DEPA 2070 – Final Report

Development Pathways for Aviation up to 2070

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List of abbreviations

AAM	Advanced Air Mobility
AC	Aircraft
ACTE	Adaptive Compliant Trailing Edge
AI	Artificial Intelligence
AIRNAF	Aircraft Noise Analyses Framework
ASK	Available Seat Kilometres
ATAG	Air Transport Action Group
ATM	Air Traffic Management
AzB	Instructions for the calculation of noise protection zones
CAGR	Compound Annual Growth Rate
CCU	Carbon Capture and Utilization
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DEA	Data Envelopment Analysis
DEPA	Development Pathways for Aviation
DLR	German Aerospace Center
DLR CON	DLR Constrained Forecast
DLR UC	DLR Unconstrained Forecast
DOC	Direct Operating Costs
eCTOL	Electrical Conventional Take-off and Landing
EIS	Entry Into Service
ETS	Emissions Trading System
eVTOL	Electric Vertical Take-off and Landing
FLOX	Flameless Oxidation
GDP	Gross Domestic Product
GVA	Gross Value Added
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNAS	Low Noise Augmentation System
LTO	Landing and Takeoff
MENA	Middle East and North Africa
MRV	Monitoring, Reporting and Verification
Mtoe	Million Tonnes of Oil Equivalent
OECD	Organisation for Economic Co-operation and Development
PtL	Power-to-Liquid
PLR	Programmed Thrust Lapse Rate
PwC	PricewaterhouseCoopers
RED	Renewable Energy Directive
RFNBOs	Renewable Fuels of Non-Biological Origin
RPK	Revenue Passenger Kilometres
SAF	Sustainable Aviation Fuels
SAT	Small Air Transport
SC	Seat Classes

SDS	Sustainable Development Scenario
SPS	Stated Policies Scenario
SSP	Shared Socioeconomic Pathway
SST	Supersonic Transport
STEEP	Society, Technology, Economy, Environment, Policies
SVS	Synthetic Vision System
TAS	True Airspeed
TBW	Truss-Braced Wing
TMS	Thermal Management System
TRL	Technology Readiness Level
UAM	Urban Air Mobility
UHBR	Ultra-High Bypass Ratio
US BEA	US Bureau of Economic Analysis
US BLS	US Bureau of Labor Statistics
VNRS	Variable Noise Reduction Systems
WEF	World Economic Forum
WET	Water-Enhanced Turbine

Content

1. Introduction

1.1. Motivation for the Project

Despite of economic downturns and other wild card effects the growth of the air transport sector remained stable during the last decades. Given its role in the globalised and dynamic world of today the aviation industry is therefore an important driver for economic growth and welfare as well as an important enabler of cultural exchange and technological progress. Advanced aviation technologies and new transportation concepts (e.g. in the field of supersonic air transport and advanced urban air mobility) will further contribute to the full exploitation of its benefits in the long-term.

In order to enable a more sustainable and more efficient development in this respect, the air transport stakeholders have put enormous effort in the preparation of a system-wide transformation during the last years. In 2016 the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was established by the International Civil Aviation Organization (ICAO). As a result, the global aviation industry represented by important stakeholders like the International Air Transport Association (IATA) committed itself to the goal of climate neutrality by 2050. The European Green Deal as introduced in 2019 and programmes like Clean Sky 1 (2008-2018) and Clean Sky 2 (2014-2024) demonstrated in parallel the European ambition to contribute significantly to a system change.

Within this context the DLR research project "**DE**velopment **P**athways for **A**viation up to **2050**" (**DEPA 2050**) was launched in 2019 to analyse the system-wide impact of the significant changes expected in the aviation sector over the next 30 years starting from 2020 onwards. The study findings showed that a trend reversal with regard to the CO_2 emissions development despite of growing aviation demand might be possible considering increased usage of sustainable aviation fuels (SAF), improved aviation technologies and progress in air traffic management optimisation. Nevertheless, this holds only for the progressive scenario assuming an accelerated entry into service (EIS) and market diffusion of promising aviation technologies.

In relation to this outcome the follow-up project "**DE**velopment **P**athways for **A**viation up to **2070**" (**DEPA 2070**) was launched in 2022 to investigate the possible improvement of aircraft technologies with the aim of CO_2 emissions reduction addressing especially the time span 2050 to 2070 to consider the resulting impacts on the needed energy mix for air carriers over the next 50 years. For this purpose, promising technologies were chosen for an integration into aircraft concept models to populate the future global fleet. As in the previous project DEPA 2050 this step formed the base to conduct a scenario-based analysis presuming two probable pathways for the potential technological progress in order to analyse the total impact of the scenario-specific aviation development. This was done by addressing the three pillars of sustainability (i.e. environment with gaseous emissions & noise, economy and society) as well as the impact on aviation infrastructure.

Following this approach, the main intention of this study was to provide a holistic and coherent view on the potential future development of the aviation sector for the time span up to 2070. This required a differentiated analysis of possible trends in the air transport sector with a special focus on the time span 2050+. In addition, a major update of the DEPA 2050 scenarios (e.g. by considering the impact of the Covid-19 pandemic and the European Green Deal) and the resulting technology and vehicle roadmaps was carried out to address the latest developments since 2021. The further extension of the research focus concentrated on the development of a highly sensitive fleet model that allows to consider the insertion of new aircraft types in the fleet including innovative propulsion. Furthermore, extended assessments of direct operating costs (DOCs) were carried out to compare aircraft performance and economic results to deviate realistic assumptions for the future fleet composition with regard to both pathways that were analysed in the project. Finally, the intention was to provide a holistic impact assessment. For this purpose, a noise assessment approach was elaborated in the project to consider also aircraft noise in the environmental domain besides the stronger focus on gaseous emissions in the previous project. In addition, the coverage of mobility and economic effects was broadened by regarding the needed infrastructure up to 2070 to illustrate what the findings of the project mean for the further development. Especially, chances and challenges should be investigated this way to estimate the framework conditions for the DEPA 2070 development pathways.

Summing up the motivation for the study, the major intention of the project was to provide a better orientation on developments that can be expected in the aviation sector over the long-term. This holds especially for the time span 2050+ which is characterized by higher uncertainty. Two development pathways (a more conservative one and a more progressive one) were modelled in this respect in the most possible level of detail in order to provide a reliable base for the concluding remarks (cf. section 7).

1.2. State of Research

As outlined in section 1.1, the major motivation for the conduction of the DEPA 2070 project was to investigate how long-term pathways for aviation may look like with a special focus on the time frame 2050+. In addition, the microscopic and holistic analysis methods of the DEPA 2050 study should be improved and extended.

With regard to other external studies and projects the temporal coverage of the time span beyond 2050 or a global focus are often out of scope.[1] This is mainly driven by the fact that the most important goals for the further development of the aviation sector refer to the year 2050 or are limited to the European area.[2] For further external studies and projects in the described field of research an integral and detailed assessment is often missing. While in some studies mainly technological potentials for a specific type of aircraft or specific market segments are regarded[3] the DEPA projects focus on all relevant and established types of market segments for air passenger transportation (i.e. mainliner/regional aircraft, business jets and aircraft used for small air transport) as well as advanced types (e.g. supersonic transportation and urban air mobility in the DEPA 2050 project). Technology potentials were investigated and evaluated with high granularity not only as input for the DEPA 2070 roadmaps but also for further consideration to develop aircraft concepts for the DEPA 2070 scenarios that are major inputs for further fleet and demand modelling. To guarantee a high-fidelity modelling in this respect, the aircraft concepts were modelled for each of the 12 ICAO seat categories and evaluated not only with regard to their technical performance but also with regard to their economic performance to achieve a most realistic fleet composition for the future based on available data.

Referring to these major components of the DEPA 2070 activities, a higher granularity and more robust results could be achieved in comparison to other studies that concentrate on the assessment of single technologies or aircraft concepts. In addition, the impact analysis is covering a broad range of different categories including the three pillars of sustainability (i.e. environment, economy and society) and was extended for DEPA 2070 for the first time by a new approach for aircraft noise estimation and by considering the impact of the DEPA 2070 scenarios on the aviation infrastructure. The latter also allowed to identify and evaluate potential challenges and bottlenecks with regard to the long-term pathways for aviation more concretely than in the previous project. Another strength of the DEPA 2070 research approach is its scalability. As results can be assessed and evaluated on mission, airport and air transport system level based on the airport-specific demand forecast up to 2070, the complexity of the air transport system and the mechanisms behind are adequately addressed. This high level of detail is not necessarily given in other research studies on the long-term future of aviation. Similarly, methodological approaches in some studies are often not made transparent.

Facing these conditions, the major intention for the DEPA 2070 project was to provide a holistic and consistent assessment about the future of aviation by addressing the latest developments since the previous project DEPA 2050 and by extending the temporal scope up to 2070. Besides the results of these assessments this report also summarises the major assumptions that were made and the methodological approaches to provide an insight into the used study framework.

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[1] Cf. Destination (2050); ATAG (2021); Clean Aviation (2024).

[2] Cf. European Commission (2025).

[3] See for example Rischmüller et al (2024); Roland Berger (2020a).

