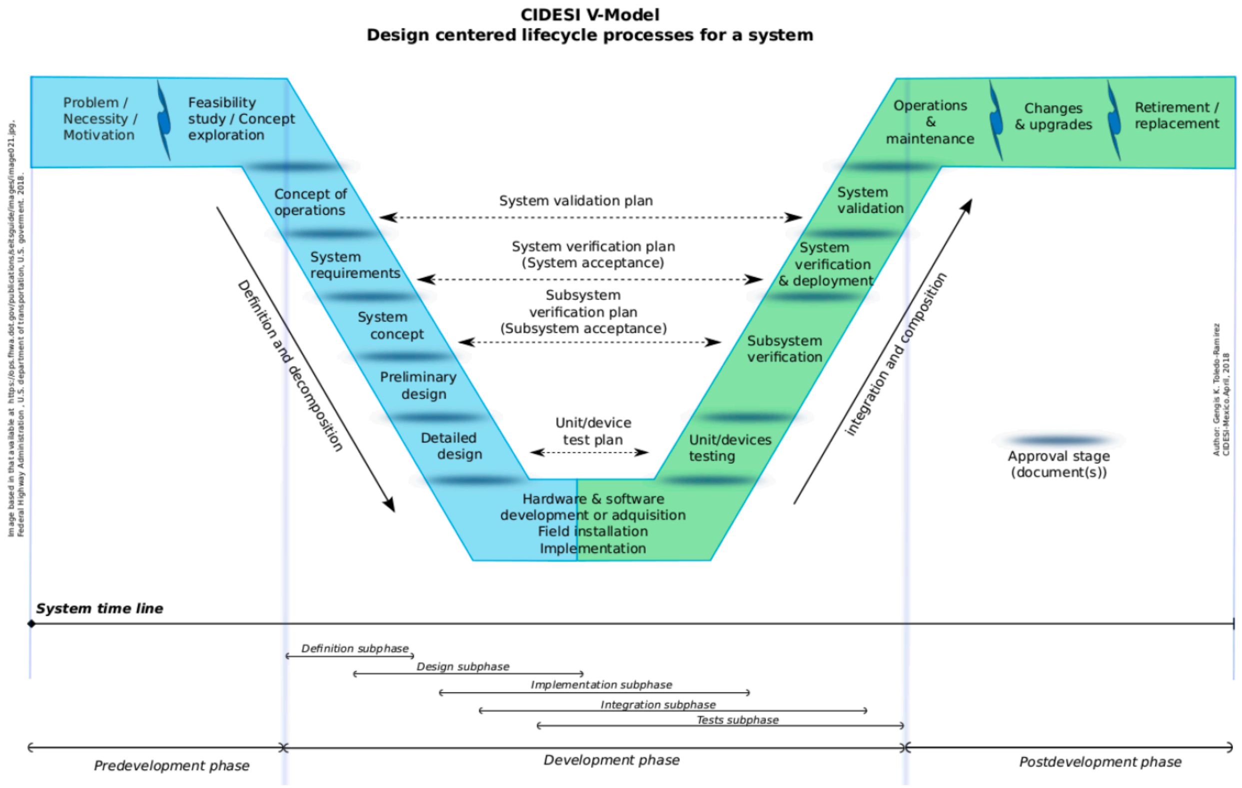

Image based in that available at https://ops.fhwa.dot.gov/publications/seitsguide/images/image021.jpg. Federal Highway Administration , U.S. department of transportation, U.S. goverment. 2018.

Author: Gengis K. Toledo-Ramirez CIDESI-Mexico,April, 2018

Figure A.1: Design-centred life cycle of a product (CIDESI V-Model - extracted from C.A. Contreras-Moreno's thesis, 2018)

The expected changes and transformation factors will emerge from deep and tight collaborations required to accelerate:

- First, vertically: the exchange and cascade of requirements between aircraft, component and system manufacturers to the different research areas and their further validation. While the high ambitions and the complexity of the newly-targeted aircraft concepts will firstly drive a down-selection of the most mature solutions to be integrated and tested in the 2020-2030 period, whereas the less mature but most innovative alternative solutions will have to be studied separately to guarantee their future integration into next generation aircraft.
- Then horizontally: the most unconventional architectures will converge in maturity thanks to more efficient explorations and trade-off capabilities as well as deeper, more robust and connected means of compliance. This will lead to faster validation and verification phases able to encompass all performance, design, economic and environmental constraints.

