TOWARDS A SUSTAINABLE AIR TRANSPORT SYSTEM

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WHITEPAPER TU DELFT - NLR

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ABBREVIATIONS

ACRONYM	DESCRIPTION
ACI	Airport Council International
AHEV	Actieprogramma Hybride Elektrisch Vliegen
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
ATM	Air traffic management
ATI	(UK) Aerospace Technology Institute
ATR	Average temperature response
BLI	Boundary layer ingestion
BPR	Bypass ratio
BSS	Battery swapping station
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAEP	Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organization
CDO	Continuous descent operations
CFRP	Carbon Fiber Reinforced Polymer
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
CORAC	(French) Civil Aviation Research Council
DAC	Direct air capture
DLT	Duurzame Luchtvaarttafel
EC	European Commission
EIS	Entry into service
ERF	Effective radiative forcing
ESG	Environmental, Social and Governance
EU	European Union
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse gases
GSE	Ground service equipment
GWP	Global warming potential
HEFA	Hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	Intermediate stop operations
LAQ	Local air quality
LCA	Life-cycle analysis

LTAG	Long-term global aspirational goal for international aviation
LuFo	German National Aeronautics Research Programme
MRO	Maintanance, repair and overhaul
NASA	National Aeronautics and Space Administration
NLR	Netherlands Aerospace Centre
NO_x	Oxides of nitrogen
O_3	Ozon
PM	Particulate matter
R&D	Research and development
RF	Radiative forcing
R&I	Research and innovation
RED	Renewable Energy Directive
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable aviation fuel
SDG	Sustainable Development Goal
SO_x	Sulphur oxides
SRIA	Strategic Research and Innovation Agenda
TR	Technology readiness
TRL	Technology readiness level
UAM	Urban Air Mobility
UHBR	Ultra-high bypass ratio
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USSR	Union of Soviet Socialist Republics
WCED	World Commission on Environment and Development
WLO	Welvaart en Leefomgeving

DEFINITIONS

The following definitions are taken from the special report “Global Warming of 1.5°C” published by IPCC in 2018 (Masson-Delmotte, et al., 2018). As such, NLR and TU Delft will use these specific definitions throughout this report. The definitions are presented in alphabetic order.

ANTHROPOGENIC EMISSIONS

Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes (LULUC), livestock production, fertilisation, waste management and industrial processes.

ANTHROPOGENIC REMOVALS

Anthropogenic removals refer to the withdrawal of GHGs from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long-term removal and storage. Carbon capture and storage (CCS) from industrial and energy-related sources, which alone does not remove CO_2 in the atmosphere, can reduce atmospheric CO_2 if it is combined with bioenergy production (BECCS).

CLIMATE CHANGE COMMITMENT

Climate change commitment is defined as the unavoidable future climate change resulting from inertia in the geophysical and socio-economic systems.

ZERO EMISSIONS COMMITMENT

The zero emissions commitment is the climate change commitment that would result from setting anthropogenic emissions to zero. It is determined by both inertia in physical climate system components (ocean, cryosphere, land surface) and carbon cycle inertia.

CLIMATE NEUTRALITY

Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local bio-geophysical effects of human activities that, for example, affect surface albedo or local climate.

CARBON DIOXIDE (CO_2)

A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUC) and of industrial processes (e.g., cement production). It is the principal[1] anthropogenic greenhouse gas (GHG) that affects the Earth’s radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1.

CARBON DIOXIDE REMOVAL (CDR)

Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of

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[1] For aviation, CO_2 emissions are considered one of the key anthropogenic emissions influencing climate.

biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

NET ZERO EMISSIONS

Net zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

NET ZERO CO_2 EMISSIONS

Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

RADIATIVE FORCING AND EFFECTIVE RADIATIVE FORCING

Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in $W\ m^{-2}$) at the tropopause or top of atmosphere due to a change in a driver of climate change, such as a change in the concentration of carbon dioxide (CO_2) or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing.

INTRODUCTION

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1. INTRODUCTION

Air transportation is a key element of modern society connecting people and economies around the globe. The industry has rapidly grown in the past decades increasing connectivity and contributing to economic development. Despite the many benefits, air transportation also has an impact on the environment. According to latest scientific publications, in 2011 aviation was responsible for approximately 3.5% of anthropogenic climate change (Lee, et al., 2020). Although technological development has steadily progressed, the growth in number of flights have increased total noise and pollutant emissions, which has a negative impact on the planet and the well-being and health of people around the world.

Awareness for sustainability, and global warming especially, has grown over the last years. According to the latest reports of the Intergovernmental Panel on Climate Change (IPCC), the rise of global average temperatures has to be limited to 1.5°C to 2°C when compared to pre-industrial levels to prevent irreversible harm to our planet. The IPCC has determined that in order to meet the 1.5°C to 2°C scenarios, net-zero carbon must be achieved by 2050 or 2070, respectively (IPCC, 2018). To realise that, aviation must play its part in response to the climate emergency by taking effective measures to reduce greenhouse gas emissions.

This Whitepaper expresses the vision of the Royal Netherlands Aerospace Centre and Delft University of Technology on the most promising technological solutions that are envisioned to contribute to reducing the environmental impact of aviation. Although human behaviour and consumption patterns play a major role in the anthropogenic effects on climate change, technological solutions are a key element to achieve these goals. Such technological solutions need to be developed quickly and may significantly impact the air transportation systems as we know it. Moreover, a continued fundamental and applied research effort will be needed addressing long term goals as well. Aviation will enter a new era characterized by innovative air vehicle concepts powered by emission-free energy sources operating in sustainable ecosystem.

1.1. NLR and TU Delft ambitions

NLR and TUD believe that climate goals for aviation should be aligned with the latest scientific insights regarding climate change. NLR and TU Delft aim to contribute to the realization of a climate neutral[2] air transport system by 2050.

The climate impact of aviation is determined by the effect of CO_2 and non-CO_2 emissions on the climate system. The IPCC stresses that, to limit global warming to 1.5°C, net zero CO_2 emissions need to be achieved by 2050 and that strong efforts need to be pursued to also reduce net non-CO_2 emissions[3].

This target is a part of the current policy proposal by the European Commission in the Green Deal. As stated by the European Commission based on the recent report by the European Union Aviation Safety Agency: “unlike CO_2 impacts, which directly correlate to the amount of fuel burned, the complexity of measuring non-CO_2 climate impacts - and the uncertainty regarding trade-offs between the various impacts - makes targeted policy development in this area more challenging”. Targets for non-CO_2 emissions from aviation

[2] No net effect on the climate system. See definition list at start of document.

[3] The non-CO_2 emissions covered by IPCC include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases.

have therefore not been fully specified for 2050[4]. Through extended high-level research within international context NLR and TU Delft aim to contribute to enhancing the understanding of non-CO_2 impacts such that the climate neutrality objective can be achieved by 2050.

NLR and TUD believe the role of universities and research institutes, is to provide the latest scientific knowledge and developing breakthroughs, quantifying and monitoring progress, and preparing innovative technological solutions for industrial market uptake.

NLR and TU Delft commit to climate action both today and in the long term by providing technological and innovative solutions that contribute to this challenge. NLR and TU Delft also commit to reducing the environmental footprint of aviation by working on solutions that reduce noise emissions, improve local air quality and reduce the impact on biodiversity and prevent resource depletion.

The strength of the partnership between NLR and TU Delft lies in the combination of fundamental and applied research. NLR and TU Delft aim to find engineering solutions by combining knowledge in an interdisciplinary way and by continuously monitoring new developments. Fundamental research is regarded an essential part of the development process towards sustainable aviation as it enables long term solutions.

1.2. Whitepaper objective and scope

This Whitepaper summarizes the vision of NLR and TU Delft on the most promising technologies that need to be developed in order to achieve the environmental goals. These technologies enable pathways towards a sustainable air transport system which takes into account climate impact, impact of the local environment and impact on resource depletion. Currently no “silver bullet” exists to tackle this challenge.

NLR and TU Delft presented their first ideas in the form of a Green Paper in February 2019 (NLR; TU Delft, 2019). This Whitepaper builds on that view by further elaborating promising technologies and associated research activities to achieve a sustainable air transport system.

As outlined in this Whitepaper, particular attention is given the climate challenge. Pathways towards a climate neutral air transport system have to be further investigated, in particular to ensure that both CO_2 and non-CO_2 emissions are taken into account. As such, this document is not intended to lay down a fixed roadmap that shows the feasibility of various pathways but aims to identify the technologies and research area’s that need further investigation to be able to reach climate neutrality. The presented research area’s include climate impact, noise impact on local communities, impact of air quality and impact on biodiversity and resource depletion both from an applied and fundamental research perspective.

State-of-the-art knowledge has been used to identify the most promising technologies which can deliver the most impact in the short, medium and long term. These technologies span the entire air transport system from aircraft development to operations combined with new energy sources. Furthermore, technologies are presented that may act as enablers in reaching the overall impact.

As time progresses, this vision needs to be updated. Some technological breakthroughs might surpass expectations, whereas others might not bring the anticipated benefits. Uncertainty on future developments

[4] Regulation EU/2018/1999 addresses non-CO_2 emissions from aviation on page 9 item (52). It states that the Commission will address such impacts based on the latest scientific progress accompanied, where appropriate, by a proposal on how best to address those effects. In part 2 Annex 5 the following list of GHG emissions is currently included: Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Sulphur hexafluoride (SF_6), Nitrogen trifluoride (NF_3), Hydrofluorocarbons (HFCs) and Perfluorocarbons (PFCs).

should however not lead to inaction, on the contrary it should lead to crucial investments into increasing our knowledge in the coming years.

The foundation for the research activities to be carried out in a national research and innovation programme can be laid out based on the vision presented in this document, along with governmental and industry initiatives, as shown in Figure 1. National research activities will strengthen the position of The Netherlands thereby enabling closer cooperation and collaboration at international level. The industrial needs include a stronger focus on the production, the supply chain and the competitive position in the market.

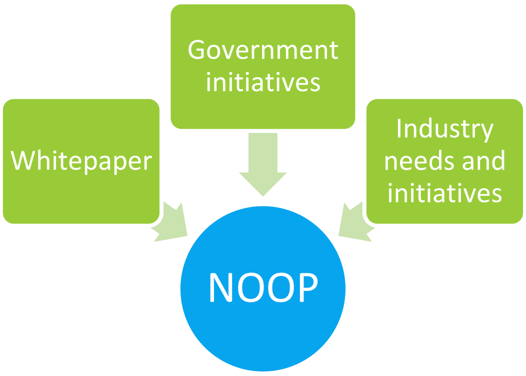

Figure 1: Context of Whitepaper as input for the national research and innovation programme (NOOP)

1.3. Structure

After the context chapter (Chapter 2), the Whitepaper details out the challenge that is currently faced by the aviation sector in Chapter 3. The environmental impact of technological solutions following three main research lines which merge into air transport level changes are described in subsequent Chapters 4 to 6. These research lines are the following:

- **Chapter 4 - Aircraft development:** includes the most relevant research areas that are related to the aircraft platform itself. This includes for example hybrid/electric propulsion systems, hydrogen-based propulsion and novel aircraft configurations including material and structures selection. It also includes research on modelling, validation and testing which is required to certify the components and systems on board the aircraft.
- **Chapter 5 - Sustainable aviation fuels and energy sources**: are an essential element to reach an absolute reduction in emissions. The sustainability of these fuels from feedstock to production and use on-board needs to be considered.
- **Chapter 6 - Operations**: considers the application of new technologies in the air transport system. It includes steps towards a climate optimal flight by choosing for example global warming optimized flight paths. Furthermore, it looks at reducing the impact of flights on local communities in terms of noise and local air quality emissions. It also includes the required infrastructure and maintenance activities.

The final two chapters apply a holistic approach, by firstly proposing research and innovations activities to accurately and effectively model and monitor the effects of R&D efforts on the relevant sustainability goals (Chapter 7), and secondly, considering policy aspects related to the transition to a more sustainable air transport system (Chapter 8).

CONTEXT

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2. CONTEXT

In 1987, the World Commission on Environment and Development (WCED) published a report which set the guiding principles for sustainable development as it is generally understood today (World Commission on Environment and Development, 1987). The "Brundtland Report" defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This social and political goal has been widely recognized and accepted, but the implementation remains challenging. There are three fundamental dimensions in achieving this goal: environmental, social and economic (often also referred to as planet, people and profit). To guide this, the United Nations have developed 17 Sustainable Development Goals (SDG's). How to achieve these goals is and remains a global challenge.

Sustainable development also applies to aviation. The following sections describe how sustainability within the aviation sector is addressed from an international and national perspective.

2.1. Global context

Within the Paris Agreement[5], the effort to address greenhouse gas emissions from international air traffic is under the authority of the International Civil Aviation Organization (ICAO) considering that international air traffic does not fall under any national jurisdiction. ICAO regularly reports its environmental activities to the United Nations Framework Convention on Climate Change (UNFCCC).

Currently, ICAO has set two aspirational goals for the international aviation sector: a fuel efficiency improvement of 2 per cent per year and carbon neutral growth from 2020 onwards, so that net carbon emissions stay level from 2020 onwards (ICAO, 2020). ICAO however recognizes that these medium-term goals are not ambitious enough to reduce aviation's absolute emissions. Therefore, last year ICAO started to work on a long-term global aspirational goal for international aviation (LTAG) in light of the 2°C and 1.5°C temperature goals of the Paris Agreement. Currently, detailed studies are conducted to explore to assess the attainability and impacts of the proposed goals. The work will be presented for adoption in 2022 at the 41st Session of the ICAO assembly.

In addition to ICAO, the civil aviation industry, through the Aviation Transport Action Group (ATAG), has set a goal to cut CO_2 emissions in half by 2050 compared to the 2005 level. The industry performed multiple analysis on how to reach these goals including the latest Waypoint 2050 scenarios published by ATAG. The most important pillars to reach these goals are fuel efficiency improvements, operational improvements, sustainable aviation fuels and energy sources, and market-based measures.

2.2. European context

The European Commission has set the ambitious target of becoming a climate neutral continent in 2050 (EC, 2019). This will be realized by achieving net zero greenhouse gas emissions in 2050 and by decoupling economic growth from resource use. The European Green Deal is the Commission's commitment to tackling climate and environmental challenges. It will include the first European Climate Law which sets a legally binding target of net zero greenhouse gas emissions by 2050 (EC, 2020b). In the proposal for this law the EC

[5] Adopted on 12 December 2015 at the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change.

stresses that it will cover all sectors of the economy. Furthermore, the proposal specifies that by 2050 any other remaining greenhouse gas emissions – not only CO_2 - should be compensated. The strategy for sustainable growth is based on a new Circular Economy Action Plan (EC, 2020a). The plan aims to ensure that the resources used are kept in the EU economy for as long as possible. A circular economy is a precondition for achieving the climate-neutrality target by 2050 and halting biodiversity loss.

Very recently the European aviation sector has committed to work together with all stakeholders and all policy-makers to achieve net zero CO_2 emissions from all flights within and departing from the EU by 2050 (Airlines for Europe, et al., 2020).

To achieve the Green Deal goals, the Clean Aviation Partnership has been proposed as one of the major Research and Innovation partnerships for aircraft development under Horizon Europe. This partnership will build upon the previous Clean Sky and Clean Sky 2 programmes. The vision and pathway to reach the Green Deal goals is outlined in the Strategic Research and Innovation Agenda (SRIA) for the proposed Clean Aviation Partnership under Horizon Europe published earlier this year (Clean Aviation Partnership, 2020b). The trajectory outlined by Clean Aviation shows two time horizons (Clean Aviation Partnership, 2020a):

- **2030**: “demonstrating and introducing low-emissions aircraft concepts exploiting the research results of Clean Aviation, making accelerated use of sustainable fuels and optimised ‘green’ operations, so these innovations can be offered to airlines and operators by 2030 for an entry into service (EIS) in the 2030-2035 timeframe.”
- **2050**: “climate neutral aviation, by exploiting future technologies matured beyond the Clean Aviation phase coupled with full deployment of sustainable aviation fuels and alternative energy carriers.”

On the operations side, the Integrated Air Traffic Management partnership under Horizon Europe is proposed as successor to SESAR and SESAR2020. As laid down in the draft proposal, the aim of the partnership is to make the European airspace the most efficient and environmentally friendly sky to fly in the world.

The energy transition in aviation will also require joint collaboration with other sectors. In particular, in terms of hydrogen propulsion, (hybrid) electric power plants and sustainable aviation fuels. Therefore projects will pursue the collaboration with, for example, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

2.3. Research programmes in neighbouring countries

In Europe, multiple other national research programmes exist which include research topics to address the environmental impact of aviation. Three national programs are detailed in the following section:

- Germany: LuFo (German National Aeronautics Research Programme)
- France: CORAC (Civil Aviation Research Council)
- UK: ATI (Aerospace Technology Institute)

GERMANY: LUFO VI-2

The focus of the second call of the sixth LuFo programme (LuFo VI-2) is reducing the environmental impact of aviation (Bundesministerium für Wirtschaft und Energie, 2020). The research performed under this program shall lead to a major reduction of CO_2 and non-CO_2 emissions, with the ultimate goal of developing zero emission aircraft. Electrification of the powertrain is seen as a possible way towards net-zero emissions.

The lower power and energy densities of the powertrain are seen as major challenges. This can be overcome by developing new configurations which optimize the interaction between aerodynamics and propulsion taking into account the scalability of electric components. This is also reflected by two program lines:

- Disruptive technologies and innovative systems (eco-efficient flying)
- Hydrogen technologies and (hybrid) electric flying (zero emission aircraft)

The budget of the German LuFo programme was around 156 million euros per year in 2018. The federal government is planning to increase the budget by an additional 90 million euros in years 2018 to 2022 (Bundesministerium für Wirtschaft und Energie, 2018). The additional funds will be used in particular for fields of digitalization and hybrid electric flying.

Furthermore, the German research community and industry have recently published the Whitepaper Zero Emission Aviation, which shows a clear focus on the pathway towards climate neutral aviation (BDLI; DLR, 2020). The vision presented in this paper includes the effects on non-CO_2 emissions on the total climate impact of aviation.

FRANCE: CORAC

The Civil Aviation Research Council (CORAC) was established in 2008 with members representing the entire French aerospace industry. France's central government recently announced that it will invest 1.5 billion euros in R&D and innovation over three years to support environmentally friendly technology and at the same time save R&D jobs which are in danger due to the COVID-19 crisis (French Government, 2020). The main goal of the investment would be to make France one of the most advanced countries in clean aircraft technologies including electrification and the transition to carbon neutral fuels such as hydrogen. Furthermore, the aim is to launch a carbon-neutral successor to the A320 which uses 100% sustainable fuels or hydrogen by 2035.

UNITED KINGDOM: AEROSPACE TECHNOLOGY INSTITUTE

ATI's strategy is to set an ambitious sustainability agenda. In multiple elements of ATI's research program the goal of creating a more sustainable air transport system is mentioned. To achieve the UK's and Europe's environmental targets the program strategy includes: more energy efficient aircraft, optimizing flight operations, more sustainable through-life engineering services, optimizing ground operations, more sustainable manufacturing, alternatives to kerosene with lower net carbon impact (ATI, 2020a). In July 2020 ATI launched the FlyZero project which will kick start exploration into a zero-carbon emission commercial aircraft (ATI, 2020b). Due to the huge impact of the Covid pandemic on the aerospace industry, ATI has increased the funding rate for industry up to the level that is allowed by European state-aid laws. In 2018 UK Government and industry have agreed jointly to commit up to 300 million pounds per year in technology out to 2026, creating a total potential investment of 3.9 billion pounds (ATI, 2018).

2.4. National context

The Dutch Ministry of Infrastructure and Water Management has set up a process to involve all relevant organizations in the discussion on how to achieve the climate goals for the aviation sector. This process and its members are in Dutch referred to as "Duurzame Luchtvaarttafel", hereafter abbreviated as DLT. The organizations involved include industry, government and research institutions. This collaboration led to establishing a joint vision which is detailed in the document "Ontwerpakkoord Duurzame Luchtvaart" expressing the following goals for international flights departing from The Netherlands:

- In 2030 CO_2 emissions are equal to the emission level of 2005[6]
- In 2050 CO_2 emissions are reduced by 50% compared to 2005
- In 2070 zero emissions are achieved.