1.3. Research Objectives

From an overall perspective the main intention of the DEPA 2070 project was to contribute to the closure of existing research gaps with regard to the DEPA 2050 project and with regard to the state of research as described in the previous section. Based on this the high-level targets of the project were defined as follows:

1. Definition, description and evaluation of possible development pathways for aviation up to 2070 in consideration of major trends in special regard of air transport market and technological developments, energy availability, infrastructure requirements and potential changes on the political and social level (e.g. as a result of the European Green Deal and the Covid-19 pandemic)
2. Detailed assessment of technology-related scenarios and corresponding consequences for sustainability and air transport infrastructure
3. Illustration and discussion of realistic further development perspectives of the air transport system in consideration of the long-term ecological, economical and societal impact

Those strategic objectives served as starting point to define more concrete goals on operational level which are described in the following section.

2. Project DEPA 2070

2.1. Objectives

Based on the strategic objectives the project DEPA 2070 was launched to provide an update and extension of the analysis that was conducted in the previous project DEPA 2050. The major intention for the continuation of the corresponding activities was in this respect to deliver two potential developments pathways for aviation up to 2070. One concentrated on very optimistic conditions for a sustainable transformation of the air transport system within the next 50 years, while the other pathway was stronger oriented on a "business-as-usual" development.

This general approach was transferred into two technology scenarios with different characteristics and different purposes. Following the DEPA 2050 scenario terminology, first a very progressive scenario was designed to demonstrate what could be possible with regard to the overall system transformation if innovative aircraft technologies and aircraft concepts as well as new types of aircraft propulsion would become available for the aviation market. For these components an earlier market entry and a stronger market diffusion was assumed to identify, describe and evaluate the resulting impact for a kind of best-case scenario. The basic requirement was to demonstrate which level of progress could be reached under very optimistic conditions in order to improve the sustainability and performance of the air transport system.

Nevertheless, if infrastructure constraints, "wild card" effects (e.g. economic crises, wars, pandemics,…) and financial pressures the aviation industry is facing should be addressed adequately together with the relatively long development cycles in aircraft manufacturing, a rather evolutionary development is more likely over the next 50 years. Thus, following the DEPA 2050 approach also a conservative scenario was designed and assessed. This scenario is based on the evolutionary development stages of air transport in relation to the past. It assumes a stronger concentration on the improvement of existing aviation technologies. Meanwhile, for new technologies only a slower market entry and a limited market diffusion is considered. The biggest difference in relation to the progressive scenario becomes in this respect clear when the energy mix is regarded. While the progressive scenario assumes an increased usage of liquid hydrogen and an earlier market entry of (hybrid-)electric propulsion in the segment of small and regional air transport, besides SAF there are no hydrogen aircraft concepts in the conservative scenario at all and the market entry of (hybrid-)electric aircraft is delayed.

Besides the development of these two technology scenarios a further objective of the DEPA 2070 project was to regard also a normative scenario that is related to the goal of carbon-neutral growth in air transport by 2050. For this purpose, existing studies on the contributions of the categories "technology", "operations, air traffic management (ATM), infrastructure", "SAF" and "market-based measures" to the reduction of CO_2 emissions in aviation were analysed and compared to the

DEPA 2070 scenarios. This enabled a detailed evaluation to estimate which contributional share of each of the mentioned categories is needed to reach the defined goal of carbon-neutral growth in air transport by 2050.

Finally, more detailed objectives for the project concentrated on the improvement and extension of the impact analysis. Taking the DEPA 2050 project as starting point the air transport demand modelling tool suite was improved. The tool suite was extended in a way that the impact of the Covid-19 pandemic on the market segments of private and business travel could be regarded and analysed in a higher resolution. Different SAF prices and availability scenarios were tested in parallel to check the robustness of different assumptions with regard to the resulting impact on ticket price and demand development. Air fare elasticities were furthermore calculated and tested for a higher regional resolution and the modelling of the impact of multi-airport regions on passengers' travel choices was improved. Finally, the fleet modelling was extended in a significant dimension in order to be capable of considering the market diffusion of new energy types in aviation. For this purpose, performance and economic assessments of the DEPA 2070 aircraft concepts were done to evaluate and prioritize the most promising aircraft concepts that might replace aircraft that has to be retired over the next 50 years.

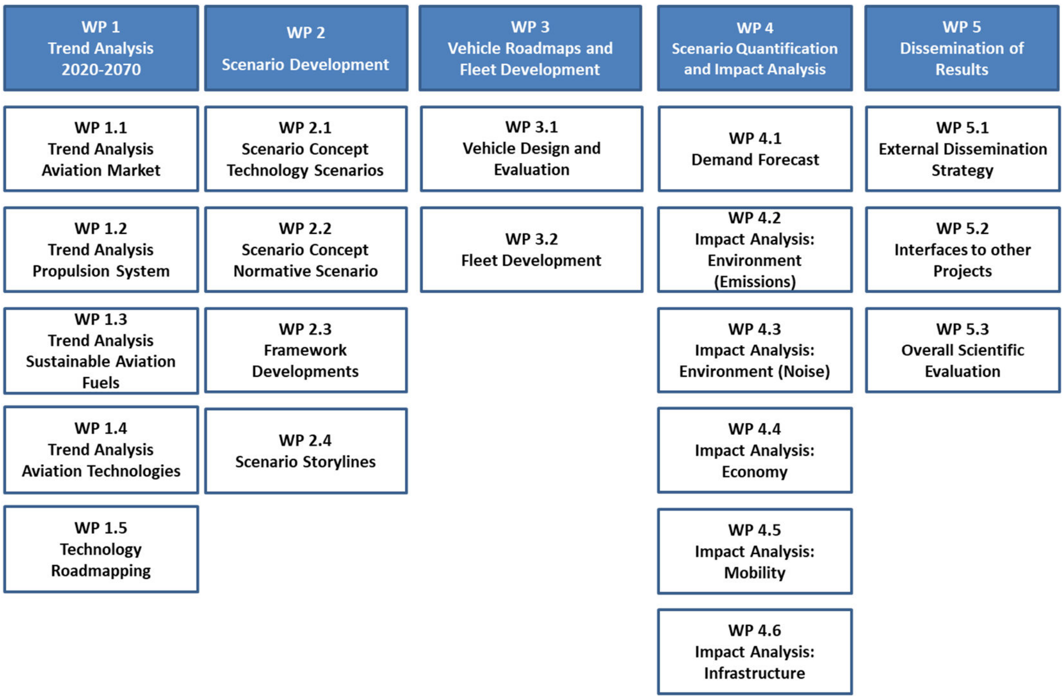
This detailed calculation of the future fleet composition was needed to conduct continuing impact analyses in the field of emissions, aircraft noise, mobility, society and infrastructure which is described in section 6 of this report.

2.2. Structure

The DEPA 2070 project was led by DLR's Institute of Air Transport. In total, six DLR institutes were part of the project:

- Institute of Aerodynamics and Flow Technology
- Institute of Electrified Aero Engines
- Institute of Air Transport
- Institute of Maintenance, Repair and Overhaul
- Institute of System Architectures in Aeronautics
- Institute of Combustion Technology

The structure of the DEPA 2070 project is given in Figure 1.



WP 1 Trend Analysis 2020-2070	WP 2 Scenario Development	WP 3 Vehicle Roadmaps and Fleet Development	WP 4 Scenario Quantification and Impact Analysis	WP 5 Dissemination of Results
WP 1.1 Trend Analysis Aviation Market	**WP 2.1 Scenario Concept Technology Scenarios**	**WP 3.1 Vehicle Design and Evaluation**	**WP 4.1 Demand Forecast**	**WP 5.1 External Dissemination Strategy**
WP 1.2 Trend Analysis Propulsion System	**WP 2.2 Scenario Concept Normative Scenario**	**WP 3.2 Fleet Development**	**WP 4.2 Impact Analysis: Environment (Emissions)**	**WP 5.2 Interfaces to other Projects**
WP 1.3 Trend Analysis Sustainable Aviation Fuels	**WP 2.3 Framework Developments**		**WP 4.3 Impact Analysis: Environment (Noise)**	**WP 5.3 Overall Scientific Evaluation**
WP 1.4 Trend Analysis Aviation Technologies	**WP 2.4 Scenario Storylines**		**WP 4.4 Impact Analysis: Economy**	
WP 1.5 Technology Roadmapping			**WP 4.5 Impact Analysis: Mobility**	
			WP 4.6 Impact Analysis: Infrastructure	

Figure 1: DEPA 2070 – Work breakdown structure

2.3. Methodology

The following figure provides an overview of the DEPA 2070 modelling and assessment framework.