The Collaborative Research Programme will have to support all these steps from the early identification of emerging technologies to their integration into viable flying configurations and deliver the innovative and valuable methods required for the discovery of unconventional configurations and the manufacturing of new overall integrated concept aircraft. **Two main research streams** complement one another:

- **Breakthrough technologies towards zero-emissions** 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** will 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 ground, up to the certified operational aircraft joining the fleet.

Each stream consists of research areas that contribute directly or indirectly to the Clean Aviation objectives, while exploratory research will be more specifically conducted to set-up the scientific knowledge base to support the long-term sustainable aviation vision, which is mandatory for the introduction of radical solutions beyond 2035 and the Clean Aviation timeframe.

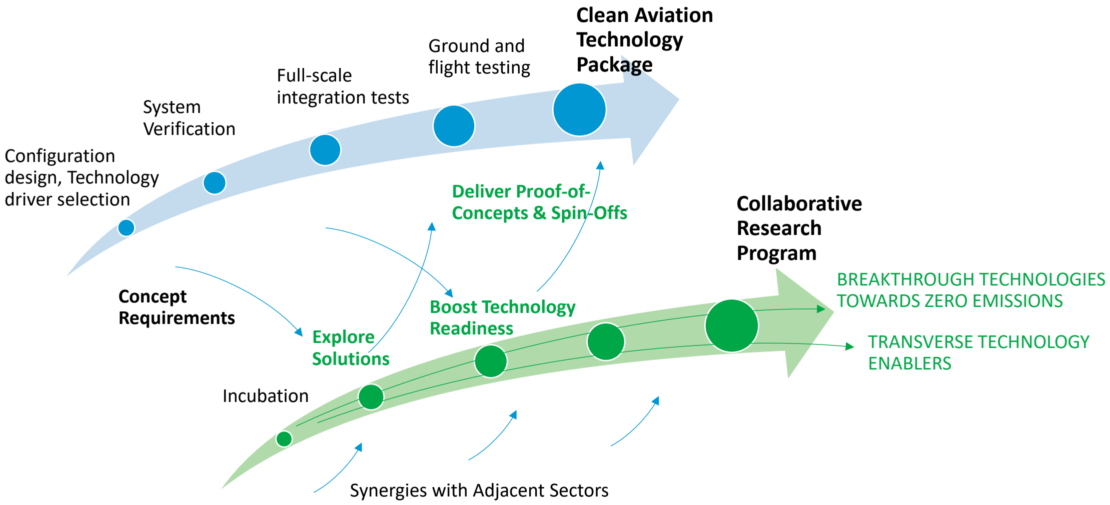

Figure A.2: Collaborative Research Approach

6.1.2. Breakthrough technologies towards zero emissions

This stream will aim to prepare all physical technologies that need to be integrated at equipment, system, power plant or aircraft levels. It will also aim to compose the innovative approaches that will contribute to the overall goal of climate neutrality. These research activities will focus on:

- new aircraft architectures, and the ability to validate the design targets at an early stage,
- new propulsion architectures and energy sources,
- advanced materials and structures including manufacturing,
- systems for efficient on-board energy management and green operations,
- reduction of noise and non-CO_2 emissions.

Axis 1: New aircraft architectures

In view of the ambitious environmental goals, new and even disruptive integrated aircraft configurations have to be explored and matured. This is driven by the trend for a significant increase in bypass ratio for next generation engines with improved efficiency and environmental performance as well as by the integration of hybrid-electric and/or distributed propulsion as an environmentally most promising but at the same time radically new technology. Together with the integrated aircraft configurations, the knowledge basis on related systems has to be increased. A disruptive new aircraft configuration shall not only drastically reduce fuel consumption and related polluting emissions, but at the same time will improve noise emissions by shielding the remaining noise sources from the ground.

Attention should be focused on these principal areas:

- Design and optimisation of disruptive solutions and conventional solutions for engine integration towards maximised efficiency. This includes:
  - making use of distributed propulsion to compensate for efficiency losses due to an increasing number of system components in a hybrid-electric architecture to maximise gains on aircraft level;

  - the integration of distributed propulsion systems on radically new airframe configurations maximising synergetic effects with the aircraft aerodynamics. This can be done by optimising the number of propulsion systems, their positioning relative to the aerodynamic surfaces and their technical specifications in order to maximise aerodynamic efficiency while at the same time minimising aerodynamic noise. This optimisation can be used to balance the sizing of aerodynamic surfaces for the requirements in different mission phases, in particular take-off and landing performance versus cruise;
  - maturation of new propulsion architecture options (e.g. distributed, Boundary Layer Ingestion (BLI), etc.) and related aircraft configurations, including flight control logics and systems for distributed propulsion and BLI;
  - continuing to develop design capabilities also for 'conventional' propulsion solutions as a back-up in case radical configuration changes turn out not to be as preferable.