Multiple working groups have been established under the DLT to elaborate and discuss possible pathways to achieve these goals. This includes two programmes which focus on short term actions that enable long term goals to be achieved. One action programme for the development of sustainable fuels and one for the development of hybrid electric aircraft (AHEV). Regarding the latter, the Dutch government has expressed the ambition to lead the way in the transition to hybrid electric aircraft.

The above stated climate goals served as a basis for the plans presented this year by the Dutch Government in the document “Verantwoord vliegen naar 2050 - Luchtvaartnota 2020-2050”. This document presents a vision for the development of the air transport system in the Netherlands between 2020 and 2050. It includes a vision on how to address the climate challenge while also improving the local environment.

FUNDING

The Dutch government does not have sector-specific research and development funding schemes. Fundamental research has instruments managed by the Dutch organization for scientific research, NWO. As a university, TU Delft obtains basic government funding for education and research, called ‘eerste geldstroom’. Applied aviation R&D is embedded in the ‘Topsectorenbeleid’, where High Tech Systems and Materials has a specific roadmap for aeronautics (Stichting Lucht- en Ruimtevaart Nederland, 2018). Projects are partially funded in Public-Private Partnerships of companies with knowledge institutes. As an applied knowledge institute, NLR receives a yearly institute subsidy that has a much broader scope than only sustainability. In the plans for a new mission-oriented innovation policy (“Missiegedreven Innovatiebeleid”), sustainable aviation is added to the mission ‘Toekomstbestendige Mobiliteitssystemen’.

[6] For ground operations CO_2 emissions are reduced to zero.

THE SUSTAINABILITY CHALLENGE

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3. THE SUSTAINABILITY CHALLENGE

Evidenced by the international and national as well as society-wide and sector-specific sustainability goals, the aviation industry is faced with a massive sustainability challenge. The impact includes the effects on climate, quality of life, local environment and resource use. These are generated by noise and pollutant emissions across the life-cycle of aircraft (operations, vehicle production, energy generation and storage, and end-of-life), as well as the resources required in these processes.

Besides the fact that aviation in general is accepted to be a so-called hard to abate sector in terms of CO_2 emissions (Energy Transitions Committee, 2018), various characteristics of the industry – or its integration in the Dutch society and economy – that make this all the more challenging. One common aspect, which aggravates this major challenge, is the anticipated steady growth of the aviation sector, as evidenced by multiple sources (EUROCONTROL, 2018; CPB; PBL, 2016; Airbus, 2019c; Boeing, 2019). Although the COVID-19 pandemic has currently decimated aviation across the globe, continued long-term global economic development trends fuel the expectation that the crisis will only delay growth rather than cause a long-term decrease. This chapter highlights the main difficulties.

3.1. The climate challenge

Through the emissions of greenhouse gases and other radiative forcing terms such as aviation-induced cloudiness, aviation has a notable impact on the global climate. Figure 2 depicts total anthropogenic CO_2 emissions against the aviation fraction of the total anthropogenic CO_2 emissions over the years 1940-2020 (Lee, et al., 2020). Although the relative contribution of aviation has decreased over the first couple of decades, even without absolute growth, the relative contribution is expected to increase as other sectors reduce or entirely abate their CO_2 emissions (Cames, Graichen, Siemons, & Cook, 2015; Pidcock & Yeo, 2016; Becken & Pant, 2020).

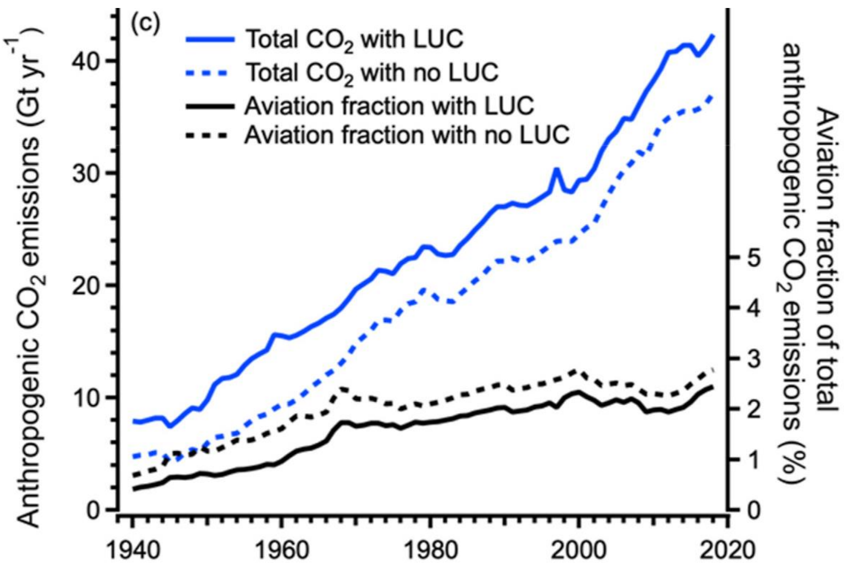


Figure 2: Total anthropogenic CO_2 emissions (Gt / year) and aviation fraction. From Lee et al. (2020).

A number of aspects of the aviation climate challenge make it especially hard: a large discrepancy between the size of activity and the amount of emission, efficiency improvement which are outpaced by growth, and the substantial impact of non-CO_2 emissions.

DISCREPANCY BETWEEN THE SIZE OF ACTIVITY AND THE AMOUNT OF EMISSIONS

First, the majority of emissions is caused by aviation activity that has little alternatives, and limited decarbonisation options: long-haul flights. The 20% longest flights by distance worldwide are associated to almost 40% of global aviation CO_2 emissions (IEA, 2020, p. 300)[7]. For Amsterdam Airport Schiphol, this discrepancy is even larger: 20% of flights emit 80% of CO_2[8]. This is graphically depicted in Figure 3. Whereas hybrid- or fully-electric aircraft are anticipated to be suitable for shorter flights and high-speed rail forms an alternative mode of transport in that market segment, both opportunities do not apply to long distance air travel. The efforts should therefore be focused on finding solutions which are also applicable to long distance flights.

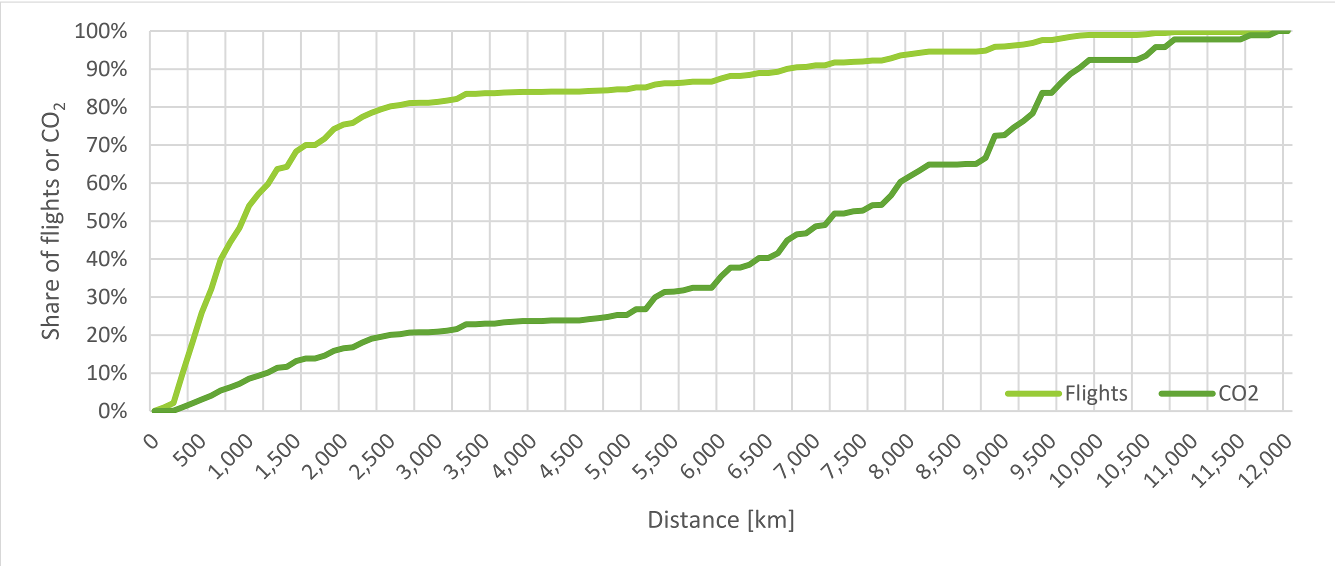


Figure 3: Share of number of flights and associated CO_2-emissions over distance, for commercial aircraft departures from Amsterdam Airport Schiphol, 2018 (NLR-analysis, 2020)

EFFICIENCY IMPROVEMENT OUTPACED BY GROWTH

Second, efficiency improvements are outpaced by the growth of air travel. Even though an aircraft operated with the high load factors realised by the industry today emits less CO_2 per passenger-kilometre than a standard gasoline car with two passengers, absolute emissions have continued to increase. Zheng and Rutherford (2020) note a compound annual fuel reduction rate of 1.3% over the period between 1960 and 2019[9], whereas total emissions from commercial aviation have increased 3.7% per annum. To reach the climate neutrality objective, efficiency improvements need to be complemented by a reduction in emissions in absolute terms. Albeit based on global data, Bruce et al. (2020) highlights the size of that challenge.

Figure 4 shows the estimated amount of CO_2 emissions in a 2050 business as usual scenario – combining sector growth according to the averaged WLO-scenario's with 1.25% annual efficiency improvements (CPB /

[7] Based on flight data from OAG (2018).
[8] Based on 2018 flight data (arrivals and departures), excluding aircraft with less than 20 seats.
[9] 1.0% over the period between 1970 and 2019.

PBL, 2015; Zheng & Rutherford, 2020; CBS, 2020b) – and compares this with the current global industry (reducing 2050 emissions to 50% of emissions in 2005) and net-zero targets.

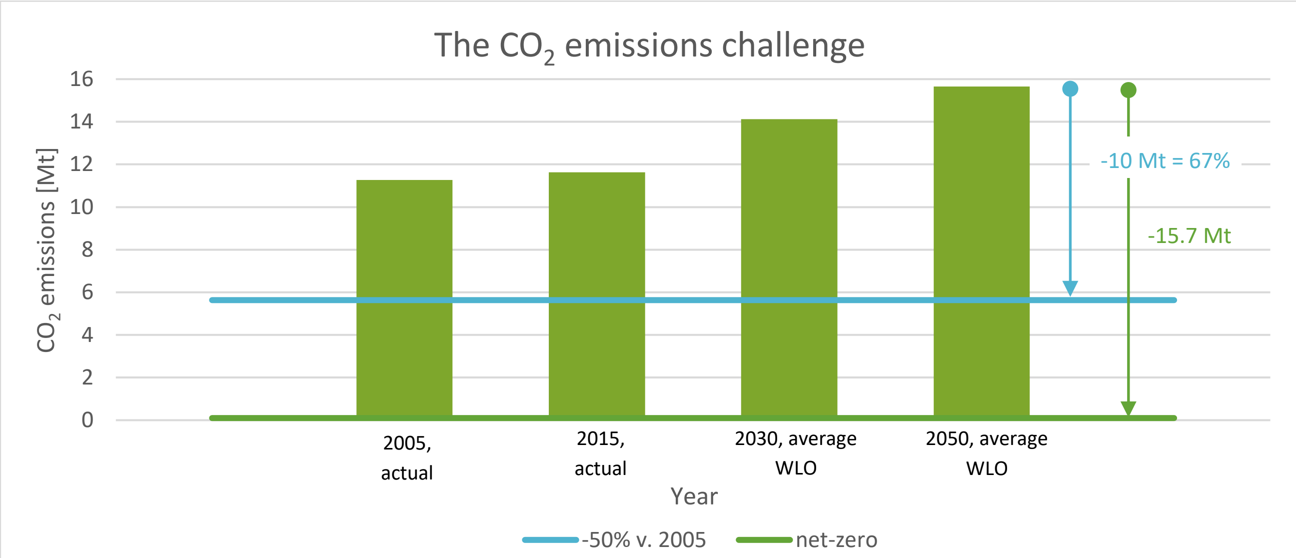


Figure 4: Historic and anticipated CO_2 emissions associated to Dutch international aviation bunkers in averaged WLO-scenario's for 2050, assuming annual efficiency improvements of 1.25%, compared to industry and net-zero targets (based on CBS, 2020b; CPB / PBL, 2015)

IMPACT OF NON-CO_2 EMISSIONS

Third, CO_2 emission is only one component of the total aviation climate impact (Grewe, et al., 2017; Grewe, 2019; Lee, et al., 2020). Although the level of scientific understanding of the formation and effect of aviation-induced cloudiness is still limited, its current contribution is estimated to be up to two times as large (66% of total) as the effect of CO_2 (33% of total). New energy sources (further treated in Chapter 4 and especially Chapter 5) hold notable decarbonisation promise, but do not all lower other emissions (Yin, Grewe, & Gierens, 2020). That especially holds for alternative fuels considered suitable for long-distance travel.

In order to mitigate the total climate impact of aviation through effective regulations and policies, the climate impact mechanisms of both non-CO_2 (NO_X, water vapour, contrail cirrus formation, SO_X, aerosols and soot) and CO_2 emissions need to be thoroughly understood. Figure 5 shows different effects of the emissions on climate forcing, such as reflected solar radiation and reflected terrestrial radiation (back to the Earth's surface) due to contrail formation in low-temperature ice-supersaturated air, or soot and sulphate direct radiative effects.

While the climate impact of CO_2 is independent of emission time and location, the effect of non-CO_2 is not. This also depends on aircraft performance characteristics (e.g. combustion temperature and efficiency), weather-related variables (such as humidity, temperature, wind), background concentration of different chemical species, time and location (longitude, latitude, altitude). Figure 5, for example, shows how contrails will (most likely) form in the troposphere in low-temperature ice-supersaturated air, while in the stratosphere contrail formation is unlikely due to the dryer air.

The various emission species have various lifetimes and impact timelines (hours, days, years, decades), and impacts (negative or positive), which should be taken into account in the process of developing the mitigating regulations and policies.

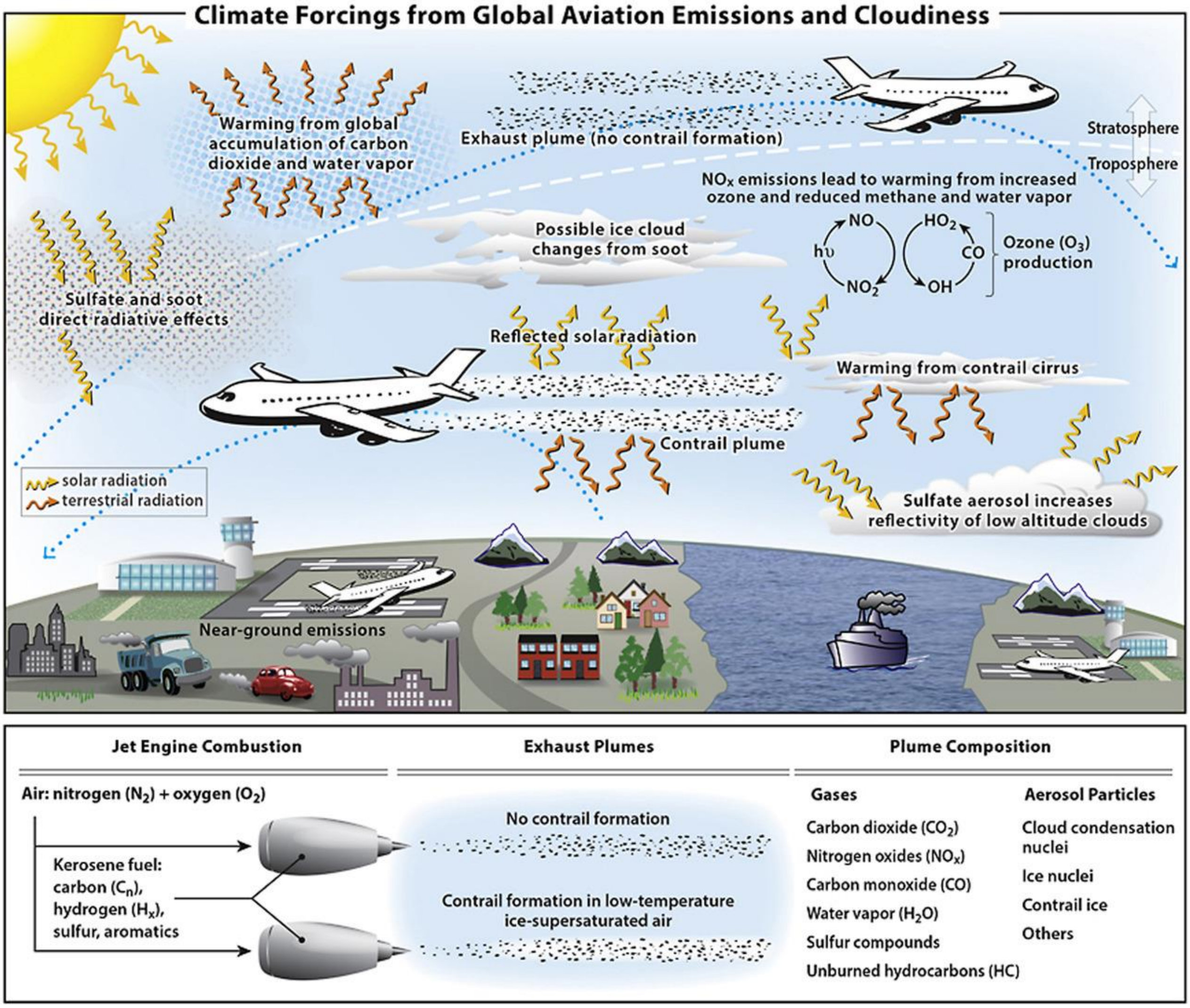


Figure 5: Overview of emissions and climate forcing from global aviation emissions and cloudiness. From Lee et al. (2020).

Figure 6 gives an overview of these positive and negative forcings, including the respective uncertainties and confidence levels.

Certain emission types stated in Figure 6 result in a positive radiative forcing, some in a negative radiative forcing, and some even in both (over different timelines or on different locations and altitudes). Certain emission types stated in Figure 6 result in a positive radiative forcing, some in a negative radiative forcing, and some even in both (over different timelines or on different locations and altitudes). This makes the assessment of the climate impact of aviation rather complex and subject to various uncertainties.

Current mitigation measures are focused on the reduction of CO_2, as these emissions have a direct and relatively well-understood effect on climate change. However, other possible CO_2 reduction measures such as more efficient engines may increase NO_X production and subsequent ozone (O_3) formation.

It should be noted that the contribution of aviation NO_X induced effective radiative forcing (ERF) and radiative forcing (RF) shown in Figure 6 might even be underestimated (Lee, et al., 2020). In various research, the methane response generally assumes steady state, while the perturbation lifetime is 12 years. When the lifetime change is taken as a transient response instead of a steady state response, the respective methane RF response reduces by 35% (Myhre, et al., 2011). This affects the Primary Mode Ozone (PMO[10]) and Stratospheric Water Vapour concentration (SWV[11]) directly and thus the reduction extends to the estimate of RF due to PMO and SWV (Grewe, Matthes, & Dahlmann, 2019).

