Next Decade European Aeronautics Research Programme (2020-2030)

A paper prepared by the Clean Sky Scientific Committee (SciCom) for submission to the Clean Sky Joint Undertaking (CSJU)

26 May 2019

Authors

Peter HECKER (SciCom Chairperson)

Trevor YOUNG (SciCom Vice-Chairperson)

Paulo Tavares DE CASTRO

David DUNFORD

Patrik FERNBERG

Christian MARI

Maria Angeles MARTIN PRATS

Janusz NARKIEWICZ

Wim PASTEUNING

Francesca SANNA-RANDACCIO

Dieter SCHMITT

Régine SUTRA ORUS

Executive Summary

Setting the scene

Aviation plays a critical role in promoting the growth and integration of the EU economy, facilitating business, citizen mobility, world trade and tourism, for example. Its global impact in 2016 – adopting a narrow definition (that is, focusing only on direct, indirect and induced effects) – has been estimated to account for 2.8% of EU28 GDP (supporting 5.7 million jobs). In Europe, this R&D intensive industry generates a significant volume of exports (€ 106 bn in 2016) with a €30 bn positive net trade balance; additionally, it is an important employer of highly skilled personnel (543 000 direct jobs in 2016). The industry is vital to the European economy and the wellbeing of its citizens. However, the industry is today facings challenges on a scale that are without historical precedence.

From the vast body of climate science literature that has been generated over the past few decades, the unequivocal conclusion that must be drawn is that steep reductions in CO_2 and other greenhouse gas emissions will be needed across almost all aspects of human activity, worldwide, to preserve life, as we know it, on our planet. Significant and urgent action will be needed over the next decade to prevent the worst-case climate-change scenarios, which involve run-away feedback cycles, happening. Worldwide, aviation's contribution to the total radiative forcing (a relative measure of the change to the energy balance of the Earth–atmosphere system with respect to the beginning of the industrial era) associated with anthropogenic activities is about 3.5%, increasing to about 4.9% when the effect of aircraft-induced cloudiness is included. Commercial transport aircraft – the main contributor to aviation's share of global radiative forcing – have become more fuel-efficient with each new generation of aircraft that are produced (annual *fuel efficiency improvement* rates across the global fleet is about 1.4% per year). But, with international aviation predicted to continue growing at about 4.9% compound annual growth for RPK (revenue passenger-kilometre) and about 5.3% annual growth rate for RTK (revenue tonne-kilometre), the problem is getting worse – not better.

Climate change mitigation, designed to accelerate the decoupling of economic growth from greenhouse gas (GHG) production in a socially fair manner, is undoubtedly society's biggest challenge. This observation must guide the prioritisation of resources for future research activities that are supported by public funding.

In addressing society's needs through judicious financial support of research into new aviation technologies, other environmental aspects must also be considered. Aviation noise and exhaust emissions continue to have a significant impact on the health of European citizens who work or live near our airports. Although modern commercial aircraft are much quieter with much reduced exhaust emissions than their predecessors, the increased air traffic means that many European citizens are today exposed to unacceptable noise levels and poor air quality. To grow the European aviation industry in a sustainable way, addressing society's greatest needs, with due regard of the Earth's natural resources is thus our mission.

Lessons learnt

The European Framework Programmes (e.g. Horizon 2020) and related research programmes, such as Clean Sky 1 (CS1) and Clean Sky 2 (CS2), have previously been assessed in considerable detail. Valuable findings regarding the high value of PPPs (public-private partnerships) in general and the programmatic goals of Clean Sky have been made. These assessments should inform decisions taken in structuring a new European aeronautics programme.

An important dimension of success in CS1 and CS2 can be seen in the development of a strong innovation pipeline, starting from fundamental research (knowledge building), progressing to technology maturation, systems integration and finally platform demonstration. The newly-introduced CS2 thematic topic calls is a promising way to initiate research on novel ideas. The responsibility for establishing call topics should be broadened to include independent think tanks or advisory panels, in addition to stakeholders/beneficiaries. In addition, more rapid technology maturation and development of retrofit solutions should be targeted to speed up exploitation routes.

The use of appropriate assessment tools – that is, Technology Readiness Level (TRL), Manufacturing Readiness Level (MRL), and System Readiness Level (SRL) – provide the necessary mechanisms for measuring and reporting progress. While TRL is commonly used in technical concept descriptions, the other two (i.e. MRL and SRL) could be applied to a greater extent.

The success of Clean Sky is in building on integration of these aspects, leveraging company, regional, national and European funding sources, linking stakeholders (e.g. academia, research establishments, industry, EASA, national governments and the European Commission) to deliver quantifiable demonstration of key technologies. Commercial stakeholder involvement from airlines and airport operators should be increased to drive more focussed and earlier technology adoption.

For future programmes, a clear European strategy with quantified objectives based on innovation and cooperation aligned to relevant SRIA (Strategic Research and Innovation Agenda) challenges is required. Developed programmes should have clear and quantified objectives, with guidelines to assess progress at appropriate intervals. It is recommended that the focus is on a limited set of objectives (potentially just one overarching objective) in order to maximise the impact of the programme. The priority should be assigned to technologies that promise substantial medium/long-term environmental benefits which will also bring a competitive advantage to the European industry. The potential of developed technologies to mitigate environmental threats should be assessed continuously throughout all stages of research using appropriate eco-design principles.

In terms of governance, an effective support structure for maintaining programme focus and integrity with the necessary flexibility to focus effort and resources is of high importance. This requires experienced project officers who have worked either in or closely with industry and have a strong understanding of the aerospace sector and relevant technologies.

The Technology Evaluator (TE) has proven to be beneficial. In addition to the technical and environmental assessments, it should cover economic assessments and place the outputs in a more commercial context supporting exploitation strategies.

The criteria established for the evaluation of proposals (which are submitted in response to calls) are a key feature in setting the direction and prioritisation for future aeronautics research. Consideration should be given to re-assessing the appropriateness of these criteria, in the light of current societal challenges. When appropriate, it should be possible to fund several projects on a single call topic.

Future research programme for aeronautics in Europe

The fundamental approach of establishing a collaborative PPP to develop complex, integrated demonstrators based on innovative technologies over a significant duration (e.g. 6-10 years) is well supported and has proven to be successful. However, future success will only be achieved by the enthusiastic involvement and support of all stakeholders and by strengthening the collaboration with such organisations as the European Defence Agency and European Space Agency, and through closer collaboration with EASA. In addition, a better integration of public-sector aeronautical funding activities, together with European, national and regional activities, would enhance the understanding of technology roadmaps, providing focused cluster activities and aiding implementation/exploitation.

The aerospace community generates positive spill-overs for other sectors and at the same time benefits from advances made in many different scientific and technical fields – for example: bio-fuels, batteries, IT technologies (e.g. cybersecurity, big data processing, connectivity and data fusion), robotics, automation (e.g. smart sensor and control elements), materials and power electronics. This ability to leverage technological advances from other sectors could be improved.

The classic evolutionary approach to product innovation is a proven and effective route; this should be retained as an essential component of any future technology programme. In parallel, radical and disruptive approaches – such as innovative electric propulsion systems – are also needed. Disruptive innovation should also come from outside the aeronautics industry, concerning, for example, Internet of Things (IoT), virtual/augmented reality (VR/AR), speech recognition, additive manufacturing, collaborative robots, autonomous vehicles and data analytics. In conclusion, it can be stated that a balance is needed between evolutionary and revolutionary approaches, and new ways of working will be needed for projects of the latter type.

The research activities spanning TRL 1–6 should be integrated into a single research programme, with the management responsibility falling under a single organisation, in order to maximise the potential benefit of the work undertaken. Specific governance models will be needed for the higher and lower TRL segments. Incremental innovation (at TRL 4–6) is key to short- and medium-term success; however, the long-term success of the European aeronautics sector depends significantly on innovations at the lower TRLs.

Education, at all levels, plays a crucial role in maintaining and expanding the competitiveness of the European aerospace industry. It is critical that the industry continues to attract the best and the brightest young minds. Innovative and disruptive ideas are continuously being developed at European universities – the challenge is to nurture this environment and to harvest promising ideas for maturation in technological programmes. More young people and women need to be involved in (or at least exposed to) European aeronautics research. An expanded role for the Clean Sky Academy is envisaged. The programme should link with funding schemes for doctoral or post-doctoral work (e.g. Marie Curie), strengthen ERASMUS mobility for students and support the work of European wide associations.

Finally, the possibility of closer collaboration with research programmes of other non-EU countries – based on common interests and secured IPR (intellectual Property Rights) – should be explored.

The way forward

To deliver the step change required to reduce significantly aviation's CO_2 contribution will require a clear and focused approach to drive key research themes and associated technology areas. As more than 90% of the global CO_2 emissions from civil aviation came from jet transport aircraft that carry 100 or more passengers, substantial reductions will be needed in this area; consequently, this should be the central focus of the research and development effort in the next research programme.

Novel aircraft configurations – incorporating, for example, distributed electric propulsors, rear fuselage concepts incorporating boundary layer ingestion (BLI), advanced wing concepts (e.g. very-high-aspect-ratio strut-braced wings or truss-braced wings with laminar flow) – coupled with advanced propulsion systems offer considerable potential to achieve this step change. To achieve success with novel aircraft configurations, focused fundamental research in design optimisation, propulsion systems, aerodynamics (including active flow control), flight controls, systems (including single pilot operation), materials, structures and manufacturing is essential.

The targeted research outputs of the next research programme should be divided into *near-term* (i.e. exploitable in the 2020–2029 timeframe), *mid-term* (i.e. exploitable in 2030–2039) and *far-term* (i.e. exploitable in 2040–2049). Future generations of aircraft or engines are described by the N+*i* nomenclature, where N represents the current generation, N+1 the next generation, N+2 the generation thereafter, and so forth. Herein, a 7½ year interval has been assumed between generations, with an entry into service of the "current generation" taken as 2020.

- *Near-term research outputs* will generally be associated with technologies that are currently in the range of TRL 4-6, and where there exists a high level of confidence of success. It is envisaged that relevant technologies addressed within CS2 (and other parallel aeronautics research programmes) will be further matured with the specific objective of early exploitation through retrofit/upgrade of the existing fleet and/or incorporation into N+1 generation aircraft. Highly-integrated large-scale demonstrators will be a vital component of the programme (to build confidence and generate new knowledge). Key technologies for demonstration include laminar flow control. Regarding the propulsion system, ultra-high efficiency gas turbine engines (possibly with variable pitch fans, improved power gearbox and advanced lean burn combustors) are envisaged.
- *Mid-term research outputs* will generally be associated with emerging technologies, where higher levels of uncertainty and significant deficits in knowledge exist. Outputs are likely to be combinations of novel solutions with conventional, well-understood technologies. Proof-of-concept demonstrators are envisaged, targeting specific applications or technologies (i.e. a building-block approach). Open rotor and unducted engine architectures and boundary layer ingestion (BLI) concepts should be targeted at the N+2 generation of SMR (short-to-medium range) passenger aircraft. Distributed all-electric or hybrid-electric propulsion should be targeted at the N+2 generation of regional aircraft.
- *Far-term research outputs* will be associated with highly-innovative, radical technologies that could, potentially, meet the 2050 environmental targets. Outputs will be the result of fundamental research (TRL 1-3) and the exploration of novel concepts. Subscale and ground demonstrators, in conjunction with numerical and experimental research, will be required to develop further understanding of the underlying principles. Distributed all-electric or hybrid propulsion should be targeted for N+3 generation of SMR passenger aircraft.

The next research programme should be structured in a way that addresses, possibly through separately managed platforms (projects), technologies that have the potential to be implemented in the N+1, N+2 and N+3 generation of aircraft. The concept of developing virtual demonstrators (i.e. reference vehicles to integrate emerging technologies) should be considered. Technologies such as distributed electric propulsion could follow a logical demonstration route, with initial application to a 19-passenger Small Air Transport (SAT) demonstrator or a 50–70-passenger regional aircraft.

Reduction of emissions can be achieved through aircraft/airline operating procedures, reducing fuel burn through management of every aspect of the flight cycle. An improved understanding is needed on how changes to flight altitudes and routes could reduce the radiative forcing associated with individual flights. The cross-over between aircraft and engine design, flight operations and atmospheric science requires greater attention.

Noise still represents a major challenge for all sectors of the aviation industry and ongoing research is needed to reduce its impact on society. Vertical lift vehicles, including rotorcraft, are a particular concern due to the forecast increase in urban operations. Rotorcraft fulfil certain roles that cannot be undertaken by other vehicle types (e.g. search & rescue, medivac); it is important that research actions continue to support such essential activities. Research actions in support of other roles undertaken by rotorcraft (e.g. VIP transport) should have a low priority.

Research in supersonic transport (SST) is not considered an EU priority as the primary output platform (vehicle) will be a high value business requirement, which the small executive aircraft market addresses. The use of public funding for the executive aircraft market is not deemed to be a priority. There is considerable interest and development in small autonomous urban mobility vehicles and there are a significant number of privately-funded developments underway. Further investment through public funding on the development of these vehicles is not deemed a priority; however, research on cross-cutting technologies that could potentially be adopted in mass transport vehicles (such as, autonomous flight, energy storage and electric propulsion) would be an appropriate use of public funding.

Concluding remarks

Europe has been at the forefront of international efforts to address environmental concerns that negatively impact human health and quality of life. Today, these efforts need to be intensified. Bold, innovative solutions will be needed to meet the unparalleled threat to society that climate change poses. Only through coordinated, collaborative efforts – involving stakeholders from academia, research institutes, SMEs and large industry – will the necessary progress be made. The next decade aeronautics research programme should target near- and mid-term outcomes through a structured framework built around a small number of carefully selected flagship demonstrators in the most relevant market sectors. In parallel, virtual demonstrators should be defined to structure research efforts on highly innovative concepts that could, potentially, meet 2050 environmental targets.

Contents

1 Introduction

Global demand for air travel is expected to continue growing over the next decades, and although average fleet efficiencies improve year-upon-year, the environmental impact of aviation is expected to progressively increase. The Clean Sky (CS) programmes – Clean Sky 1 (CS1) and Clean Sky 2 (CS2) – were designed, in part, to mature promising technologies that have the potential to mitigate the environmental damage caused by aircraft. These programmes have achieved many notable successes, both in terms of advancing technologies for new aircraft and in terms of improving aircraft operations. Addressing environment concerns must remain the overarching goal for any future European aeronautics research programme.

This paper was requested of the Scientific Committee of Clean Sky by the Interim Director of Clean Sky in mid-2018, to provide a vision of key technology research, development and demonstration that would benefit the aims of Clean Sky and support the future competitiveness of the European aerospace industry as a major global player.

The paper is not intended to be an exhaustive analysis; instead, the objective is to provide a basis for developing further understanding in support of future programme needs, envisaging – where possible – an integrated approach involving industry, research establishments and academia through national, regional and EC funded activities. The process leading to the generation of this document has been aided by discussions with industrial and academic partners currently active in CS programmes or other EC-funded projects. This involvement was facilitated by two well-attended workshops, which took place in Brussels on 29 November 2018 and 24 January 2019.