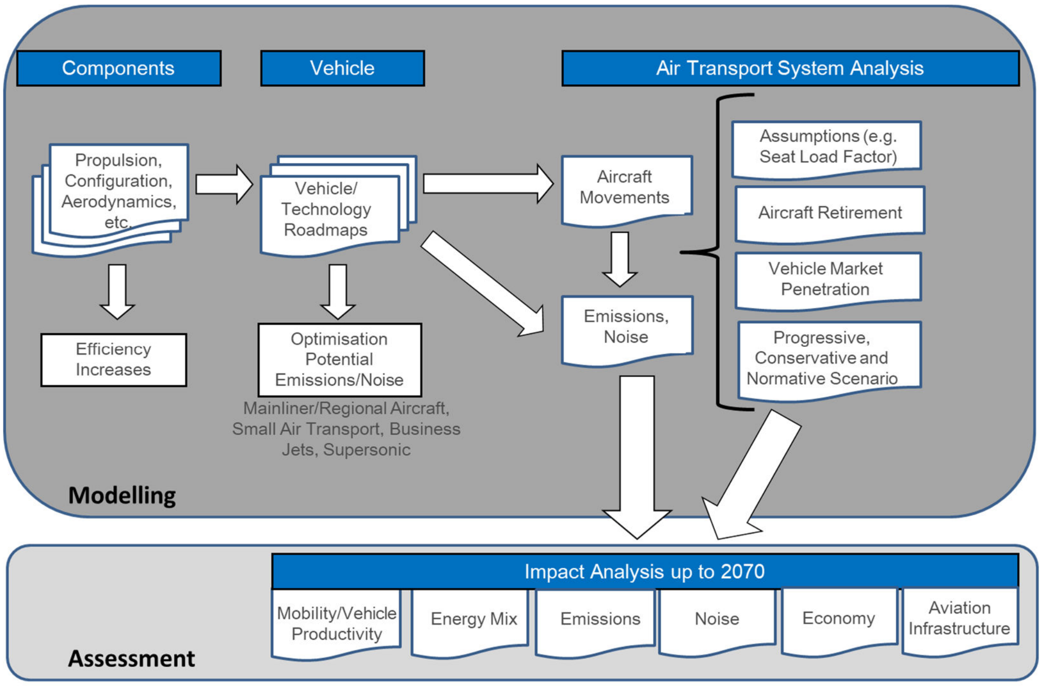


Figure 2: DEPA 2070 – Modelling and assessment framework

As in the previous project DEPA 2050 the research focus was based on a bottom-up approach by starting the modelling on the technology component level and by completing it on the air transport system level. The detailed analysis allowed in this respect to discuss individual impacts on technology, aircraft, airport and air transport system level and to check the potential development over the long-term for a progressive and a conservative development pathway until 2070. Thus, a highly diversified analysis of the impact study results was possible as well as a comparison between the assumed progressive and the conservative pathway.

The corresponding methodological approaches are outlined in more detail in the following sections in relation to the separate working steps.

3. Trend Analysis 2020-2070

3.1. Aviation Market Development

The trend analysis for the aviation market development concentrated on aviation external and internal developments. For the external developments the focus was put on the most important drivers of air transport development in the long-term. Meanwhile, the analysis of the air transport internal trends was conducted from the perspective of different aviation stakeholders (i.e. airlines, airports and passengers). Results of both analyses are presented in the following two sections.

3.1.1. External trends

Starting point for the analysis of the external trends in the aviation market were the most important developments in the field of economy and demography. With regard to global GDP development a stable economic growth is expected over the next decades which is nevertheless not equally distributed around the globe. In addition, the centre of gravity will shift towards the southeast in the next years as outlined in chapter 4.1.1 in more detail. This means optimal conditions for aviation growth in this world region while a rather slower growth or even stagnation can be expected in the Western hemisphere.

This effect is reinforced by the demographic development in certain world regions. While population growth in the highly industrialised countries is mainly stagnating, a high population growth is expected for Asia and especially Africa. Together with the economic growth prospects for Southeast Asia and particularly China this means optimal conditions for air transportation demand up to 2070. Meanwhile, for Africa a lower GDP growth is forecasted but the high population growth means also a significant growth perspective for a currently underestimated market.[4]

Further demographic shifts are accelerating this development. As the population in Asia and Africa is younger there might be a higher affinity to travel for business and private purposes as a kind of catch-up effect. Nevertheless, also the population in Europe and North America where rather a moderate growth can be expected might travel with a higher frequency in the future based on a more stable economic situation. As a result, all markets remain important in the future but the demographic background of air passengers on global scale might be signified by a higher diversity as today. This trend means for airlines and airports that the target groups and their needs might significantly change over the next decades as an important trend that is already obvious. In addition, it can be expected that the attitude towards flying and social values in general will surely be different in the next 50 years and this has to be addressed in strategical planning.

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[4] Cf. Aerospace Technology Insitute (2022).

Meanwhile, a rather smaller impact can be related to the Covid-19 pandemic. While there have been serious concerns that the aviation sector will never be the same again after the year 2020, the market already shows a similar recovery as with regard to earlier crises even though not in the same speed for all world regions. Also, the fear that business travel is not needed anymore due to an increased usage of video conferences did not come true. Nevertheless, as a negative trend it can be observed that the uncertainty in the aviation business has become higher over the last years. One reason consists of the different crises mentioned before (including also the Russo-Ukrainian war) while also the geopolitical framework conditions have changed. This is especially obvious in the emerging risk of a global trade war based on a policy change in the U.S. which might also heavily impact the aviation industry over the next years including not only travel but especially supply chains.[5] This creates additional challenges for the sustainable transformation of the air transport sector due to rising uncertainty linked to investment decisions.

In addition, the general conditions in the aviation sector include many challenges and this will surely persist in the long-term as most challenges are linked to the structure of the sector that can not be changed. Figure 3 which is based on Porter's "Five Forces model" reflects in this respect the framework conditions from the perspective of the airline industry.

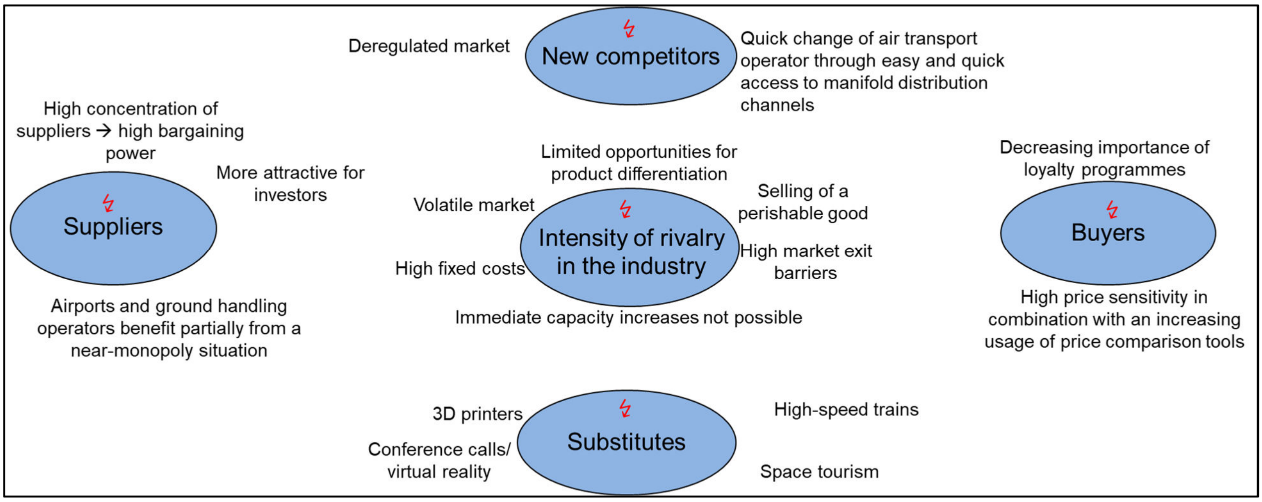

Figure 3: Continuing challenges within the airline industry (Five Forces according to Porter)

Vice versa, many challenges for other important stakeholders are the same (i.e. airports, aircraft manufacturers, air traffic management) and have to be considered also for the analysis of the internal trends in the aviation market that are described in the following.

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[5] Cf. https://skift.com/2025/04/03/us-tariffs-cloud-airline-industry-outlook-as-stocks-plummet/.

3.1.2. Internal trends

With regard to the airline business some important trends could be identified for the next 50 years. One remaining trend is the higher diversity in the airline industry with regard to different operators and business models. The last revolution in the market took place in the 1990s with the rise of low cost carriers and consequently more competition in the market. At the same time more and more mergers as well as alliance formations took place. Thus, it is likely that there will also be high dynamics with regard to the future airline market development including market entries and exits of established business concepts but also a rising number of innovative players with regard to new transportation concepts (e.g. in the field of UAM/AAM, supersonic transport and (hybrid-)electric transport). Another trend refers to airline routing which might significantly change due to changing future markets (e.g. Asia), optimisations in relation to the chosen business models but also a need for operational changes due to ATM regulation, other operational constraints and sustainability issues. For example, intermediate stop operations could play a more important role in the future. Corresponding impacts can be expected for the fleet development and accordingly for aircraft manufacturers. This includes aircraft retirement and renewal rates as well as shifts in aircraft size, range and passenger capacity which are also outlined in sub-chapter 5.2.3 within this study report.

For airports and air fields safety and security aspects will be a remaining trend to be addressed in future planning. This refers to tasks related to the integration of new air vehicle concepts in existing traffic operations, the role as intermodal hub or traffic node and optimised security and safety procedures in the light of improved methods and technologies (e.g. with regard to highly automatized processes, blockchain technology, artificial intelligence, …). In addition, journeys should not only become smarter and easier this way. Passenger comfort should also increase. Thus, another long-term trend is to create the passenger journey as an attractive experience for air passengers. As a result, especially the bigger hubs will have a stronger interest in increasing their attractiveness as a destination for an intermediate stop for air passengers. This might be realised by higher investments in shopping and leisure facilities at the airport and a stronger cooperation with the city/region in the surrounding to improve the awareness as a touristic hotspot.