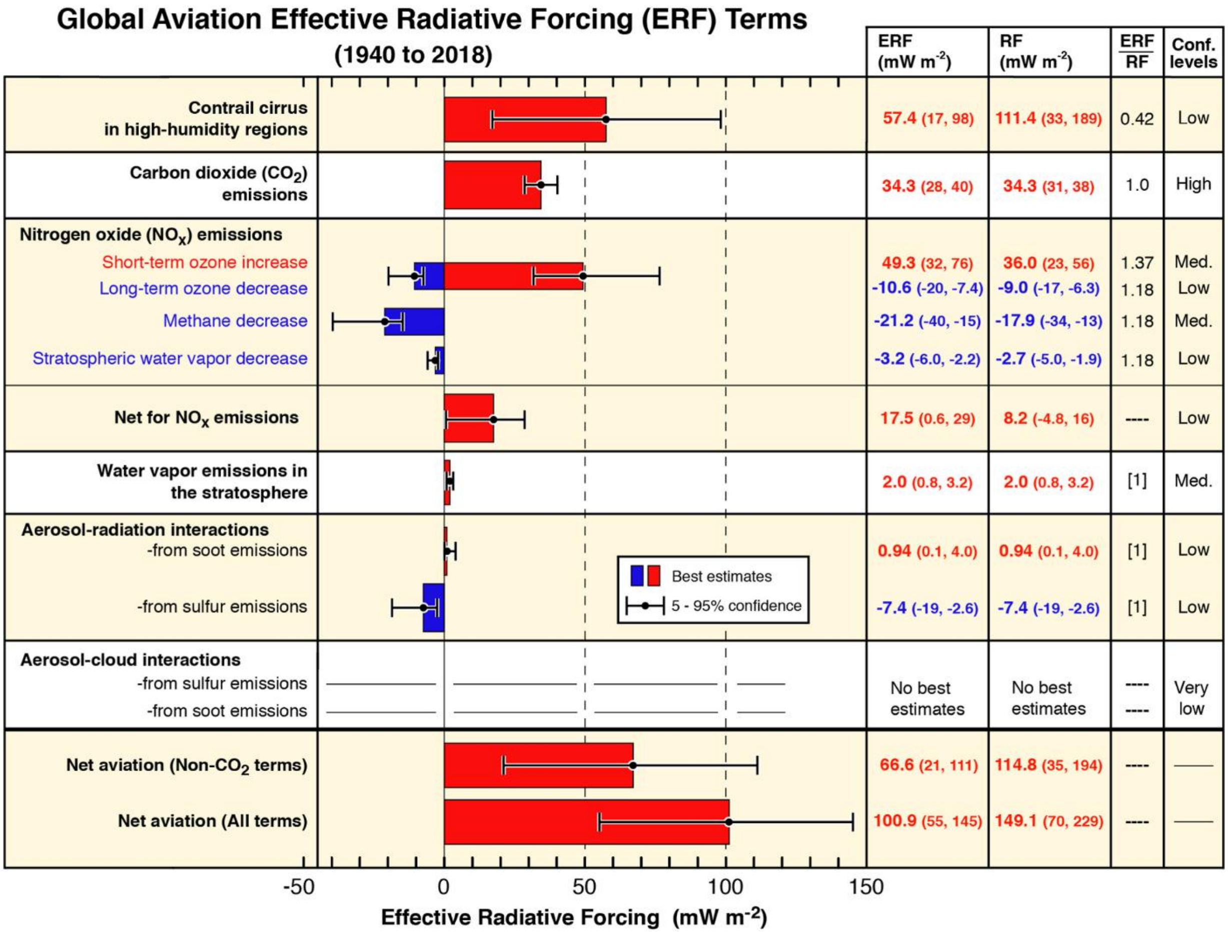


Figure 6: ERF best estimates and 5-95% confidence intervals for climate forcing terms from global aviation from 1940 to 2018. Red bars show a warming effect and blue bars show a cooling effect. From Lee et al. (2020).

Furthermore, research to the contribution of NO_X on ozone formation is generally approached as a linear relationship through a sensitivity analysis or the perturbation method. These methods are not suitable to assess source contributions for nonlinear relationships. The relationship between aviation NO_X and ozone formation is nonlinear, so applying the sensitivity- or perturbation method results in an underestimated contribution of NO_X. These aspects of the assessment of aviation NO_X contribution should be taken into account in further research.

3.2. The local environmental challenge

In a densely populated country as The Netherlands, aviation activity is never far away. This especially holds for the Randstad region, which is home to some 50% of the population and from which 90% of all

[10] Effect of decrease in background ozone due to decrease in methane, which is a precursor of ozone.
[11] Effect of reduction in stratospheric water vapour due to reduced methane in the atmosphere which decomposes in water vapour and carbon dioxide.

commercial flights to or from the major Dutch airports land and take off (CBS, 2020a; Roosien, Peerlings, & Jabben, 2020). The future of Dutch aviation and the development of Dutch airports has been debated for decades, but has intensified over the last few years (e.g. Mebius, 2020; Stil, 2020a; Stil, 2020b; Obbink, 2020; Bröer, 2007; Liebe, Preisendörfer, & Enzler, 2020).

As such, in addition to contributing to climate neutral aviation, a major challenge for aviation is to decrease its negative impacts on the local environment. Noise and emissions both play an important role.

NOISE, ANNOYANCE AND PUBLIC ACCEPTANCE

First, noise influences annoyance and quality of life (Job, 1988; Vader, 2007), but is also associated to numerous health effects, such as sleep disturbance and heart disease (Kranjec, et al., 2019). Due to technological and operational improvements, noise per aircraft movement has gone down (ICAO, 2019 Environmental Report, 2019a), but the number of airports handling more than 50,000 annual aircraft movements is expected to increase from 82 to 110, thereby affecting new populations, and increasing overall noise impact (EASA, EEA, & EUROCONTROL, 2019).

In 2018, the World Health Organization published their long-awaited Environmental Noise Guidelines that include recommendations for aircraft noise exposure that are lower than current Dutch regulations. A strong recommendation of 45 dB(A) L_{den} and 40 dB(A) L_{night} are given, where Dutch regulations for Schiphol have limitations for the number of affected houses within 48 dB(A) L_{den} and 40 dB(A) L_{night} respectively (Welkers, van Kempen, Helder, Verheijden, & van Poll, 2018). An estimated 45 dB(A) L_{den} contour is shown in Figure 7. Implementing a 45 dB(A) L_{den} would have a significant economic impact in the area of Schiphol and should therefore be carefully examined in relation to the estimated health benefits.

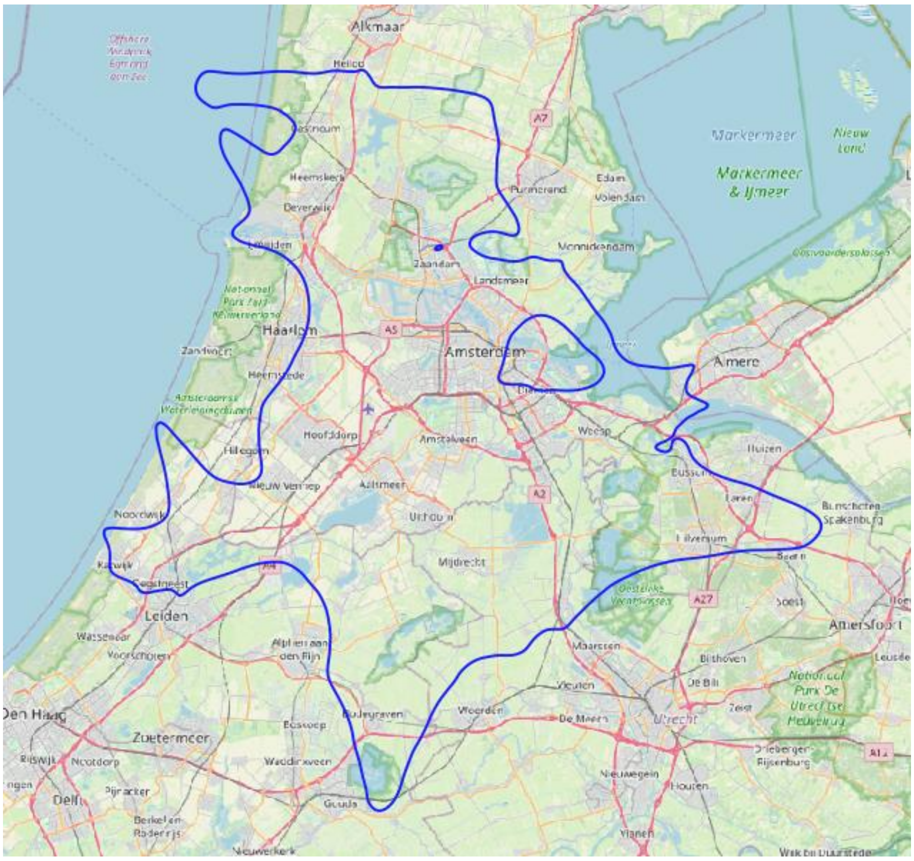


Figure 7: An estimation of a 45 dB(A) L_{den} contour around Schiphol airport

Next to the objective of reducing noise at the source, ICAO's Balanced Approach[12], visualised in Figure 8, calls for mitigating the negative effects of noise by land-use planning, noise abatement procedures and operating restrictions (ICAO, n.d.). Several of these influence (development) capacity, or introduce a trade-off between aviation development and opportunities for housing. Given the Netherlands has one of the highest population densities in the European Union (the Randstad area in particular), such issues might be more pressing compared to other countries (eurostat, 2018; eurostat, 2020). Innovative solutions and more refined metrics that capture negative externalities more accurately than current ones might inspire new ways to noise management.

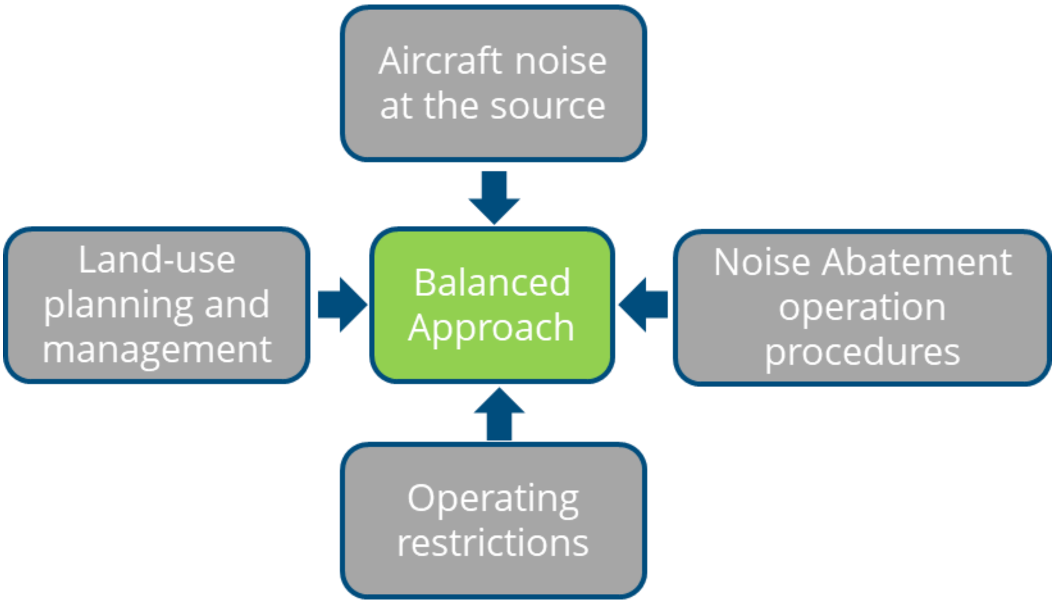


Figure 8: The ICAO Balanced approach, based on ICAO (n.d.)

LOCAL AIR QUALITY AND BIODIVERSITY

Local air quality (LAQ) can be described as the concentration of pollutants in the ambient atmosphere that can directly impact public health and the natural environment. Aviation activities involve several vehicles (next to aircraft) that emit gases and particulate matter that is of negative influence on the LAQ. On the airport, the emission sources are dominated by aircraft, GSE, vehicles, energy generation facilities, fuel storage and handling, fire training, engine testing and infrastructure construction work and maintenance. Another contributor is ground transportation to the airport.

NO2, PM10, PM2,5 and ultra-fine particles

The most important pollutants that affect local air quality are concentrations of NO_2 and particulate matter (PM_{10} en $PM_{2,5}$). PM_{10} typically consists of particles measuring a diameter of 10 micrometre or less. For $PM_{2,5}$ this is 2,5 micrometre or less. Next to these particles, ultra-fine particles play an important role ($PM_{0,1}$) with a very small diameter: less than 0,1 micrometre.

Health effects

Particulate matter does have health effects. The effects of particulate matter have been researched by (amongst others) the Gezondheidsraad (2018). Long lasting exposure to particulate matter can have the following consequences (Janssen, et al., 2011; Kovacic & Somanathan, 2014):

[12] Implemented in European legislation through Regulation (EU) 598/2014.

- Mortality or shortened lifespan; and/or
- Heart and vascular disease, narrowed blood vessels, increased heart beat or blood clotting; and/or
- Lung cancer, COPD, decreased lung function, asthmatic symptoms or worsening of those, increase of respiratory complaints like coughing, shortening of breath.

More research is necessary on the effects of (ultra) fine particles in relation to aviation. The dispersion of UFP and mitigation methods have to be developed. Next to technological improvements on engines also the mitigation of UFP near the source (after 'burning' the fuel) is important for the local air quality and health of people.

Effect on biodiversity

Exhaust gases and particles leaving the aircraft do not only affect climate but also have impact on forest and nature reserve. Deposition of a.o. nitrogen oxides (NO_X) are harmful for nature when they reach above a certain threshold value, also called the "critical deposition level". This critical deposition level indicates at what level changes to vegetation will start to take place. Species of plants could disappear, resulting in a less species richness. Not only aviation is responsible for the effect as described here, also road traffic, agriculture and energy production facilities contribute to the NO_X emission, with deposition of it as a consequence (PBL, 2010). As a result, the quality of biodiversity of the forest and nature reserve decreases.

Apart from the NO_X effects, (ultra) fine particles do also affect the health of animals and plants. Even aircraft noise is disturbing wild life. This has its effects on birdsong (Gil, Honarmand, Pascual, Pérez-Mena, & Macías Garcia, 2015), breeding patterns from both insects and birds, blood pressure of small mammals (Chesser, Caldwell, & Harvey, 1975). Besides, SO_X (when it reacts with NO_X) could result in acid rain. The consequences of climate change can have far reaching consequences for the current state of the ecosystem. It is expected that the increase in temperature of the Northern hemisphere will result in a decrease of biodiversity in forest and nature reserve (NASA, 2020).

3.3. The resource challenge

If global consumption trends continue, by 2050 one planet Earth will not be sufficient but three planets would be required (EC, 2020a). In 2050, waste production is expected to increase by 70% while the global consumption of materials such as biomass, fossil fuels, metals and minerals is expected to double (EC, 2020a). The economy must therefore be reshaped to decouple growth from resource use. A circular economy, or circularity, is an economic system of closed loops in which raw materials, components and products lose their value as little as possible, renewable energy sources are used and systems thinking is at the core[13]. Though a number of small-scale initiatives have already been initiated, there is no circular plan for the Dutch aviation system, in line with national targets to become fully circular by 2050 (Government of the Netherlands, n.d.).

Each component in a circular economy must be circular, and so the interaction among all components. Translated in an air transport system, air vehicles which are circular need to function according to circular operational directives within circular infrastructures and according to a circular business model.

Aviation is already familiar and accustomed to many of the characteristics of circularity: aircraft are designed to be durable, to remain in service for a very long time period (in the order of decades); maintenance, repair

[13] Ellen MacArthur Foundation

and overhaul activities are regular part of aircraft operations; many airlines do not own aircraft but lease them based on the seasonal demand and schedule. Those are good circular practices, but to achieve a fully circular model, circularity needs to be present in the entire aviation ecosystem. In practical terms, implementing circular economy in aviation means that aircraft needs to be designed according to circular principles, such as design for reuse, design for repair, design for remanufacturing, and others.

Manufacturing also needs to be circular, in terms of manufacturing technologies, energy consumption and materials used. Circular materials are not per se only bio-based, of natural origin or recycled, but indeed those materials could be implemented in aeronautical structures. The energy source for propulsion also needs to be circular, which means renewable and net-zero emission. Aircraft needs to be operated in circular operations within a circular ecosystem. This means that aircraft should fly in the most circular way, in terms of routes, and that the required ground operations shall also be organized in a circular way. When aircraft reach retirement, there are currently limited activities for the so-called end-of-life. Some vehicles are partially dismantled and valuable components (e.g. engines) are recovered and directed to the second-hand market. Reuse of the entirety of the airframe is not standard practice, as it is not the recycling of the materials themselves; wrecks are then left parked in few areas worldwide without further exploitation. This leaves an incredible amount of resources untapped and the reason for this waste comes down to no economic value in pursuing a full reuse of the asset, also as a consequence of design choices which do not enable reusing, remanufacturing and recycling and of a market and regulations which favour virgin materials (at a lower price) over recycled materials.

In addition to reducing or eliminating the environmental footprint connected to manufacturing aircraft and their end-of-life, enabling a circular approach to aeronautical material use can enable tackling two additional issues related to critical materials: their scarcity and regulations related to their origin.

In the transition towards cleaner energy sources, the demand for electric batteries escalated exponentially (EC, 2018). The discrepancy between the forecasted demand for the materials needed for the manufacturing of electric batteries and the availability in Europe and at global level poses a serious threat towards the implementation of emission-free energy solutions, also in aviation. In addition to the availability issue, the majority of the materials needed for electrification are classified as critical raw materials (EC, n.d.). Those materials will fall within the conflict material EU regulation (EC, 2017), which comes into effect in 2021. This regulation will limit the import of critical raw materials from high risk countries. A transition to a circular economy for aeronautical and critical materials, and the development and implementation of the related technologies, will guarantee a sustainable and reliable provision of needed resources.

4

4. AIRCRAFT DEVELOPMENT

Sustainable aviation requires the development of aircraft that are climate neutral, produce less noise and that use less energy per flight. Less energy per flight can be reached by reducing drag, which can be achieved by improving aerodynamics and lowering aircraft weight, see Figure 9. This chapter presents the key technological aircraft developments that enable sustainable aviation.

Figure 9: Improvements of aircraft leading to a lower energy consumption enhance each other. Mass and thus weight reductions have a positive effect on lift, drag, thrust and energy consumption, leading to less fuel to start with, leading to less mass, which results in a "snow-ball" effect.

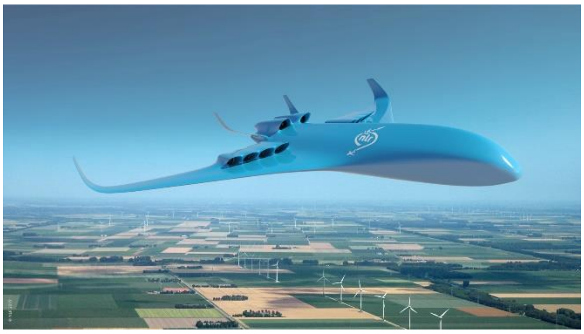
Technologies are considered that address the sustainability of aircraft operations, as well as the sustainability of aircraft production and end-of-life. These technologies require fundamental changes to all systems and subsystems and are therefore of major importance for the research program. Benefits from various technology areas are interlinked and the sustainability potential will depend on the category of aircraft. Expected benefits are summarized for their most relevant aircraft categories. The technology areas that promise the largest development towards more sustainable aircraft are in:

1. Electrified powertrains and propulsion systems (Section 4.2)
2. Hydrogen fuelled aircraft (Section 4.3)
3. Innovative energy-efficient aircraft configurations (Section 4.4)

Aircraft propulsion may benefit from innovations in electrical components that are ongoing in other sectors like automotive and covers technologies that enable the partial or full electrification of aircraft propulsion systems or powertrain components. These include electric motors, power electronics, electric power sources and energy carriers (including alternative fuels or hydrogen) that can be installed to improve the energetic efficiency of the aircraft powertrain or the overall climate impact. Various definitions and classifications of hybrid electric propulsion are currently in use. Here we adopt a generic definition characterized as "partial or full electrification of the propulsive powertrain". Hybrid electric propulsion requires technology developments of hybrid electric powertrain architectures and developments of high-power, low-weight electric components. These components can be applied to support a conventional combustion engine in a hybrid-electric powertrain architecture, or they can completely replace the combustion engine yielding a full electric powertrain architecture depending on the application and vehicle class.

The technology area for hydrogen fuelled aircraft covers all technologies that are required for hydrogen-based propulsion, which may also require components for electrification of the powertrain. This can be achieved in two different ways: thermal power generation through hydrogen combustion in the aircraft's gas turbine engine, or electric power generation through electrochemical reaction of hydrogen in a fuel cell. Hydrogen combustion in gas turbines creates thrust by burning hydrogen instead of kerosene. It requires a redesign of the combustion stage of the gas turbine, but maintains the benefits of the aviation-proven gas turbine technology like very high specific power and adequate operating envelope. Technology developments for well-controlled hydrogen storage, transport and metering are required. Hydrogen fuel cell power generation also requires the technology developments for hydrogen storage, transport and metering, and additionally for efficient and power-dense fuel cell stacks and all the components in the electric drivetrain. Both types of hydrogen-based propulsion can be applied separately, or in combinations of the two in which case a hybrid-hydrogen powertrain results.