- Revisiting aircraft configurations taking into account new energy storage and management systems:

  - thermal management of all components making use of synergetic effects and minimising adverse effects on cooling drag; issues such as electromagnetic compatibility, arcing and flow control have to be carefully addressed at aircraft level;
  - energy storage management for new energy sources, including cryogenic hydrogen storage, as part of the disruptive aircraft architectures (e.g. blended wing body configurations).

Axis 2: New propulsion architectures and energy sources

Propulsion and power systems adopting innovative and disruptive technologies and energy sources (drop-in fuels, non-drop-in fuels, batteries and fuel cells) for aircraft propulsion, energy savings and on-board energy generation are key enablers to reach the primary objective of Clean Aviation.

Research and innovation activities on thermal engines and power plants are important to support the transition to sustainable energy sources. Both drop-in and non-drop-in sustainable aviation fuels (SAF) and the electrification of air transport, e.g. the early deployment and widespread introduction of sustainable drop-in energy sources will only be possible if the overall energy consumption of aircraft engines is greatly reduced.

Specific research activities should be dedicated to drop-in SAF with the objective to enable their unconstrained use, in order to retrofit the current aircraft fleet ('quick gains') and ground infrastructure.

For further improvements of the efficiency of thermal-based (gas turbine) engines, specific technologies and knowledge bases will have to be developed to enable the unconstrained use of non-drop-in fuels. This includes the maturation of new propulsion architecture options (including electric/hybrid-electric systems) to be able to deliver the required optimal propulsion and power systems across the different range classes to the aviation market.

Attention will focus on the following areas, supplementing the identified Clean Aviation solutions and supporting the future developments of the Clean Aviation concepts:

- revolutionary thermal engine architectures, introducing advanced thermodynamic cycles to significantly reduce all forms of emissions. Mature variable cycles, piston engines, recuperation and heat exchangers, steam injection, etc.;
- specification of the requirements for batteries and fuel cells in order to develop the high energy and power density solutions needed for aviation. This includes the energy storage management and control, energy harvesting, thermal management (heating issues) and electric power management. It will also take recyclability and safety aspects into account. Demonstration is planned at subsystem level;
- study innovative combustors for H_2, CH_4, and liquefied natural gas fuels to supplement the first demonstrations and explore feasibility of fuels other than those selected in Clean Aviation;

- Ultra High By-Pass Ratio (UHBPR) gas turbine thermal engines, introducing increasingly complex configurations and technologies (increased electrification, low- and high-pressure modules, lower weight, higher operating pressures and temperatures, advanced materials, etc.).
- both highly distributed engines as well as large size engines pose a problem to achieve their integration in a way that maximises the overall aircraft efficiency. Research in this highly multi-disciplinary area is also needed.

A key element for the acceleration of the green energy transition in aviation will be a dedicated area in the EU Hydrogen and Fuel Cell Initiative and European Battery research, which accommodates these very high requirements for aviation and ensures a European technology breakthrough of this value chain in air transportation.

Axis 3: Advanced materials and structures including manufacturing

Reduction of aircraft's weight, as an enabler to reduce fuel consumption, is largely based upon the introduction of advanced materials and their efficient integration into the structure and the implementation of efficient manufacturing processes.

To achieve this threefold objective, efforts need to be focused on the following indicative areas:

- advanced materials with higher specific properties, enhanced damage tolerance or multifunctional characteristics such as thermoplastic/bio-/nano-filled composites, nano-crystalline materials and bio-polymers;
- advanced chemical and electrically benign or active structural options, with low carbon vis-a-vis low energy and resource footprints;
- next generation thermal dynamic and light optical material concepts;
- efficient structural joining methods (e.g. adhesive bonding) and repair methods for composite structures;
- integration of structural health monitoring (SHM) concepts based on efficient and extended non-destructive testing (NDT) techniques into the structure to promote the damage tolerance design philosophy;
- novel manufacturing processes and technologies such as additive manufacturing (AM) and disruptive, fast and cost-efficient out-of-the-autoclave manufacturing processes for thermoplastic materials, aiming for higher quality of produced aeronautical parts, reduced manufacturing costs and carbon footprint.