Finally, also passenger expectations might change. As described in in the previous section the number of air passengers will grow and target groups for airlines and airports will become more heterogeneous. Thus, their motivation to travel and their requirements will be different. Some of the corresponding future trends are already obvious today. While some passengers might completely concentrate on sustainability issues which could mean a continuous balancing between the need to fly and compensation opportunities, for other passengers a more comfortable journey might have the highest priority. This might also mean that the requirements for a higher quality, reliability and punctuality in relation to a flight journey might increase. For the air transport stakeholders on the supply side this might also lead to new challenges considering that air transport will nearly double over the next 50 years. Thus, the focus should be put on a higher efficiency to handle the growing amount of air traffic and balancing it with the passengers' expectations. Optimised airport processes and seamless and smart air travel are key factors for success in this respect. Progress might in this context also be reached by the important trends of personalisation and digitalisation. Those factors are crucial for enabling airlines and airports to adapt the whole journey to individual passenger needs. Correspondingly, on-board services might be customized, cabin design can be planned more flexibly and individual passenger's interests can be better fulfilled.

However, another important long-term trend will be the price awareness and the price sensitivity of customers. Uncertainty about the long-term development of ticket prices will remain. While the low cost carrier boom and potential future improvements with regard to aircraft and ATM efficiency are likely and have a positive impact on ticket price reductions, higher energy costs, increasing competition and the general economic climate which is currently affected by inflation and a rising number of tariffs in many countries might lead to higher prices in the long-term. Thus, it is even more important to improve air journeys in relation to other aspects. As a major requirement careful and flexible planning approaches will be needed to quickly adapt to new market environments and changing framework conditions.

Finally, it has to be concluded that the internal trends within the aviation market are complex and they will be strongly impacted by the external trends that were outlined in the section before. Nevertheless, the development of the internal trends and the underlying chances and challenges can be steered by the aviation stakeholders themselves to a certain extent. A good understanding of the needs of each stakeholder group and a continuous exchange will therefore be crucial to optimize the air transport system and to shape the market conditions for future air transport in the best way.

3.2. Propulsion Technologies

The trend analysis for propulsion technologies covers both a review of conventional propulsion technologies including hydrogen combustion as well as a specific focus on the feasibility of electrified propulsion. In collaboration with the scenario framework (see section 4.1), technology EIS dates were agreed for further consideration within the DEPA 2070 project vehicle and fleet development assessments. These EIS dates were derived to represent the technical feasibility of the described propulsion technologies to be used for vehicle and fleet assessments. Any limitation from a subsequent infrastructure point of view (i.e. if a sufficient hydrogen infrastructure is available) was not considered within these dates.

3.2.1. Electrified Propulsion Technologies

The trend analysis for electrified propulsion technologies focused on electric propulsion components and derived a connection between component specific technology projections and the associated range predictions for electric aircraft.

The investigation involved summarising electrified propulsion topologies, identifying key components, and projecting the advancements of individual technologies with respect to relevant key metrics such as specific power and efficiency. Two technology development scenarios were generated to cover both a conservative as well as a progressive development scenario up to the year 2070. These component projections were then applied to an overall assessment of all-/ hybrid-electric powertrains for various aircraft classes. Further details on the investigated powertrain architecture, the component technology projections as well as the calculation framework are available within the associated publication by Link and de Graaf.[6]

The subsequent assessment highlighted the increasing potential of electrified propulsion from 2025 to 2070 under different development scenarios – a conservative and a progressive scenario. Both emphasised the impact of the thermal management system (TMS) on the powertrain development. The assessment identified the fuel cells as well as the TMS as the key mass contributors. An improvement of their respective specific power and specific heat rejection significantly impact the predicted aircraft ranges – particularly in current and near-term technology levels. Feasibility target values fuel cell specific power and TMS specific heat rejection have been summarized. Negligence with regards to TMS effects in preliminary design may lead to an overly optimistic prediction of achievable aircraft range. For detailed results please refer to Link and de Graaf.[7]

The same framework was used to generate data for what-if studies with regard to the DEPA 2070 impact analysis on mobility (see section 6.4) with a focus on the potential connectivity impacts of battery electric small air transport (SAT) aircraft. The data provided was based on the technology projections of the individual components of the electrified powertrain. The presented range analysis was based on a battery-electric SAT aircraft in the form of a retro-fit of a Do228. The analysis essentially included the impact of the changed passenger, powertrain, fuel and battery masses but does not include volumetric implications and potential further developments at aircraft level. Alternative drive concepts based on fuel cells were also not considered for this study. The limiting driver for the calculated ranges is primarily the specific energy of the battery. As part of the impact analysis on mobility, the data provided ensured a consistent view within the DEPA 2070 project. Nevertheless, there is potential to determine other range values for SAT aircraft in case of more detailed considerations on aircraft design or when taking other drive concepts into account.

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[6] Cf. Link, A., de Graaf, S. (2024).

[7] Cf. Ibid.

3.2.2. Conventional Propulsion Technologies

While electric propulsion systems offer promising pathways towards sustainable aviation, conventional propulsion technologies will continue to have a crucial role in the transition to a more sustainable aircraft. Advancements in conventional propulsion architectures, including ultra-high bypass ratio (UHBR) engines, open rotors, and Composite Cycle engines, are essential for improving fuel efficiency and reducing carbon emissions in the near to mid-term. These technologies use existing infrastructure while providing significant performance gains. The following section presents an overview of potential upcoming propulsion technologies and their expected EIS.

Propulsion Related Technology	Short Description	EIS
Geared Turbofan Engine[8] [9]	The geared turbofan is a type of turbofan aircraft engine with a planetary gearbox between the low pressure compressor / turbine and the fan, enabling each to spin at its optimum speed. The benefit of the design is lower fuel consumption and much quieter operation. The drawback is that it increases weight and adds complexity.	Already Available - Advanced for new Configurations from 2035
Ultra High Bypass Ratio Engines (UHBR)[10] [11]	UHBR engines optimize fuel efficiency and reduce emissions. They feature a large bypass airflow, achieved through innovative fan designs, resulting in improved efficiency, extended range, and lower operating costs. UHBR engines produce lower emissions and noise levels, aligning with sustainability goals.	Already Available - Advanced for new Configurations from 2035
Open Rotor[12]	Open rotor engines, or unducted fans, feature large, counter-rotating propellers exposed to airflow. They offer improved fuel efficiency, reduced emissions, and	2035-2040

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[8] Cf. Bertsch et al. (2019).
[9] Cf. MTU Technologies (2025).
[10] Cf. Coelho Barbosa, F. (2021).
[11] Cf. Giesecke et al. (2018).
[12] Cf. San Benito Pastor et al. (2021).

Propulsion Related Technology	Short Description	EIS
	extended range. Their lighter weight and decreased drag enhance overall efficiency. Advanced aerodynamics minimize noise, making them compliant with noise regulations. Challenges include safety considerations and noise/vibration mitigation.	
Water-Enhanced Turbine (WET) Cycle Engine[13] [14]	WET Cycle engines incorporate water injection to improve efficiency and performance. Water reduces nitrogen oxides (NO_x) emissions and lowers peak combustion temperatures, enhancing air quality and meeting environmental regulations. It increases power output, fuel efficiency, and thrust. Water injection compensates for lower air density at high altitudes, improving engine performance. WET Cycle engines also contribute to noise reduction.	2040-2045
Flameless Oxidation (FLOX) Combustion Chambers[15]	FLOX combustion chambers achieve efficient and low-emission combustion in gas turbine engines. They use staged combustion to control temperature distribution and minimize NO_x emissions. FLOX chambers promote stable, flameless combustion, reducing soot and providing quieter operation. Precise control enables optimization of combustion efficiency and compliance with environmental regulations.	2040-2045

Table 1: Overview upcoming propulsion technologies and their expected EIS

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[13] Cf. Pouzolz et al. (2020).
[14] Cf. Kaiser, S., Schmitz, O. (2022).
[15] Cf. Lammel et al. (2022).