Innovative aircraft configurations can be applied to improve aircraft efficiency and to lower the noise impact. In addition, the synergy with the other two technologies, i.e. hybrid-electric aircraft propulsion and hydrogen powered aircraft, introduces many possibilities for innovative aircraft configurations with improved efficiency. Firstly, more electrified propulsion is a strong enabler for innovative propulsive technologies such as boundary layer ingestion and distributed propulsion. Secondly, such innovative propulsive architectures can be well combined with innovative airframes, such as blended wing body aircraft or the Flying-V. Thirdly, ongoing developments of component technologies are additional enablers for innovative aircraft configurations, for example advanced light weight composite materials that enable aerodynamically efficient high-aspect ratio wings.



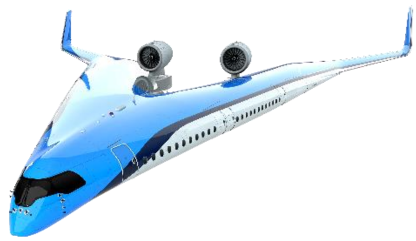


Figure 10: BWB concept (left) and Flying-V concept (right).

4.1. Application of technologies per aircraft category

The foreseen aircraft development for more sustainable aviation will be different for different aircraft categories, since different technological solutions are expected to provide the largest improvement depending on application area and the energy requirements of the different vehicle classes.

For small aircraft the full electric solution applying power supply from batteries is emerging and it is expected to mature over the next years. However, due to the limited energy-to-weight ratio of batteries and the expected limited growth potential, full electric propulsion will develop only for small aircraft and some regional aircraft applications. Fully electric aircraft do not emit pollutants of any sort during operation.

Hybrid-electric technology, interesting from its opportunity of combining different propulsion types and energy sources, is expected to provide improvements for the regional and short-range aircraft in the mid-term (ERA, 2020). As the system design space is rather extensive and due to the uncertainty in the various technologies envisioned extended research is promoted as is evidenced from the preliminary Clean Aviation research agenda (Clean Aviation Partnership, 2020b). Hydrogen as energy carrier has the potential for improving sustainability of regional, short, medium and long-range aircraft on the long term.

Drop-in fuels can be applied for any aircraft category and seem most interesting for larger classes, as alternatives might take more time to become available.

The expected development for the different aircraft categories is indicated in Table 1.

Table 1: Potential of different techniques per aircraft category, also based on forecasts by McKinsey & Company (2020) for the EC and ATAG (2020). Timeline is based on entry into service. SAF = drop-in Sustainable Aviation Fuel, e = hybrid electric or full electric, H_2 = hydrogen

Aircraft category	2020	2025	2030	2035	2040	2045	2050
Commuter < 19 pax	SAF	SAF / e	SAF / e	SAF / e	SAF / e	SAF / e	SAF / e
Regional 20-80 pax	SAF	SAF	SAF / e / H_2	SAF / e / H_2	SAF / e / H_2	SAF / e / H_2	SAF / e / H_2
Short-range 81-165 pax	SAF	SAF	SAF	SAF / e / H_2	SAF / e / H_2	SAF / e / H_2	SAF / e / H_2
Medium range 166-250 pax	SAF	SAF	SAF	SAF	SAF / H_2	SAF / H_2	SAF / H_2
Long range > 250 pax	SAF	SAF	SAF	SAF	SAF	SAF	SAF / H_2

The benefits that the technologies discussed in this chapter bring, differ for different aircraft classes and applications. In terms of technology development, these benefits are mostly expressed in terms of improvements in energy efficiency, or, put differently, reducing the amount of energy required to operate particular flight.

Large innovations in airframe technology, such as lighter structures and improvements in aerodynamics (higher aspect ratio wings, laminar flow, etc.), are foreseen to yield improvements of approximately 10 to 20%. Another contribution of some 10 to 20% can be made by major improvements in propulsion technology, such as ultra-high bypass ratio turbofans, open rotor configurations or innovative concepts such as boundary layer ingestion. Combined, technologies from the late 2020s are anticipated to reduce energy demand by some 30%. Smaller aircraft, such as the short-range model listed in Table 1, are expected to enter the market first (between 2030 and 2035), as applying the aforementioned technologies to larger aircraft often requires some additional research and development efforts.

For the aircraft categories with seating capacities below 100 passengers, additional improvements in terms of reducing CO_2 are foreseen. Smaller aircraft are best-suited for electric propulsion. Aircraft in the commuter-class specifically, might become fully electrified in the next decade (ERA, 2020). For regional aircraft, hybrid-electric propulsion or the use of hydrogen fuel cells seem more likely. Even in case such an aircraft will remain (partly) kerosene-powered, current trends of moving (back) from regional jets to propeller-driven models (Hemmerdinger, 2020), realise additional savings in the order of 10 to 20% (ATR, 2018; Babikian, Lukachko, & Waitz, 2002; Ryerson & Hansen, 2010). This way, efficiency improvements of 50% are deemed achievable in the regional segment by 2030 to 2035[14].

For kerosene-powered aircraft, lower energy requirements directly translate into lower fuel burn and lower CO_2 emissions. As Chapter 5 will show, sustainable aviation fuels can further reduce net CO_2 emissions. This is shown in Table 2, which provides a rough overview of major technologies and their application to aircraft categories, together with possible entry into service and anticipated CO_2 emissions reduction. Technologies making smaller contributions, such as the hybridisation of APU-functions, riblets, advanced wingtips, gapless movables, gust load alleviation, weight savings from more electric systems, and so on are not listed individually. In some cases, they might contribute to independent savings, in other cases, they might enable further development or application of major technologies and thereby realising a larger emissions reduction.

Table 2: Anticipated entry into service of new technologies for various aircraft categories, with their expected CO_2 emissions reduction (based on e.g. Goold, 2018; Liu, Elham, Horst, & Hepperle, 2018; Clean Sky JU, 2015; Clean Aviation Partnership, 2020b; McKinsey & Company, 2020)

Aircraft category	EIS	Major technologies	CO_2 emissions reduction
Commuter < 19 pax	2025 - 2030	Alternative energy carriers (e.g. hybrid- or fully electric, hydrogen fuel cells, batteries) with innovative propulsion concepts (e.g. distributed propulsion).	Near 100%, depending on selected technology
Regional 20-80 pax	2030 – 2035	Hybrid-electric or hydrogen-powered (fuel cell or combustion), distributed propulsion, improvements in structural and aerodynamic efficiency.	50% + SAF, up to 100% for hydrogen
Short range 81-165 pax	2030 – 2035	Ultra-high bypass ratio turbofans (possibly open rotor), high-aspect ratio wings, (hybrid-) laminar flow, more efficient fuselage structure, possibly hydrogen-powered (fuel cell or direct combustion, depending on size)	30% + SAF, up to 100% for hydrogen
Medium range 166-250 pax	2030 – 2040	Ultra-high bypass ratio turbofans (possibly open rotor), high-aspect ratio wings, (hybrid-) laminar flow, more efficient fuselage structure, possibly hydrogen-powered (direct combustion most likely)	30% + SAF, up to 100% for hydrogen
Long range > 250 pax	2035 – 2040		30% + SAF, up to 100% for hydrogen

The impact on non-CO_2 effects is more difficult to quantify. Generally speaking, and as illustrated in Figure 11, many emissions are proportional to fuel burn. Higher energy efficiencies therefore also lead to reductions in, for example, water vapour emissions. However, some emissions, such as NO_X, do not scale with fuel burn. Rather, some improvements in engine technology that contribute to a reduction in fuel burn and CO_2 emissions, actually yield an increase in NO_X emission. On the other hand, aircraft using hydrogen fuel cells offer the advantage of zero CO_2 and NO_X (McKinsey & Company, 2020).

[14] As for the larger aircraft, market introduction between 2030 and 2035 requires technology readiness between 2025 and 2030.

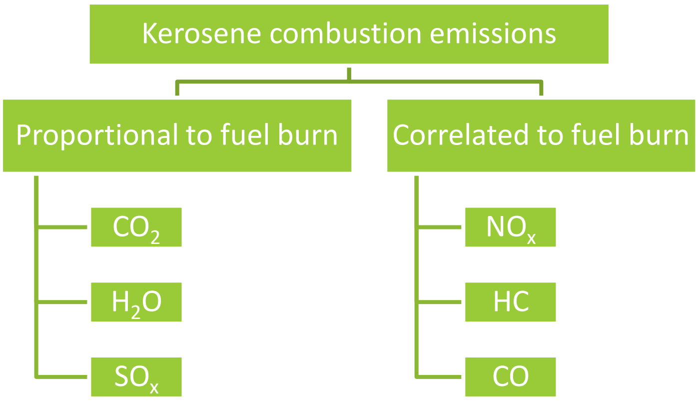


Figure 11: Proportional and correlated kerosene combustion emissions (Schaefer & Bartosch, 2013).

The example above shows a difficult dilemma: lower CO_2 emissions reduces global warming, but increased NO_X increases the climate impact of aviation. The optimal balance, as of now, remains unknown – highlighting the crucial need for additional research. Further detailed in Section 7.1, that should address fundamental understanding of the effects of particular emissions on the climate. In turn, that knowledge can inform and be applied in aircraft and technology development (Radhakrishnan, et al., 2020).

Even though improved understanding of non-CO_2 effects might adjust the focus of aircraft development for improved sustainability, increasing energy efficiency without a doubt is a path crucial to pursue: it directly reduces greenhouse gas emissions proportional to fuel burn and reduces aviation's demand for potentially scarce (renewable) energy.

4.2. Electrified powertrains and propulsion systems

Electric propulsion has the large benefit of a high energy efficiency compared with propulsion through combustion. Electric powertrain energy losses are roughly half the loss of the best thermal engine powertrains. The main challenge for electric propulsion is light weight storage of energy on board. Batteries are very heavy in comparison to kerosene for the same amount of energy. In other words: the specific energy – the amount of energy per kg - of batteries is very low, about 50 times lower than kerosene. Therefore, batteries are currently not feasible as energy carriers for large and long range aircraft because such aircraft are very energy intensive. For example, current large aircraft like Boeing 777 or Airbus A380 carry about 40% of their take-off weight in fuel. Small and short-range aircraft are much less energy intensive, with fuel needs down to about 10% of their take-off weight, making them more suitable for electric propulsion.

Electric propulsion can be combined with propulsion by conventional thermal engines, such that the total required propulsive power is partly produced by both systems. Such combined propulsion is referred to as hybrid electric propulsion, where the power ratio of the electric propulsion system and the thermal engines can be anything between 0 (non-electric propulsion) and 1 (all-electric propulsion). The hybrid electric propulsion system architecture can have many different combinations of thermal engine and electric components, but the main architectures that are considered are illustrated in Figure 12.

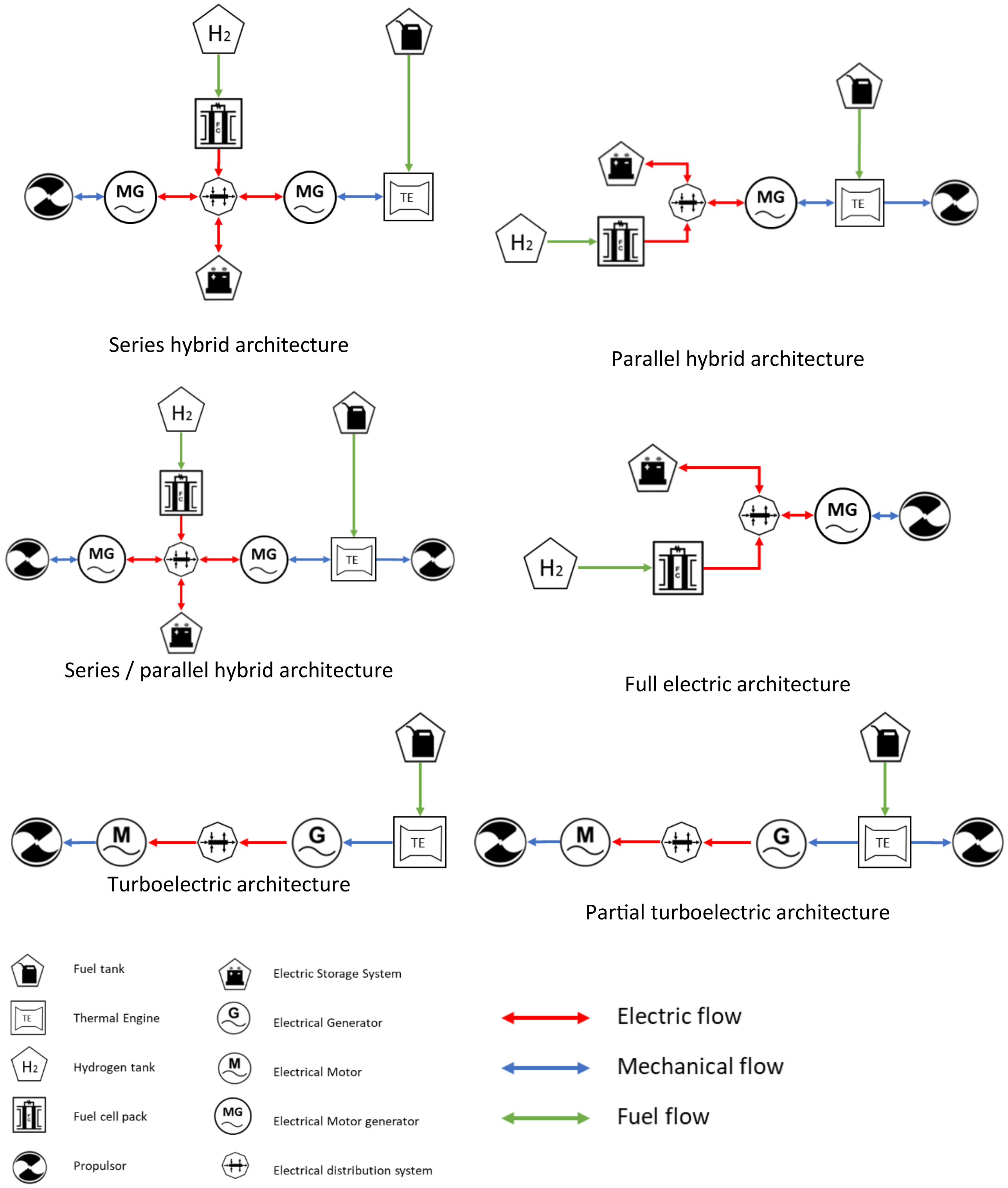


Figure 12: Hybrid electric propulsion architectures (modified from Felder, 2015).

The main hybrid electric propulsion architectures are: parallel-hybrid, series-hybrid and series/parallel partial hybrid. Besides these variants of hybrid electric propulsion, there is also turbo-electric propulsion. In contrast with hybrid electric propulsion, turbo-electric propulsion does not rely on any battery as electric energy carrier. Instead, energy storage is fully achieved by fuel, which is partly or fully converted by a conventional thermal engine and electric generator into electric power. The electric power is used to drive an electric propulsion system.

Development of components for these all-electric, hybrid electric and turbo-electric propulsion systems and research on how to optimally apply these components in the powertrains of the aircraft is necessary to harvest the benefits. Weight of aircraft components plays a larger role than for vehicles on land or water. When compiling a powertrain, the challenge is to optimize the choice of components and layouts such that the benefits in one aspect do not lead to inefficiencies in other aspects. Multidisciplinary optimisation, based on thorough knowledge and modelling of the different aspects, for both the components of the aircraft as the architecture of the power train is necessary. As the electrical power necessary for propulsion is much higher than the electrical power applied nowadays in aircraft a special focus will be on high power electrical components and electromagnetic interference.

Hybrid electric aircraft can apply traditional aviation fuels, but the higher efficiency of these aircraft may also be enhanced in combination with new energy sources such as hydrogen and batteries. The main areas of research and development that will specifically boost hybrid electric aircraft development are:

- Electric components and their integration in aircraft:
    - Batteries with increased energy- and power density
    - Battery management systems
    - Power distribution
    - Generators
    - High-power electric motors
    - E-compressors
    - Thermal management
    - Electromagnetic compatibility
    - Arcing and high voltage power systems
    - Superconducting electrical transmission and motor systems (in combination with cryogenic hydrogen)
    - Wiring and cooling
    - More Electric Aircraft/non propulsive power systems
- Powertrain optimisation:
    - Hybrid Electric drive train design and optimisation
    - Modelling and Simulation and Component sizing
    - Cooling systems

4.3. Hydrogen fuelled aircraft

This section covers all technologies that are required for hydrogen-based propulsion through both hydrogen combustion in the aircraft's gas turbine engine, or electric power generation through electrochemical reaction of hydrogen in a fuel cell.

> **ALTERNATIVE FUELS BESIDES HYDROGEN**
> In addition to using liquid hydrogen as an aircraft energy source, researchers are investigating other fuels. The AHEAD-project, for example, looks at application of liquefied natural gas (LNG). A multi-fuel aircraft might also be an interesting approach, especially given the opportunities with respect to reducing radiative forcing (Grewe, et al., 2016).

4.3.1. Hydrogen as aviation fuel

To reduce emissions and in particular CO_2 emissions, research has been performed on the possibility of using alternative energy sources to power the aircraft (EC, 2005; Brewer, 1991). Recent studies show a renewed interest in hydrogen as a particularly well-suited alternative (McKinsey & Company, 2020). Hydrogen can be used directly as fuel in the aircraft combustion engine or in combination with fuels cells and electric motors. If produced sustainably, hydrogen can be considered a zero-carbon fuel, as no CO_2 is emitted during use.

Hydrogen as aircraft fuel has in fact a long research history and the concept is already proven in flight. Hydrogen demonstrator aircraft were built in the 1950's in the USA (NACA-Lewis liquid hydrogen flight test program, using a modified B-57B Canberra military aircraft) and in the 1980's in the USSR (Tupolev Tu-155, a modified Tu-154 civil jetliner), see Figure 13.

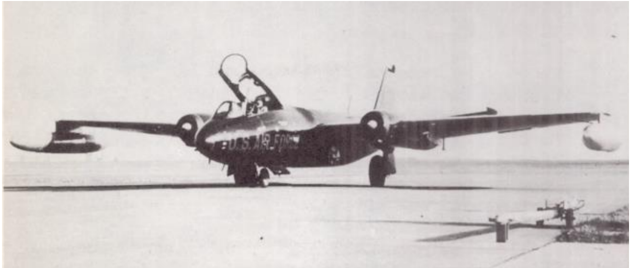


Figure 13, left: B-57B aircraft with one engine capable of running on hydrogen (NACA, 1957). Right: Tu-155 aircraft with one engine capable of running on hydrogen (Tupolev, n.d.). Both aircraft made several test flights with the engine fuelled by hydrogen.

The test flights showed that hydrogen propulsion as a concept was feasible and had various advantageous aspects, but not enough to overcome its disadvantages, most prominently the logistics problem of needing liquid hydrogen to be available on all airport in addition to kerosene (Brewer, 1991). These trade-offs did, however, not take environmental impact into account. Later studies (Brewer, 1991; Khandelwal, Karakurt, Sekaran, Sethi, & Singh, 2013) and a very recent overview analysis (McKinsey & Company, 2020) highlight the major environmental benefits compared to kerosene and also compared to synthetic fuel generated with sustainably generated energy, see Figure 14.

Hydrogen propulsion's major advantages are the lack of any in-flight CO_2 emission, near or total elimination of soot (particulate matter) and sulphate and the foreseen major reduction (gas turbine) or elimination (fuel cell) of NO_X emission. Other advantages are a high energy-to-mass ratio but this is offset by the need for voluminous and heavy hydrogen fuel tanks. Other disadvantages are a much higher volume even when liquified (about 4 times the volume of kerosene for the same amount of energy), and also a considerably larger emission of water or water vapour (about 2½ times the amount compared to kerosene). The climate impact of water vapour from hydrogen combustion needs significant additional research effort, especially the induced formation of contrails and cirrus clouds, so that mitigations such as cruising at lower altitude can be assessed.