Such areas constitute a strong enabler to new innovative aircraft configurations, new fuselages, and more globally to new and wider trade-offs implying holistic multi-criteria design optimisation approaches to structures with regard to MRO, quality, cost, environmental footprint and recyclability/reusability aspects. For this reason, structural design, like other domains, will benefit from the transverse innovative methods and capabilities (see next section).

Axis 4: Systems for efficient on-board energy management and green operations

The research topics will tackle emission reductions by enabling aircraft to fly cleaner operations through the following items:

- a reduction of the overall on-board energy consumption:
  - more efficient activation and load logics of all aircraft systems to reach less energy consumption;
  - next power generation and electrical systems able to efficiently support the increasing power demand – a new power generation, conversion and management system is expected throughout; involving firstly high-voltage and high-speed electrical generators that provide more power while being lighter and more compact, and secondly, light and compact high-density power electronics and electrical power grid;
  - systems that have less impact on the key aircraft design criteria (weight, specific fuel consumption, drag etc.) and small on-board footprint – for instance, disruptive digital communication systems within the

  aircraft, with the air traffic control and other aircraft, including permanent, resilient, high throughput, cyber-secured and cost-effective connectivity enabled by active low profile sat-com antenna;
  - disruptive electrical wiring system, power bus and optical fibre backbone deployed all along the aircraft for a simplified and more flexible electrical and digital wiring will create disruption in systems due to simpler manufacturing/equipping processes and will consequently lead to a huge potential weight reduction and an enhanced reconfigurability and upgradability.

- aircraft energy management, which can be further optimised through:

  - adapted climb-cruise-approach profiles driven by airline constraints, weather effects, traffic etc. The flight management system will integrate new functions for trajectory optimisation, en-route formation flight, or ground operation management to include zero-CO_2 push back and taxiing phases. In addition, a multi-sensor real-time fusion platform could enable high integrity localisation, remote vision-based navigation, and automatic trajectory management based on detect-and-avoid function. Challenges include sensors based on fusion of artificial intelligence with new disruptive sensors (e.g. radar, weather, infra-red or camera);
  - system health monitoring functions able to detect, identify and monitor any source of over-energy consumption and requiring rapid ground maintenance.

- more autonomous and automated flights and ground aircraft operations.

  - the increasing complexity of the on-board and ground systems will require disruptive approaches for future flight automation through pilot assistance, and autonomy involving an artificial co-pilot;
  - a reduction of up to 10% of the CO_2 emissions well before 2050 because some of the solutions will be able to enter into service via linefitting and retrofitting before 2030;
  - a safety level ten times higher than today's level, reducing from 10 to 1 the number of accidents per 100 million flight hours.

These new systems will be key to support efficient on-board energy management and to contribute to emission reductions while improving safety and helping to mitigate a coming pilot shortage in an environment where traffic density will double. The potentially higher acquisition costs of new 'greener' technologies like disruptive autonomous systems will be balanced by airlines by significantly reduced operating costs and life-cycle-costs. These new aircraft will therefore remain attractive and affordable as the main condition for rapid market penetration in the early 2030s.

Axis 5: Reduction of noise and non-CO_2 emissions

While Clean Aviation concepts will tackle the primary demonstrations and validation of the most mature technologies, Axis 5 should be dedicated to a wider exploration of the means for reducing the atmospheric impact of other non-CO_2, gaseous emissions (NOx, soot, water vapour) as well as environmental impacts like noise, which penalise health and wellbeing of citizens. This research area will thus be a key enabler for the social acceptability of aviation transport.

The introduction of new energy sources for the propulsion of future aircraft will lead to innovative engines for which a specific effort will be required to better understand and quantify the emission of pollutants such as NOx and soot. Efforts in this field shall comprise:

- research on the physics of reactive flows and development of combustors adapted to the new drop-in and non-drop-in fuels;
- the modelling of the dispersion and transformation of the species produced by the engine;
- studies to make the link between emissions in the near-field with their impact in the vicinity of airports and on the formation of contrails.

Considering noise emissions, if the main focus remains the reduction of noise sources, additional aspects such as noise propagation and perception need to be further investigated. More precisely, attention needs to be focused on the areas outlined below.