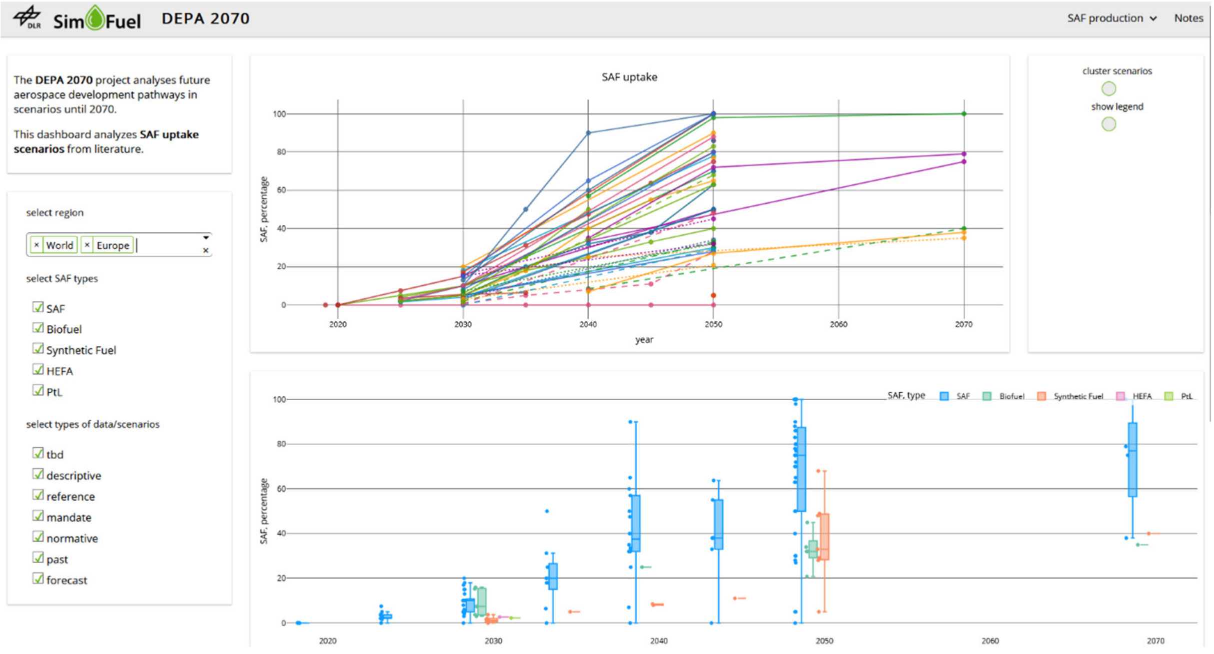
3.3. Sustainable Aviation Fuels

SAF is widely regarded as a crucial element in the global transition to a decarbonized aviation sector. Time is a critical factor in this transition, and SAF offers a clear pathway toward achieving the necessary emissions reductions. It is now a matter of executing this solution, with governments, industry leaders, and stakeholders working collaboratively to scale its production, diversify feedstock range and accelerate the widespread adoption of SAF. This collaborative effort is considered crucial for achieving meaningful reductions in climate impact by 2050 and beyond. As the aviation industry seeks to align with international climate goals, increasingly stringent regulatory frameworks paired with incentives strive to create conditions that support the growth of the SAF industry. This chapter is structured to explore key aspects related to SAF development and its future trajectory as a cornerstone of aviation’s decarbonization strategy. In this context, it also illustrates the role for the DEPA 2070 scenarios.

3.3.1. Comprehensive Review of SAF Development Reports

A systematic literature review study was conducted for the SAF-related trend analysis in the DEPA 2070 project. This review encompassed 27 reports from key organizations including the ICAO, the International Council on Clean Transportation (ICCT), the World Economic Forum (WEF), PricewaterhouseCoopers (PwC), Argus Media, and the Air Transport Action Group (ATAG). The study focused on reports published between 2019 and 2023. Specific attention was paid to collecting comprehensive data on SAF uptake, including percentage age share, total production volumes, production pathways, and regional distribution.

The literature review revealed methodological challenges that complicate a comprehensive SAF trend analysis. Foremost among these were highly divergent assumptions across different scenarios, coupled with inconsistent nomenclature across sources. Regional data availability proved particularly problematic, with most existing research predominantly focusing on the United States, Europe, and global aggregates, despite the strong growth of air transport in other regions like Asia. The temporal scope of available data presented another critical limitation, with most sources providing projections only up to 2030 or 2050, leaving a significant gap in understanding long-term developments up to 2070. The high dynamics of SAF technological advancements presents additional challenges, including the rapid scale-up of production and ongoing development of new production pathways. The research also highlighted the sector's extreme dependence on political framework conditions, which introduce additional layers of uncertainty. Furthermore, the intricate links between sectors are noteworthy, as out-of-sector actions, such as the electrification of road transport or subsidies for Diesel, can have a substantial impact on the availability of SAF and the decarbonization efforts within aviation. Each report was analysed to extract its data for various scenario types, ranging from conservative baseline projections to ambitious decarbonization scenarios. To enhance data accessibility and interpretability, the literature study results were integrated into an interactive dashboard (Figure 4), allowing for dynamic visualization of SAF development trends (Figure 5 and Figure 6). The dashboard offers selectable regions including global, European, and United Kingdom-specific views, enabling stakeholders to explore regional variations in SAF production and adoption. Another key output of this study was a detailed map of production facilities (Figure 7), which visually represents the geographical distribution and diversity of SAF production pathways. This geospatial visualization provides an overview of the current global SAF landscape, highlighting regional differences in technological capabilities, feedstock availability, and production strategies.



The **DEPA 2070** project analyses future aerospace development pathways in scenarios until 2070.

This dashboard analyzes **SAF uptake scenarios** from literature.

select region

× World × Europe

select SAF types

☑ SAF
☑ Biofuel
☑ Synthetic Fuel
☑ HEFA
☑ PtL

select types of data/scenarios

☑ tbd
☑ descriptive
☑ reference
☑ mandate
☑ normative
☑ past
☑ forecast

Figure 4: Dashboard for DEPA 2070 SAF uptake scenarios

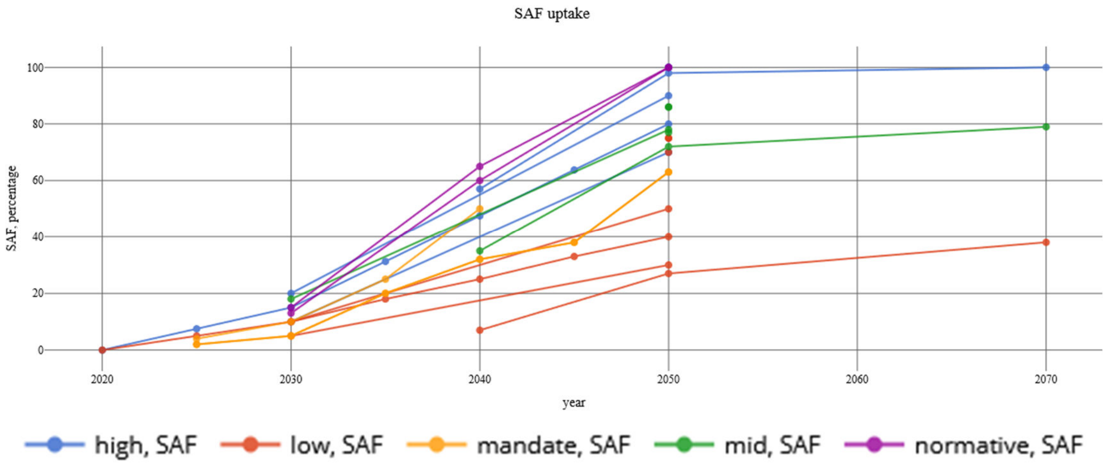


Figure 5: SAF share with assigned scenarios

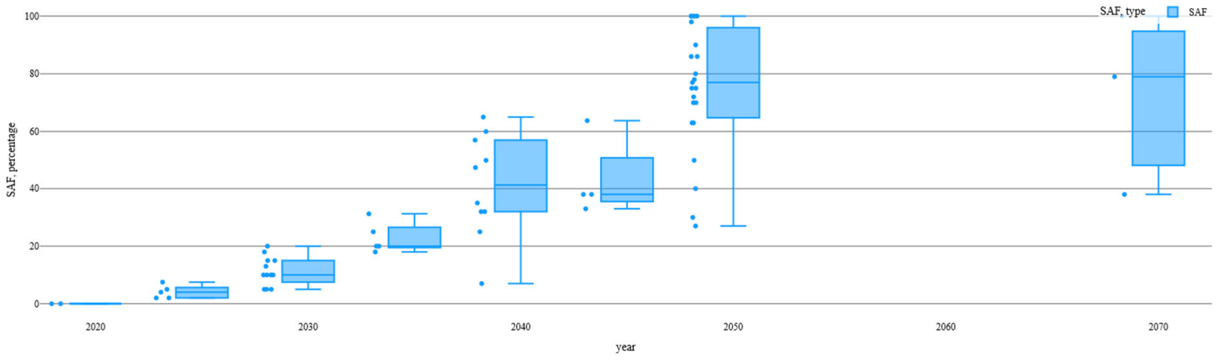


Figure 6 Distribution and variability in SAF shares (dots: individual data points, box: middle 50% of the data, line: median, whisker: min to max)