Change of in-flight emissions and emission related effects[1]

	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	Climate impact reduction potential[4]
Synfuel	-0% / -100% (Net)[3]	-0%	-0%	-10-40%	-30-60%[3]
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

Ongoing scientific debate about **full climate** impact, in particular:
- Contrail/cirrus formation
- Aggregate measure

Total climate impact could be 2 to 4 times compared to CO_2 emissions alone

1. Assuming decarbonized production and transportation of fuels in 2050
2. 10 times lower climate impact than from CO_2 emissions
3. Net CO_2 neutral if produced with CO_2 captured from the air
4. Measured in CO_2 equivalent compared to full climate impact of kerosene-powered aviation

Figure 14: Comparison of climate impact from hydrogen propulsion and synfuel, compared to kerosene-fuelled aircraft, timeframe until 2100 (McKinsey & Company, 2020)

aircraft concepts, fuelled with liquid hydrogen and combustion in gas turbines complemented by embedded electric motors and fuel cells, resulting in a hydrogen hybrid-electric propulsion architecture. It is Airbus' ambition that the programme delivers a hydrogen-fuelled aircraft with commercial entry into service in 2035. First flight of a demonstrator aircraft is planned for 2025.

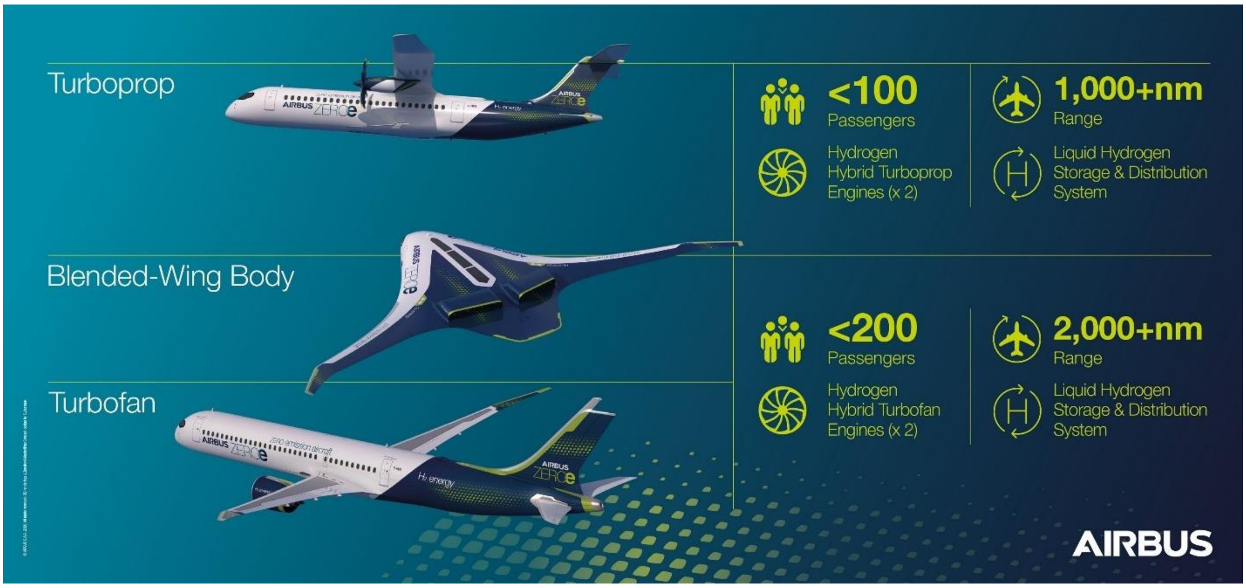


Figure 15: Airbus ZEROe aircraft concepts towards a hydrogen-fuelled aircraft that commercially enters into service in 2035 (Airbus, 2020).

Despite the shocking images in the public memory of the Hindenburg accident, hydrogen safety is not regarded as an insurmountable issue, but rather as a system engineering topic that can be handled with aviation's rigorous safety management processes (Khandelwal, Karakurt, Sekaran, Sethi, & Singh, 2013).

There is no reason why hydrogen aircraft could not be made as safe as kerosene aircraft, but it requires an extensive research and standardisation effort to obtain that level. Moreover, the effect of reduced passenger capacity of hydrogen aircraft (due to the large volume occupied by the hydrogen) necessitates market studies to check the economic viability of the proposed concepts.

4.3.2. Hydrogen storage and distribution system

Although hydrogen has a much higher energy-to-mass ratio than kerosene, it is in an extremely impractical state at atmospheric pressure and temperature, being a low-density gas. In order to reach a manageable volume, it must either be highly compressed (300-850 bar) or cryogenically cooled to liquid state (-253°C). Where kerosene is stored at ambient pressure and temperature in aircraft structures that double as structural elements, hydrogen needs strong high-pressure vessels or highly insulated cryogenic tanks. State-of-the-art hydrogen tanks have a gravimetric index (the weight fraction of the hydrogen in a full tank) of only about 5 % for pressure vessels (700 bar type IV) and about 15-20% for cryogenic tanks (Bruce, et al., 2020; McKinsey & Company, 2020). Table 3 compares gaseous and liquid storage. High-pressure storage is easier to manage but the relatively large and heavy tanks likely limit the application to drones, small aircraft, and short-range regional aircraft.

Table 3: Comparison between gaseous and liquid hydrogen. The targets above are derived from Clean Aviation Partnership (2020b) and US DoE automotive targets (gaseous storage, Office of Energy Efficiency & Renewable Energy, 2020).

	Advantages	Disadvantages	State-of-the-art gravimetric index	Target gravimetric index
High-pressure H_2 storage (gas)	Can be stored for long duration. Cheaper to produce	Larger and heavier than liquid storage	4.5 %	6.5 %
Cryogenic H_2 storage (liquid)	Less volume than gas storage Tanks lighter than gas tanks	Hydrogen liquefaction step requires more energy than gas compression. Boil-off needs to be managed	15-20 %	35-38 %

A hydrogen fuel distribution system will require many new aspects to be developed: vaporisation of liquid hydrogen, distribution of liquid or high-pressure hydrogen, pressure regulation. Ducts, pumps, valves and other equipment must be compatible with hydrogen and the extremely low temperatures in case of liquid. Safety requirements will lead to dedicated design solutions, for example double-walled piping. Extensive research is required to obtain an optimal solution with respect to weight, volume, performance and cost that satisfies the safety constraints.

Main topics of storage and distribution technology to be investigated in future research are shown in Table 4.

Table 4: Main topics of storage and distribution technology to be investigated in future research

Area	Topic or goal
Cryogenic and high-pressure storage tanks (5-30 ton H_2)	Improve energy to weight ratio
	Develop advanced materials and shapes
	For liquid hydrogen: • improve insulation • boil-off management and/or active in-aircraft refrigeration
Structural tank	Integration of hydrogen storage and aircraft structural functions
Safe liquid hydrogen	Safe venting of boiled-off hydrogen
Leakage mitigation, detection and contingency	E.g. dual-walled tanks and ducting, leakage sensing, nitrogen inerting/purging systems
Thermal management	Insulation, vaporisation, heat exchangers, support for cooling of other systems (e.g. superconductive electric wiring or turbine sections)
Hydrogen distribution equipment	Liquid/gaseous hydrogen ducting, pumps, valves, metering, couplings
Tank instrumentation	Quantity and level sensor for hydrogen, notably liquid
Certification	Safety analyses and certification processes

4.3.3. Combustion in turbine engines

Direct combustion of hydrogen in an aircraft engine is possible with relatively small changes to current gas turbine technology, limited mostly to the combustor (Cryoplane , 2000). Because hydrogen contains no carbon, not only CO_2 but also soot (particulate matter) emission is nearly or totally eliminated. Nitrogen oxide emissions still occur because of the high temperatures in the combustor. However, there is potential for considerable improvement because the wide flammability range of hydrogen allows lean combustion which limits NO_X formation – this is an important area of research.

Main topics of hydrogen burning gas turbine technology to be investigated in future research are shown in Table 5.

Table 5: Main topics of hydrogen burning gas turbine technology to be investigated in future research

Area	Topic or goal
Combustor	Adaptation of the combustion chamber
	Hydrogen injection systems
	Lean-fuel injection/mixture technologies for lower NO_X emissions
	Flashback resistance
Aircraft integration	Integration (from tank to engine) in terms of heat management and transient operations
Certification	Safety analyses and certification processes

4.3.4. Hydrogen fuel cells

Instead of combusting, hydrogen can be converted to electricity through a chemical reaction in a fuel cell, and the aircraft can be propelled with a suitably sized electric propulsion system. Fuel cells use oxygen from the surrounding air for the reaction, which results in pure water as reaction product. In contrast to gas turbines, fuel cell exhaust water can be collected in liquid form, which may allow water management strategies that prevent or reduce contrail or cirrus formation.

Although other fuel cell technologies exist, the most mature type is low-temperature proton-exchange membrane (LT-PEM, <100°C). Efficiencies of this type are around 50-60 % (hydrogen lower heating value), leading to heat generation inside the fuel cell stack. High-power fuel cell installations require substantial cooling provisions consisting of pumped loops and heat exchangers. Because fuel cell efficiency suffers at lower pressure conditions, air must be compressed with an electric air compressor when operating at higher altitudes. In addition, a humidifier is required to prevent dry-out of the fuel cell's membranes, usually with the water that forms in the reaction. These components external to the core fuel cell are called "balance of plant" components.

Typical state-of-the-art fuel cell specific densities (power to weight ratio) are around 1-2 kW/kg. This applies to the core fuel cell stack and excludes the 'balance of plant' components and the cooling system. Targeted performance of future fuel cell systems suitable for use in aviation is 1,5 – 2 kW/kg for fuel cell stack, 'balance of plant' and cooling system combined. This requires research and development of optimised components in addition to the core fuel cell stack.

Main topics of fuel cell system technology to be investigated in future research are shown in Table 6.

Table 6: Main topics of fuel cell system technology to be investigated in future research

Area	Topic or goal
Fuel cell stack	Improvement of power density and reliability of fuel cell stacks with ratings up to 10 MW
Thermal management	Optimised cooling systems including pumps, valves, heat exchangers, accumulators, ducting and radiators.
Air management	Air humidification systems, compressors or turbocompressors, heat exchangers, water retrieval systems
Water management	Exhaust water management to limit contrail or cirrus generation
System-level optimisation	System engineering addressing system-level optimisation including safety / redundancy provisions
Aircraft integration	Integration of electric / structural /thermal functions of fuel cell system, propulsion motor and electronic inverter
Certification	Safety analyses and certification processes

4.4. Innovative aircraft configurations

Within the Clean Sky 2 programme of the European Commission, TU Delft and NLR work together with other partners towards demonstrating novel integrated aerodynamic and propulsion concepts. The developments are foreseen to be continued and extended as described in the EC Clean Aviation programme (Clean Aviation Partnership, 2020b). Innovative configurations enable an optimal integration of various technologies. This section describes the most promising developments.

4.4.1. Optimal airframe shape

Apart from the changing the energy source to reduce GHG emission a prominent role is played by the overall aircraft configuration selected to perform the mission. A multitude of examples of novel configurations exist many of which were developed within national or EU-funded programs. Within the Clean Sky 2 programme of the European Commission, TU Delft and NLR work together with other partners towards demonstrating novel integrated aerodynamic and propulsion concepts. The developments are foreseen to be continued and extended as described in the EC Clean Aviation programme (Clean Aviation Partnership, 2020b). Innovative configurations enable an optimal integration of various technologies. Note that improved aircraft fuel efficiency beyond the state of the art traditional turbofan powered tube & wing concepts, novel configurations are foreseen that rely on improvements in areas like: lightweight materials, propulsion system interaction, aerodynamic and flight mechanical behaviour. This section provides a brief summary on the promising developments that were evaluated and promoted over the past years.

4.4.2. Optimal airframe shape

The shape of aircraft is directly related to the aerodynamic drag and therefore to its energy consumption. Novel configurations like the Blended Wing Body (BWB) and the flying-wing type of aircraft (a.o. the Flying-V) integrate the functions of generating aerodynamic lift and providing space for passengers and cargo. As a result, the aerodynamic efficiency, in terms of the lift to drag ratio, of these concepts is expected to be larger than for traditional tube-and-wing configuration aircraft. Typical reduction in fuel burn for these novel AC layouts in the range 10-15% are found. Aircraft development as described in this section may result in configurations such as provided in Figure 16, for the details on these concepts the reader is referred to the publication by Hoogreef et al. (2019).

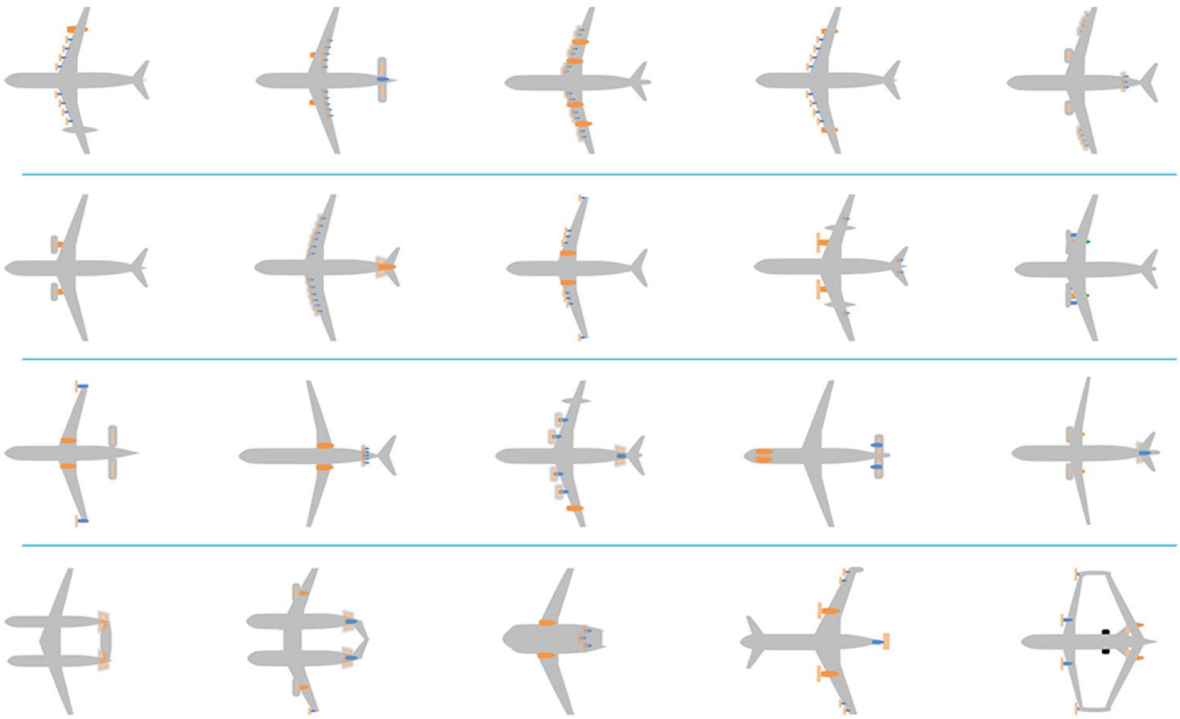


Figure 16: Overview of 35 different concepts to meeting top-level aircraft requirements roughly based on the Airbus A320. Potential radical airliner designs are being evaluated under Clean Sky 2's Large Passenger Aircraft integrated aircraft demonstration program (Hoogreef, Vos, de Vries, & Veldhuis, 2019).

The additional space in the more voluminous wings may particularly be beneficial for carrying hydrogen, which is known to require more space than kerosene because of the hydrogen's smaller gravimetric energy density. Hence the positioning of the storage tanks requires a careful optimization in these new configurations. Moreover, earlier research has indicated that the application of multifuel-engines can be ideally combined with alternative BWB type of aircraft layout. An notable example is the concept that developed in the EU-funded project AHEAD. By combining the alternative energy sources (liquid hydrogen, LNG and bio-kerosene) with an efficient AC planform is was estimated that 20-25% lower radiative forcing can obtained compared to a traditional reference aircraft (Grewe, et al., 2016).

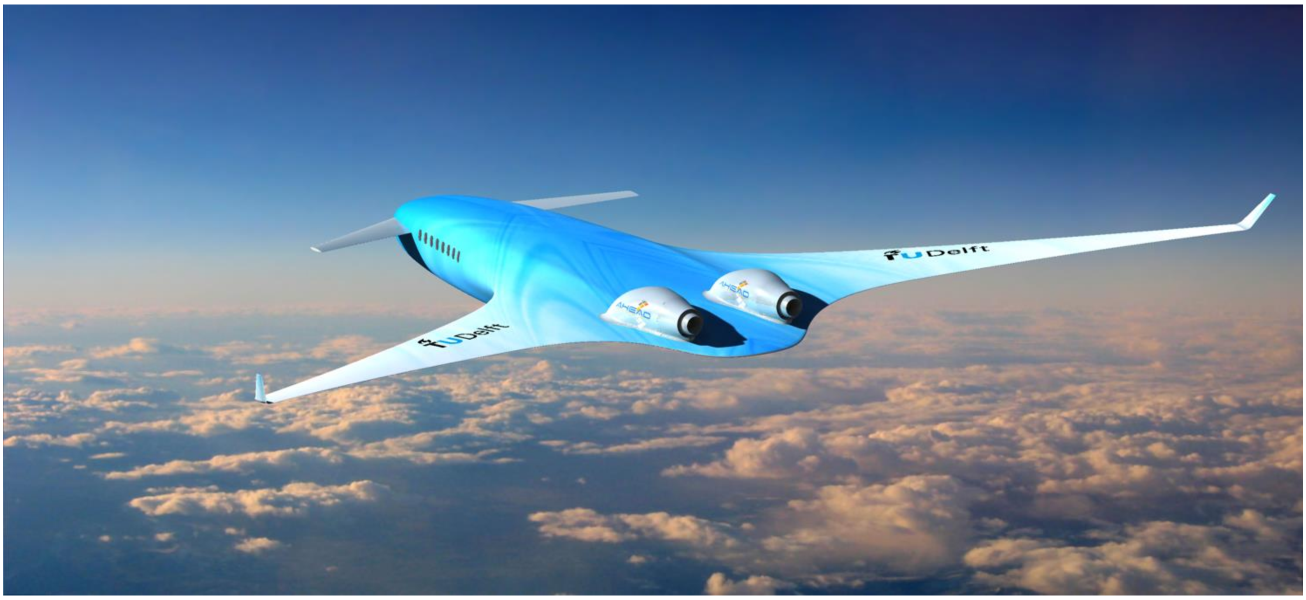


Figure 17: Multifuel BWB aircraft concept defined in the AHEAD project (Grewe, et al., 2016)

It should be clear that selecting any of the proposed alternative AC layouts, as sketched in Figure 16, requires an extensive and in-depth analysis of fuel performance, structural layout, flight mechanical behaviour and handling qualities. Moreover, determination of the consequences on costs, safety, operational limitation and MRO are non-trivial tasks which is the reason why these radically novel design have only been investigated up to the conceptual design level. The imminent need to arrive more sustainable AC design will very likely change this.

4.4.3. Optimal integration of propulsion concepts

The development towards more fuel-efficient aircraft over the past decades has shown that the most prominent role was performed by the engine, on the basis of maintaining the well-known single, twin en four engine tube and wing designs. With better kerosene-based engines and electrically powered systems becoming available as well as considering alternative energy sources like hydrogen, an improved fuel efficiency can be obtained by adapting and optimizing the integration of the propulsion system in the aircraft. Notable examples are: the distributed propulsion concept, novel open-rotor applications (like over-the-wing blow and contra-rotating propfan) and last but not least boundary layer ingestion. Some examples are provided in Figure 18.

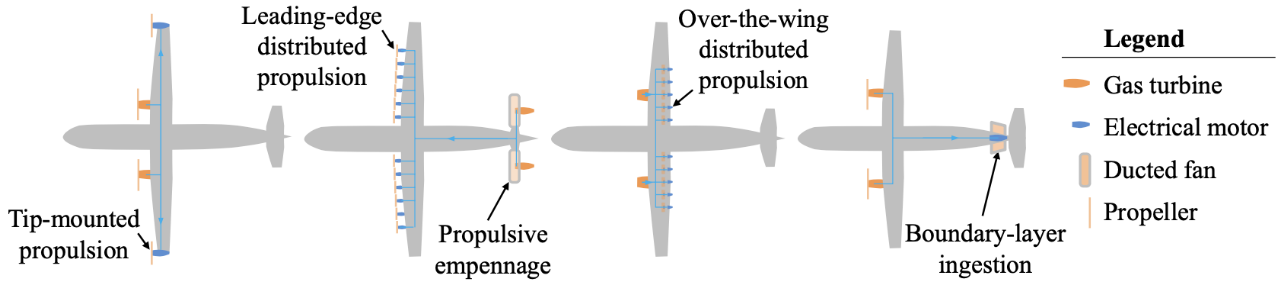


Figure 18: Examples of (partial-) turboelectric aircraft configurations utilizing distributed propulsion (de Vries, Hoogreef, & Vos, 2020)

In most cases the proposed novel integration concepts rely on three key aspects:

- better open rotor based propulsive efficiency increase
- beneficial aero-propulsive interaction effects
- utilization of novel engines combinations (a.o. hybrid-electric propulsion).