- Aircraft noise reduction strategies shall be taken into consideration when new developments to reduce carbon emissions for aircraft are developed. This could be achieved through processes in which noise at source should be envisaged in trade-offs with other issues (safety, pollution, energy) in a 'low noise by design' approach.
- Understanding noise sources of new entrants to the air transport system such as urban air vehicles for logistics or air taxis for mobility and noise propagation in urban environments.
- Filling the gap between deterministic measured noise levels and how noise is perceived in order to develop adapted solutions to reduce noise in the vicinity of airports.
- Noise regulation adaptations need to be anticipated for some specific air transport, e.g. in the context of renewed interest in supersonic flight.

6.1.3. Transverse technology enablers

This second research stream consists of specifying, establishing and implementing all means able to accelerate the growth of the individual technologies needed to achieve zero emissions and their integration at system and aircraft levels. As illustrated in **Figure A.1**: Collaborative Research will support (through new methods and tools): the discovery of new technologies; the selection of more efficient designs and integrated system functions; as well as new validation and manufacturing processes. Collaborative Research aims to address the following complementary axes:

- multi-level and multi-disciplinary modelling/simulation for technology selection and integration;
- the next generation of experimental methods;
- digitalisation (manufacturing and maintenance, repair and overhaul, prediction methods, model-based system engineering (MBSE));
- close coordination with future certification requirements;
- Industry 4.0;
- circular holistic design for more global impacts.

Axis 1: Multi-level and multi-disciplinary modelling and simulation methods for deeper technology selection and integration

Now aviation is requested to make a giant leap forward towards zero CO_2 emissions. Since aircraft configurations lie outside the well-researched conventional domain, numerical simulations will need to be relied on very strongly to guide this process (even more than before). This calls for a holistic and integrated (multi-physics) approach, e.g. the traditional way of working where the airframe and propulsion systems are considered in isolation can no longer be pursued when studying for instance boundary layer ingestion type integrated solutions or complex full aircraft acoustics. Multi-level and multi-criteria optimisations will be finally affordable thanks to digital transformation and will boost both new architecture selections and the introduction of innovations in aviation.

In short, the following developments are required to enable:

- exploration of feasible and compliant design options. Confidence and shorter time response of the models used for trade-offs will be required, while the range of the design criteria will be extended for a faster and more robust concept selection. This includes re-evaluating and re-designing algorithms. Reduced order modelling (ROM), AI, deep learning and maybe even quantum computing can help here, as well as a more extensive intercompany collaboration (co-located teams, multidisciplinary teams);

- holistic analyses at system, component or aircraft levels. More global trade-off techniques will be developed to scale-up with the end-to-end development life-cycle of new aircraft concepts and to cope with engineering, manufacturing and market constraints;
- simulations of a wider range of coupled physics, such as combinations of aerodynamics, aero-acoustics, aero-elastics, etc. (integrated tools). Multi-level and multi-criteria optimisations will result from the digital transformation and boost new architecture selections;
- modelling of the engineering and manufacturing processes, and of the physical interactions between humans, products and machines will, together with real data acquisition, allow both validation and optimisation of processes and operations.

Axis 2: The next generation of experimental methods

New sets of requirements induced by the more integrated low/zero carbon demonstrators will lead to the emergence of new environmental test conditions, new test protocols, risk analyses or certification constraints. The new propulsive architectures will enhance the level of validation excellence and push for more innovative and digital or hybrid means of compliance.

In this area again, the digital technologies will make any testing phases of a development more cost-effective, efficient, prevention-based, fully integrated and seamlessly managed. Significant benefits will come from exploiting digital twins for virtual or hybrid testing, needed to predict actual component performances on failure cases or operating conditions different from the ones tested. Potential key problems on radical system architectures will therefore be identified early and corrected.

Major cost reductions can be achieved by further developing scaled flight testing. Scaled models allow for relatively quick technology testing and validation and have the potential to significantly accelerate the development cycle of retrofit technologies and new configurations.

More sophisticated means of compliance will result in specifying and developing new specific research, testing and validation environments.

Axis 3: Digitalisation

Digitalisation will clearly open the door to end-to-end design methods, reconciling innovation discovery, product engineering, manufacturing and further customer support via online services. It will benefit a more global, shortened and dynamic development of the Clean Aviation demonstrators in preparation for the future aircraft development life cycle.