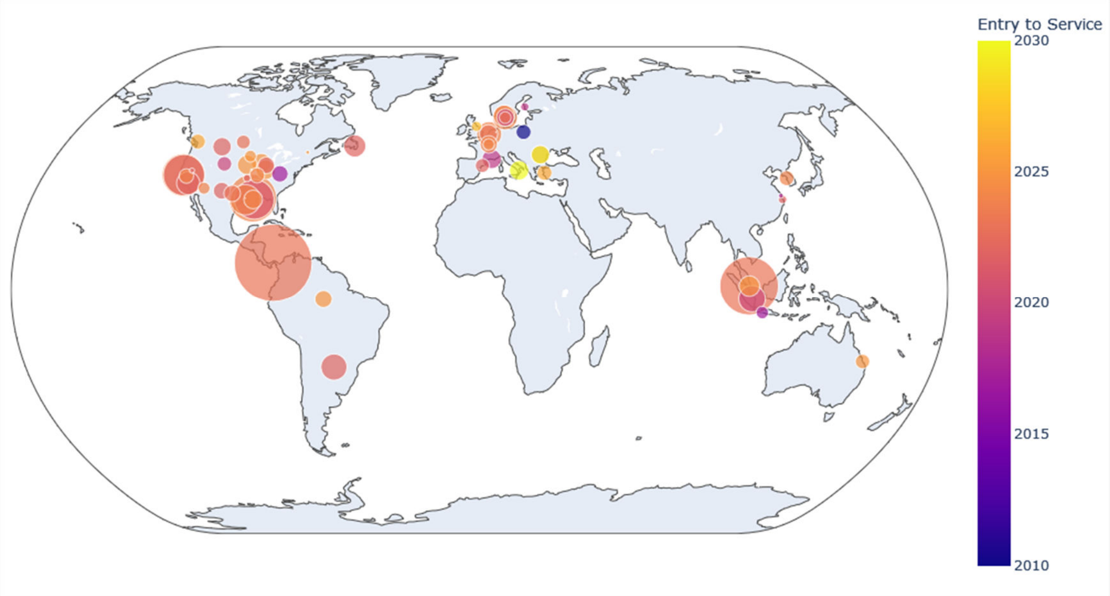
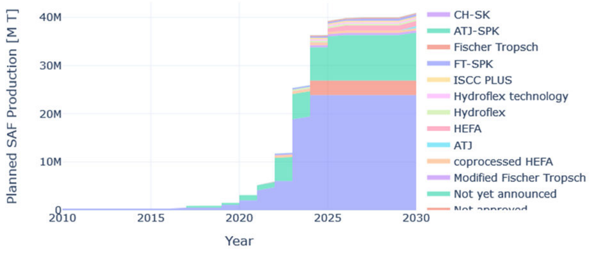


Figure 7: SAF production facilities, colored by their announced EIS. Size of the markers corresponds to production capacity



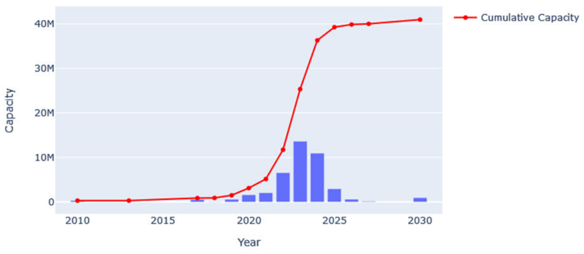


Figure 8: Planned SAF production by fuel type

Figure 9: Planned SAF production capacity over time

3.3.2. Current Status of SAF Standardization and Certification

Sustainable Aviation Fuels must meet a rigorous approval process, certification standards and continuous fuel quality to guarantee aviation safety. The primary organizations setting these industry standards are ASTM International and the UK's Ministry of Defence (MoD) through its Defense Standard (DefStan). To date, eight distinct pathways for synthetic blending components (SBCs) are approved under ASTM D7566 specification, each Annex representing a unique production technology and feedstock approach. These approved pathways include: A1 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), A2 Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK), A3 Synthetic Iso-Paraffin (SIP), A4 Fischer-Tropsch Synthetic Kerosene with Aromatics (FT-SKA), A5 Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), A6 Catalytic Hydrothermolysis Jet fuel (CHJ), A7 Hydroprocessed Hydrocarbons-HEFA (HHC-HEFA), and A8 Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA). Additionally, three pathways for co-processing are approved under ASTM D1655. Co-processing refers to the integration of renewable feedstocks alongside fossil-based feedstocks into existing processes in petroleum refineries. The approved pathways are co-processing of glycerides, fatty acids, and esters (A1.2.2.1), co-processing of hydrocarbons derived from synthesis gas via the Fischer-Tropsch process (A1.2.2.2), and co-processing of hydrocarbons derived from hydroprocessed glycerides, fatty acids, and esters (A1.2.2.3). To assess the fraction of renewable materials, radiocarbon dating (14C) is employed. Numerous additional synthetic blending components and production pathways are currently being developed, further expanding the potential feedstock sources and production pathways for sustainable aviation fuels. Several are already undergoing assessment within the ASTM D4054 evaluation process to create a new Annex in ASTM D7566. Furthermore, higher co-processing limits for renewable feedstocks up to 30% are currently discussed providing an inexpensive solution to increase the SAF share by using existing refinery infrastructure.

3.3.3. Feedstock and Production Pathway Diversification

Diversification represents a critical strategy in expanding SAF production, addressing both environmental sustainability and supply chain resilience. In this context, the EU Renewable Energy Directive (RED) sets sustainability criteria and imposes strong restrictions on energy and feedstocks, e.g. to avoid conflicts with food production.[16] Beyond traditional biomass sources like agricultural residues and waste cooking oils, researchers are exploring advanced feedstock options including algae-based biomass, which can be cultivated on non-arable land, municipal solid waste, forestry waste, and even carbon captured directly from the air or industrial emissions. Emerging technologies enable the conversion of these diverse feedstocks through various biochemical and thermochemical processes. Key factors to consider are regional differences in feedstock availability and variations in other necessary resources like water and electricity.

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[16] Cf. European Union (2018).

Some regions have abundant lignocellulose biomass, others near-unlimited potential for Power-to-Liquid (PtL) fuels. PtL fuels are synthetic fuels produced by converting renewable electricity into liquid hydrocarbons, typically using carbon dioxide (CO_2) and water (H_2O) as feedstocks. The process involves several steps, including the electrolysis of water to generate hydrogen, which is then combined with CO_2 or CO in a chemical reaction, such as the Fischer-Tropsch synthesis, to produce liquid fuels. Electricity-based liquid fuels offer a viable solution, particularly in regions with high population density and limited space for additional land use or in areas with challenging agricultural conditions, such as deserts. Renewable energy emerges as a crucial factor, with emphasis on both availability and price – with the Middle East and North Africa (MENA) region’s and South American region's being highlighted as having exceptional potential for PtL fuel production due to their abundant solar[17] and wind resources (e.g. in Chile and Argentina)[18], respectively. The diversification of SAF production pathways not only mitigates the risk of over-relying on a single feedstock but also supports circular economy principles by utilising waste streams. It reduces competition with food production, and provides economic opportunities for different geographical regions while progressively decreasing the aviation industry's carbon footprint.

3.3.4. Legislative Landscape and Global SAF Policy Development

The global legislative environment for SAF is experiencing rapid and dynamic development, with an increasing number of jurisdictions implementing targeted policies to accelerate SAF adoption. In the European Union, the RefuelEU Aviation initiative established concrete SAF quotas, setting a precedent for regulatory intervention, with increasing SAF blending obligations starting at 2% in 2025 and reaching 70% by 2050, while also requiring that a specific share comes from Renewable Fuels of Non-Biological Origin (RFNBOs), namely e-fuels (PtL) produced from renewable electricity (cf. Figure 10).[19] Similar mandates were introduced in the United Kingdom, Japan, Malaysia, Brazil, Singapore, and Indonesia, demonstrating a growing international commitment to aviation decarbonization. Complementing RefuelEU Aviation, the EU RED established sustainability criteria that SAF must meet to count toward renewable energy targets, including minimum greenhouse gas emission savings (e.g. 65% for post-2021 installations) and restrictions on feedstocks with a high risk of indirect land-use.[20] The directive's multiplier mechanism, which allows SAF and RFNBOs to be counted 1.2 and 1.5 times their energy content toward renewable energy targets, respectively, as well as a zero emissions rating of SAF in the EU Emissions Trading System (ETS) provide additional incentives for fuel producers to invest in aviation fuels rather than road transport applications.[21]

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[17] Cf. Viebahn et al. (2022).
[18] Cf. Pfennig et al. (2021).
[19] Cf. European Commission (2021).
[20] Cf. Council of the European Union (2023).
[21] Cf. EASA (2025).

Beyond the focus of DEPA 2070 on CO_2 lifecycle emissions, it remains essential to recognize the potential significance of non-CO_2 emissions, acknowledging the existing uncertainties in their precise quantification. As aviation's climate impact could be twice as severe when non-CO_2 emissions are included alongside carbon dioxide,[22] overlooking these impacts could lead to counterproductive policy incentives. In this context, the EU Commission implemented a monitoring, reporting, and verification (MRV) system for non-CO_2 aviation effects starting January 1, 2025, calculating CO_2 equivalents per flight using flight, aircraft, fuel property, performance, and weather data.[23] By the end of 2027, it will report on the results and, if needed, propose legislation to address these effects.