2 Setting the Scene

Aviation plays a critical role in promoting the growth and integration of the EU economy, facilitating business, citizen mobility, world trade and tourism, for example. Its global impact in 2016 – adopting a narrow definition[1] – has been estimated to account for 2.8% of EU28 GDP (supporting 5.7 million jobs) [1]. When the impact of tourism made possible by air transport[2] is included, aviation's contribution to EU28 GDP raises to 4.2% (supporting 9.4 million jobs). Aviation, however, also contributes to climate change (e.g. it is responsible for 13.4% of all transport greenhouse gas (GHG) emissions in EU28 in 2016), noise and air quality. Furthermore, its environmental impact is increasing [2].

Aeronautics is a vital component of aviation and the European industry over the past 40 years has become a leading player in this global sector. In Europe, this R&D intensive industry generates a significant volume of exports (€ 106 bn in 2016) with a €30 bn positive net trade balance; additionally, it is an important employer of highly-skilled personnel (543 000 direct jobs in 2016) [3].

The European aeronautic sector is confronted with important challenges in the 21st century. On one hand, it faces the necessity to reduce its environmental impact, which is increasing due to rapid growth in air traffic [2]. On the other hand, in all segments of the industry, competitive rivalry is becoming fiercer with respect to established players (e.g. in the U.S., Canada and Brazil) and emerging players (e.g. in China and Russia), where major programmes have been launched to support aeronautics developments. Government policy plays a key role in this industry. Due to the synergies between military and commercial aviation research, European aircraft manufacturers can suffer a competitive

[1] That is focusing only on direct, indirect and induced effects – see Ref. [1], p. 83.
[2] This is the so called "tourism catalytic effect" – see Ref. [1], p. 83.

disadvantage when compared to manufacturers in countries with large and centralised defence budgets, such as the USA and China. The might of the U.S. aerospace and defence research budget is illustrated by AIA (Aerospace Industries Association) [4]. When considering aerospace and defence-related R&D, spending by U.S. industry in 2017 reached $16.6 billion, while spending by the U.S. government amounted to $83.9 billion (14% by NASA and 86% by the U.S. Department of Defense (DoD)). Furthermore, U.S. government funding in this area is ramping up. It is expected that in 2019 the DoD R&D budget for aircraft and related systems will increase by 23% [5]. In the European case, the negative effect of lower expenditure on military aircraft can be worsened by duplication of R&D (research and development) in member states to maintain independent capabilities. The EU Defence Action Plan and the proposed European Defence Fund are initial steps in addressing these issues.

The European industry needs to develop and deploy major technological advances to face these challenges in a rapidly-evolving technology scenario. Aeronautics programmes are characterized by high risks – both technically and commercially – with long timescales and low profitability. Relying solely on private investment would lead to a sub-optimal level of innovation in this important sector. Thus, a new large-scale, long-term dedicated programme with public funding and aligned to defined priorities (discussed later in this paper) is needed to support civil aeronautics research in Europe.

The effort to define a strategic roadmap for aeronautical research accelerated in 2001 with the landmark report *European Aeronautics: A Vision for 2020* [6][3], which led to the creation of the Advisory Council for Aeronautics Research (ACARE). ACARE defined a Strategic Research Agenda (SRA) [7] in 2004 to provide a common vision for the European Air Transport System up to 2020. The two top-level objectives were "meeting society's needs and securing global leadership to Europe".[4] Vision 2020 was then extended towards 2050 by Flightpath 2050 [8], published in 2011. The two main challenges continue to be "meeting the needs of our citizens and maintaining global leadership". Society's needs are articulated along different dimensions (such as connectivity, mobility, climate change mitigation, safety and security), identifying for each of these objectives more specific goals (e.g. for mobility, a target of door-to-door travel in Europe in 4 hours for 90% of the population and very stringent environmental targets). No explicit ranking of society's needs was provided. However, when sketching Europe Air Transport in 2050, the report presents a section on "innovation", which is wholly dedicated to technologies developed for environmental protection, implicitly recognizing the pivotal role of climate change mitigation for aeronautics research.

3 Environmental Challenges

3.1 Climate Change: A Global Perspective

The impacts of global warming on human activities are well described by the Intergovernmental Panel on Climate Change (IPCC) in references [9, 10], for example. These impacts are a consequence of (a) mean temperature increases in most land and ocean regions; (b) extreme temperatures in many regions; (c) increase in frequency or intensity of heavy precipitation in several regions (leading to damage and flooding); (d) increase in intensity or frequency of droughts in some regions (with associated crop failures and wildfires); (e) global sea level rise (resulting in flooding of low-level coastal areas); (f) reduction in terrestrial biodiversity; and (g) ocean acidification and reduction in water

---

[3] Research Commissioner Philippe Busquin had an important role in initiating the process.

[4] In SRA1, society's needs were articulated in five challenges, viz. quality and affordability, environment, safety, ATS efficiency and security.

oxygen levels (causing significant damage to marine ecosystems). In the words of William Nordhaus, 2018 Nobel prize winner for economics, “Humans are putting the planet in peril” [11].

The 2018 IPCC Special Report on global warming of 1.5 °C above pre-industrial levels [10, 12], taken together with the most recent IPCC Assessment Report on Climate Change [9], paints a stark picture of the impact that global warming will have on our day-to-day lives and those of future generations. It identifies climate-related risks to health, livelihoods, food and water security, human safety and economic growth – all of which are projected to be detrimentally affected by a global warming of 1.5 °C and to be significantly further affected by a mere 0.5 °C extra warming. The following conclusion was reached: global anthropogenic (i.e. resulting from human activity) CO_2 emissions must decline to reach net zero around 2050 to ensure no or limited overshoot of 1.5 °C [12]. Non-CO_2 GHG emissions in this scenario must also undergo dramatic reductions.

The rational conclusion that can be drawn from the aforementioned studies – and from the vast body of climate science literature that has been generated over the past few decades – is that steep reductions in CO_2 and other GHG emissions will be needed across almost all aspects of human activity, worldwide. Significant and urgent action is needed over the next decade to mitigate the worst-case scenarios involving run-away feedback cycles. This urgent need for action has inspired *A clean planet for all* [13], the European Commission’s long-term vision for a competitive and climate-neutral economy by 2050. Climate change mitigation, designed to accelerate the decoupling of economic growth from GHG production in a socially fair manner, is undoubtedly society’s biggest challenge. This observation must guide the prioritisation of resources for future research activities that are supported by public funding.

3.2 Aviation and Climate Change

The annual contribution of global aviation to the total radiative forcing (RF)[5] associated with anthropogenic activities is considered to be about 3.5%, increasing to about 4.9% when the effects of aircraft-induced cloudiness (AIC) are included [14]. The envisaged increase in air traffic, however, is a major concern when viewed together with the current rate of technological improvement. ICAO’s *2016 Environmental Report* [15] provides a forecast of fuel burn and CO_2 production based on several postulated scenarios. For this projection, the ICAO Committee on Aviation Environmental Protection (CAEP) adopted a baseline 20-year forecast for international aviation[6] of 4.9% compound annual growth for RPK (revenue passenger-kilometre) and a 5.3% annual growth rate for RTK (revenue tonne-kilometre). This is broadly in line with industry 20-year market forecasts [16, 17]. A key metric in establishing a forecast of future fuel burn is the annual *fuel efficiency improvement rate*. Baseline improvements of 1.39% – 1.40% per year were assumed. The CAEP model was used to predict annual CO_2 emissions, due to international aviation, using the maximum anticipated fuel consumption in 2020 as a reference (in line with the aspiration of carbon-neutral growth from 2020 onwards) [16]. The projection shows a CO_2 overshoot (i.e. above the 2020 level) of 523 Mt (million metric tonnes) by 2040 and 1039 Mt by 2050 [15].

Several organisations have set global GHG emission targets for aviation (often with different baselines and implementation dates). One such target – which has been widely discussed and subsequently

[5] Radiative forcing (RF) is a measure of the change to the energy balance of the Earth–atmosphere system with respect to the beginning of the industrial era.
[6] In 2010, international aviation accounted for approximately 65% of global aviation fuel consumption; this is expected to rise to nearly 70% by 2050 [15].

adopted by other organisations – was promulgated by the Air Transport Action Group (ATAG)[7]. In 2008, the organisation adopted the highly ambitious goal of a 50% reduction in net aviation CO_2 emissions by 2050, relative to 2005 levels [18]. This is consistent with the target currently advocated by IATA [19].

Market-based (economic) mechanisms are seen by many as an effective means to limit GHG aviation emissions. It is highly likely that future mechanisms will extend well beyond the EU ETS (Emissions Trading Scheme)[8] and those endorsed by ICAO under CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [20].

A principal challenge, then, for the aeronautics industry as a whole is to generate a significant step-change in the annual fuel efficiency improvement rate. Past experiences, however, have shown that this will not easily be achieved. In fact, there are several reasons to be pessimistic about the likelihood of the global aviation industry exceeding the baseline fuel efficiency improvement rates assumed by ICAO in their 2016 Environmental Report [15] under a "business as usual" approach:

a) The adoption rates of new technologies (such as those developed in CS1 and CS2) in the worldwide fleet is relatively slow. This is evident from work conducted in the CS2 Technology Evaluator (TE), where the impact of Clean Sky developed technologies is being continuously assessed, considering the likely technology uptake within the worldwide fleet.

b) Airbus and Boeing (who effectively share a duopoly in the jet transport aircraft market, which is the single largest contributor to aviation emissions) have a massive backlog of orders for current aircraft types: 7415 jet transport aircraft for Airbus and 5964 aircraft for Boeing (Sept. 2018) [21]. Based on 2017 production levels, this represents 10-year and 7.8-year backlogs for Airbus and Boeing, respectively [21]. The commercial pressure to deliver such large volumes is likely to limit the appetite of the manufacturers to take risks with new technologies, which could potentially provide the necessary steep reductions in emissions.

c) Incremental improvements in technology often require ever-increasing resources (i.e. time, money, equipment) and greater amounts of human ingenuity – simply stated: the low hanging fruit gets picked first.

Unlike terrestrial or marine sources of GHGs, jet transport aircraft emit pollutants into the upper troposphere and lower stratosphere, causing changes to the chemistry of the air – thus altering the delicate balance between the amount of heat entering and leaving the atmosphere. The emissions also create contrails and induce cirrus formation in cold, ice-supersaturated air. Whereas, scientific understanding of the impact of CO_2 is reasonably mature, there is a greater level of uncertainty regarding the impact of contrails and aviation induced cloudiness (AIC) as regards radiative forcing [14]. Improved aircraft efficiency (i.e. fuel-burn per passenger-km) will directly bring down CO_2 production[9]. NO_x reduction, however, requires changes to the manner in which the fuel is combusted – a topic that is of considerable interest in CS.

From an atmospheric science perspective, there appears to be a lack of in-depth understanding as to how changes to flight altitudes (e.g. whether the aircraft is above or below the tropopause) and routes (e.g. within regions prone to contrails or AIC formation) could reduce the radiative forcing associated

[7] ATAG is an umbrella organisation representing aviation industry stakeholders (including airports, airlines, airframe and engine manufacturers, air navigation service providers, airline pilot and air traffic controller unions, chambers of commerce, tourism and trade partners, ground transportation and communications providers).

[8] At present only flights between airports in the European Economic Area are included in the EU ETS (Ref. [2], Chapter 6).

[9] CO_2 emissions are targeted in the newly-recommended ICAO certification standard for fuel efficiency in cruise (to be published in ICAO Annex 16, Vol. III). There is concern, however, that the standard is not strict enough to yield meaningful reductions in emissions [22].

with the flight. From an aircraft design perspective, it is the minimisation of the overall environmental impact that needs to be considered. It is this cross-over between aircraft and engine design, flight operations and atmospheric science that requires further investment in a future European Aeronautics Research Programme.

3.3 Noise

Noise is an important subject for the better acceptance of air transport in society. Strict noise regulations are needed to protect the population living within the vicinity of an airport. On the other hand, noise regulations are often seen as an economic growth-limiting factor in Europe.

There is a huge potential for improving airline operations based on commercial aircraft if they were so quiet during take-off and landing that they would have no "significant noise signature" outside the airport boundaries. If this existed there would be a clear target and incentive for the aircraft industry to use aircraft noise as a design criterion (parallel to the fuel burn). This would enable aircraft designs for a 24-hour day-and-night operation at the large European airports. Today, nearly all major European airports have fairly severe restrictions and are not allowing flight operations during night-time periods.

There is a need for two basic tasks from the scientific and technological side, which need to be done and should be part of a new European Aeronautics Research Programme:

a) Compare all metrics for noise assessment, which are existing today and are in use, but very different in assessing the annoyance of persons. Basic research and comparison of noise metrics is needed to specify/select the best suited metric for noise measurement during night flight operations and specify the noise boundary around the airport/runway.

b) Define in a systematic way the allowable noise level that is tolerable and can be proposed internationally via ICAO as a noise standard for night-time operations. One such study was conducted by the DLR in 2007 [23, 24], where several test subjects volunteered to have their sleep patterns monitored while being exposed to different noise events. Such studies could be repeated to provide a basis for a European noise standard for night-time operations, which could form a basis for negotiations with other national regulatory bodies.

3.4 Local Air Quality

Airports have become one of the largest single sources of localized pollution in certain developed regions of the world, as terrestrial pollution due to other sources is progressively reduced [25]. Aircraft operations, of course, are only responsible for a portion of this environmental damage and the associated impact on human health. Typically, about 10% of aviation emissions are emitted below 3000 ft (during the takeoff and landing cycle and during ground operations). The pollutants CO (carbon monoxide) and HC (hydrocarbons) are exceptions as about 30% is emitted below 3000 ft, when the engines are operating at low combustion efficiencies [26].

Forecast analyses conducted by the CAEP (ICAO) [15] into aircraft emissions that affect local air quality (LAQ), concluded that NO_x emissions below 3000 ft will increase by 2.1 to 2.8 times from 2010 to 2040, depending on scenario assumptions. Similarly, the increase in PM (particulate matter) is expected to be about three-fold over this time period. The challenge for the aviation industry to address the issue of local air quality is well recognised.

3.5 Environmental Protection: Life Cycle Considerations

The aerospace industry is a large consumer of natural resources. Minimizing the environmental impact of the manufacture, operation and end-of-life disposal of aircraft are key aspects in the evolution of this global industry to a more environmentally sustainable basis. Several topics are described in this section as an illustration of the issues that deserve attention within a new aeronautics research programme.

3.5.1 *Electronic part life cycle and obsolescence in aeronautics and general industry*

The electronics industry is one of the most dynamic sectors of the world economy. Many of the electronic parts that compose a product have a life cycle that is significantly shorter than the life cycle of the product. This problem is prevalent in many avionics and military systems. These problems are exacerbated by manufacturing that takes place over long periods of time and the high cost of system qualification or certification that make design refreshes using newer parts an expensive undertaking. Methodologies exist [27, 28] to predict the obsolescence of electronic parts to improve the analysis of the life cycle of products. Manufacturers are also providing tools to help OEMs (Original Equipment Manufacturers) and product developers to manage the problem of obsolescence, and plan for when the end-of-life (EOL) notices are placed on parts that will soon cease to be produced, repaired and supported by component vendors [29].