Numerous sources are available in which the current state of the art as well projected future developments are sketched. Without going into the details of all aspects that play a role in optimization of propulsion integration the two most prominent concepts will be concisely discussed here. At this moment they are part of ongoing international research and development program and as such interesting to Dutch R&D entities and industry to join. NLR and TU Delft are already part of a number of consortia but a more extensive role of the Dutch aviation sector will certainly be needed to remain a strong position in Europe.

BOUNDARY LAYER INGESTION

In traditional aircraft configurations, with engines under the wing, the propulsive and drag forces are essentially separated: they act in different locations. This results in a momentum deficit behind the wing, and an excess of momentum behind the engine (in the wake), which basically results in wasted (kinetic) energy that does not contribute to propelling the aircraft. This wasted energy can be reduced by putting the propulsor in the wake of the wing (or the wake of the fuselage), a concept known as “boundary layer ingestion” or “wake-filling”. This is shown in Figure 19.

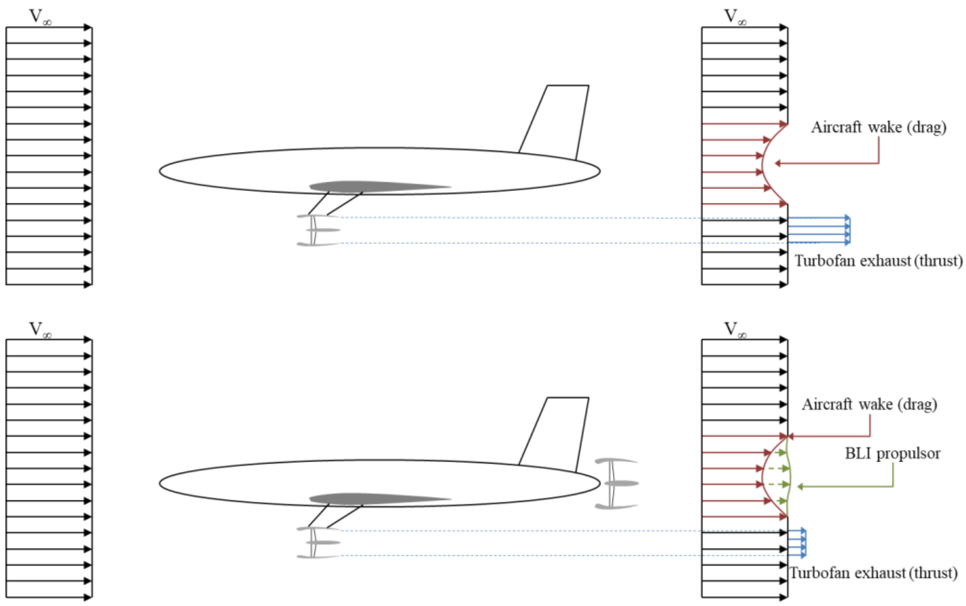


Figure 19: The turbofan has to generate enough thrust to overcome the aircraft's drag (top). A boundary-layer ingesting propulsor could accelerate the slower moving air in the aircraft wake (bottom). The turbofans could then be downsized, since they have to generate less thrust, which leads to weight savings and drag reductions, increasing the overall efficiency (NLR).

By applying the BLI principle the total fuel efficiency may be enhanced by about 5%-15%, highly dependent on the chosen configuration and the flight speed. As is shown in several scientific publications a very attractive layout is the one in which the fuselage boundary is fully captured by a tail mounted propulsor. Figure 20 shows 3 designs that make use of this design.

Figure 20: Examples of novel aircraft concepts that utilize boundary layer ingestion (BLI), a) MIT D08 design (MIT, 2010; Drela, 2010; NASA, 2010), b) Propulsive fuselage concept (CENTRELINE, 2017), c) TU Delft APPU project (TU Delft, 2020)

Albeit being very promising for future sustainable aircraft, the highly integrated character of the propulsion system and the opportunity to select novel drive trains based on SAF the BLI concepts, requires extensive additional research on the aerodynamics, flight mechanics, thermodynamics and noise of the integrated system. Worldwide research is ongoing to which the Dutch aviation sector could contribute significantly.

DISTRIBUTED & HYBRID PROPULSION

Distributed propulsion (DP) promises an additional increase in aircraft propulsive efficiency, albeit under the restriction that the flight speed is lowered compared to traditional turbofan aircraft. As the name suggests, concepts that apply distributed propulsion have a larger number of smaller propellers, compared to traditional designs. This has several advantages, for example allowing the application of boundary layer ingestion along larger parts of the wing or the fuselage (CENTRELINE, 2017). As overall efficiency is reduced if one large combustion engine is replaced by several smaller ones, distributed propulsion is most relevant for electrically driven propellers. One way is which distributed propulsion maybe contributing beneficially to the aircraft's fuel economy is through the reduction of the wing area in the case the propulsors are installed along the leading edge.

Additional to the potential performance increase benefits, installing the engines, for example, on top of the aircraft will lead to shielding of the engine noise. This may alleviate the noise hindrance around airports.

The energy source for driving electrical motors (besides gas turbines in the case of medium range missions) is either, batteries, hydrogen fuel cells, a combustion engine driving an electric generator, or a combination of these. In this respect distributed propulsion is often associated with hybrid-electric propulsion. A typical example of designs that employ distributed propulsion are presented in Figure 21.

Figure 21: Distributed propulsion applied to a 19 seater electric aircraft (NLR).

Over the past years, research performed by academia, research establishments and industry suggest that the typical reduction of in-flight CHG emission range from 100% for very small general aviation type of aircraft to about 10%-20% for regional and SMR (small and medium range) DP-concepts. It is important to note that in most cases DP-aircraft utilize some form of open/ducted rotor which exhibit their optimum propulsive efficiency at flight speeds (Mach numbers in the range 0.4-0.6) well below that of SMR (Mach number 0.75-0.8). As a result, typical missions may change towards a "lower-and-slower" regime, which has consequences for the market position of operators. This additional factor in the equation complexifies the optimization process for DP-based aircraft. Furthermore, given the large number of topics to address in the DP-drive train development (both from the perspective of energy source and propulsion subsystem elements) it seems that, like was mentioned for BLI-based propulsion, DP is envisioned to be an interesting topic to be embraced by Dutch R&D entities and industry.

4.5. Enabling technologies

Whether or not novel and innovative aircraft system and subsystems designs will be feasible in near future will be largely dependent on major developments/breakthroughs in the various disciplines that support the design process, like: aerodynamics, structures, engine design, flight mechanics and energy source & production. As a result, it is helpful to shortly discuss the so-called 'enabling technologies' that are being developed and which, if incorporated in a synergistic ways, will allow speeding up the process of sustainable aircraft design. As the number of disciplines involved is largest and the number of fundamental and applied technologies is huge, hereafter only a limited number of enabling technologies will be addressed. Some of these are at very low TRL level being investigated at academic levels, while other are supported by industry at higher TRL. Two research fields will be discussed briefly: aerodynamics and structures & materials.

4.5.1. Aerodynamics

Introducing improved aerodynamic behaviour of aircraft components will directly result in reducing the energy consumption, hence increasing the fuel efficiency of the aircraft. The key forces to be considered are the lift force and the drag force.

To start with the latter, it is interesting to note that significant drag reduction may be obtained by laminarizing the airframe. This can be achieved by:

1. Smoothing the airframe's surface which will postpone the so-called boundary layer transition process (from laminar to turbulent flow). This can be achieved by utilizing fiber reinforced surface structures (a.o. Fiber-metal laminates, FML). One of the reasons that laminarization by this passive means now becomes more interesting is the drive towards lower-and-slower aircraft as discussed above. The associated lower value of the so-called Reynolds number is a necessity to enable a useful amount of laminarization. With the extensive knowhow on FML, the Netherlands is well prepared to take a prominent position in the international arena.
2. Utilizing smart flow control techniques like boundary layer suction (BLS) and/or wall cooling. This technique, albeit being quite complex, show a huge potential with respect to drag reduction. If well designed and certified it may lead to a drag reduction (and likewise energy reduction) somewhere between 25-50%. At academic level the Netherlands is well-recognized in the area of BLS. A next step will be needed to further develop this technique in close cooperation with industry.

Novel ways on turbulent drag reduction are also explored. However, the underlying aerodynamic phenomena are less understood than those occurring on the laminarization process. Drag reduction in the order of 1%-2% are expected in due time.

An additional way to reduce the drag force at a given (required) lift coefficient is found in the application of surface shape optimization and shape control. Both required the application of modern materials (see below). Given the established position that Dutch researchers, active in this field have, it is anticipated that an important role can be played at international level. The amount of drag reduction (hence reduction in fuel consumption) is hard to give as the technique is very much dependent on the application at hand. Order 2%-5% reduction in drag force is foreseen. On the side of aero-elastic optimization, additional aerodynamic performance related improvement may be obtained by active flutter control, gust load alleviation both leading to a lighter wing. It should be noted that the enabling character of many of these techniques is found in the snowball effect (lighter structure > lower drag > lower engine weight > lighter structure > …, as shown in Figure 9). For the enormous amount of information on these structure-based effects, the reader is referred to open literature.

Another structures-based aerodynamic optimization leading to lower drag is the wing shape adaptation by applying a high aspect ratio wing, a folding wing, a morphing wing or a strut or truss braced wing.

Figure 22: Artist impression of the Boeing SUGAR Volt concept, utilising a truss-braced high aspect ratio wing (NASA, 2010; Bradley & Droney, 2011; Bradley & Droney, 2015; Wall & Meyer, 2017)

The most prominent lift related improvement, that potentially reduces overall fuel consumption (and noise) of future aircraft, is based on an indirect effect. In case the (expected) trend towards point-to-point operation of future aircraft is maintained[15], there will be an increased need to operate aircraft from shorter runways which in turn necessitates improved field performance in the form of Short Take Off and Landing (STOL). Hence, there will be a need to improve high lift performance, with high lift devices that work in close interaction with the open rotor propulsion system that may be set up in distributed fashion (see above). As a result, extended research is required on the integrated rotor-wing-flaps system that improve lift capabilities without increasing the aircraft's mass. With the key Dutch knowledge base in design and manufacturing of flaps/high lift systems and control Dutch industry would be ready to support the development of future sustainable aircraft in an indirect way as well.

4.5.2. Structures and materials

Estimates indicate that there could be approximatively 40 000 aircraft, of different category and type, in the world in 2017, and about 150 000 vehicles have ever been manufactured. Even when focusing at one typical

[15] A clear market analysis is pending.

passenger airplane, for example an Airbus A320, the structural weight ranges in the order of the tens of ton of materials.

The majority of aircraft now in service are made out of a standard design, of fuselage and wing, built out of a limited range of materials, namely metals and composites. Radical changes need to happen at this level to enable new propulsion system to be fully integrated and to lower the environmental footprint of the airframe structure itself and to enable a sustainable production for the future airplanes.

Airframe materials transition from metal to composite in the 1980s. Despite having provided significant weight saving, composite materials, such as carbon fibre reinforced plastic (CFRP), have not been yet fully exploited given limitations on design, certification requirements and manufacturing technologies. Fully enabling the industrial application of composite materials shall lead to further reduction in structural weight, material usage and energy consumptions, for example when only composite materials can be applied in all structural components of the airframe. But the environmental impact of manufacturing CFRP is much higher than metals (Jennings, 2015). Incorporating sustainability indicators, next to weight and performance indicators, at conceptual design phase would enable to assess what material choice has the lowest overall environmental impact.

New manufacturing technologies will enable the market implementation of materials, which have been topic of research or applied in other sectors for many decades, such as metamaterials and smart materials, with additional functionalities (e.g. shape morphing). New types of composites, for example bio-based or recycled, and ceramics materials can also benefit from the potential of additive manufacturing and other innovative manufacturing technologies and processes.

Regarding bio-based materials and recycled (metal and composite) materials, pilot applications have already been considered in non-critical components of the airframe. The main focus for those categories of materials shall be to determine their material properties at the level necessary for application in primary structures, subject to stricter certification and safety requirements.

Coupling manufacturing technologies, such as composite technologies and additive manufacturing, with ICT solutions will allow to monitor the quality of the components, reducing the scrap rates (and therefore the waste) and enabling the generation for each component of a virtual duplicate, a digital twin, which can be used to monitor the structural integrity, when combined with inspections or structural health monitoring systems.

Next to this, smart manufacturing will allow to implement more advanced design approaches, such as structural and topology optimization and biomimicry, which have been so far constrained by manufacturing and design software limitations. Other design approaches which are to be implemented, especially in connection to the implementation of circular economy in aviation structures, are: design for reuse, for repair, for disassemble, for remanufacturing, for recycling.

Aspects to be investigated in future research are:

- New composite and ceramics materials
- Additive manufacturing (including artificial intelligence)
- Assessment of material compatibility with hydrogen in terms of leakage and embrittlement given cryogenic temperatures and a vibrating environment
- Metamaterials
- Smart materials with additional functionalities

- Bio-based materials
- Recycled materials (metal and composite)
- Structural design practices:
    - Optimization techniques (structural, topological, …)
    - Smart structures (morphing, …)
    - Eco-design directives and biomimicry
    - Connection with circularity: design for reuse, for repair, for disassemble, for remanufacturing, for recycling

SUSTAINABLE FUELS AND ENERGY SOURCES

5

5. SUSTAINABLE FUELS AND ENERGY SOURCES

Sustainable energy sources are essential to reach climate neutrality by 2050. As shown in Chapter 4, the energy sources used to power the aircraft may vary depending on the aircraft type and the type of propulsion system. This variation is due to the differences in gravimetric and volumetric energy density of the various energy carriers. Its current energy density prohibits application of batteries on long haul flights, but leaves potential for use in small and regional aircraft. The energy density of hydrogen is 3 times higher than kerosene, but it requires at least 4 times the volume (in liquid form). In the coming decades, hydrogen is foreseen for short and medium range aircraft, whereas long haul flights are expected to continue to rely largely on liquid hydrocarbons (as shown previously in Table 1).

To reach the climate goals, a massive scale-up of the production of sustainable fuels and energy sources is required. The uptake of sustainable aviation fuels is currently limited to less than 1% of worldwide jet fuel consumption (ICAO, 2019 Environmental Report, 2019a). In order to reach full deployment by 2050, the market for sustainable fuels must scale-up at an unprecedented pace, highlighting that energy efficiency improvements are crucial to ensure a lower amount of energy – more easily met in terms of production – is required overall.

Research that enables the deployment of sustainable fuels and energy sources requires a holistic approach. This includes factors such as climate impact, security of supply and social acceptance, technical performance and cost-effectiveness. These elements are further elaborated in this chapter.

DEFINITIONS

Fuels which are compatible with current aircraft and which can be blended with conventional jet fuel are called “drop-in” fuels. Development and management of fuel standards, as well as their application, is done by the American Society for Testing and Materials (ASTM) within its International Committee D02.J0.06. Currently 8 conversion pathways have been approved to be blended with Jet-A/Jet-A1 (CAAFI, 2020). Most pathways are currently certified for blending levels up to 50%. Increasing blending levels above 50% to potentially 100% is often referred to as “nearly-drop-in” fuels, because minor changes may be required for example to the sealings of the engines.

Fuels that require substantial changes to the aircraft (in terms of propulsion system and/or structure) in combination with new infrastructure are called “non-drop-in” fuels. Examples of non-drop-in fuels are liquid hydrogen and methane.

5.1. Chemical composition and related climate impact

The chemical composition of sustainable fuels influences emissions during combustion. In particular, it can have a major impact on soot, sulphur, NO_X and water vapour emissions. Further research is required to analyse the effect of a different chemical composition on non-CO_2 emissions and their related climate impact.

The blending of biofuels with jet-A1, both during flight tests and ground tests, showed that these fuels lead to lower soot emissions and thereby reduce contrail and cirrus formation (DLR, 2018). Blends with synthetic fuels, such as power to liquid kerosene, also contain lower levels of sulphur and aromatics which lead to lower soot emissions. If power to liquid kerosene is blended up to 100%, the study “Hydrogen powered aviation" estimates that the formation of contrail and cirrus clouds may be reduced by 10% to 30% (McKinsey & Company, 2020). The study also estimates that the use of synthetic fuels may therefore reduce the overall climate impact by 30% to 60%, assuming a fully carbon neutral production process (McKinsey & Company, 2020).

As stated in the aircraft development chapter, the combustion of hydrogen leads to a total elimination of carbon dioxide, carbon monoxide, soot, sulphuric acid, and unburnt hydrocarbons. Furthermore, a major reduction of NO_X emission is foreseen through optimized design of the engine (Cryoplane , 2000). The combustion however increases water vapour emissions by a factor 2.6 compared to a mass of kerosene of same energy content (Cryoplane , 2000). It is of major importance to assess the total climate effect of hydrogen combustion. The contrail characteristic behind hydrogen engines may vary substantially from kerosene as there are fewer condensation nuclei (such as soot and sulphuric acids). The study "Hydrogen powered aviation" estimates that the formation of contrail and cirrus clouds may be reduced by 30% to 50% . The study also estimates that the use of hydrogen combustion may therefore reduce the overall climate impact by 50% to 75%, assuming a fully carbon neutral production process (McKinsey & Company, 2020).

Another major advantage of lower soot, sulphur and NO_X emissions is an improvement in local air quality, which has a positive impact on the health of people living in close proximity to the airport. The effect of using synthetic fuel blends (up to 100%) and hydrogen on local air quality needs further investigation.

5.2. Sustainability and availability

The energy used to power the aircraft fleet (for all aircraft types) must originate from sustainable sources, such as biomass and renewable electricity. Currently, multiple types of sustainable aviation fuels can reach 80% reduction in GHG emissions over the life-cycle (ICAO, CORSIA Eligible Fuels, 2019b). Some pathways, such as the production of hydrogen or power to liquid kerosene, are potentially fully carbon-neutral.

Research is required that assesses the availability of biomass feedstocks and renewable power production while taking into account sustainability constraints. These constrains should ensure that feedstocks do not compete with food production, do not cause land use changes, prevent the displacement of land, and preserve biodiversity. Sustainable power production through solar, wind and hydroelectric energy is potentially unlimited, but it may be difficult to scale up these supplies sufficiently fast to meet global demand (Hansen, Breyer, & Lund, 2019). Especially in the 2030 timeframe renewable energy production will remain scarce taking into account the demand from all sectors of the economy. For the production of hydrogen through electrolysis, the availability of water should also be considered.

SUSTAINABILITY CRITERIA

Sustainability criteria for the production of sustainable fuels include environmental, social and economic aspects. The Roundtable on Sustainable Biomaterials (RSB) criteria for example include: legality; planning, monitoring and continuous improvement; greenhouse gas emissions; human and labour rights; rural and social development; local food security; conservation; soil; water; air; use of technology, inputs, and management of waste; and land rights (Roundtable on Sustainable Biomaterials, 2016). In the EU the minimum sustainability criteria are currently covered by the Renewable Energy Directive (RED) and its recast towards 2030 (RED II). Research on the overall the sustainability of the fuel provides insights into the most beneficial options which also contribute to the UN Sustainable Development Goals.

DIVERSIFICATION AND REGIONAL SUPPLY CHAINS

The types of feedstocks and production processes will diversify as aviation moves away from fossil sources. The availability of renewable sources will vary per region. Depending on their geographical location, some countries may have abundant solar or wind energy, urban area's may have a larger availability of municipal solid waste, and agricultural regions may have a lager availability of agricultural residues. It is therefore expected that regional supply chains will be established.

Assessing the availability of feedstocks will also enable diversifying the mix of feedstocks. Interesting feedstocks to consider for the production of biofuels include biomass waste and residues, lignocellulosic energy crops aquatic crops. For the production of power to liquid fuels, concentrated carbon sources may also be considered as an intermediate solution. For the long term, carbon removal technologies should be considered.