All included capabilities can be associated with the more general concept of 'working agility', a way to:

- understand, rationalise and better integrate the constraints and design rules between different disciplines;
- simplify and speed up processes to quickly identify weak spots; and
- make the whole decision process leaner, in turn making it more effective.

The digital approach will therefore allow:

- digital solutions, including complementary end-to-end shared digital aircraft 'twins' to allow continuity and traceability from the top requirements up to the detailed simulations or the test results, as a strong enabler for compliance demonstration and certification. It will contribute to seamless exchanges of models for the creation and the continuous execution of pyramids of models (MBSE-wise), executed through automated data flows;
- collaborative design and exchanges through integrated views of the product characteristics created throughout its lifecycle. Sharing and synthesising a wider spectrum of data will break the traditional frontiers

between disciplines generally induced by various sources, frameworks and standards. New methods and physical working innovation spaces will naturally be required to exploit this new data availability, energise and accelerate innovation discovery, product architecture and convergence in a multidisciplinary context (virtual reality rooms, mixed reality devices, multidisciplinary dash boarding).

In addition, this approach considers the role of the future operators using the technology including human strengths and weaknesses by means of a thorough human-in-the-loop design, supporting acceptance and accelerated use of new technologies.

Digital transformation activities will focus on the most efficient technologies, as well as their maturity for an effective integration and demonstration through the aeronautical industry and supply chain, assuming the following foundations:

- standards for continuous integration: the enhancement of industrial data exchanges through international and open standards for leaner and faster connections between businesses, suppliers and customers, and more locally between internal departments of companies, will allow for the development of cohesion regarding the aeronautical products, their design and production between different OEMs, suppliers and other involved partners;
- cloud technologies will ease communication by direct access to data from any terminal (engineering, production data etc.) and fast exchanges of any industrial information;
- big data and analytics, including techniques using data pulled from various sources, which in the context of Industry 4.0 will be adapted to allow decision-making, personalised performance support and personalised training in real time;
- cyber security, which will secure communication channels including data exchange without negatively affecting network performance, ensuring confidentiality, integrity and availability of data. Furthermore, it will ensure resilience in case security is compromised;
- augmented reality technologies will be developed and adapted to the aeronautical production and maintenance environment, allowing visualisation of the production environment by superimposing real and simulated objects;
- autonomous, flexible, communicative robots will provide the aeronautical industry with a broader range of manufacturing capabilities;
- industrial internet of things will introduce real communication technologies within physical components operated by logistics or manufacturing, enabling interactions between them or directly with the products, machines or assembly lines.

All these technologies will support more informed decision-making and a faster process, but the end-to-end development of the new system and aircraft technologies will not be possible without innovations regarding means of compliance for the design, validation and verification of the initial product requirements. 'Explore and Mature' will therefore elaborate on numerical and experimental methods.

A close alignment of requirements between Clean Aviation and other EU partnerships and programmes (e.g. the Electronic Components and Systems for European Leadership Joint Undertaking) will be beneficial in maximising the impact.

Axis 4: Developing future certification processes and requirements

In order to ensure that disruptive new technologies will meet high levels of safety and reliability and to reduce the development time and cost to bring new products to market and into service, a close coordination towards future certification requirements and safety standards is needed, thus involving the European Union Aviation Safety Agency (EASA) early in the research phase. Timely introduction to the market of new and disruptive technologies will therefore require upfront identification of any potential regulatory issue(s) as soon as possible with the appropriate authorities.

An upstream interaction with EASA must be planned and resourced to define new processes, standards and a more agile regulatory framework for any future ambitions including embedded systems, equipment, software for hybrid systems and autonomous functions, such as:

- a life-cycle process for a streamlined certification of new technologies and concepts;
- secure multi-scale and multi-physics models for qualification;
- virtualisation technologies for scaled testing;
- integration into a digital platform demonstration;
- building blocks and enabling technologies for a digital certification to shorten the innovation cycle.

A similar approach should be followed for operational requirements, allowing operators to introduce the new technologies into service. For operational requirements, the review shall be limited to the identification of any significant issue or showstopper that may prevent entry into service of the proposed new aircraft or technology.

Axis 5: Industry 4.0

With the ambition of end-to-end sustainability Clean Aviation will consider the environmental footprint of the complete life cycle. New materials, their future production processes and assembly techniques are key complementary contributors. To manufacture new parts on time and at cost requires new basic materials and techniques for simplification and streamlining the production processes, based on the respective new basic materials being used.