3.5.2 *Platinum-free fuel cells and batteries*

Fuel cells, which can be used in electric vehicles (EVs), offer several advantages over internal combustion engines, including higher efficiency, quieter operation and lower emissions. A critical barrier to fuel cell adoption is the cost of platinum, making the development of alternative catalyst materials a key driver for large-scale implementation [30]. Platinum (Pt) and Pt-based catalysts have been widely proven to be the most efficient catalysts. Unfortunately, the scarcity, high cost, poor stability, crossover effect and CO (carbon monoxide) poisoning of Pt and Pt-based materials restrict their further development [31]. Carbon-based nanomaterials, especially the non-precious metal porous carbon-based materials (NPC), have been considered as the most promising replacement for Pt and thus attract extensive attention, since its high specific surface area and easy regulation can significantly increase the active sites and mass transfer of electrocatalyst [32, 33]. Although experimental studies are still at an early stage, theoretical studies show that these non-Pt and metal-free catalysts have a promising future in electrocatalysis. However, further research needs to be carried out on these catalysts to effectively reach the fuel cell industry in the near future [34].

3.5.3 *Toxic materials in the aerospace industry*

Electroplated cadmium and hard chromium have been used extensively as protective coatings for the most demanding aerospace applications. Despite having excellent technical performance and low deposition costs, these coatings are being phased out from industrial usage because of the serious health and environmental hazards they present. Cadmium is highly toxic in its metallic form, and the plating bath contains lethal cyanides. Chromium, while being completely benign in its metallic form, is usually deposited from highly toxic hexavalent chromium solutions that are targeted by strict environmental regulations. General industry has been working under cadmium and hexavalent chromium bans for years, while the aerospace and military have been exempt from the respective regulations. New developments on both hard chromium and cadmium alternative materials and technologies are underway [35, 36]. Materials such as tungsten carbide coating [37] and AlumiPlate [38] are starting to be used to replace hard chromium and cadmium in the aeronautical industry.

3.5.4 *Ethical issues*

The ethical integrity of companies is important as industries face challenges that arise from different social and environmental responsibilities. Child labour is one such issue that is currently impacting children in underdeveloped countries, such as the Democratic Republic of Congo (DRC) or Rwanda, as they mine coltan [39]. The elements niobium and tantalum, which are extracted from coltan, have a wide range of uses; but just less than 20% comes from recycling sources, the rest is newly mined [40]. Tantalum is also used to make high-temperature alloys for jet engines and air- and land-based turbines. Nickel-tantalum superalloys are used in jet engines, ships and missiles since the 1980s.

4 Lessons Learnt from Horizon 2020, Clean Sky 1 and Clean Sky 2

4.1 Programme Evaluations

The European Framework Programmes (e.g. Horizon 2020) and related research programmes, such as CS1 and CS2, have previously been assessed in considerable detail through various assessment mechanisms – for example: H2020 Interim Evaluation (2017) [41], Clean Sky Final Evaluation (2017) [42] and Clean Sky 2 Interim Evaluation (2017) [43]. The CS Scientific Committee recognises these findings and wishes to deliver additional and specific recommendations on lessons learnt from these programmes.

The recommendations refer to both the scientific and technical considerations on one hand and implementation and governance considerations on the other hand. A third dimension is defined at programme level, where the strategy involves fundamental research (knowledge building), leading to technology maturation and systems integration and finally platform demonstration. The use of appropriate assessment tools – that is, Technology Readiness Level (TRL), Manufacturing Readiness Level (MRL), and System Readiness Level (SRL) – provide the necessary mechanisms for assessing and reporting progress. While TRL is commonly used in technical concept descriptions, the other two (i.e. MRL and SRL) could be applied to a greater extent. The success of Clean Sky is in building on the integration of these aspects, leveraging company, regional, national and European funding sources, effectively linking stakeholders (e.g. academia, research establishments, industry, national governments and the European Commission) to deliver quantifiable demonstration of key technologies.

4.2 Areas for Improvement

However, there are areas where improvements can be made. A clear European strategy needs to be defined with quantified objectives based on innovation and cooperation. This should encompass relevant SRIA (Strategic Research and Innovation Agenda) challenges within programmes having clear and quantified objectives and relevant guidelines to assess progress. These objectives could, potentially, be directed at topics that range from specific fuel consumption (SFC), noise, CO_2 and NO_x emissions, local air quality, direct operating cost to industrial competitiveness and job creation. The CS Scientific Committee, however, recommends focusing on a limited set of objectives (potentially even only one overarching objective) in order to maximise the impact of the programme.

To support these selected objectives, increased commercial stakeholder involvement from airlines and airport operators would be an advantage, driving more focussed and earlier technology adoption. The synergies and complementarities between the different funding mechanisms need strengthening, but with the caveat that TRL 1 and 2 research is a key element in harvesting new ideas and developing disruptive technologies for the future. By adopting and continuing the thematic topic approach Clean Sky will be ready to collect and support ideas in a more cohesive way, aligned to future perceived requirements. This approach would connect to the innovation pipeline and should involve all relevant stakeholders, not only from industry and research, but also actors such as airlines, airports and regulatory bodies.

Another key area to be addressed in a future programme is the achievement of more rapid technology maturation (i.e. accelerating the progression through the TRLs). The aerospace industry rightly maintains a strong safety ethos as a cornerstone to flight operations. This can, however, slow down the development of promising technology into useful products. Opportunities should be sought for early adoption of these technologies – for example, via retrofit or incorporation in changes required during maintenance cycles or through more flexible and quicker certification procedures.

Essential elements for success in a research programme are implementation and governance. It is important to have an effective support structure to maintain programme focus and integrity with the necessary flexibility to focus effort (financial, programme, resources, etc.) to achieve the desired outcomes. Allowing a more dynamic evolution of content may be helpful to adjust the work programme, but always ensuring a competitive element in defining and assigning work shares. The current Call for Proposal (CfP) process provides this degree of flexibility to focus on technical requirements supporting demonstration. The “proposal pipeline” (i.e. Work Plan, calls, evaluations and negotiations) is well established – however, it has an associated timeline (usually around 12 months from concept to contract).

The proposal financing structure should be better adjusted to national/institutional regulations, as economic situation and the process of research financing differ in various countries, concerning limitations for project financing parts (personnel, equipment, overheads etc.).

Clean Sky has benefited from experienced project officers who have either worked in or closely with industry and have a strong understanding of the aerospace sector and relevant technologies. It is strongly recommended to stick to this principle, as an efficient management of SPDs (Strategic Platform Demonstrators) requires this level of expertise. The use of a Technology Evaluator (TE) to provide assessed outputs in a global context has proven to be beneficial and fully supported by industry partners. Further development of this to cover not just technology but economic assessments and place the outputs in a more commercial context would strengthen the understanding of assessed benefits. Such assessment would be supported by continuous monitoring of exploitation strategies and intentions to support quick transitions along the innovation pipeline into products and markets. Additional guidance should be provided through the definition of primary strategic research areas of common interest with other sectors of aeronautics and space, as well as such external actors as military agencies (e.g. EDA) and the automotive and IT sectors.

Beyond the Technology Evaluator, further horizontal activities such as eco-design and Life Cycle Assessment are delivering additional value into the programme. While the dimension of environment and sustainability in aviation is considered to be of utmost value, a next programme should target a higher level of integration in the programme.

4.3 Proposal Evaluation and Research Prioritisation

The criteria established for the evaluation of proposals (which are submitted in response to calls) are a key feature in setting the direction and prioritisation for future aeronautics research projects. Consideration should be given to re-assessing the appropriateness of the existing criteria in the light of changing societal challenges (see Chapter 3). For example, the current *one-size-fits-all* approach does not provide an adequate framework for discriminating between (1) a low-risk concept that can yield a small evolutionary benefit and (2) a high-risk concept that could, potentially, yield a step-change improvement. Alternative mechanisms are needed to evaluate highly innovative and potentially high-risk concepts. When appropriate, it should be possible to fund several projects on a single call topic. Mechanisms to synthesize outputs from projects conducted in parallel need to be developed to maximize exploitation potential of the outputs. This could take the form of a combined workshop or the generation of a combined synthesis report, for example.

In CS2, equal value is given to the following criteria: excellence, impact and implementation. Impact is assessed under the following headings: (a) environmental impact (energy efficiency and CO_2, noise, local air quality, life-cycle impact); (b) impact on future product competitiveness; (c) enhanced mobility; and (d) contribution to European competitiveness. Some of these criteria may have minor relevance to particular technology topic. Therefore, a flexible approach would be beneficial for instance by implementation of weighting factors depending on the topic. The impact criteria should be evaluated against widely agreed and quantifiable targets. When technologies are expected to increase competitiveness but do not result in significant environmental benefits, consideration should be given to reducing its weighting. The priority should be assigned to technologies promoting in the medium/long-term substantial environmental benefits; such technologies will indirectly yield a competitive advantage in the market place.

Projects in Clean Sky vary significantly in terms of budget and consortia size. Consequently, the project management structures should reflect these aspects. It would be beneficial to identify and communicate best practice policies across the different setups. The respective processes for collecting experiences and building policies should be standardized and be part of the guidance material. This will allow for improved efficiency in managing projects.

The two-stage evaluation procedure has shown to be effective. To further improve the efficiency of the evaluation process, the first stage evaluation should be based on only one criterion: excellence (which is the most essential consideration for new research).

5 Future Research Programme for Aeronautics in Europe

5.1 Research Timeline and Technology Implementation Timeframes

A key aspect of any large research programme is the establishment of technology maturation timelines leading to the exploitation of these technologies in future generations of aircraft. This global view is critically important as it provides a framework for the development of technology roadmaps for key technologies. In Figure 5.1, a theoretical framework using the N+*i* nomenclature[10] has been adopted to describe future generations of aircraft or engines, where N represents the current generation, N+1 the next generation, N+2 the generation thereafter, and so forth. A 7½ year interval has been assumed between generations, with an entry into service (EIS) of the "current generation" taken as 2020.

The research outputs of the *Next Decade European Aeronautics Research Programme* can be divided into near-term (i.e. exploitable within the 2020–2029 timeframe), mid-term (i.e. exploitable within the 2030–2039 timeframe) and far-term (i.e. exploitable within the 2040–2049 timeframe).

[10] The idealised timeline model provides a convenient shorthand to describe opportunities for technology exploitation. The N+*i* generations are based on a somewhat arbitrary interval between future entry-into-service (EIS) dates of new commercial aircraft or engine types or major derivatives thereof. The start date (i.e. Nth generation) is customarily selected to suit the particular application; consequently, the 2020 Nth generation baseline adopted herein will not necessary align with other strategy documents (e.g. from NASA) or even internal CS2 reports (e.g. in LPA WP 1.1).

- Near-term research outputs will generally be associated with technologies that are currently in the range of TRL 4–6, and where there exists a high level of confidence of success. It is envisaged that relevant technologies addressed within CS2 (and other parallel aeronautics research programmes) will be further matured with the specific objective of early exploitation through retrofit/upgrade of the existing fleet and/or incorporation into N+1 aircraft. Highly-integrated large-scale demonstrators will be a vital component of the programme (to build confidence and generate new knowledge).
- Mid-term research outputs will generally be associated with emerging technologies, where higher levels of uncertainty and significant deficits in knowledge exist. Outputs are likely to be combinations of novel solutions with conventional, well-understood technologies. Proof-of-concept demonstrators are envisaged, targeting specific applications or technologies (i.e. a building-block approach to technology maturation).
- Far-term research outputs will be associated with highly-innovative, radical technologies that could, potentially, meet the 2050 environmental targets. Outputs will be the result of fundamental research and the exploration of novel concepts. Subscale and ground demonstrators, in conjunction with numerical and experimental research, will be required to develop further understanding of the underlying principles.

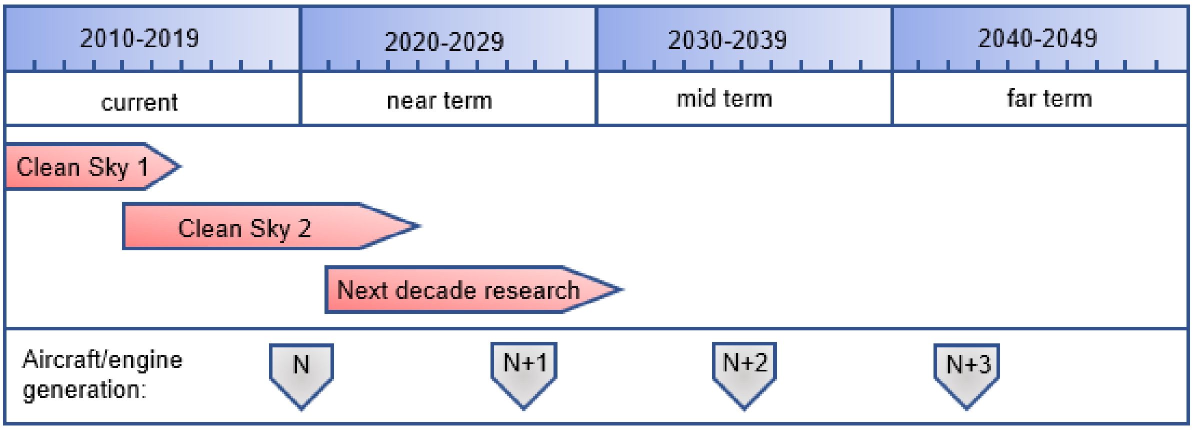

Figure 5.1: *Timeline for Aeronautics Research Programmes*

5.2 Structure and Implementation of a Research Programme

While there are many refinements and improvements that can be made to the structure and mechanisms set up by the Clean Sky JU to manage CS1 and CS2, the fundamental approach of establishing a collaborative Public Private Partnership (PPP) – whose goal it is to develop complex, integrated demonstrators based on innovative technologies, over a 10-year period – is well supported. Clearly, any future EU aeronautics research programme should reflect the variety of situations and aspirations of the stakeholders, and a consultative process will be necessary to achieve success.

5.2.1 *Stakeholders*

It is recognised that success will only be achieved by the enthusiastic involvement and support of all stakeholders representing many different sectors: industry, including SMEs; academia; research establishments; national and regional governments; and the EC. It is only through the integration of all relevant European actors through the research and development chain – from concept initiation to full implementation – that meaningful progress in tackling the key challenges will be made. This approach is necessary to strengthen the European innovation eco-system.

One specific change that should be considered at European level is to expand the role of EASA in regard to R&D and education – such as those undertaken by the U.S. Federal Aviation Administration (FAA), which, further to funding research projects, also promotes conferences, workshops and so forth, on emerging scientific and technological topics aligned with its mission. Such reinforcement of EASA's role is upheld by Article 86 of EU Regulation 2018/1139 [44], in particular, numbers 3 and 5 (number 2 points to the interaction of EASA and the EC concerning relevant EC Framework programmes).

Consideration should be given to exploiting synergies concerning aeronautics research managed or performed by the European Defence Agency. The space research and development led by the European Space Agency should also be considered as a source of new solutions in aeronautics (e.g. regarding material science, sensors, navigation and communication systems).

5.2.2 *Education*

Education, at all levels, plays a crucial role in maintaining and expanding the competitiveness of the European aerospace industry. A stronger consideration and embedding of educational elements in a future programme will generate positive benefits in multiple dimensions.