5.3. Technological learning and economic viability

For the pathways currently certified in ASTM, the production processes have different technology readiness levels depending on the feedstocks used. Most technology readiness levels are currently ranging between 3 and 6, while a few are near or at commercial maturity (E4tech (UK) Ltd & studio Gear Up, 2019). The integration of multiple process steps has often yet to be demonstrated on a commercial scale. Research is required in order to reach commercial maturity (TRL 8 to 9). The only pathway which is currently commercially available is hydroprocessed esters and fatty acids (HEFA). Production pathways such as Fischer-Tropsch gasification, power to liquid Fischer-Tropsch and alcohol-to-jet catalysis may reach commercial maturity in the coming years. New pathways such as aerobic fermentation, pyrolysis and aqueous phase reforming may reach commercial maturity in the longer term.

PROCESS EFFICIENCY

Research is required to assess the techno-economic performance of different production routes to identify potential improvements in the chemical processes. To identify energy losses, the technical performance of the production process can be analysed in terms of fuel efficiency and total efficiency. Fuel efficiency is analysed by comparing the amount of energy stored in the fuel in relation to the amount of energy input by electricity or biomass. The overall efficiency is analysed by taking into account by-products such as electricity or district heating.

IMPACT OF POLICY MEASURES ON ECONOMIC VIABILITY

Research is also required to estimate the production costs based on both feedstock types and capital expenditures. This research enables identifying which factors mostly influence the cost-competitiveness of various routes. Economic viability is currently strongly linked with policies and regulations. As the price of drop-in fuels ranges from 2 to 7 times the price of conventional jet fuel (IATA, 2015), research is required to assess the most effective policy measures to stimulate and increase the uptake of SAF in both the short, medium and long term. This research includes the effect of input and output subsidies, contracts for difference, carbon pricing and other policy incentives.

OPERATIONS

6

6. OPERATIONS

New aircraft technologies can only deliver wide impact if they can be absorbed in the air transport system. Therefore, operations and infrastructure need to be adapted in order to accommodate the before described new technologies. Besides supporting new technologies and vehicles, numerous operational changes themselves can make a positive impact on sustainability.

Section 6.1 discusses research and innovation required to reduce the climate impact of flying, focused on the cruise phase of the flight and applicable to both the current and possibly revolutionary future air transport system designs. Section 6.2 looks at the local environmental impact and how research can help reducing these. Section 6.3 discusses the operational and infrastructural changes needed to accommodate the innovative technologies described in Chapter 4. Last, Section 6.4 discusses potential sustainability improvements in terms of maintenance, repair and overhaul (MRO).

6.1. Climate optimal flight

Climate optimal flight aims to reduce the climate impact of flying by operational changes. Operational changes can reduce the climate impact of flying in two ways: climate-optimised routing and operational improvements to reduce energy consumption.

6.1.1. Climate-optimised routing

Climate-optimising aircraft routes entails minimizing or preventing flight through climate sensitive areas and altitudes. Especially, balancing CO_2 and non-CO_2 impacts is key. Figure 25 shows a roadmap towards implementing this in operational practice.

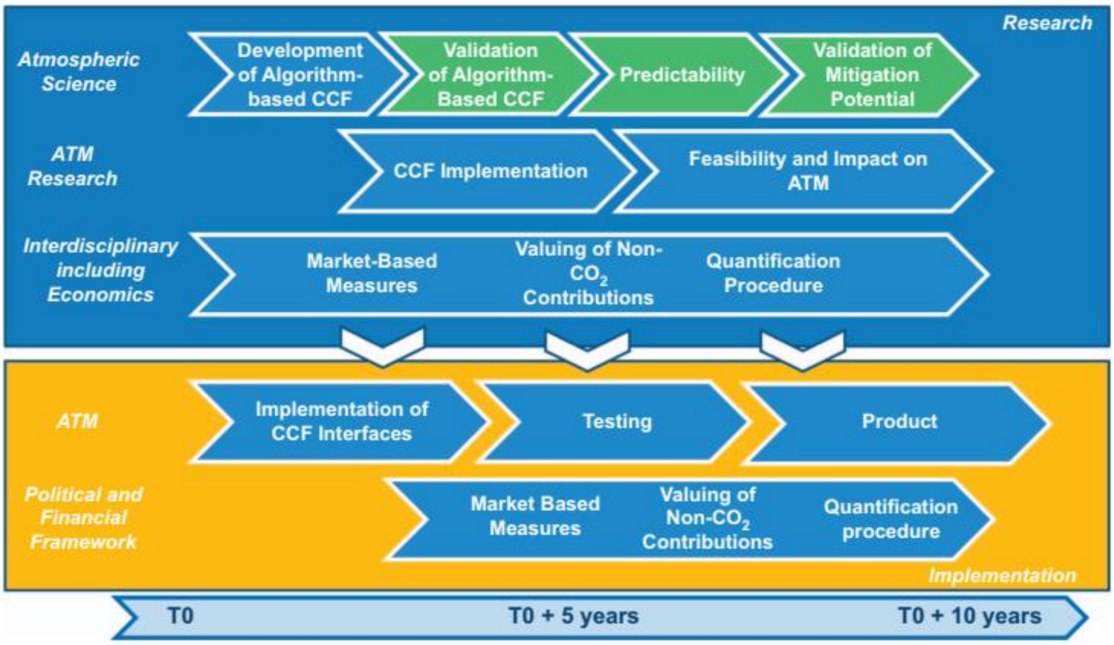


Figure 23: Roadmap for implementing climate-optimised routing. Research activities are shown in blue, implementation in orange and validation in green. From Grewe et al. (2017).

CLIMATE SENSITIVE AREAS

Associated to the non-CO_2 impacts of aviation (discussed in Section 3.1), aircraft routings can be adjusted to circumvent the most climate sensitive areas of airspace. Climate sensitive areas provide physical and chemical environments which stimulate the processes associated with a negative climate impact, for example areas where contrails more easily form (Grewe, et al., 2017; Yin, Grewe, & Gierens, 2020). By detouring around climate sensitive areas, the climate impact of the flight can be reduced. As the location and climate sensitivity of these areas is highly dependent on local environmental properties, circumnavigating these is however easier said than done. Being able to estimate more accurately and earlier where climate sensitive areas are or will be is a key research challenge.

FLIGHT ALTITUDE

Besides the lateral climate sensitivity variability, climate impact of aviation emissions also depends on the altitude of emissions, due to the variable physical and chemical properties of the atmosphere over different altitudes. For example, at higher altitudes in the troposphere, NO_X has a larger warming effect than at lower altitudes, due to the longer lifetime at higher altitudes, which results in higher O_3 production. While flying at lower altitudes results in a smaller warming effect from NO_X, it implies higher fuel use and thus more CO_2 aircraft emissions. With increasing ambient temperature, the true airspeed will decrease when flying at lower altitudes, which will also result in increased direct operating cost. If aircraft are designed for lower cruise altitudes and cruise speeds, the overall climate impact could be optimally reduced by flying lower. In order to optimise this design, the non-CO_2 and CO_2 impacts with respect to altitude should be further investigated, along with the respective influence on operating costs and business models.

FINDING THE OPTIMAL LOW CO_2 AND NON-CO_2 IMPACT

Whereas detouring around climate sensitive areas or flying at lower altitudes decrease non-CO_2 climate impacts, these concepts increase the flight distance or reduce true airspeed and thereby increase energy consumption. Due to an increase in energy consumption, CO_2 and other combustion-related emissions increase. Therefore, both CO_2 and non-CO_2 emission impacts must be assessed and adverse effects need to be identified and averted. That goes for emissions, but also for operating cost.

6.1.2. Reducing energy use

Reducing energy consumption is a second way of reducing aviation's contribution to climate change. This can be achieved by more energy-efficient aircraft, but also by operational innovations that reduce flight distance, remove altitude restrictions, allow to make better use of favourable weather patterns (e.g. tailwinds), and enabling and implementing new operational concepts.

EN-ROUTE EFFICIENCY

Improving en-route efficiency is a key way of reducing aviation energy use in the short term. Horizontal en-route efficiency, a measure for how optimal current flight routes are in terms of distance, is currently approximately 6% and goals are set to reduce this to approximately 2% (EUROCONTROL, 2019; Presidency of the Council of the European Union, 2019; SESAR JU, 2019; IATA; AEA & ERA, 2013). Defragmentation of airspace – either digitally or physically – is a key enabler for this, but requires research addressing data-sharing and cooperation between Air Navigation Service Providers. Additionally, aspects related to airspace design, such as the implementation of Free Route Airspace (FRA, in which aircraft no longer have to fly from waypoint to waypoint but can choose more direct routes) and Advanced Flexible Use of Airspace (AFUA, enabling commercial flights to use unused military airspace), can improve en-route efficiency. Research and innovation challenges mostly concern the development of technological innovations in support of the aforementioned measures.

One step beyond what is discussed above would be moving from shortest-distance routes towards minimum-energy routes, for example utilizing favourable tail winds. As the conditions for highest energy-efficiency will depend on location and time and might vary from aircraft to aircraft (due to design choices made) or flight to flight (due to operational conditions), this requires cooperation and likely data exchange between air traffic control officers and aircraft or their crews.

FORMATION FLIGHT

One of the more revolutionary possibilities of reducing energy usage are forms of extended formation flight[16] (Warwick, 2020; Flanzer, Bieniawski, & Brown, 2020; Norris, 2019; Airbus, 2019a; Airbus, 2019b). Inspired by the way birds fly in groups, aircraft fly in closer proximity[17] to each other allowing the trailing aircraft to benefit from the upwash of the leading aircraft. This is anticipated to yield fuel savings of 2 to 5% for each two aircraft that can be paired up. Unanswered questions regarding the system-wide emissions reduction potential, cost/benefit sharing and required air traffic management procedures are relevant research directions to pursue.

INTERMEDIATE STOP OPERATIONS

Intermediate stop operations (ISO) – in which long flights are split up into multiple shorter segments[18] - might be a solution that can have benefits in a relatively short timeframe. Research shows fuel burn reductions of 5 to 10% for missions of 5000 to 7000 kilometres and above (Brok, Hagstroem, Junior, & Matthes, 2010; Lammering, Anton, Risse, & Franz, 2011; Bergmans & den Boer, 2012; Hartjes & Bos, 2015; Linke, Grewe, & Gollnick, 2017), with exact benefits depending on routes and the availability of appropriately located intermediate airports.

Intermediate stop operations for long range routes might be an interesting opportunity, but for medium haul routes operated using alternatively propelled aircraft (as discussed in Section 0), shorter routes might be a necessity due to range limitations of hybrid- or battery-electric aircraft. In both this and the ISO-case, aircraft productivity might be reduced, likely affecting the revenue potential of airlines. Especially for shorter routes, network-analyses of anticipated benefits and most in-demand locations for such intermediate stop-overs can guide airport development and possibly associated airspace design.

SUPPORTING ATM INFRASTRUCTURE AND AIRCRAFT EQUIPMENT

The successful and safe implementation of many of these operational changes is contingent on the right supporting ATM infrastructure and aircraft on-board equipment. Although this work concerns higher TRL, integration of new technologies into aircraft currently operated (e.g. through upgrades) is important to ensuring the full potential of innovative operational concepts.

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[16] This is also known by *wake energy retrieval*, *cooperative trajectories* and various other terms.
[17] This will be on the order of one or multiple nautical miles.
[18] This way, the aircraft has to carry less fuel, which in turn reduces the fuel consumption.

6.2. Improving local quality of life

Reducing the local environmental impact of aviation activity requires efforts in a substantial number of areas by a multitude of stakeholders. This section discerns between operations on the ground and operations in the first (and last) phases of flight.

AIRCRAFT GROUND EMISSIONS

In 2019, Royal Schiphol Group set as a target for 2030 to have its airport operations zero-emission at Amsterdam Schiphol, Eindhoven, Rotterdam The Hague and Lelystad (Royal Schiphol Group, 2019). This target, however, does not include the emissions from aircraft itself. And even though fuel burn on the ground is limited compared to fuel consumption during flight, gaseous and noise emissions make a notable impact on the local environment.

Further scoping the focus on aircraft, research should work towards solutions that can be applied to existing fleets as easily as possible – in order to ensure a rapid impact. Probably the most important opportunity lies in reducing taxi-emissions, either through more efficient taxi routes and/or airport lay-outs, applying single engine taxi or moving toward zero-emission taxi, using for example in-wheel electric motors or alternatively powered trucks that can tow the airport between apron and runway. Schiphol has trialled the latter option earlier in 2020 (Royal Schiphol Group, 2020). Although no evaluation report of that trial has been published, in general, key challenges for wider operational deployment remain, both with respect to technology (e.g. effect on the aircraft landing gear), energy sources (e.g. bio-diesel, electric or hydrogen-powered) and operational aspects (e.g. safety). Moving towards a more or completely autonomous system would reduce cost and thereby increase the appeal of this option for operators, but also require research work on especially safety aspects and integration into current operating procedures.

IN-FLIGHT EMISSIONS AND INTERDEPENDENCIES

Reducing the negative local environmental impact of aircraft flying in the vicinity of the airport currently requires a careful balancing act between noise and emissions. Circumnavigating urban areas for example increases flight distances, and thereby yields additional fuel consumption and associated emissions. Better understanding these interdependencies, for example in terms of the impact of various emissions on overall quality of life, should be a key research priority in the coming years, as this will help make well-supported and research-based (policy) choices. Research efforts could for example help determine what balance between noise and emissions is most supported by society.

On the other hand, some current or anticipated future operational procedures yield synergistic effects in terms of both noise and gaseous emissions. Continuous descent and climb operations (CDO and CCO, respectively) are key examples. Especially the extent to which CDO is and can be implemented in operation leaves room for improvement. In order to enable the use of these procedures in busier air space, key topics for current and future research include separating inbound and outbound flows in 4D-trajectories, merging and sequencing mechanisms that support CDO (e.g. point merge), accurate (short-term) weather forecasts, ATC system support, and flight procedure and airspace design.

In terms of reducing noise and annoyance, community engagement is key. The European Horizon 2020-project ANIMA that examines non-acoustical factors to noise annoyance has already found evidence this is essential for ensuring noise-reduction measures are recognized by the public (Nicolescu, 2019). This has also been acknowledged by organisations as ACI and CANSO (ACI, 2019). It does not need to be said that with the current social media platforms and interconnectivity, adverse noise impacts are earlier and more broadly noticed and discussed than before.

6.3. Infrastructure

Chapter 4 discussed several aircraft configurations: (hybrid)-electric aircraft, hydrogen powered aircraft and conventional aircraft. For the latter it is assumed that SAF is used in this chapter. In fact, these configurations come down on three different categories of energy carriers: batteries, hydrogen and SAF. The fuelling process, whether that is charging or either changing the battery or really fuelling the aircraft with SAF, is for each category different. This means that in the transition towards 2050, airports need to be ready to accommodate the different ways of fuelling the aircraft. This will have a huge impact on the current airport infrastructure and operations, imposing new challenges in the very near future. This section will briefly touch upon the challenges that are ahead of these (new) aircraft configurations in terms of infrastructure and airport operations.

(Hybrid)-electric aircraft need to be charged (and refuelled) during stops. Facilitating an aircraft with a full battery can be done in two ways; either by charging the on-board battery of the aircraft or by swapping batteries. The main challenge for plug-in charging an aircraft is the charging time, as an operational constraint is the turnaround time. Using (multiple) fast chargers could compete with turnaround times of conventional aircraft. However, it would impact peak power, required form the grid.

Battery Swapping Stations (BSSs) would overcome the limitations of charging time and temperature constraints, where depleted batteries can be swapped by fully charged ones. However, BSSs are costly as you need a (robotic) infrastructure for the station as well as much more space than a regular charging point. Besides you would need multiple batteries, which is an investment. Another limitation is the aircraft itself: it needs to be designed to have its battery easily swapped.

Up to now, multiple studies to charging configurations and different types of charging have been done for the automotive industry. The operational constraints for an airport are different than for cars, especially if it comes to turnaround time. Besides, the studies done on aircraft charging cover only single type of sustainable aircraft; not a mixed fleet of electric and hydrogen or SAF aircraft. As it comes to energy demand and for example onsite production of hydrogen, this would severely impact energy consumption of the airport if it would be combined with battery powered aircraft. On top of that, electrification of the GSE and other equipment around the airport is not taken into account in current studies, while these are important too for reducing climate impact. Keeping in mind the life cycle and especially the low emission requirement of future aircrafts, fuel and energy production from renewable sources has to be considered.

In this regard, supplying the tremendous energy demand of aircrafts is quite challenging. New regulations and working methods have to be developed. For turnaround operations optimization models need to be developed to find an optimum for the energy demand while at the same time maintaining competitive turnaround times. Also energy storage becomes important, i.e. the optimization of the required storage capacity in dependence of energy availability from fluctuating renewable sources and aircrafts energy requirement (based on turnaround time).

6.4. Maintenance, repair and overhaul

Maintenance, repair and overhaul (MRO) solutions are fundamental to keep assets in service as long as possible. Keeping assets in use is a fundamental pillar in sustainability, as first of all it will reduce the amount of raw material and resources needed for the production of new assets. Also more economic value is retained by maintaining existing assets, rather than by dismantling assets and reusing their parts or components, and even more value than by recycling the materials assets are made of. For aircraft, MRO comes down to the ability to identify damage, monitor its evolution, and to the repair possibilities offered by the structure and the location of the damage.

Specific advancements in MRO technologies can enable to keep current aircraft types in service longer; in particular, the integration of multiple inspection methods at once and the implementations of more efficient inspection solutions (for example performed by remotely controlled drones), combined with advancements in repair solutions and their certification. On the other hand, new technologies implemented in aircraft concepts would require the development of new solutions to perform maintenance, repair and overhaul activities. For example in systems for hydrogen-powered aircraft, detection of leakages is of paramount importance, together with the reliability of the subcomponents of the system, such as pumps and valves. Aircraft with batteries would need to be designed to ensure accessibility and ease to replacement of the batteries. Concepts such structural batteries and hydrogen tanks will require combining inspection requirements and repair solutions which ensure both the structural integrity of the airframe and the safety of the energy storage system. The introduction of new materials (e.g. bio-based materials) will also require further research about MRO technologies compatible with non-traditional aerospace materials. In the case of recycled composites, regulations do require validation of uniformly random distribution of the chopped fibres. Such validation is beyond the state-of-the-art and therefore the introduction of components made out of recycled composites is limited.

IMPACT MONITORING

7. IMPACT MONITORING

Given the size and importance of the sustainability challenge presented in Chapter 3, it is imperative to realise significant progress in the next few years. In order to ensure progress, this chapter describes research activities to model the uptake and impact of the various solutions described in the previous chapters.

7.1. Climate impact

Previously shown in Section 3.1, the level of scientific understanding of various climate impacts differs. This needs to be improved in order to better direct research and innovation resources and efforts, and prevent currently unforeseen side-effects of particular technological or operational changes. In order to define effective mitigation measures, both the CO_2 and non-CO_2 climate impacts must be thoroughly understood. Based on this knowledge, models and tools can assist in quantifying the impact of research and innovation output.

Specifically, increasing scientific understanding of non-CO_2 effects on climate change, such as NO_X, SO_X, water vapour and contrail cirrus formations. Research must be focused on understanding and quantifying the underlying uncertainties and background physical/chemical processes. Uncertainties in background processes that influence the climate impact of non-CO_2 emissions centre for example around the difficulties in accurately simulating ice nucleation in the background of the atmosphere, which influences the soot-cloud interaction.

With an increased scientific understanding it can be better assessed which factors cause certain increases or decreases in climate impact, according to which the mitigation measures can be designed respectively. With a better scientific understanding of non-CO_2 climate impacts, the effects of a single parameter and the overall effect of certain mitigation measures can be better quantified.

MODELLING

Through Global Circulation Models (GCM) and Earth System Models the climate impacts of these species have been modelled, but the results are highly dependent on the input data set (aircraft emissions) and assumptions in the model (such as resolutions in atmospheric dynamics or background concentrations and chemical processes), causing different researches and models to output various ranges of climate impact indicator values such as global warming potential (GWP) or average temperature response (ATR) values.

In order to model the impact of mitigation measures (such as new technologies or operational improvements) on climate and aviation processes, it is of interest to model the effects on different spatial and time scales, i.e. for individual aircraft and various fleet sizes. Also, the location and timelines over which the mitigation measures are implemented are of interest to model, as the various emission types impact various scales (regional versus global) and timelines (hours, days, weeks, months, years, centuries).

In order to do so, aircraft performance, air traffic, GCM Earth System models should be combined to assess the impact of aviation climate mitigation measures properly. Up until now, the aircraft performance and air traffic models have been separated from GCM and Earth System models, which generally use emission datasets as input to calculate the impact of aviation. If these models are better integrated, the emissions of aircraft can be directly translated to climate impact.