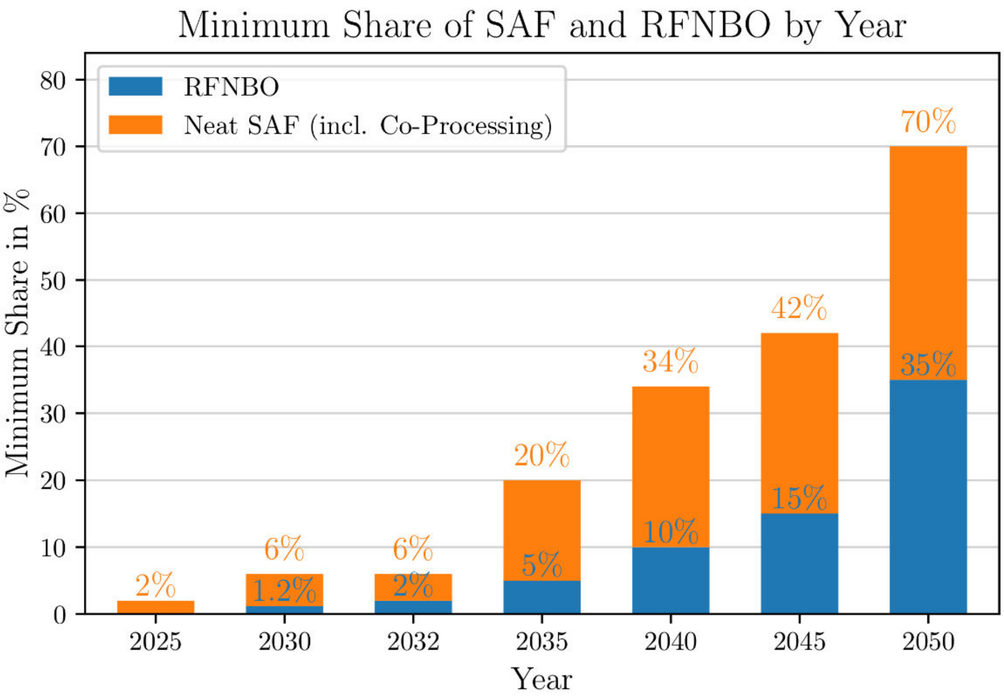

Figure 10: RefuelEU Aviation SAF quotas

The United States has pursued a dual approach, implementing the SAF Grand Challenge[24] alongside the Inflation Reduction Act,[25] which provide significant incentives by tax credits for SAF production and funding for its development. Canada enacted the Clean Fuel Standard,[26] also supporting the transition to low-carbon aviation fuels. Emerging markets are also actively developing SAF policies, with legislative initiatives or mandates in various stages of development in countries including Chile,

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[22] Cf. Lee et al. (2021).

[23] Cf. European Commission (2024).

[24] Cf. U.S. Department of Agriculture, Department of Energy, and Department of Transportation: Synthetic Aviation Fuel Grand Challenge (2022).

[25] Cf. U.S. Congress. (2022).

[26] Cf. Government of Canada. (2021).

Turkey, India, China, Australia, and New Zealand. This global policy landscape reflects an increasingly coordinated approach to addressing aviation's carbon emissions, with regulatory frameworks evolving to support the scaling of sustainable fuel technologies across different regional contexts.

3.3.5. Towards 100% neat Sustainable Aviation Fuel Usage

Until now, synthetic blending components may comprise no more than half of any jet fuel mixture, with conventional fuel making up the remainder. The industry's collective efforts are directed at increasing blending ratios and achieving standardization of fully synthetic kerosene. A two-step strategy has been developed to transition to 100% neat SAF. The first step focuses on developing fully synthetic aviation turbine fuel that mimics traditional kerosene, making it 100% compatible with existing aircraft fleets and infrastructure as a drop-in replacement. The second step aims to create non-drop-in fully synthetic aviation turbine fuel with enhanced properties, though this will require the distribution to designated aircraft and adapted infrastructure since this will be a new fuel grade, different from Jet A/A-1. The specification for fleet-wide 100% drop-in SAF (fully formulated synthetic Jet A/A-1) is nearing the balloting stage, with options including single synthetic components meeting specifications through approved pathways like CHJ (A6), FT-SKA (A4), and ATJ-SKA (A8), or blends of multiple approved synthetic components from Annexes A1 through A8. Meanwhile, for the more advanced non-drop-in SAFs intended for designated aircraft, a standard specification for aromatic free Paraffinic Synthetic Aviation Turbine Test Fuel is under development, representing an initial shift away from traditional kerosene towards improved fuel properties.

3.3.6. Assumptions for the DEPA 2070 Scenarios

Advanced SAF production pathways have the potential to significantly reduce carbon emissions, with some emerging technologies demonstrating the capability to achieve up to 80% lower lifecycle greenhouse gas emissions compared to traditional fossil jet fuels.[27] On this basis, SAF is assumed to deliver an 80% reduction in lifecycle CO_2 emissions compared to conventional kerosene across the DEPA 2070 scenarios. With respect to entry into service, 100% drop-in (fully) synthetic aviation turbine fuel is anticipated to become commercially available between 2025 (progressive estimate) and 2028 (conservative estimate). The property-optimized 100% non-drop-in variant, which requires dedicated storage facilities and specialized operational safety protocols, is expected to enter service between 2030 and 2035 in the progressive scenario. Technical standards are therefore not be seen as a restrictive factor to allow the growing share of SAF within the ReFuelEU Aviation timeline.

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[27] Cf. Prussi et al. (2021).

3.4. Aircraft Technologies

The systematic identification, evaluation, and structuring of future aircraft technologies are essential for guiding future developments in aviation. To address this, a threefold approach has been established in the wider context of the DEPA 2070 project, consisting of Aircraft Technology Scouting, the development of a Technology Database, and Aircraft Technology Roadmapping. The Technology Scouting involves the continuous screening and assessment of novel technologies with potential impact on future aircraft design and operations with the potential to enhance the environmental performance of an aircraft. This process integrates various sources, including academic research, industry reports, and patent analyses, to capture relevant advancements in aerodynamics, propulsion, structures, and systems. Building upon this, Aircraft Technology Roadmapping provides a structured methodology to align technological developments with long-term strategic goals. By mapping out technology maturity, dependencies, and expected benefits, roadmapping enables informed decision-making regarding research investments and industrial adoption pathways. To support these activities, a Technology Database for Aircraft Technologies has been developed. This database serves as a centralized repository for systematically collected technology data, including performance characteristics and maturity levels of the scouted technologies. It facilitates comparative analysis and traceability, ensuring a transparent and data-driven approach to technology assessment.

While a more detailed description of all three elements can be found in a master thesis and a separate paper[28] this report focuses specifically on the Technology Database. The database structure, its methodology for data collection and categorization, as well as its role in supporting technology assessment, are presented in the following sections.

3.5. Technology Roadmaps

The evaluation of single aircraft technologies is essential for understanding their potential impact on future aircraft concepts. Each technology is assessed individually based on key parameters such as EIS, Technology Readiness Level (TRL), expected Technology Impact, and possible Integration Pathways. To systematically capture and visualize these aspects, technologies are positioned on a Technology Roadmap, aligning their expected development with industry needs and strategic goals. This enables decision-makers to identify critical technologies, assess maturity gaps, and prioritize research efforts accordingly.

To facilitate the structured exploration of such technologies, different platforms were evaluated as a basis for a future Technology Explorer. The open-source tool AppFlowy was tested for the

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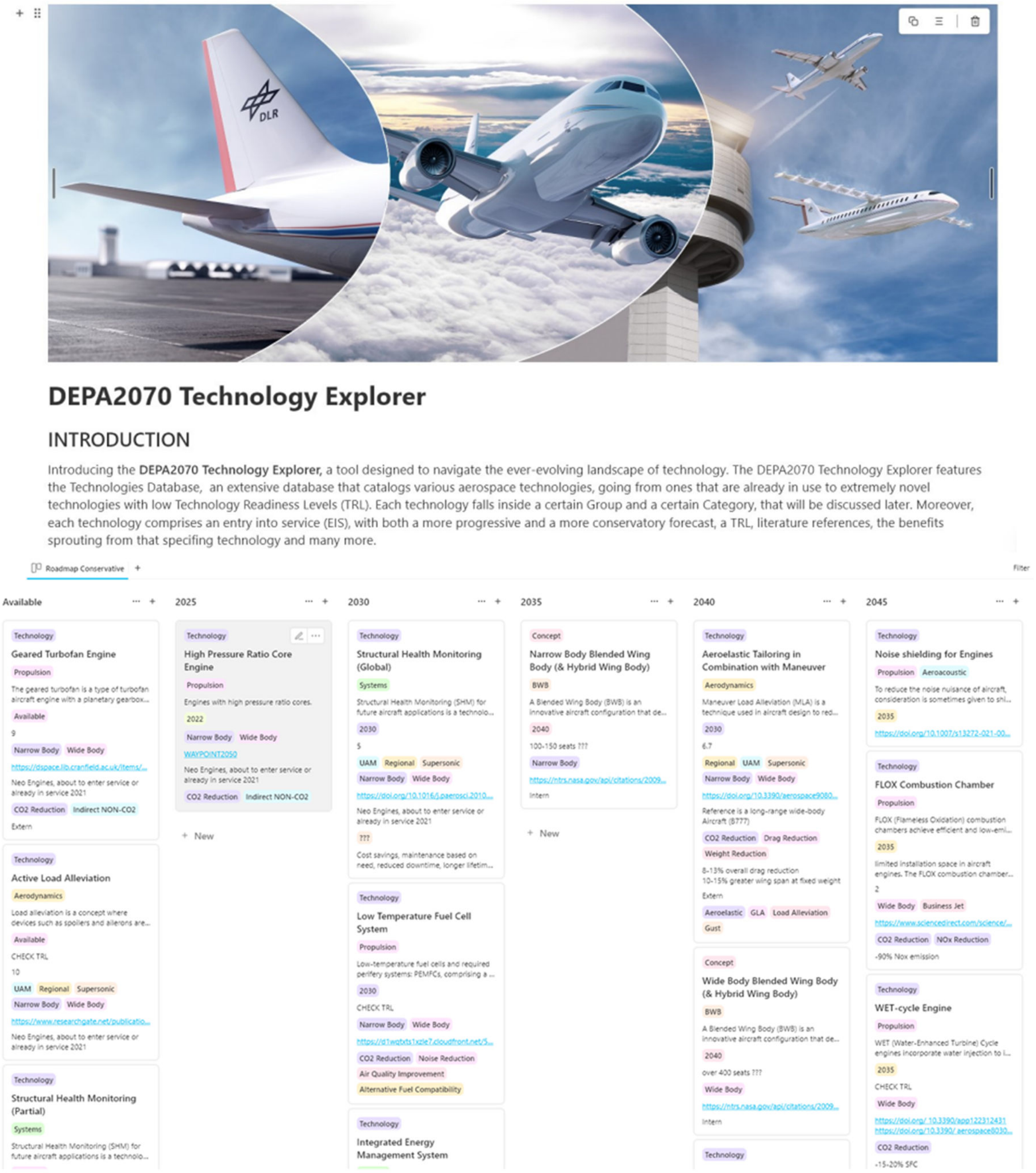
[28] Cf. Weber, L. (2023), Chapter 3.2.1, 3.2.3 and 3.4.; Weber, L. et al. (2024).