The involvement of academia in research and innovation will attract the next generation of scientists and engineers and raise the interest of young people and women in relevant scientific and technical areas. In addition, innovative and disruptive ideas developed at European universities could be transferred through such linkages into the industrial environment, to be exploited with greater speed. All this could be achieved by promoting the involvement of young people and women at all academic levels (e.g. Bachelor, Master and PhD students, and postdoctoral researchers) in the projects and supporting them in future research programmes. Ultimately, an increased interest in entrepreneurship and founding new start-up companies could be achieved, further enhancing the competitiveness of European industries.

A stronger interaction between industry and academia should be targeted to enable a continuous evolution of academic syllabi that would satisfy the needs of an evolving industry, providing a better educated workforce with relevant engineering skills. Consequently, aeronautical and aerospace related education and R&D in academia should be actively promoted. Primarily this should be achieved through a closer integration of academia into a research and innovation programme. As a complement to existing national initiatives, contributions to this goal may come through funding of doctoral or post-doctoral grants (such as the Marie Curie or equivalent schemes), from strengthening ERASMUS mobility of students and academic staff, and by supporting the work of European-wide associations (e.g. EASN, Pegasus). In addition, low TRL projects stimulated through calls for proposals (especially Thematic Topic CfPs) are a platform for involving doctoral students in relevant research activities. An expanded role for the Clean Sky Academy is envisaged to facilitate these objectives.

More attention should be paid to the exposure of aeronautics to primary and secondary school pupils. At that age, the interest of young people in prospective careers takes shape. Secondary education is an important consideration for the industry's future manufacturing workforce.

5.2.3 *Balance between low and high TRLs and associated governance issues*

In CS1 and CS2, there was an emphasis on research at the higher end of the TRL range for which public funding is permissible (i.e. TRL 3–6). The PPP model, developed in Clean Sky, has been shown to be an effective method to identify and mature key technologies at these levels. Furthermore, as industry partners contribute significant capital and human resources, they have a vested interest to identify relevant and promising technologies for the work programme.

Lower TRL research (i.e. TRL 1 and 2) has also been undertaken in CS1 and CS2 – often driven by the need to develop a particular technology for a particular demonstrator. Additionally, the use of Thematic Topic CfPs has further promoted “blue sky” low TRL research within CS2. In parallel, low TRL aeronautics research, funded by the EC in H2020, has been coordinated by INEA (Innovation and Networks Executive Agency) independently of the Clean Sky JU.

The goal of producing relevant research outcomes for the near-, mid- and far-term timeframes (see Section 5.1), however, will require a more balanced approach with research efforts spanning the TRL range from 1 to 6. Incremental innovation and evolutionary improvements (at TRL 4–6) are key to short- and medium-term success; however, the long-term success of the European aeronautics sector depends significantly on innovations at the lower TRLs. The research activities spanning TRL 1–6 should be integrated into a single research programme, with the management responsibility falling under a single organisation in order to maximise the potential benefit of the work undertaken and to eliminate duplication of effort. Under such an organisational structure, it is expected that synergies across the TRL range (associated with different work packages) will be identified and exploited. Revised procedures for the development of low TRL call topics will, however, be needed (the lessons learnt in managing the Thematic Topics in CS2 will prove beneficial in this regard).

5.2.4 *Needs and solutions according to market segments*

The civil aviation (air vehicle) market comprises several sectors – herein, the following sector breakdown has been adopted:

1. Commercial passenger and cargo transport (i.e. single-aisle short-to-medium range aircraft; medium-to-long haul widebody aircraft[11], regional aircraft and dedicated air cargo aircraft);
2. Supersonic aircraft;
3. Vertical lift air vehicles (including conventional helicopters and autonomous urban mobility vehicles);
4. Executive aircraft (including business jets); and
5. Small air transport (considered to be civil aircraft of 19 passengers or less).

Such categorizations of air vehicles are helpful in establishing needs, priorities and technical solutions for the aeronautics industry. The approach has also been shown to be useful in structuring large research programme (such as CS1 and CS2).

Chapters 7 and 8 describe how technological solutions differ across these segments and which of these technologies represent priorities for the Next Decade European Aeronautics Research Programme.

5.2.5 *National and regional alignments*

The aeronautics sector has a high scientific and technical level, which tends to have a knock-on effect on other industries, raising the technical sophistication within affected regions. The contribution of the aeronautics industry to regional and national economies should not only be measured by the direct contribution of the sector to the associated GDP, but it should also include this indirect effect. It is thus desirable that aeronautics research be conducted throughout Europe. Without compromising quality, a greater number and greater diversity of stakeholders all over the EU should be involved in future aeronautics research activities.

Better integration of public-sector aeronautical funding activities, together with European, national and regional activities, would strengthen the understanding of technology roadmaps, providing focused cluster activities and aiding implementation/exploitation. A closer collaboration between

[11] There is a clear overlap between market segments, as described by Airbus in their Global Market Forecast 2018-2037 [16]. Both single aisle and widebody types operate on medium-haul routes.

representatives of member states and the Clean Sky JU as well as EC will be beneficial. In addition, formal links between the funding instruments and supporting processes at EC, national and regional level should be established. Clean Sky and the EC includes representatives of member states and national experts within their structures. This should be an effective conduit to produce this more integrated approach.

5.2.6 *Synergies with other sectors*

The aerospace community generates positive spill-overs into other sectors and at the same time benefits from advances made in many different scientific and technical fields, some of which are of a transversal nature. Cross fertilization of advances in different industrial sectors and academic disciplines can be of mutual benefit. The automotive sector is a good example: its manufacturing leadership – for example, in lean manufacturing, automation, supply-chain practices – are providing useful knowledge transferable to the aeronautics sector, to meet the challenges associated with increased production rates. In Europe, it has been recognized that research on battery technologies and new production capacity is imperative to reduce environmental impact and improve competitiveness of the automotive sector [45]. A road map for the subsequent years, with concrete actions until 2020, has been formulated. Without providing any detailed foresights on the actual optimal battery technologies, it is a clear that certain elements of the aeronautical sector could benefit from a better alignment with future battery technology roadmaps.

Sustainable Aviation Fuels (SAFs) – currently approved for use as a blend with conventional jet fuel in civil air transport – are another area offering synergistic benefits (see also Section 6.3.5). Methods for up-scaled production of these sustainable drop-in fuels (i.e. fuels that can be used in existing aircraft without modification) are being developed and introduced on the market. Recent figures indicate that 0.004% of total fuel used by aviation in 2017 are bio-fuels [1]. These tiny volumes are expected to increase over the coming years; the challenge will be to achieve the necessary production levels and distribution networks required for large-scale commercial airline operations. SAF will play an important role in the transition towards a more environmentally-friendly aviation industry and deserve attention when devising the next steps in aeronautics research.

Other areas requiring monitoring include IT technologies, such as cybersecurity, “big data” processing, connectivity and data fusion, autonomy, artificial intelligence, and so forth. Sensor technology (e.g. MEMS), power electronics, improved systems architectures among other technology areas will be important factors for implementing new cockpit concepts (e.g. single pilot operation), ATM procedures, increased safety standard, etc.

5.3 Evolutionary and Disruptive Elements in a Research Programme

5.3.1 *Evolutionary research elements*

Most technical improvements in the aeronautics industry are today made by progressive improvements (evolutionary developments) to existing designs, rather than from completely radical new concepts. In this respect, the existing Clean Sky approach is a superb way to collaboratively innovate and mature promising ideas. This classic evolutionary approach to research leading to product introduction is a proven and effective route and should remain a solid basis for future technology developments.

The typical pyramid approach, which has many lower TRL projects, utilising a breadth of research providers (academic organisations, research establishments, etc.), is needed to innovate and introduce technologies from other sectors (e.g. IT, sensors, human factors and communications). The availability of results from completed EC funded projects needs to be improved to avoid duplication effort and to allow researchers to build on prior knowledge. Where possible, information at low TRL should be made open source. As the TRL associated with a particular technology rises, the value of the IP (Intellectual Property) too rises – and, naturally, this needs to be protected to achieve a final return on investment for industrial companies and to generate revenue for European industry.

5.3.2 *Disruptive research elements*

In addition to the evolutionary approach to product development (described above) – which is needed to address near- and mid-term targets – more radical, disruptive approaches will be needed to address the 2050 targets. A typical technology development programme, producing incremental improvements to existing air vehicles, will not yield the CO_2 emissions reductions needed to address the challenges described earlier in Chapter 3. For example, to meet the ATAG/IATA target [18, 19] – that is, a 50% reduction in net aviation CO_2 emissions by 2050, relative to 2005 levels – while allowing for an assumed 3.2% annual growth[12] in payload–distance travelled, will require a reduction of greater than 80% in the key metric[13] of CO_2e per kg-km [46]. More radical approaches will be needed. Innovations in electric and hybrid-electric propulsion (for short-haul routes) and improved fuel efficiency, coupled with significantly increased use of low carbon fuels (for mid- to long-haul routes), will be central to meeting this enormous challenge.

The development of enabling technologies for the Factory of the Future remains a key component for future commercial success in the aviation industry. Disruptive technology advances like those on the Internet of Things (IoT), virtual and augmented reality (VR/AR), speech and handwriting recognition, additive manufacturing, collaborative robots, autonomous vehicles, and data analytics are to be widely implanted in many industries in the upcoming years. These technologies will have a big impact for aircraft makers, giving place to new markets, and new value chains. However, aircraft manufacturing has been traditionally resistant to the introduction of technology leaps in the production process, even those considered game changers in other sectors. This is, in part, due to the complexity of modern aircraft and the strict safety requirements in the commercial aircraft industry. It is also the result of a reluctance to depart from tried-and-tested, traditional methods. But this is precisely what is needed: innovation “outside the box”.

R&D is the most important driver for company innovations. The European Commission is fostering R&D policies as a priority, as outlined in the policy document *Europe 2020 Flagship Initiative Innovation Union* [47]. The adoption and diffusion of new and disruptive technologies will give Europe a technological lead to ensure that Europe secures the returns from its innovation in terms of economic growth and job creation. The "first mover advantage" can boost productivity, resource efficiency and market share.

5.3.3 *Governance*

The programme structures and procedures that has evolved in CS1 and CS2 are very effective. The procedures, however, is not optimally designed to stimulate and manage research on wholly new and radical concepts – which could, potentially, lead to step performance improvements. At the heart of this difficulty is risk management. As radical concepts introduce a greater likelihood of failure, there may need to be a different model for high risk endeavours. Different approaches to (a) call topic formulation, (b) project planning, and (c) project management and oversight for such projects should be explored. For example, such call topics could be established by independent think tanks (or advisory

---

[12] The assumed figure of 3.2% annual growth in Ref. [46] is on the low end of the forecast range (see also Section 3.2).

[13] CO_2e/kg-km is carbon dioxide equivalent per kilogram–kilometre. Note that there are some variations in the precise definitions adopted for CO_2e.

panels) rather than by stakeholders/beneficiaries. The thematic topics in the recent CS2 calls are a promising first step in this direction. When appropriate, it should be possible to fund several projects on a single call topic (see also Section 4.3). In terms of project governance, greater flexibility will be needed to change the direction of such projects or to shut it them down if necessary – quickly and efficiently. The procedures for changing a project's direction should be reformed to enable a faster response time, while still ensuring that the lessons learnt, and knowledge gained are well documented and effectively disseminated.

In conclusion, it can be stated that a balance is needed between evolutionary and revolutionary approaches, and new ways of working need to be evolved for projects of the latter type.

5.4 Non-EU Research Programmes

R&D to advance aircraft design and manufacturing is actively pursued worldwide. In Europe, a vision for the future of aviation is served by the ACARE Strategic Research & Innovation Agenda (SRIA, 2017 update), organized in two volumes: the first provides the context for R&D to be performed [48] and the second [49] listing the many R&D tasks relevant to pursue the ACARE SRIA.

In the U.S., the aeronautics side of NASA (Aeronautics Research Mission Directorate – ARMD) is very active in the same fields. The medium- and long-term strategy pursued are discussed in *NASA Aeronautics: Strategic Implementation Plan* (2017) [50, 51]. Reference [52] contains other relevant information – namely, concise presentations of the set of "strategic thrusts", which are research areas guiding ARMD's response to global trends affecting aviation: (1) safe, efficient growth in global operations; (2) innovation in commercial supersonic aircraft; (3) ultra-efficient commercial vehicles; (4) transition to alternative propulsion and energy; (5) real-time system-wide safety assurance; and (6) assured autonomy for aviation transformation. Item 3 is divided into two parts: 3A (ultra-efficient commercial vehicles subsonic transport) and 3B (vertical lift strategic direction). Furthermore, defence activities (e.g. of the Defense Advanced Research Projects Agency, DARPA) may lead at some point to advances in civil aeronautics.

Other publicly available prospective studies include the report *Commercial aircraft propulsion and energy systems research – Reducing global carbon emissions* (2016) [53], prepared by the Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions for the U.S. National Academies of Sciences, Engineering and Medicine.

Elsewhere, development of the aeronautical industry also evolves together with supporting research efforts. In Japan, the Aeronautical Technology Directorate [54] of JAXA (Japan Aerospace Exploration Agency) is active in civil aeronautics through current programmes as the *Environment-Conscious Aircraft Technology Program* (ECAT) aiming at sustainability in aeronautics, *Safety Technology for Aviation and Disaster-Relief Program* (STAR) aiming at a safe and secure society, *Sky Frontier Program*, challenging new frontiers of air transportation, *Aeronautical Science and Basic Technology Research Program* for the creation of novel technologies, and the *Next Generation Aeronautical Innovation Hub Center* [55]. Russia, China, Canada and Brazil should also be mentioned for their capabilities in designing and manufacturing passenger-transport aircraft. In particular, Embraer is leader in the market of up to 130 passengers. The importance of Russia in the civil aeronautics field is suggested by the members of the Union of Aviation Industrialists of Russia [56]; whereas in China, CAE (Chinese Aeronautical Establishment) is a state aeronautics research organization created in 1960 and leading a research system complex of 36 research institutes, aiming at being the chief innovator of aeronautical science and technology in China [57].

The possibility of collaborative research activities with other non-EU countries, based on common interests and secured IPR, should be explored (until now, this was done on a case-by-case basis).

6 Technologies and Research Themes

6.1 Overview

CS1 and CS2 addressed a vast array of technologies spanning all major aeronautics disciplines (e.g. propulsion, aerodynamics, materials, structures, aircraft systems, avionics and flight controls) as applied to large passenger aircraft, regional aircraft, business jets, rotorcraft and small air transport (SAT) vehicles. At the end of CS2, certain technologies will have reached a level of maturity that will allow them to be exploited in future production aircraft. Many, however, will not and will require further research and development to bring them to the level that they can be meaningfully deployed. In this chapter, an outline is provided of the key technologies and research themes that should be considered in the context of a new European Aeronautics Research Programme.

6.2 Novel Aircraft Concepts and Configurations

The classical swept-wing and tube-fuselage concept, powered by two to four jet engines, has shown its excellent efficiency regarding fuel and cost, as well as operability at modern airports. A lot of experience and detailed knowledge has been accumulated in the design offices of the aircraft manufacturers and this aircraft concept will probably dominate in the next decades over more novel concepts for new aircraft, being proposed to the market. Operators and the airport infrastructure are also adapted to these aircraft types. Nevertheless, the well-established concepts must be challenged when societal needs, major political constraints or promising new technologies (indicating major cost or operational efficiency benefits) appear.