New frontiers have opened for aviation, largely by introducing Industry 4.0 concepts and digital solutions including: automation, tolerance management, supply chain optimisation and streamlining, on condition maintenance as well as manufacturing and material techniques, such as additive manufacturing, thermoplastics, ceramics, multifunctional and smart materials, hybrid metal-composites. An effective systemic approach between Clean Aviation and several Horizon Europe initiatives, such as Made by Europe, Climate Neutral and Circular Industry, European Institute of Innovation and Technology (EIT) Manufacturing and EIT Raw Material is key to maximise the results.

The main drivers structuring this 2030 Vision for Industry 4.0 are related to:

- process lead-time reduction by 50%;
- fast production ramp-up in two years and full industrial maturity at Aircraft 10;
- more autonomous and safe production systems;
- end-to-end sustainability: no-waste production and zero environmental impact;
- industrial architecture for platform concept enabling disruptive hydrogen technologies;
- human operations in future industrial systems.

The research actions that the partners expect to launch will naturally be assigned to:

- end-to-end sustainability: no-waste production and zero environment impact:
  - recyclable and reusable materials for high rate and maintenance operations;
  - no landfill waste (consumables).
- industrial architecture for platform concepts that can enable disruptive hydrogen technologies:
  - upfront definition of industrial system to ensure ramp-up capabilities and the cut-over from legacy production;
  - effectively and efficiently shop floor (architecture for modelling tools) – integration of learning, capacity and cost into a modelling approach:

    - pre-production line;
    - simulation;
    - systems design for manufacturing.

- human operations in future industrial systems:
  - establish testing concepts related to workplace design and employee qualification supported by artificial intelligence;
  - integration of employees into fully connected and flexible autonomous production systems.

Axis 6: Circular holistic design for more global impacts

From the initial research and modelling studies, up to the industrialisation of the product, its manufacturing, operational life and recycling, all emissions produced along the full end-to-end life cycle of the products have to be tackled. The total emission reductions expected by the aviation sector start from the optimal use of energy, materials and resources involved in product development, production, operation and maintenance, repair and overhaul. This justifies continuous holistic analyses of all design and manufacturing decisions and their associated impacts on eco-design, recyclability, reusability and resource depletion. Minimising these impacts along the full aircraft lifecycle have become environmental requirements for new aircraft programmes.

First, various and efficient strategies have to be elaborated to ensure:

- early and continuous identification and avoidance of hazardous non-REACH compliant materials;
- optimisation of energy consumption all along the development life-cycle;
- eco-design strategies at the levels of companies and supply chains.

In addition, in view of imminent market growth the aeronautical industry needs to anticipate and address the requirements for eco-compliant products with possible retrofit capability, developing effective technologies and assessment tools to be able to reach the same levels of eco-compliance that exist by other sectors. This infers not only production and logistical handling effects but also efforts towards acceptance by customers in line with their expectations for eco-friendliness and comfortable use.

6.1.4. A collaborative research programme to anchor the green aviation foundations

The broad range of breakthrough technologies explored and matured in the Collaborative Research programme responds to the challenges set by the Green Deal at the heart of the European Commission’s agenda. While not directly linked to the demonstration projects launched in the Clean Aviation programme, Collaborative Research has to be aligned and strongly interlinked with the activities in the Partnership, maximising synergies between the two programmes.

The synergies between Collaborative Research and the Clean Aviation partnership work can be followed up in two directions.

1. Research conducted through the demonstration projects can reveal innovative technologies and methods that – while promising with respect to the climate targets – cannot achieve the required maturity level in time or are too risky to be considered for the demonstrators. These alternative, and potentially even more disruptive paths should be taken up by Collaborative Research for further exploration and maturation.
2. The results of upstream research on technologies and methods that are not directly linked to the Clean Aviation demonstration projects, but can significantly contribute to climate neutrality, can be implemented in the second phase of the Clean Aviation programme.

In order to achieve this strong interlink, the respective roadmaps and calls have to be aligned at defined crossover points.

ACITURRI
AERnnova
AIRBUS
ASD
AeroSpace and Defence Industries
Association of Europe

Avio Aero
A GE Aviation Business
CIRA
Centro Italiano Ricerche Aerospaziali
DASSAULT AVIATION
DLR

EASA
European Aviation Safety Agency
easn
EREA
evektor

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INCAS
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iSQ
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