The validation of the currently modelled overall non-CO_2 climate impact is not possible through measurement data, since no measurements have been performed for climate impact of for example NO_X or soot.

MEASURING

Due to the high variability of the aforementioned variables and the dynamic character of the atmospheric processes, the precise climate impact of the non-CO_2 emissions have not yet been quantified through measurements. For example, it is possible to measure NO_X or soot emitted by aircraft (through in-situ measurements), but current technologies are not able to measure or visualize the resulting specific NO_X-O_3 mechanisms or soot-cloud interactions resulting in specific RF values in the atmosphere.

In recent researches, attempts have been made to increase the scientific understanding of the NO_X-O_3 mechanism in the atmosphere. The production of O_3 from aviation emitted NO_X depends on various parameters, such as background concentrations of NO_X, temperature, wavelength of incoming solar radiation, and competing background chemical reactions. Previous research has attempted to identify the path of NO_X emitted in certain locations in a weather pattern up to the production of ozone. These kinds of insights are essential as it contributes to better understanding where and when certain emitted NO_X will produce ozone, which will contribute to designing measurement campaigns of aviation induced O_3.

The assessment of these kind of uncertainties that influence the climate impact of non-CO_2 could contribute to designing measurement campaigns for non-CO_2 climate impacts of aviation. This increases the scientific understanding of the both the individual and overall climate impact of non-CO_2 emissions.

Besides in-situ measurements also measurements with remote-sensing techniques could contribute largely to the increase in scientific understanding of the climate impact of aviation. However, current remote-sensing technologies do not possess sufficient vertical resolution to adequately measure and visualize aircraft specific emissions and their subsequent climate effects.

ASSESSING CLIMATE IMPACT OF AVIATION ON A BROADER SCALE

An aspect that is often overseen is that the climate impact of aviation is not solely attributed to in-flight or LTO emissions. Life-cycle greenhouse gas emissions and their climate impact during production, operation and end-of-life for aircraft (and possible alternative modes of transport) are important to assess. This is specifically relevant with respect to emerging technologies, such as (hybrid-)electric aircraft and electric taxi concepts. Although the in-flight emissions of electric aircraft are zero, the energy generation for the needed electrical energy in the batteries may require CO_2 intensive processes. A green alternative is to generate this energy through solar- or wind farms, however, these options require large investments and commitments of airports.

Furthermore, the maintenance, production and end-of-life of aircraft emissions should be further investigated. Sustainable and low-emissions options should be further investigated to reduce overall life-cycle greenhouse gas emissions.

7.2. Local environmental impact

Numerous models and metrics exist for assessing the local environmental impact of current operations. New types of aircraft, innovative configurations or increased understanding of annoyance and stress, however, might require extension or updating of these. The following section discuss these needs for noise (Section 7.2.1) and air quality (Section 7.2.2).

7.2.1. Noise

For assessing the impact of the new technologies and operations, accompanying noise prediction models should be developed. To validate and further develop these models, ground-based noise measurement stations should be used. The noise prediction models should:

- Analyse the effect of new technologies on noise emissions during various flight phases.
- Allow for optimizing the operations for low-noise.
- Provide noise (annoyance) level footprints.

The noise prediction models should allow for easy and rapid adaptation to the introduction of new aviation technologies.

In addition, efforts need towards

- The use of measurements for continuous validation of the noise model predictions.
- Transparent communication to communities.
- Realization of metrics that reflect the noise annoyance and are accepted as such by the communities.
- Analysis of the effect of these emissions on health and quality of life around airports.

7.2.2. Air quality

For assessing the impact of the new technologies and operations, accompanying air quality prediction models should be developed.

- Analyse the effect of new aircraft technology, alternative energy sources and fuels on the emissions that affect air quality.
- Analyse the effect of these emissions on health and quality of life around airports.
- Improve understanding of how cruise-level emissions impact air quality.
- Analyse inter-dependence between aviation's air quality and other sectors' impacts.
- Improve understanding and modelling capabilities of aviation's nitrogen deposition impacts.

7.3. Resource impact

The resources used within the air transport systems is varied, ranging from materials for airframe structures, to construction materials for airports and infrastructures, from electronics, to textile for interiors and furniture, to food and other disposable and perishable materials, next to energy and water.

A number of metrics to evaluate the environmental footprint of resources already exists, such as life-cycle assessments (LCA), environmental, social & governance (ESG) rating, circularity indicators (Ellen MacArthur Foundation, 2017), cradle-to-cradle indicators, emissions measurements. Currently, monitoring the usage and the environmental impact of this variety of resources is strongly dependent on the state-of-art practices and standards within a specific industry. Though sustainability indicators are still being developed in the majority of industries and sectors, in some sectors sustainability practices are in a more mature stage of implementation than within aviation. This means indicators and standards are developed in other sectors, but their applicability within aviation is not verified. Research on those metrics shall assess the need for the development of brand-new indicators specific for aviation or the modifications needed to existing metrics in order to apply them to aviation resources.

A commonly used tool with regard to airframe materials and manufacturing is LCA. Nonetheless, such assessment does not cover the overall, cradle-to-cradle, impact, as in most assessments it narrows down to in-house processes, without accounting what happens up- and down-stream. The need for comprehensive, from mining to grave, LCA approach is urgent in order to fully evaluate the environmental impact of aircraft manufacturing and material flows.

An obstacle to the implementation of resource impact assessment is that EU policies giving directives for recyclability, circularity and end of life aspects, exclude aviation and means of transport in general. For example, the Directive 2012/27/EU addresses eco-design requirements for energy-related products, and it excludes transport. Directive 2005/64/EC addresses end-of-life requirements for the automotive sector; a similar directive for the aviation would enable resource impact in the sector.

AIR TRANSPORT SYSTEM CHANGES AND POLICY

8

8. AIR TRANSPORT SYSTEM CHANGES AND POLICY

Fundamental changes to the air transport system are required in the coming decades to reach the environmental goals described in this Whitepaper. First of all, the timeframe for reaching entry into service of new technologies needs to speed up. Secondly, these new technologies may have fundamental implications on the way our air transport system functions. Last but not least, understanding these changes will allow to define, implement and evaluate suitable policy measures.

8.1. Enabling a reduction in time and cost to market entry

Ambitious goals have been formulated to improve sustainability of aviation. To meet the time frame of these goals the smooth and quick market entry of new aircraft types and technologies has to be facilitated. To enable this, modelling, validation and testing is key. Besides these, safety, smooth qualification and certification is crucial.

8.1.1. Modelling, validation and testing

Essential for developing the next generation of aircraft for the different categories is that we fully understand the improvements towards sustainability and the performance of the aircraft. Furthermore, bringing the next generation to the market in due time and with low development costs requires an optimized development process. Modelling all aspects of the aircraft and its environment, simulating operations and validating the results, eventually with tests, needs to be improved for the development of the next generation aircraft. To understand the interaction of various components multidisciplinary design optimisation can be used. Specifically, for the development of hybrid electric propulsion and hydrogen burning engines, testing can be performed using specific propulsion test benches. Finally, using functional, scaled flight and full-scale demonstrators helps to test and implement new technological developments.

8.1.2. Safety, qualification and certification

Flight safety is paramount for any aircraft operation. All new technology shall be qualified and the new aircraft types shall be certified. To assess the impacts on flight safety, a thorough knowledge of all aspects of the technology, including the failure cases, is essential. This applies to a fundamental level, to the application level, to component, to subsystem level, to system level and to aircraft level. Currently, some work on this is already in progress; this happens amongst others in EUROCAE and SAE standardisation Working Groups, aiming to generate standardized views and accepted means of compliance for the new technology and components. The knowledge about failure mechanisms and adequate qualification will lead to aircraft with the new technology that can be certified to the same high flight safety levels as we now have for current technology. New challenges appear if benefits of applying Artificial Intelligence in aircraft systems are introduced. As this will take time, generating the knowledge soon and introducing robust but flexible and fast procedures will allow to introduce the new technology in the pace indicated in section 4.1. Especially for hydrogen much of the knowledge of the technology and failure cases are new and, for instance, redundancy of systems, leakage detection and evacuation mechanisms are to be addressed.

8.2. Air transport system changes

As presented in Chapter 4, electrical aircraft propulsion – albeit battery-powered, hybrid-electric or using hydrogen fuel cells – is most feasible for commuter and regional aircraft travelling short distances. For flights within Europe nowadays single aisle aircraft are mainly used. If these aircraft were to be substituted with (potentially more climate-friendly) smaller electric aircraft of 20 to 50 seats, the number of flights required to transport the same amount of passengers would increase substantially. This is even more so if these flights also include multiple stop operations to allow for battery swapping/charging. For European and Dutch airports, the effects of increasing the number of flights needs to be assessed in terms of airport capacity and noise impact on the local community. As these aircraft are smaller, it may be possible to perform these flights from smaller regional airports instead of larger hubs. These changes may change existing business models and create new ones.

Another major change in flight schedules and frequency can be expected if jet aircraft are substituted by turboprops. Hybrid-electric turboprops typically fly slower (below Mach 0.7) and at lower cruise altitude. For hydrogen-powered aircraft, these impacts are most likely much more limited. McKinsey & Company (2020) note refuelling times as a challenge for implementing hydrogen-powered aircraft. On the other hand, that mostly affects cost, fleet and airport size, but does not seem to be a system-level change. Similarly, cruise speeds are largely maintained compared to what is currently observed.

Mostly irrespective of the energy source used (with the possible exception of zero-emission propulsion technologies), flight routes may be subject to day-to-day variations to avoid climate sensitive regions. As also indicated in Section 6.1.1, these changes may have cost implications for airlines and affect air traffic management procedures.

8.3. Assess the range of policy measures

A variety of policies measures are currently implemented or under study or development to reduce the environmental impact of aviation. To assess the economic and environmental impact of policy measures, analysis tools can be used to compare newly developed sustainability scenarios to the business-as-usual scenario. This requires assumptions on aircraft technology characteristics based on fleet development, a demand forecast, estimates of the overall aircraft operating costs, estimates of in-flight emissions and related climate impact, and estimates of the overall economic impact. These analysis tools (such as AERO-MS) provide a quantitative description of the effects of policy measures on all relevant actors (airlines, consumers, governments and manufacturers).

WAY FORWARD

9

9. WAY FORWARD

The future of aviation is depending on its ability to make the transition towards a fully sustainable system. Aviation has to reinvent itself in every aspect; from design and manufacturing to operation and decommissioning. After a short summary of the vision presented in this whitepaper the process towards a supporting research and development programme is sketched.

9.1. Towards a Climate Neutral Air Transport System

This Whitepaper presents a pathway towards a climate neutral air transport system which has a lower impact on the environment and which is based on the circularity principles.

To achieve this, radical changes are necessary. This requires the development of new aircraft concepts, components and powertrains, sustainable fuels and energy sources and operational changes to implement these new technologies. Furthermore, enabling processes and technologies need to further developed irrespective of their direct contribution to a particular design.

Assessment of the progress towards a climate neutral air transport system is essential and should be combined with an assessment on the impact it has on local communities and the environment. This requires improved models for impact assessment at aircraft, airport and air transport level.

To support this transition, policy and regulation should be developed in parallel to provide the boundary conditions for all the stakeholders to play their part. The main stakeholders and their roles are:

- Research: to develop the technology;
- Aircraft Industry: to develop the products;
- Chemical Industry: to develop the sustainable fuels;
- Airports: to provide the necessary infrastructure;
- Airlines: to procure the aircraft;
- Passengers: to choose the sustainable alternative.

9.2. Towards a National Research and Development Programme (NOOP)

Aviation is a global business. Not just in operating the aircraft, but also in the research and development phases as well as the supply chain for the production. Because of the sheer size of the challenge aviation is facing also the solution needs a global effort. In aerospace research and development the ecosystem is typically organised per continent, mainly the United States of America and Europe. Currently Europe has the strongest focus on reducing the climate impact of aviation, where the ecosystem is organising itself to reach the European Green Deal objectives in current Horizon 2020 and future Horizon Europe research frameworks.

The NOOP will have to be closely aligned with European programs such as Clean Aviation and Integrated ATM to avoid overlap and to prepare Dutch research institutes and companies to play a substantial role in the research programs and eventually be part of the supply chain. For large commercial aircraft, the Dutch contribution will support more integrated demonstrations on the European level. For smaller platforms, demonstrations can be achieved on a national level. For operational developments, The Netherlands could facilitate large scale demonstrations.

The view presented by NLR and TU Delft in this Whitepaper is meant to support setting up a dedicated national research and innovation programme for sustainable aviation. The Dutch programme called “Nationaal Onderzoeks- en Ontwikkelingsprogramma” (NOOP), will bring together knowledge institutes and universities with industry and government to work on new technological concepts. This programme will enable establishing the Netherlands as centre of excellence for sustainable aviation.

Cooperation with other knowledge and research institutes, as well as with large and small industry players, is key to realise the sustainability objectives. In the Dutch aerospace sector the Triple Helix model depicted in Figure 24 has been successful for decades. Although a leading role may be expected from NLR and TU Delft, given their fields of expertise, the research topics addressed are intended to be carried out with other Dutch universities and research institutes such as TNO and KNMI.

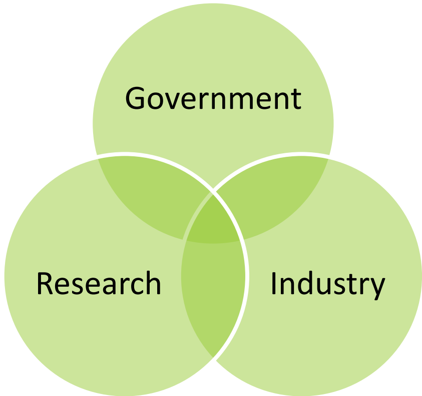

Figure 24: Triple helix structure of the Dutch aviation R&D ecosystem

Within the NOOP, knowledge institutes are working at the front-end of the innovation chain, but do not manufacture or operate aircraft. This means that industrial partners, such as manufacturers and airlines, will also play an increasingly important role during the course of the NOOP to maximize the positive impact for the Dutch society and industry.

FORESEEN OBJECTIVES FOR NOOP

The research and development programme aims to contribute to the following objectives:

- Enable pathways to achieve the environmental goals and support the sustainable development of a climate neutral air transport system:
  - Develop aircraft with net-zero climate impact;
  - Develop net-zero climate impact operations;
  - Reduce resources use;
  - Reduce noise emissions;
  - Improve air quality.
- Serve as research support and scientific background for all partners in the “Duurzame Luchtvaarttafel”.
- Expand the knowledge base leading to added value for the Dutch aviation sector:
  - Address both fundamental research and application-oriented research;
  - Set-up a technology watch for enabling technologies;

- Enable closer cooperation and collaboration with European and international partners.

APPROACH: FROM WHITEPAPER TO NOOP

In the aviation industry the implementation into products of results from exploratory research has long lead times. Technologies need to mature before they can be certified and applied in commercial applications. Currently, aircraft are designed to have a lifespan of 20 to 30 years and can take up to 15 years to develop from concept to entry into commercial service. In the future, lead times to introduce new technologies should be shortened, by gathering research information faster and more efficiently, by digitalisation of the certification process and by increasing the attractiveness and enforcement of new solutions through policy measures. To have a substantial impact by 2050, new aircraft need to enter the market in the 2030's. This means disruptive innovations need to be developed the coming years in order to be implemented in the next generation aircraft. It is essential to start performing the supporting research as soon as possible to ensure it enables reaching the long-term goal of climate neutrality in 2050. The relation between research and application in the aviation industry to reach the environmental goals is given in Figure 25.

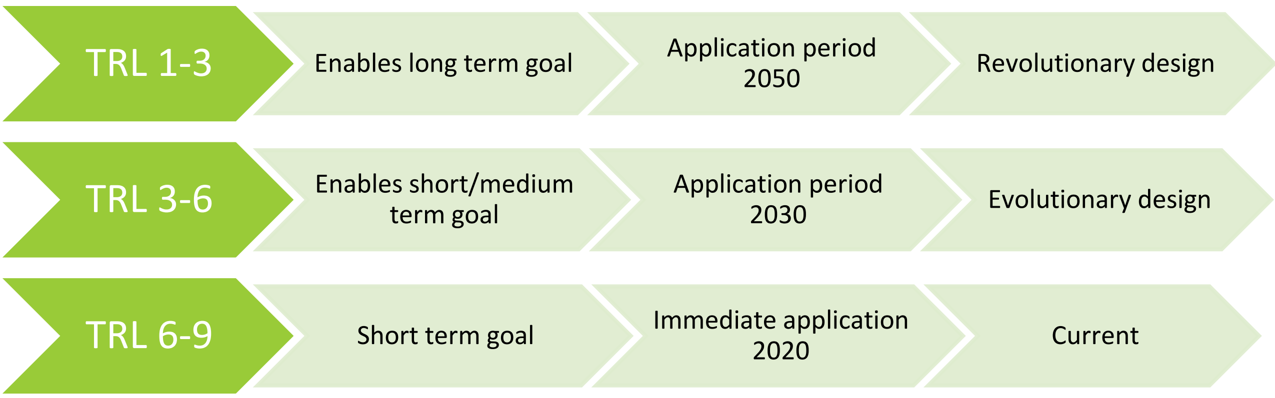

Figure 25: Relation between research activities and expected application period in the market in order to meet environmental goals.

After the publication of this Whitepaper, further steps need to be taken to implement the vision presented in this document into a national research and innovation programme. The following steps are foreseen:

1. Further elaborate the selected R&D topics based on NL strengths and NL position within international context to establish The Netherlands as a centre of excellence for sustainable aviation.
2. Further elaborate the selected R&D topics based on industry opportunities and business cases.
3. Implementation of a Technology watch framework that allows timely update of the of state-of-the-art technologies.

For each of the promising research topics presented in this Whitepaper, multiple organisations needs to be identified best suited to perform the work in an impactful and collaborative manner. For numerous topics, cooperation and collaboration with other European or international partners may be essential. This will strengthen alliances with partners and increase the competitive position of the Netherlands within the international context.

To increase the competitiveness of the Dutch aviation industry, close collaboration needs to be established to ensure innovations can be applied in an industrial context. This innovation chain, as shown in Figure 26 , starts with fundamental research, followed by application-based research, leading to technological risk minimization in demonstration projects which can be scaled-up to industrial applications. Based on the phase of the R&D, different players are active and involved. In the more fundamental phase where the outcome is uncertain, mainly the knowledge institutes will perform the work with guidance from industry and government. As the maturity of the technology increases, industry will play a larger and more active role as risks are lower. In a phase where the technology will mostly be matured to industrialisation the knowledge institutes' role will be decreasing. Funding instruments and cooperation mechanisms will have to be tailored to these different phases in technology maturation.

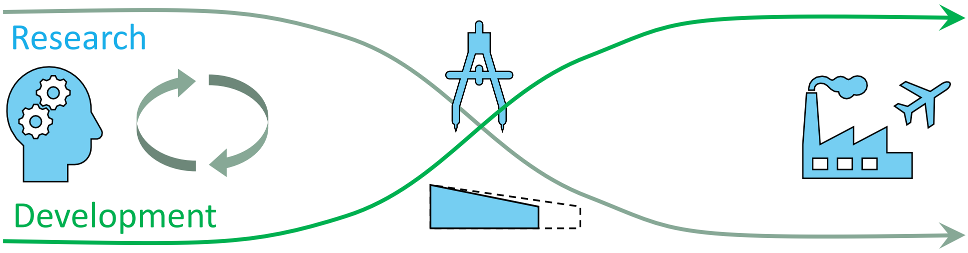

Figure 26: From research and innovation to industrial application

GOVERNANCE

Next to the technical topics elaborated in this whitepaper, the governance of the programme and financial instruments will have to be elaborated among the partners of the "Duurzame Luchtvaarttafel". The current organisational structure of Action Programmes and existing collaboration projects has to be incorporated with the NOOP. Figure 27 shows the different TRL ranges where customised financial instruments are necessary. Depending on the technology readiness level, different funding rates can be applied in accordance with European state-aid law. All these levels have European funding instruments as well, which requires a close harmonisation and coordination.

A necessary part of this governance is a continuous updating process of the list of technologies based on the latest insights, thereby creating a monitoring and evaluation loop.

Figure 27: Timeline from research to development and subsequent action, linked to TRL levels.

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