The following novel aircraft concepts have shown in several well-prepared studies, that they have a remarkable potential for a further step improvement in fuel burn and related emissions. This, therefore, deserves a more detailed assessment.

a) Electro-hybrid propulsion aircraft

The more electric aircraft (MEA) and the all-electric aircraft (AEA) have been technology drivers during the past 20 years and more. On the smaller end of air vehicles, there is widespread interest today in electrically-driven flying vehicles with significant breakthroughs for UAVs, SAT and also in sailplanes. First electrical air taxis are being developed and tested. But for the large air transport system, electrically-driven air transport vehicles are not yet feasible. The power density of batteries or other electrical storage devices is not yet sufficiently high to allow flights with around 20 passengers over a range of 500 km.

Electrically-driven small propellers integrated with the wing (before, after or above the wing surface) can improve the aerodynamic efficiency of the wing. Furthermore, such distributed propulsion concepts can use the propellers not only as propulsors but also as control devices and flow augmenters; thus, allowing for completely new flow/thrust considerations in the overall wing design. The electrically-driven propellers can increase the local lift and can be used for roll, pitch or yaw control. The high-lift system can be simplified by a clever installation of the multi-propeller design. The classical two engine aircraft concept requires that even with an engine failure during takeoff, the aircraft must be flyable with one-engine inoperative. With a multi-engine design, the safety requirement for an engine loss during takeoff is a lesser constraint. This opens a completely new design space, which could reduce the overall propulsive power needed to be installed on the aircraft. There is, however, in the case of hybrid-electric propulsion, a penalty to be paid as the electricity has to be generated on board via an engine driving a generator, which will distribute the electricity to the electrical machines (motors). Much research is still needed to comprehensively analyse the potential of such vehicles taking into account all key considerations (e.g. weight, flying qualities, aeroelastic instabilities).

These advances in aircraft concept design must be enabled by an evolution of the aircraft electrical distribution system[14]. Different options for future aircraft distribution systems are being investigated for both DC distribution and AC distribution schemes. AC distribution is based on the assumption that electrical generators are and will always be based on electrical machines. DC distribution will bring greater flexibility into the aircraft network, along with possible advantages in terms of weight reductions. DC power sources can be batteries, fuel cell, solar panels, etc. as well as electric generators. The DC distribution level is expected to reach kilovolt level to support the power required by the propulsion motors.

In future AEA, power required will be in the order of tens of megawatts. Efficiencies of state-of-the-art power converters make them unable to manage such high power. A similar problem arises in current protection and circuit breakers devices. These devices are not prepared to support higher voltages and currents. New technologies and solutions need to be studied and implemented to increase the efficiency of power converters and to make solid state circuit breakers suitable for such conditions. Furthermore, other problems are envisaged. For instance, arcing events due to the high voltage can be an undesired drawback of the increase of voltage levels. This effect can be worsened by a degradation in the isolation material of wires and connectors. Compatibility with current aircraft architecture should be considered. This means that 28VDC loads, 270VDC loads and 115VAC loads will be included inside new aircraft in the near future. Point of Load (POL) converters shall be used to drive 28VDC from a higher voltage.

Several activities need to be carried out to prepare the forthcoming electrical architecture of a next generation of aircraft. The following are highlighted as key activities:

1. To study the pros and cons of a DC power distribution architecture and set a realistic technology roadmap;
2. To set up a test rig of megawatts with the ability to simulate different kind of generators and loads (it should be modular, scalable, versatile and flexible);
3. To increase the efficiency of the power converters digitally controlled and to optimize power topology, modulation techniques and digital control (aeronautic normative, heat losses, weight, size and electromagnetic compatibility issues should be considered in this process);
4. To test and increase the capability of solid-state circuit breaker devices; and
5. To study and solve the problem posed by the arcing phenomena inside aircraft.

b) Novel fuselage rear-end concepts with Boundary Layer Ingestion (BLI)

The installation of an engine at the rear end of a fuselage to ingest the boundary layer of the fuselage is an interesting concept that could improve the overall thrust-drag characteristics of the aircraft. Recent research has shown an aerodynamic improvement potential, but with a significant negative impact on the design of the engine and its installation at the rear end of the fuselage. Several studies are underway today and first results are looking very interesting[15].

---

[14] Some possible reference architectures are described in Ref. [58].

[15] Research is undertaken in CS2, LPA WP1.1.3.6, CfP 09-LPA-01-58 and in the EU-funded CENTRELINE project [59].

A 10% improvement potential is claimed in some studies [59]. Additional multidisciplinary studies and validation tests in wind tunnels, ground demonstrators and flight test will be required to establish confidence in the predicted fuel burn improvement as results from different studies vary widely.

c) Advanced wing concepts

Many studies into alternative lifting systems (surfaces) for aircraft have been studied (as described by Torenbeek [60], for example). From time to time, all these possible lifting concepts have to be reinvestigated, as new materials, flow control concepts and new Integrated methodologies are developed, which may lead to a new evaluation of these aircraft concepts. Two concepts are mentioned below as illustrations, where recent research has identified a performance improvement potential for specific aircraft categories – these are the box-wing aircraft concept and the strut-braced / truss braced wing concept.

(i) Box-wing aircraft concepts

Following a theory from Ludwig Prandtl from the 1920s, a box-wing concept can have a reduction in induced drag of more than 30%. Several studies by Frediani (TU Pisa, Italy) have indicated this improvement potential (especially where a span constraint is imposed). However, independent studies have not yet confirmed this potential. The EU-funded project PARSIFAL [61], using high fidelity codes from ONERA, is now being used to assess the aerodynamic improvement potential. Follow-on studies are needed to prepare the scientific basis for such innovative aircraft concepts.

(ii) Very high aspect ratio strut-braced wing (SBW) or truss-braced wing (TBW) concepts

Several large-scale studies [62, 63] on the merits of very-high aspect ratio wings (of about 19), incorporating folding outboard wing panels, have been conducted over the past two decades. There is also ongoing research in CS2[16]. These aircraft design concepts, which are mostly directed at the short-to-medium range (SMR) passenger aircraft market, employ natural laminar flow (NLF) aerofoils with a strut or truss brace wing[17] rather than the traditional cantilever wing design. Cruise speeds are likely to be about 10% lower than the current generation of SMR aircraft. Significant reductions in induced drag are possible (offsetting the additional skin friction and interference drag associated with the struts/trusses). Developing a lightweight wing with the desired aeroelastic properties will require substantial research involving numerical optimization and experimental validation – nonetheless, this remains one of the more promising novel concepts, which warrants further research attention.

6.3 Propulsion System

6.3.1 *Electric and hybrid-electric propulsion*

Electro-hybrid propulsion means either (1) conventional aeroengines dedicated to propulsion, but electrically assisted during certain mission phases, with energy on board being provided by electrical generation system(s) (e.g. fuel cells, batteries, turboshaft generator), or (2) electric propulsive engines, fully supplied by the such electric generation system(s). Studies to be performed should be directed not only at conventional electrical devices (e.g. power generation, distribution and electric machines for propulsion) but also at embedded electrical assistance to turbo-engines and the related Full Authority Digital Control needed to master the operability of this new type of engine thermodynamic cycle.

The non-propulsive and propulsive electrical system solutions that have to be developed cover:

[16] Research is undertaken in Clean Sky 2 LPA and in thematic topic CS2-2019-fP10-THT-07.

[17] Strut-braced and truss-braced wing concepts are very similar – the latter incorporates one or more vertical truss to support the wing.

- *Flyable technologies:* novel battery and fuel cells concepts as energy supply and storage, high power/high energy density power electronics, human safety solutions (electrical and magnetic), high voltage technologies (e.g. distribution cables and system protection). Solutions have been developed in other industries, such as marine and rail, but the size and mass of such systems is not compatible with aviation needs.
- *New architectures and standards:* to minimize the weight of the electrical system, new architectures and new electrical network standards are required.
- *New methodologies:* new methods and tools are required to allow global electrical system optimisation, including consideration of electromagnetic compatibility, weight and cost. Here considerable benefit could be achieved using multidisciplinary methods and tools.

6.3.2 *Advanced turbofans*

Considerable environmental benefits can be achieved in the short-to-medium term through the continued development of ultrahigh efficiency gas turbine engines. It is critical that the evolutionary developments, which are currently underway, are accelerated. Technologies that could provide incremental improvements include variable pitch fans, improved power gearboxes (PGBs), advanced lean burn combustors and weight reduction through innovative design and material deployment (e.g. in low/medium temperature modules of the engine as well as parts exposed to ultra-high temperatures). Further optimisation of power offtakes (bleed and mechanical), taking into account new technologies for the storage of non-propulsive energy on board the aircraft, is another topic worthy of consideration. Additionally, the ongoing development of ultrahigh bypass ratio engines has created new integration challenges, which are still to be fully resolved (e.g. regarding acoustic treatment for new generations of short nacelles).

6.3.3 *Open rotor (OR) gas turbines*

Open rotor (OR) engine architectures have shown considerable promise in terms of improved specific fuel consumption (SFC), with the potential to outperform conventional turbofan engines (-15% fuel burn has been demonstrated). To quantify the benefits at an aircraft platform level, however, it requires detailed airframe-engine integration research. Such integrated airframe-engine studies are needed to determine the best configuration of open rotor (e.g. pusher or puller, twin contra-rotating unducted or single rotor with unducted Outlet Guide Vanes), considering such diverse topics as pylon design, airframe shielding and noise (both external and internal through vibration).

6.3.4 *Boundary Layer Ingestion (BLI)*

Boundary Layer Ingestion (BLI) technology (mentioned earlier in Section 6.2) has the potential to significantly reduce fuel burn[18]. The concept, which provides a beneficial drag reduction on the airframe, however, creates significant challenges for the engine. Although BLI is not considered to be engine technology, *per se*, changes to the mechanical and aerodynamic design of the fan and compressor due to the ingestion of the sluggish air in the boundary layer are needed. The design issues to be considered include high energy aerodynamic fluctuations (the engine has to be designed with more margin for operability and will hence have reduced efficiency) and the reduced mass flow rate per square meter of inlet area (and hence increased fuel burn).

6.3.5 *Alternative fuels*

The widespread use of alternative aviation fuels (i.e. non-petroleum-based fuels) are considered essential to meeting the ATAG/IATA 2050 global CO_2 emissions target (see Section 3.2). A variety of biomass feedstocks can be used to produce SAF (i.e. aviation fuels that are sustainable in terms of

---

[18] Predictions regarding the net benefits of BLI vary considerably. Research activities are currently underway in LPA IADP WP 1.1 and AIR ITD TS A-1 to reduce the level of uncertainty regarding this technology.

environmental, societal and economic factors) [53]. Not all alternative fuels, however, result in a net life-cycle GHG reduction. The main thrust concerning alternative fuels, in recent years, has been directed at the production of drop-in fuels, which are essentially equivalent to conventional petroleum-based jet fuels. Approvals (per ASTM D7566) have been granted for several drop-in fuels to be used on commercial operations, usually in a 50–50 blend. Certain alternative fuels, in future, may qualify for use without blending. The overarching research objective in future aviation research programmes concerning SAF is reducing lifecycle GHG emissions.

Cryogenic fuels (e.g. liquified natural gas or liquid hydrogen) have been identified – for several decades, now – as candidate alternative fuels for aircraft propulsion. These non-petroleum fuels offer significant benefits in terms of reducing GHG emissions. The integration and safety challenges associated with these fuels, however, are substantial. The energy density per unit volume of cryogenic fuels is about one-half to one-quarter of the value for conventional jet fuel [53]. Consequently, novel aircraft configurations (e.g. Blended Wing Body) will be required to accommodate the increased tank volumes. Whereas, electric and hybrid-electric propulsion (see Section 6.3.1) offer a possible long-term solution for short-haul operations, alternative fuels will be required for mid-to-long haul operations. Cryogenic fuels also offer opportunities for non-propulsive energy (NPE) applications (e.g. cabin systems).

6.4 Design optimisation

Aircraft design is a multidisciplinary endeavour requiring a lot of different disciplines: aerodynamics, flight-controls, structures, materials, propulsion, systems (incl. cabins), manufacturing, etc.

Aerodynamics is still the major art to design the lifting wing concept. The CFD methods in aerodynamics have achieved a very high standard, where the verification and validation phase of wind tunnel and flight tests have shown that excellent and consistent results can be achieved in the latest aircraft developments (e.g. B787 and A350). The high-fidelity CFD tools, developed by Airbus and its research partners, have proven to deliver for the classical aircraft configurations excellent results, where only final tests and wind tunnel checks are required for confirmation before final flight tests.

For aerodynamics, for example, evolutionary multi-objective optimization algorithms (EMOA) as well as topology optimization are of continuing interest. For the fuselage, a combination of detailed local FEM analyses of panel buckling may be applied as failure constraints in the global level optimisation. Multidisciplinary design optimization (MDO) for the conceptual phase of aircraft design, considering the disciplines of aerodynamics, structures and control for large aircraft design is possible. Mission-based aircraft preliminary design optimization methodology tailored for the assessment of adaptive technologies may be pursued; each subspace representing a different mission stage instead of the traditional aircraft design disciplines. It is tailored for the assessment of adaptive solutions, where the optimum design is mission stage dependent [64]. Morphing structures provide another avenue for design improvement. Optimised designs using curvilinear, oblique and evenly distributed straight stiffeners may be conceived [65].

6.5 Aerodynamics and flow control

The next big steps in aerodynamics are related to laminar flow concepts. The drag reduction potential of Natural Laminar Flow (NLF) on a wing of a large passenger aircraft was demonstrated in the BLADE project (CS1 flagship demonstrator). The key research questions now concern the manufacture, operations and service reliability of such designs for application to regional and SMR aircraft. Hybrid Laminar Flow Control (HLFC), including passive suction systems, has been a focus in CS2 and in several

EC and national funded programmes, with inflight demonstration on the empennage (in the FP7 project AFLoNext) and the development of a ground demonstrator of an HLFC wing (in LPA IADP). The next step should be a flight demonstration of an HLFC wing, with application to long-range aircraft.

Active flow control devices have shown considerable potential to address specific flow problems (e.g. flow disturbances and losses associated pylon/wing junctions). Further work is needed to mature these promising technologies, which can open up the design space for future novel configurations.

6.6 Systems

For supporting the overall objective of decarbonisation the air transport system, two main categories of research and innovation will be of specific importance: systems aimed at reducing emissions along the whole mission (i.e. including air and ground phases) and systems aimed at reduced cost of operation, thus compensating for the more expensive decarbonisation technologies.

Significant contributions are still required in further developing avionics, including bus technologies, sensors and actuators as well as energy generation and conversion systems to reduce weight, size and power consumption. In addition, more mature technologies, systems and functions are required for enabling new ways of operating aircraft – for example: horizontal technologies supporting single-pilot cockpits, autonomous or remote operation of aircraft, deeper integration of systems related to cabin, cockpit and airline operation, and new approaches allowing advance operational capabilities with less or cheaper equipment on board.

Research is required to address key enablers for future systems, especially related to hybrid or full electric aircraft, potentially equipped with distributed propulsion requiring a totally different approach in the flight control regime.

In addition, there are several cross-cutting topics, which require consideration, such as

- Enablers in the domain of digitalisation (artificial intelligence, machine learning, etc.);
- New capabilities and methods in simulation, verification, validation and certification;
- Holistic approach to aircraft modelling as system of systems, combining aerodynamic loads, structure response and control;
- Introduction of advanced computational architectures in avionics (e.g. GPUs enabling new functions in CNS); and
- Data security.

Finally, widening the perimeter into systems supporting maintenance, repair and operations (MRO) as well as linking with airline operations, are gaining significance and should be included in a future aeronautics research programme.

6.7 Structures

Progress in aircraft structures goes in parallel with progress in materials. Numerical simulation advances include damage assessment and real-time damage monitoring in conjunction with advanced sensing. This is a burgeoning field where advances in manufacturing, optimization and prediction of mechanical performance will continue to occupy many engineers and researchers. Fatigue is a critical aspect of the structural design of aircraft; optimisation for fatigue of structural connections will continue to be of interest. Damage management involves damage prediction, damage tolerance substantiation, structural health monitoring (SHM), self-healing capabilities, repairs (as in MRO) and so forth. Prediction of mechanical performance in advance to actual physical testing may be pursued with contributions of multiscale models (mesomechanics). Composite structures with fibre placement according to structural optimization, reawakening long-standing ideas of geodesic architectures, involve both design and manufacturing challenges.

6.8 Materials and Manufacturing

It is essential that materials and manufacturing remains a highly prioritised area of research during the next decade. This means that the development of lightweight structural materials, such as composites, ceramics, metal alloys et cetera need continued support in an integrated research programme. Developments of an incremental, or evolutionary, nature need to be complemented by appropriate support for research on disruptive material technologies, which will be required for mid- to far-term applications (see Fig. 5.1). Examples of potential disruptive research are structural multifunctional materials, nano-engineered materials and battery technologies adapted to aeronautic specific needs . Research of an incremental nature needs to continue with the aim of enhancing material properties, while maintaining or reducing cost and environmental impact.

It is foreseen that the European value-chain (including SME, equipment and tier-one suppliers) will benefit strongly from continued investments in collaborative research in the area of materials and manufacturing. Research in areas such as additive manufacturing, out-of-autoclave composite manufacturing, digitalization, automation, cost efficient tooling, high-speed machining, quality and joining technologies (including the use of structural adhesives) should be maintained. The key drivers include maintenance of quality (safety), cost- and resource-efficient, high-volume production, through-life costs and environmental benefits.

The general aim of part count reduction to reduce weight and/or cost is valid for both composite material and metallic components. To further exploit these possibilities, production of composites must seek elimination of time consuming non-added value operations and increase production rates. Similarly, the unprecedented geometrical design freedom provided by additive manufacturing create needs for new design methodologies and structural optimization approaches. It should also be recognized that manufacturing methods have implications in the fatigue and fracture strength due to residual stresses, microstructural features, and possible stress concentration effects. These are all aspects that need continuing research and standardization efforts. High speed machining (HSM) is a proven technology with advantages as concerns high material removal rate, good surface finish, low cutting forces and temperature, among others. Notwithstanding the increasing interest in additive manufacturing, HSM is likely to continue being used for metallic components in the foreseeable future.

6.9 Eco-design

Suitable means for considering and continuously evaluating the entire socio-economic and life-cycle perspective, including use of scarce or toxic components should be compulsory throughout all levels of future aeronautics research. This can be successfully achieved if scientifically proven and non-biased methods, agreed by both scientific community and industries are used to provide the metrics by which the expected impacts are estimated. While eco-design principles and their tools (e.g. Life Cycle Analysis) are gaining use and acceptance there remains challenges that motivates continued efforts towards more unified and standardized eco-design procedures in future programs.

6.10 Cabin

The cabin design is an important feature for airlines. The cabin is the main differentiator between different airlines and each airline tries to show to the passengers the national or corporate identity in terms of colours, decoration, design, comfort and in-flight entertainment system (IFE). The airline manufacturer has a different strategy; knowing, that each airline will try to have their individual cabin layout, regarding seats, lights, colours, etc. In the cabin, the manufacturer is interested to define a common cabin-system architecture, which provides the platform for all safety-related aspects like emergency evacuation features etc. for the cabin. This basic platform is defined to allow the integration of all airline specific features with respect to decoration, colours, comfort, entertainment and light in the cabin. Decoupling the cabin – as far as possible – from the aircraft structure will, in future, allow for a more complete cabin system to be installed during final assembly, thus reducing cost and assembly time. The big challenges for the future include a) fast cabin reconfiguration; b) reduced/low energy demand; c) individual entertainment programs per seat; d) simple connectivity for all sorts of smartphone/tablet devices; e) comfort features and well-feeling ambiance; f) intelligent cabin systems including sensors monitoring the state of passenger as well as equipment; and g) functions sharing information with cockpit and Airline Operations Centres (AOCs).

6.11 Flight Operations

Air Traffic Management (ATM) and the operational considerations how aircraft are integrated in the air transport sector are playing a vital role in decarbonising the industry and reducing emissions. On the one hand, immediate and direct gains in reducing environmental footprint can be achieved through technologies supporting new operations such as selecting optimal cruise levels, for example (investigated in CS2 to a certain extent). On the other hand, new aircraft capabilities going hand in hand with new concepts of operation may reduce the cost of flight, which then may compensate potential extra costs caused by introducing greener technologies. Finally, as full electric or hybrid electric aircraft are at the horizon, solutions for integrating them into the air space need to be investigated.

For all three categories (i.e. direct environmental impact, indirect environmental impact and new vehicle capabilities), a joint perspective between research at the ATM domain and the vehicle domain need to be developed. In the current setup, these two perspectives are dealt with in two separate entities: Clean Sky JU and SESAR 2020. Having established a close collaboration already at the current stage, a fully synchronised way of working may be required in the future. Defining future concepts of operation requires precise understanding of the capabilities of future aircraft and vice versa.

The first category of solutions supporting direct environmental impact in operating aircraft in the airspace is related to reducing noise and gaseous emissions in all phases of flight, from gate to gate including the turn-around process. Potential areas of innovation could include:

- Optimizing trajectories in speed and altitude, depending on the aircraft and onboard systems, to reduce the net environmental impact of the flight;
- Advanced Flight Management Systems (FMS) allowing for full air/ground integration and more efficient flight guidance;
- Improved ground operations, including autonomous electric taxiing; and
- Formation flying by two or more aircraft flying in close proximity to reduce the drag.

Most of these approaches require new and enabling functions and technologies in systems, specifically in communication, surveillance and navigation.

The second category for enabling decarbonisation is indirectly through introducing cost reductions. This could include such topics as, single pilot operations and autonomous operations (at least for air cargo), requiring appropriately interacting architectures, functions and systems on board, advanced infrastructure on ground and innovative concepts of operation. Certainly, a significant change of stakeholders' roles will go hand in hand with this innovation.

Finally, radically new aircraft may have significantly different performance and flight characteristics, which may require new ways of integrating them into the air transport system. Potentially electric motors for propulsion will have totally different noise characteristics but will enable at the same time for new noise abatement procedures, taking benefit from distributed propulsion. In addition, different speeds and altitude regimes populated by these new aircraft will require for new solutions in the systems domain for integrating them efficiently into the air space considering a fleet mix of conventional and radically different aircraft. Potential topics, therefore, could include:

- New flight control and flight management techniques, enabling noise abatement using new propulsion options; and
- New solutions allowing for integrating aircraft with different characteristics and performance parameters and potentially different degree of controllability in the ATM context.

6.12 Reducing Time for Operational Implementation of Technology

To address the emissions challenge described earlier in Section 3.2, new technologies need to be introduced earlier in the air transport system. Innovative ideas can only contribute to real reductions in GHG emissions once in operation. It is imperative that the time taken to get technologies successfully demonstrated at TRL 5 and 6 in research programmes (such as Clean Sky) into service is dramatically cut. The implementation of innovative concepts and products can be accelerated by (a) Demonstration of new ideas in an operational environment (i.e. low TRL technology in a high TRL environment), and (b) Retrofitting of new technology into existing aircraft. Changes to aircraft will require early involvement of the certification authorities, operators, ATM and airports to assess the implications for all stakeholders.

6.13 Research to Support Policymakers

Legislation and regulation will play an ever-increasing role when it comes to tackling the causes of climate change (this, of course, is true for all sectors of the global economy, not only for air transport). In respect of reducing emissions, aircraft manufacturers have always considered the reduction of fuel burn per tonne-kilometre (or per passenger-kilometre) to be a principal design driver in the development of new aircraft. This was, however, driven by economic, rather than environmental, considerations (inefficient aeroplanes are not competitive and do not sell well). The focus needs to shift towards considering more directly the environmental impact of aviation. New national and international policies designed to limit aviation GHG emissions will be introduced over the next decades. Clean Sky can play an important role in informing policyholders by conducting independent scientific research and study.

7 Market Segmentation, Transverse and Enabling Actions

7.1 Segmentation of Air Transport

For the purpose of developing a strategy policy for aeronautics research, it is convenient to consider the various air vehicle types in terms of market sector. Common technologies and challenges, which apply to two or more sectors, can be identified through this approach. Strategies to exploit synergistic technologies across different sectors can also be developed, and structures established within a research programme to facilitate cross-fertilisation of ideas from one sector to another. It is recognised that any segmentation approach is by nature a simplistic representation of the industry – with inherent shortcomings – nonetheless, it can be a useful mechanism to provide a global view of the industrial sector, which can aid in the development of research strategies.

7.2 Commercial Passenger and Cargo Transport Aircraft

By far, the largest contributor to aviation environmental damage is large commercial aircraft. More than 90% of the global CO_2 emissions from civil aircraft operations are generated by single-aisle and widebody jet transport aircraft that carry 100 or more passengers [53]. It is also well recognised that the longer-range sectors are responsible for a very high percentage of these emissions. ATAG [66] maintain that “around 80% of aviation CO_2 emissions are emitted from flights of over 1500 kilometres”. Furthermore, as discussed earlier in Chapter 3, the demand for air travel continues to grow, with air traffic (measured in terms of passenger-km or tonne-km) doubling every 15 years. Consequently, this market sector warrants the highest priority in terms of publicly-funded research.

7.2.1 *Single-aisle short-to-medium range “mass transport” aircraft*

This market segment is critically important for aircraft manufacturers. At this moment, the two aircraft families from Airbus (A320) and Boeing (B737) dominate this market segment. New entrants from Russia (Sukhoi Superjet 100) and China (ARJ21 and C919) are preparing competitive products, but at this moment the products are almost exclusively for their home markets. The high production rate (>700 aircraft/year) and large production backlog (7 – 10 years) will make it difficult to introduce radical new concepts in the near- to mid-term (N+1 and N+2). Within this timeframe, there will be mostly evolutionary steps in innovation, with technologies to reduce cost of production, introduce more fuel-efficient engines (A320 neo) and other evolutionary technologies (see Sections 5.3.1, 6.3 and 6.6, for example). For N+3 generation of SMR passenger aircraft, however, distributed all-electric or hybrid propulsion should be targeted.

7.2.2 *Medium-to-long-haul “mass transport” widebody aircraft*

Widebody aircraft are essential for international and transcontinental air transport. The latest aircraft designs (Boeing B787 and Airbus A350) are the most complex and technically most sophisticated aircraft designs. These aircraft will need kerosene-type fuel to fulfil their long-range missions; it is expected that alternative greener fuels will play a key role in reducing net CO_2 emissions. Engine, airframe and flow control (e.g. HLFC) technologies developed in CS2 can provide an important contribution to the greening of this segment; further development will be needed.

There could be a significant potential to reduce CO_2 emissions if aircraft manufacturers produce aircraft optimised for a shorter range and airlines operate long distance routes with an intermediate stop. (Reducing the aircraft design range from 8500 nm to 4500 nm will reduce the block fuel and hence the CO_2 emissions by ~15% [67].) However, the market interests from aircraft manufacturers and the competition between airlines will not support this “rational climate benefit”. Although at the present time, political interventions seem not to be successful in a worldwide competitive airline and national environment, this may change if public policy on aviation emissions, as now foreseen, becomes more stringent [68].

7.2.3 *Regional aircraft*

This market segment could be the entry point for novel aircraft concepts, at least at the lower end. A lot of research work and demonstration of the feasibility will be needed to reduce the risk and shows the benefits of these novel concepts. Other features such as single pilot operation, short takeoff and landing capability and operating from smaller airfields could reduce the market-entry barriers (see also Section 7.6). New hybrid-electrical aircraft concepts may provide the chances for new air operational routes in less densely populated areas, where the infrastructural cost for trains and road may be much higher than just the infrastructure for several new and small airfields. The target should be a MEA or AEA for the N+2 aircraft generation.

7.2.4 *Air cargo*

Air cargo is a rapidly growing market sector, with its own unique requirements. A specific strategy is required for this market sector. For example, it is highly probable that this market sector will be an early adopter of single pilot operation (SPO) and, in time, fully autonomous technologies with no pilot on board. New hybrid-electrical aircraft vehicles may provide the opportunities for dedicated simple and small cargo aircraft, which will not only be derived from converted passenger aircraft but designed specifically for air cargo operations and compete successfully with road and rail transport vehicles.

7.3 Supersonic Transportation

There is renewed interest in supersonic transport (SST) aircraft – particularly in the U.S., where several companies are working to develop supersonic business jets (Aerion, Spike) and a 55-seat airliner (Boom). Much of the innovation concerns the mitigation of the sonic boom at ground level by novel design concepts [69]. NASA, in April 2018, awarded a $247.5 million contract to build an X-plane that will employ so-called “quite supersonic” technologies (by tailoring the aircraft’s shape, the sonic boom can appear as a quick series of soft thumps at ground level).

The certification basis for such aircraft, however, is unclear as there are currently no specific SST standards. A preliminary environmental assessment of the abovementioned SST concepts by the ICCT (International Council on Clean Transportation) concluded that these aircraft are unlikely to comply with existing standards for subsonic aircraft [70]. The most likely configuration of an SST aircraft was estimated to exceed NO_x and CO_2 limits by 40% and 70%, respectively [70]. The same source reported that “in the best-case scenario, the modelled SST burned 3 times as much fuel per business-class passenger relative to recently certified subsonic aircraft; in the worst case, it burned 9 times as much fuel compared to an economy-class passenger on a subsonic flight”. Concerning noise, the ICCT [70] reported that emerging SST aircraft “are likely to fail current (2018) and perhaps historical (2006) landing and takeoff noise standards”.

The energy-efficiency penalty of supersonic travel (typically Mach 1.6–2.2), compared to high subsonic travel (typically Mach 0.78—0.86), is easily explained by fundamental physics. Supersonic travel will always require considerably greater amounts of energy per passenger-kilometre. Whereas, it could be argued that Europe should maintain a level of expertise in SST research to counter the U.S. developments for reasons of competitiveness, the reality is that there are more pressing societal concerns (discussed in Chapter 3). It is therefore recommended that SST is not considered to be a priority within a future European aeronautics research programme. The exception should be research in support of the development of European certification standards[19].

7.4 Vertical Lift Air Vehicles, Including Rotorcraft

7.4.1 *Conventional helicopters*

Conventional helicopters play a vital role in modern society, providing a service which cannot be met by other transportation means – for example: search and rescue, medical evacuation and so forth. It is important that research continues to support such essential services for society. Research actions in support of other roles (e.g. VIP transport) is seen to have a lower priority. Rotorcraft noise is a considerable annoyance factor for urban society. This factor, taking into account the forecast increase in helicopter traffic, warrants specific attention within a future research programme.

7.4.2 *Autonomous urban mobility vehicles*

There is considerable interest, in Europe and internationally, in the emerging technologies associated with autonomous electrically-powered urban mobility vehicles. Both Airbus and Boeing have displayed an interest in the sector. But, there is also keen interest from new entrants to aviation, such as Uber in the USA and Audi in Europe, who are working on air taxi concepts. In China, EHang (a drone manufacture) made an autonomous air taxi demonstration flight with their 2Hang 184.

As these developments are already underway with extensive private funding and as there is limited need for large-scale integrated demonstration of complex technologies requiring multi-organisation collaboration (such requirements underpinned CS1 and CS2), it is recommended that this sector does not play a significant role in a future Clean Sky type research programme. It is not recommended that this sector be elevated to ITD (Integrated Technology Demonstrator) status. There are, however, several enabling technical areas, where there should be involvement – for example:

a) Research directed at infrastructure and flight operations (not the air vehicle itself), in collaboration with SESAR;
b) Innovative technology developments in electric energy storage and electric propulsion (which can be adopted for use in larger air vehicle, e.g. general aviation, regional aircraft); and
c) Autonomous flight systems (urban mobility vehicles are likely to be early adopters of such technology, which could later be applied to other larger air vehicles).

7.5 Executive Aircraft

This is a very specific and small market segment, with the demand for different aircraft types, depending on range and size. These aircraft will profit from the general technology developments, discussed earlier in Chapter 6. No specific action or demonstrator is recommended for executive aircraft due to the relatively small environmental footprint associated with this market sector. The priority for publicly funded research for this sector is thus seen as low. Nonetheless, several technologies that will be actively pursued for larger commercial passenger aircraft (e.g. new materials and manufacturing processes, SHM, advanced avionic systems, NLF and HLFC) can be applied to future business jets to produce more fuel efficient and competitive products.

[19] There are currently no European noise or CO_2 certification standards for SST aircraft and engine emission standards are "considered to be outdated" [2].

7.6 Small Air Transport

Small air transport (SAT) reflects operations performed by aircraft carrying up to 19 passengers. The research of related technologies was done in CS2 as a Transverse Action (TA), driven by several small aircraft manufacturers. This type of transport may play a vital role for the regions of Europe with less developed road and railway infrastructure (e.g. in southern and eastern parts of Europe). The development of efficient aircraft, with a low environmental impact, capable of operating from a range of airfields (with different levels of infrastructure), would be important for local societies, revitalizing their economies. There also a potential market outside EU for such aircraft. Due to their low cost and small size, SAT vehicles could be an excellent platform for implementing – and maturing – novel, disruptive technologies in materials, structure, propulsion and systems, for example.

There are active programmes [71, 72] intending to deliver full electric propulsion systems for a SAT platform at 9–12 passengers via demonstration by the early 2020s with intention to reach 19 passengers. A commercial island-hopping route is planned for 2021 [73]. This is feasible with current off-the-shelf technologies and will be an important stepping stone for electric propulsion on a 50–70 passenger platform aimed at the N+2 aircraft generation.

8 Priorities and Demonstrators

8.1 Identified Priorities

The technologies identified in this chapter have been selected for their expected capability of offering a substantial contribution to mitigate climate change and other environmental degradations and for having, at the same time, the potential to be deployed in the market by 2050 or before. This prioritization is aligned with the European Commission's long-term strategic vision for research, innovation and deployment, as set out in the report *A Clean Planet for All*[20]. The dramatically increasing risks of a climate disaster (documented by scientific evidence, as described in Chapter 3), the growing concern of European citizens regarding this issue, coupled with the growth of aviation worldwide and the slow uptake of technological improvements require that climate change mitigation be set as the main priority for the Next Decade European Aeronautics Research Programme.

The development and deployment of new low- or zero-carbon technologies will result in a major boost to the competitiveness of the European aeronautics industry in the medium-to-long term. World demand in this market segment is expected to grow rapidly and large investments in research, development and deployment in this technological field are already taking place in other competing regions, such as the USA and China.

8.2 Strategy and Purpose of Demonstrators

The portfolio of research topics that need to be considered within a future European Aeronautics Research Programme is extensive. By focusing on large scale demonstrators, key technology bricks will be developed that can be employed in diverse ways to address current and emerging challenges. Indeed, this was a central feature of CS1 and CS2, which had an explicit goal to develop integrated technology demonstrations (ITDs) at large system level.

[20] Ref. [13] p. 18 states that "climate is at the heart of Horizon Europe".

The validation of promising technologies – for example, by demonstration at TRL 5 or 6 – is a critical step to be taken to develop innovative, new ideas into mature products. This overarching objective provided, for many work packages in CS1 and CS2, a clear direction and a set of measurable targets. Defining demonstrators helped identify key technologies and competencies, TRL maturation timelines, decision gates and so forth. The ability to undertake large-scale, multi-disciplinary demonstration of highly integrated and complex technologies is, in fact, the essential feature that sets Clean Sky apart from most other national and industry funded aeronautics research programmes.

This focus on demonstrators has proven to be a successful strategy in CS1 and CS2 – and should be retained as a key feature of any future European aeronautics research programme. It must be recognised, though, that the selection of demonstrators requires careful thought and deliberation due to their high cost and their impact on work package definition (changing direction once a project has started increases cost and causes programme delays).

In addition to the development of traditional flight demonstrators (FDs), ground-based demonstrators (GBDs) and system test beds, the use of virtual demonstrators is recommended. Virtual demonstrators can be hypothetical reference vehicles that provide a framework to identify key enabling technologies, assess the current state of the art of components and systems, and define TRL maturation timelines to achieve an integrated future solution. Such an approach provides a structure to define work packages and intermediate goals.

8.3 Main Demonstrators

Thirteen demonstrators are identified in Table 8.1, below. This is not intended to be a comprehensive list; rather, it has been established as a starting point for discussions with stakeholders.

Table 8.1: *Main Demonstrators*

No.	Topic	Comments
Disruptive technologies		
1	Hybrid-electric propulsion (HEP) (see Section 6.2)	An advanced GBD to explore HEP technologies. Several facilities are envisaged. This should consider: a) Electrical energy distribution from generator/batteries to motors. b) Energy conversion from different liquid fuel to electricity. c) GBD of HEP system architecture (incl. system and propulsion units).
2	Distributed-electric propulsion (DEP) (see Section 6.2)	WTT of DEP concepts, aerodynamic interaction from wing and propulsor, control concepts from differential propulsors. Promising concepts should be validated by FD.
3	FD to assess future electrical technologies (see Sections 6.2a & 6.3.1)	Develop a GBD and FD at 50–70 pax, range > 1500 nm to provide a test bed for technology assessment building on potential technologies developed for smaller 9–19 pax platform. This will utilise technologies assessed in other listed demonstrators above with sub demonstrators to demonstrate electric / hybrid electric propulsion, aerodynamics / novel configuration and systems / energy conversion.
4	Scaled demonstration of novel configurations (see Section 6.2)	Good process has been made in CS2 in the design and analysis of novel aircraft configurations (in LPA IADP and AIR ITD). In parallel, the first prototypes of scaled flying demonstrators of passenger transport aircraft are being developed (in LPA). It is proposed that both sets of activities be continued, leading to flight testing of scaled demonstrators. These results, together with WTT and numerical simulation, should feed into the down-selection of promising candidates for future development.

5	Boundary Layer Ingestion (BLI) (see Section 6.3.4)	a) WTT and GBD of BLI, leading to the physical integration of a propulsor unit into a representative fuselage rear end. b) Proof-of-concept FTD of the most promising architecture(s).
6	Autonomous operations (see Sections 6.6 & 6.11)	Ground demonstrators on new cockpit and flight operation principles, including single pilot operation, autonomous operation and remote operation. A consolidated and integrated demonstration in a relevant environment should be targeted including interfaces to airline operations and Air Traffic Management.
Evolutionary technologies		
7	Advanced propulsive system (see Section 6.3)	Based on the results obtained in CS2 in LPA WP 1.1 (and elsewhere), a full-scale flight demonstration is recommended of the most promising advanced propulsive system architecture (e.g. open rotor, or variable pitch fan coupled with powered gearbox).
8	Electrically-assisted turbofan (see Section 6.3)	GBD without any non-propulsive energy extraction aimed at demonstrating a 15–20% thrust-to-weight ratio improvement. Tests will encompass whole system response to all unsteady flight commands or external hazards, and investigate all improvements related to electrical assistance and its ability to respond instantaneously to power requests (under the generic term of operability, including safety).
9	Hybrid Laminar Flow Control (HLFC) on wings (see Section 6.5)	Building mainly on (a) the FD and GBD of HLFC on the empennage in LPA and AFLoNext, and (b) GBD of HLFC on the wing in LPA, the next step should be a flight demonstrator for HLFC on an aircraft wing at representative transonic conditions. Both technical and operation issues need to be addressed. The technology is required to reduce fuel burn on mid-to-long range aircraft.
10	Non-propulsive energy (NPE) (see Section 6.2)	GBD of advanced concepts for NPE technologies. Innovative architectures for energy storage and distribution (e.g. fuel cells, batteries, flexible APU) have been considered for non-propulsive applications on aircraft to reduce overall energy consumption.
11	Advanced fuselage manufacturing demonstrator (see Sections 6.7 & 6.8)	The design, manufacture and ground test of a highly integrated, structurally-representative fuselage segment (single aisle airliner) to demonstrate advanced manufacturing concepts that will reduce cost and FAL time is recommended. Key aspects to be demonstrated are automated “future factory” concepts utilising state-of-the-art collaborative robots (cobots).
Transversal technologies		
12	Virtual demonstrator for certification (see Sections 6.12 & 8.2)	Development of a full virtual aircraft to prepare certification by virtual demonstration including systems certification. It could be several virtual demonstrators depending of the certification process & the interdependency between the models. Selection of simple test cases and the proposed steps to prepare the strategy for virtual certification elements (cabin evacuation, static tests, fatigue tests, etc.).
13	Eco-design principles (proof of concept for specific selected items) (see Section 6.9, for example but relevant for all activities)	Eco-design principles have been developed in CS and CS2. Selected items, agreed by both scientific community and industries, are used to validate the metrics and confirm the expected impacts. Life Cycle Analysis will be demonstrated for selected items and prepare the scientific basis for future unified and standardized eco-design procedures.

Notes: FD = flight demonstrator/demonstration
GBD = ground-based demonstrator/demonstration
WTT = wind tunnel test

9 Concluding Remarks

The aviation industry is vital to the European economy and the wellbeing of its citizens. However, the sector is also an increasing source of GHG emissions. While total European emissions decreased by 22% in 2017 from 1990, transport was an exception (20% rise), with emissions from international aviation more than doubling [74]. Although fleet fuel efficiency increased over this time, this was not sufficient to compensate for the robust growth in air transport. To achieve the Paris agreement goals and reach climate neutrality by 2050, the Commission has stated that “all sectors of the economy should contribute to achieving the necessary emission reductions, including international aviation” [74]. However, decarbonising aviation is more challenging than for other industries. The sector is characterized by long innovation cycles, complex system integration, high energy density storage requirements (which hampers electrification) and higher safety standards than many other sectors.

For the European aviation industry to transition to a sustainable basis, a massive research, development and demonstration effort is needed to deliver the necessary deep reductions in GHG emissions. Such effort requires substantial time and resources, with public financial support and strong governance. There is no single solution to reduce aviation GHG emissions – the programme should thus be structured in a way that simultaneously addresses the challenge through several coordinated and interacting mechanisms. Research activities spanning TRL 1–6 should be integrated into a single programme, with the management responsibility falling under a single organisation, to maximise the potential benefit of the work. Specific governance models will be needed for the higher and lower TRL segments. Incremental innovation (at TRL 4–6) is key to short- and medium-term success; however, the long-term success of the European aeronautics sector depends significantly on innovations at the lower TRLs. The classic evolutionary approach to product innovation is viewed as an essential component of a future aeronautics programme. In parallel, radical and disruptive approaches – such as innovative electric propulsion systems and electrical architectures within potential new aircraft configurations – will be needed. Disruptive innovation should also come from outside the aeronautics industry (e.g. in energy storage). Success will depend on the correct balance between evolutionary and revolutionary approaches.

The next decade aeronautics research programme should target near- and mid-term outcomes through a structured framework built around a small number of carefully selected flagship demonstrators in the most relevant market sectors. In parallel, virtual demonstrators (i.e. reference vehicles to integrate emerging technologies) should be defined to facilitate research efforts on highly innovative concepts that could, potentially, meet 2050 environmental targets (e.g. in energy storage). The programme should be structured in a way that addresses, possibly through separately managed platforms (projects), technologies that have the potential to be implemented in the N+1, N+2 and N+3 generation of aircraft in the stated timescales. Technologies such as distributed electric propulsion could follow a logical demonstration route, with initial application to a 19-passenger Small Air Transport (SAT) demonstrator or a 50–70-passenger regional aircraft.

Europe has been at the forefront of international efforts to address environmental concerns that negatively impact human health and quality of life. Today, these efforts need to be intensified. Bold, innovative solutions will be needed to meet the unparalleled threat to society that climate change poses. Only through coordinated, collaborative efforts – involving stakeholders from academia, research institutes, SMEs and large industry – will the necessary progress be made.

List of Abbreviations

ACARE	Advisory Council for Aeronautics Research
AEA	All Electric Aircraft
AIA	Aerospace Industries Association
AIC	Aircraft-Induced Cloudiness
AOC	Airline Operations Centre
APU	Auxiliary Power Unit
ARMD	Aeronautics Research Mission Directorate
ATAG	Air Transport Action Group
ATM	Air Traffic Management
BLI	Boundary Layer Ingestion
CAEP	Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
CfP	Call for Proposal
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CNS	Communication, Navigation and Surveillance
CS	Clean Sky
CS1	Clean Sky 1
CS2	Clean Sky 2
CSJU	Clean Sky Joint Undertaking
DLR	German Aerospace Center
EASA	European Aviation Safety Agency
EASN	European Aeronautics Science Network
EC	European Commission
ECON	Economy (cruise)
EDA	European Defence Agency
EIS	Entry into Service
EMOA	Evolutionary Multi-Objective Optimization Algorithms
EOL	End Of Life
ETS	Emissions Trading Scheme
EV	Electric Vehicle
FAA	Federal Aviation Administration
FAL	Final Assembly Line
FD	Flight Demonstrator / Demonstration
FEM	Finite Element Method
FMS	Flight Management System
GBD	Ground-Based Demonstrator / Demonstration
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPU	Graphical Processing Unit
HSM	High Speed Machining
HLFC	Hybrid Laminar Flow Control
HVDC	High Voltage Direct Current
IADP	Innovative Aircraft Demonstrator Platform
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IFE	In-Flight Entertainment
INEA	Innovation and Networks Executive Agency
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Rights

IT	Information Technology
ITD	Integrated Technology Demonstrator
JAXA	Japan Aerospace Exploration Agency
LAQ	Local Air Quality
LPA	Large Passenger Aircraft
LRC	Long Range Cruise
MDO	Multidisciplinary Design Optimization
MEA	More Electric Aircraft
MEMS	Microelectromechanical Systems
MRC	Maximum Range Cruise
MRL	Manufacturing Readiness Level
MRO	Maintenance, Repair and Operations
NLF	Natural Laminar Flow
OEM	Original Equipment Manufacturer
OR	Open Rotor
pax	Passengers
PGB	Power Gearbox
POL	Point of Load
RF	Radiative Forcing
RPK	Revenue Passenger-Kilometre
RTK	Revenue Tonne-Kilometre
SAT	Small Air Transport
SAF	Sustainable Aviation Fuel(s)
SBW	Strut-Braced Wing
SESAR	Single European Sky ATM Research
SFC	Specific Fuel Consumption
SHM	Structural Health Monitoring
SME	Small or Medium-Sized Enterprise
SPD	Strategic Platform Demonstrator
SPO	Single Pilot Operation
SRIA	Strategic Research and Innovation Agenda
SRL	System Readiness Level
SST	Supersonic Transport
TA	Transversal Activity
TBW	Truss-Braced Wing
TE	Technology Evaluator
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
WTT	Wind Tunnel Test

References

[1] ATAG, "Aviation benefits beyond borders", Air Transport Action Group, Geneva, Switzerland, Oct. 2018. Available from www.atag.org/.

[2] EASA, EEA, and EUROCONTROL, "European aviation environmental report 2019", nd. Available from www.easa.europa.eu/eaer/.

[3] ASD, "2017 Facts & Figures", The Aerospace and Defence Industries Association of Europe, Brussels. Available from www.asd-europe.org/.

[4] AIA, "2018 Facts & Figures: US Aerospace and Defense", Aerospace Industries Association, Arlington, USA. Available from www.aia-aerospace.org/.

[5] Freedberg, S., Jr., "DoD R&D soars 24%, procurement up 15%; army up most ", Breaking Defense [online], 12 Feb. 2018. Available from https://breakingdefense.com/2018/02/dod-r-army-up-most/.

[6] The Group of Personalities, "European aeronautics: A vision for 2020. Meeting society's needs and winning global leadership.", European Commission, Luxembourg, Jan. 2001.

[7] ACARE, "Strategic research agenda SRA-2", Advisory Council for Aeronautics Research in Europe, www.acare4europe.org, Oct. 2004.

[8] The High Level Group on Aviation Research, "Flightpath 2050 Europe's vision for aviation", European Commission, Brussels, 2011.

[9] IPCC, "Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report", Intergovernmental Panel on Climate Change, Geneva, Switzerland.

[10] IPCC, "Global warming of 1.5 °C", Special Report SR1.5, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 6 Oct. 2018.

[11] Nordhaus, W., *The climate casino: Risk, uncertainty and economics for a warming world*, Yale University Press, New Haven, USA, 2013.

[12] IPCC, "Global warming of 1.5 °C: Summary for policymakers", Special Report SR1.5, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 6 Oct. 2018.

[13] European Commission, "A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy", COM(2018) 773 final, Brussels, 28 Nov. 2018.

[14] Lee, D.S., Fahey, D.W., Forster, P.M., *et al.*, "Aviation and global climate change in the 21st century", *Atmospheric Environment*, Vol. 43, pp. 3520-3537, 2009.

[15] ICAO, "Environmental report 2016 : Aviation and climate change", Environment Branch, International Civil Aviation Organization, Montréal, Canada, 2016.

[16] Airbus, "Global market forecast: Global networks, global citizens 2018-2037", Airbus S.A.S., Blagnac, France, 2018.

[17] Boeing, "Commercial market outlook 2018-2037", Seattle, WA, 2018.

[18] EASA, EEA, and EUROCONTROL, "European aviation environmental report 2016", nd. Available from www.easa.europa.eu/eaer/.

[19] IATA, "Climate change: Three targets and four pillars", International Air Transport Association [website], Montréal, Canada, Retrieved Apr. 2019. Available from https://www.iata.org/policy/environment/pages/climate-change.aspx.

[20] ICAO, "Assembly 39th session: Report of the executive committee on agenda item 22", A39-WP/530, International Civil Aviation Organization, Montréal, Canada, 6 Oct. 2016.

[21] Oestergaard, J.K., "Airbus and Boeing report August 2018 commercial aircraft orders and deliveries", Forecast International, Newtown, CT, USA, 19 Sep. 2018. https:\\blog.forecastinternational.com/wordpress/.

[22] Graver, B. and Rutherford, D., "U.S. passenger jets under ICAO's CO2 standard, 2018-2038", Working paper 2018-25, International Council on Clean Transporation (ICCT), Washington, DC, 2 Oct. 2018. Available from www.theicct.org/.

[23] Mathias, B., *Der Schutz vor nächtlichem Fluglärm*, Symposium at University of Leipzig, Germany, 20 Jan. 2007.

[24] Elmenhorst, E.-M. and Mathias, B., "Fluglärmwirkungen (night flight noise impact)", Forschungsbericht 2004-11/D, Cologne, Germany, March 2008. ISSN 1434-8454.

[25] Marias, K. and Waitz, I.A., "Air transport and the environment", in *The global airline industry*, Belobaba, P., Barnhart, C., and Odoni, A. (Eds.), Wiley, Chichester, UK, pp. 405-440, 2009.

[26] FAA, "Aviation emissions, impacts & mitigation : A primer", Office of Environment and Energy, Federal Aviation Administration, Washington, DC, Jan. 2015.

[27] Solomon, R., Sandborn, P.A., and Pecht, M.G., "Electronic part life cycle concepts and obsolescence forecasting", *IEEE Trans. on Components and Packaging Technologies*, Vol. 23, Iss. 4, pp. 707-717, 2000.

[28] Nelson, R.S., III, and Sandborn, P., "Strategic management of component obsolescence", *Int. J. of Product Lifecycle Management*, Vol. 6, Iss. 2, 2012.

[29] RS-Components, "Obsolescence-Manager", Retrieved Jan. 2019. Available from https://www.rs-online.com/designspark/obsolescence-manager.

[30] Anon, "New catalyst for hydrogen production is a step toward clean fuel", PHYS.ORG, 16 Jan 2018. Available from https://phys.org/news/2018-01-catalyst-hydrogen-production-fuel.html.

[31] Råde, I., *Requirement and availability of scarce metals for fuel-cell and battery electric vehicles* [Doctoral thesis], Chalmers University, Sweden, 2001.

[32] Zion, N., Friedman, A., Levy, N., and Elbaz, L., "Bioinspired electrocatalysis of oxygen reduction reaction in fuel cells using molecular catalysts", *Adv Mater*, Vol. 30, Iss. 41, 2018.

[33] Unni, S.M., Illathvalappil, R., Bhange, S.N., *et al.*, "Carbon nanohorn-derived graphene nanotubes as a platinum-free fuel cell cathode", *Appl. Mater. Interfaces*, Vol. 7, Iss. 43, pp. 24256–24264, 2015.

[34] Raj, C.R., Samanta, A., Noh, S.H., *et al.*, "Emerging new generation electrocatalysts for the oxygen reduction reaction", *J. Materials Chemistry A*, Vol. 29, 2016.

[35] Bielawski, M., "Hard chromium plating alternative technologies", *Canadian Aeronautics and Space Journal*, Vol. 46(3), pp. 140-149, 2000.

[36] Bielawski, M., "Alternative technologies and coatings for electroplated cadmium and hard chromium", *Canadian Aeronautics and Space Journal*, Vol. 56(3), pp. 67-80, 2011.

[37] Zheng, Y., "Plating hard chrome plating alternative technologies - HVOF tungsten carbide coating", *Advanced Materials Research*, Vol. 712-715, pp. 395-398, 2013.

[38] Donaldson, K., Legg, K., and Vallejo, G., "High purity electrodeposited AlumiPlate® aluminum as a cadmium plating replacement", *National Association for Surface Finishing Annual Conference and Trade Show*, Rosemount, Illinois, USA, 13-15 June 2011.

[39] Moodie, A., "Amid legal uncertainty on conflict minerals, alternatives emerge", *The Guardian [online]*, 23 Apr. 2014. Available from https://www.theguardian.com/sustainable-business/conflict-free-minerals-ruling-litigation-apple-intel.

[40] USGS, "Minerals Information", U.S Geological Survey [online], Retrieved Jan. 2019. Available from https://minerals.usgs.gov/minerals/pubs/commodity/niobium/.

[41] Directorate-General for Research and Innovation (European Commission), "Interim evaluation of Horizon 2020", 16 Aug. 2016. ISBN 978-92-79-69545-2.

[42] Atkinson, C., Pfeiffer, H., Doerffer, P., *et al.*, "Final evaluation of the Clean Sky Joint Undertaking (2008-2016) operating under FP7 ", Brussels, June 2017. Available from https://ec.europa.eu/research/evaluations/pdf/cs.pdf.

[43] Atkinson, C., Pfeiffer, H., Doerffer, P., *et al.*, "Interim Evaluation of the Clean Sky 2 Joint Undertaking (2014-2016) operating under Horizon 2020", June 2017. Available from https://ec.europa.eu/research/evaluations/pdf/cs2.pdf.

[44] European Union, "On common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency", Regulation (EU) 2018/1139, Brussels, Belgium, 4 July 2018. Published in *Official Journal of the European Union,* Vol. L 212, 22 Aug. 2018.
[45] European Commission, "European Battery Alliance", Retrieved January 2019. Available from https://ec.europa.eu/growth/industry/policy/european-battery-alliance.
[46] Hileman, J.I., De la Rosa Blanco, E., Bonnefoy, P.A., and Carter, N.A., "The carbon dioxide challenge facing aviation", *Progress in Aerospace Sciences*, Vol. 63, pp. 84-95, 2013.
[47] Directorate-General for Research and Innovation, "Europe 2020 flagship initiative innovation union ", SEC(2010) 1161, European Commission, Brussels, Belgium, 2011. Available at https://ec.europa.eu/research/innovation-union/pdf/innovation-union-communication-brochure_en.pdf.
[48] ACARE, "Strategic research & innovation agenda: 2017 update", Vol. 1, Advisory Council for Aeronautics Research in Europe, www.acare4europe.org, 2017.
[49] ACARE, "Strategic research & innovation agenda: 2017 update", Vol. 2, Advisory Council for Aeronautics Research in Europe, www.acare4europe.org, 2017.
[50] NASA, "Strategic implementation plan: 2017 update", NP-2017-01-2352-HQ, Aeronautics Research Mission Directorate, National Aeronautics and Space Administration, Washington, DC, 2017. Available from https://www.nasa.gov/aeroresearch/strategy.
[51] NASA, "New aviation horizons initiative and complementary investments", NP-2016-06-2167-HQ, National Aeronautics and Space Administration, Washington, DC, 2016. Available from https://www.nasa.gov/sites/default/files/atoms/files/nasa-aero-10-yr-plan-508-reduced.pdf.
[52] NASA, "Strategic plan 2018", National Aeronautics and Space Administration, Washington, DC, 12 Feb. 2018. Available from https://www.nasa.gov/sites/default/files/atoms/files/nasa_2018_strategic_plan.pdf.
[53] Thole, K.A., Whitlow, W., Jr., Benzakein, M.J.*, et al.*, *Commercial aircraft propulsion and energy systems research: Reducing global carbon emissions*, The National Academies Press, Washington, DC, 2016.
[54] JAXA, "Aeronautical technology research", Japan Aerospace Exploration Agency, Retrieved Feb. 2019 [website]. Available from http://global.jaxa.jp/projects/aero/index.html.
[55] JAXA, "Explore to realize", Nov. 2017. Available from http://global.jaxa.jp/activity/pr/brochure/general.html
[56] Union of Aviation Industrialists of Russia, Retrieved Feb. 2019 [website]. Available from http://www.aviationunion.org/list_members.php.
[57] CAE, Chinese Aeronautical Establishment, Retrieved Feb. 2019 [website]. Available from http://www.cae.ac.cn/En/About/Strategic/.
[58] Jones, C.E., Norman, P.J., Galloway, S.J.*, et al.*, "Comparison of candidate architectures for future distributed propulsion aircraft", *IEEE Trans. Appl. Supercond.*, Vol. 26, Iss. 6, 2016.
[59] Anon, "CENTRELINE project: EU Grant agreement No 723242", *Policy Workshop*, Brussels, 1 Feb. 2019.
[60] Torenbeek, E., *Advanced aircraft design*, John Wiley & Sons, Chichester, UK, 2013.
[61] Anon, "PARSIFAL project: EU Grant Agreement No 723149", Retrieved Jan. 2019. Available from http://parsifalproject.eu/.
[62] Bradley, M.K. and Droney, C.K., "Subsonic ultra green aircraft research: Phase I final report", CR-2011-216847, NASA Langley Research Center, Hampton. VA, USA, Apr. 2011.
[63] Bradley, M.K. and Droney, C.K., "Subsonic ultra green aircraft research: Phase II: N+4 Advanced concept development", CR-2012-217556, NASA Langley Research Center, Hampton. VA, USA, May 2012.
[64] Albuquerque, P.F., Gamboa, P.V., and Silvestre, M.A., "Mission-based multidisciplinary aircraft design optimization methodology tailored for adaptive technologies", *Journal of Aircraft*, Vol. 55, Iss. 2, pp. 755-770, 2017.

[65] Yang, W., Yue, Z., Li, L., and Wang, P., "Optimization design of unitized panels with stiffeners in different formats using the evolutionary strategy with covariance matrix adaptation", *Proceedings of the IMechE, Part G: Journal of Aerospace Engineering*, Vol. 231, pp. 1563-1573, 2017.

[66] ATAG, "Facts & figures", Air Transport Action Group [website], Retrieved Apr. 2019. Available from https://www.atag.org/.

[67] Egelhofer, R., Marizy, C., and Cros, C., "Climate impact of aircraft technology and design changes", *Air Transportation*, Vol. 12, Iss. 2, pp. 72-97, 2007.

[68] Committee on Climate Change, "Net Zero: The UK's contribution to stopping global warming", Committee on Climate Change, London, UK, 2 May 2019. Available from https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/.

[69] Sun, Y. and Smith, H., "Review and prospect of supersonic business jet design", *Progress in Aerospace Sciences*, Vol. 90, pp. 12-38, 2017.

[70] Kharina, A., MacDonald, T., and Rutherford, D., "Environmental performance of emerging supersonic transport aircraft", Working Paper 2018-12, International Council on Clean Transportation (ICCT), Washington DC, 17 July 2018. Available from www.theicct.org/.

[71] Catchpole, D., "Zunum runs into financing trouble", AINonline [website], Retrieved Apr. 2019. Available from https://www.ainonline.com/aviation-news/air-transport/2019-01-03/zunum-runs-financing-trouble.

[72] Sarsfield, K., "Eviation secures funding for all-electric Alice", FlightGlobal [website], Retrieved Apr. 2019. Available from https://www.flightglobal.com/news/articles/eviation-secures-funding-for-all-electric-alice-454830/.

[73] Arnaud, S., "Electric planes taking to the skies in a world first for Scottish island", *The Press & Journal*, 16 Oct. 2018. Available from https://www.pressandjournal.co.uk/fp/news/islands/orkney/1586403/electric-planes-taking-to-the-skies-in-a-world-first-for-scottish-island/.

[74] European Commission, "In-depth analysis in support of the Commission Communication COM (2018) 773", European Commission, Brussels, 28 Nov. 2018.