capability to manage and visualize technology data efficiently. Key evaluation criteria included their flexibility in structuring technology attributes, ease of data entry and retrieval, and suitability for collaborative research environments as data interoperability between different technical solutions. The envisioned Technology Explorer aims to provide an interactive framework for analysing emerging aircraft technologies, integrating detailed information such as EIS, TRL, Technology Impact, and additional integration opportunities. This approach ensures a dynamic and data-driven assessment process, supporting informed decision-making in aviation technology development.



DEPA2070 Technology Explorer

INTRODUCTION

Introducing the **DEPA2070 Technology Explorer,** a tool designed to navigate the ever-evolving landscape of technology. The DEPA2070 Technology Explorer features the Technologies Database, an extensive database that catalogs various aerospace technologies, going from ones that are already in use to extremely novel technologies with low Technology Readiness Levels (TRL). Each technology falls inside a certain Group and a certain Category, that will be discussed later. Moreover, each technology comprises an entry into service (EIS), with both a more progressive and a more conservatory forecast, a TRL, literature references, the benefits sprouting from that specifing technology and many more.

Available

Technology
Geared Turbofan Engine
Propulsion
The geared turbofan is a type of turbofan aircraft engine with a planetary gearbox...
Available
9
Narrow Body Wide Body
https://dspace.lib.cranfield.ac.uk/items/...
Neo Engines, about to enter service or already in service 2021
CO2 Reduction Indirect NON-CO2
Extern

Technology
Active Load Alleviation
Aerodynamics
Load alleviation is a concept where devices such as spoilers and ailerons are...
Available
CHECK TRL
10
UAM Regional Supersonic
Narrow Body Wide Body
https://www.researchgate.net/publicatio...
Neo Engines, about to enter service or already in service 2021

Technology
Structural Health Monitoring (Partial)
Systems
Structural Health Monitoring (SHM) for future aircraft applications is a technolo...

2025

Technology
High Pressure Ratio Core Engine
Propulsion
Engines with high pressure ratio cores.
2022
Narrow Body Wide Body
WAYPOINT2050
Neo Engines, about to enter service or already in service 2021
CO2 Reduction Indirect NON-CO2

2030

Technology
Structural Health Monitoring (Global)
Systems
Structural Health Monitoring (SHM) for future aircraft applications is a technolo...
2030
5
UAM Regional Supersonic
Narrow Body Wide Body
https://doi.org/10.1016/j.paerosci.2010...
Neo Engines, about to enter service or already in service 2021
???
Cost savings, maintenance based on need, reduced downtime, longer lifetim...

Technology
Low Temperature Fuel Cell System
Propulsion
Low-temperature fuel cells and required perifery systems: PEMFCs, comprising a ...
2030
CHECK TRL
Narrow Body Wide Body
https://d1wqtxts1xzle7.cloudfront.net/5...
CO2 Reduction Noise Reduction
Air Quality Improvement
Alternative Fuel Compatibility

Technology
Integrated Energy Management System

2035

Concept
Narrow Body Blended Wing Body (& Hybrid Wing Body)
BWB
A Blended Wing Body (BWB) is an innovative aircraft configuration that de...
2040
100-150 seats ???
Narrow Body
https://ntrs.nasa.gov/api/citations/2009...
Intern

2040

Technology
Aeroelastic Tailoring in Combination with Maneuver
Aerodynamics
Maneuver Load Alleviation (MLA) is a technique used in aircraft design to red...
2030
6.7
Regional UAM Supersonic
Narrow Body Wide Body
https://doi.org/10.3390/aerospace9080...
Reference is a long-range wide-body Aircraft (B777)
CO2 Reduction Drag Reduction
Weight Reduction
8-13% overall drag reduction
10-15% greater wing span at fixed weight
Extern
Aeroelastic GLA Load Alleviation
Gust

Concept
Wide Body Blended Wing Body (& Hybrid Wing Body)
BWB
A Blended Wing Body (BWB) is an innovative aircraft configuration that de...
2040
over 400 seats ???
Wide Body
https://ntrs.nasa.gov/api/citations/2009...
Intern

Technology

2045

Technology
Noise shielding for Engines
Propulsion Aeroacoustic
To reduce the noise nuisance of aircraft, consideration is sometimes given to shi...
2035
https://doi.org/10.1007/s13272-021-00...

Technology
FLOX Combustion Chamber
Propulsion
FLOX (Flameless Oxidation) combustion chambers achieve efficient and low-emi...
2035
limited installation space in aircraft engines. The FLOX combustion chamber...
2
Wide Body Business Jet
https://www.sciencedirect.com/science/...
CO2 Reduction NOx Reduction
-90% Nox emission

Technology
WET-cycle Engine
Propulsion
WET (Water-Enhanced Turbine) Cycle engines incorporate water injection to i...
2035
CHECK TRL
Wide Body
https://doi.org/ 10.3390/app122312431
https://doi.org/10.3390/ aerospace8030...
CO2 Reduction
-15-20% SFC

Figure 11: Example view of the DEPA 2070 Technology Explorer in AppFlowy

To explore the potential of structured roadmapping in combination with an aircraft technology database, AppFlowy was utilised to develop a DEPA 2070 Technology Explorer. This tool aims to provide users with a flexible interface for analysing future aircraft technologies. The explorer enables users to visualize technologies either in a roadmap view, highlighting their development timelines and interdependencies, or in a structured list format for comparative analysis. Additionally, detailed views offer in-depth insights into individual technologies, supporting a systematic assessment of their potential impact, interdependencies and references. This approach facilitates a more integrated and interactive way of managing technology roadmaps and their implications. An example view of the DEPA 2070 Technology Explorer is displayed in the figure above.

Beyond mapping individual aircraft technologies, DEPA 2070 also aimed to develop dedicated vehicle roadmaps for different market segments, including mainliner, regional, SAT and supersonic aircraft. These roadmaps were created in relation to the vehicle design process (cf. section 5.1.1) to ensure a comprehensive representation of technological evolution within each segment. This formed the base for further scenario development (cf. section 4.1). In this chapter, only aggregated vehicle roadmaps are presented, while section 5.1.1 refines them by showing corresponding trendlines, providing a more detailed view of future aviation developments in the mainliner and regional segment. In addition, detailed vehicle roadmaps for all aircraft segments are provided in section 4.1.2.

Mainliner

The mainliner segment, which includes commercial narrow-body and wide-body aircraft, plays a crucial role in the aviation sector as it represents the largest share of air traffic and its contribution to aviation’s overall emission is highly significant. Given their high utilisation rates and long operational lifetimes, improving efficiency and sustainability of these aircraft is essential for meeting long-term climate goals. The displayed vehicle roadmaps in chapter 4.1.2 outline the potential technological development in the mainliner, regional, business jet, SAT and supersonic segment to achieve these objectives. In addition to these roadmaps, this chapter presents additional aircraft technologies (excluding propulsion technologies) in the mainliner segment which can be relevant for a more sustainable aircraft in the future.

Technology	Category	Potential Entry into Service
Aeroelastic Tailoring + GLA/MLA	Aerodynamic	2030-2040
Riblets	Aerodynamic	2030-2040
Multi-Winglet System	Aerodynamic	2040-2050
Aerogel Structures	Structue & Materials	2040-2050

Technology	Category	Potential Entry into Service
Lightweight Cabin Interiors	Structue & Materials	2035-2045
Global Structural Health Monitoring	Systems	2030-2040
Adaptive Environmental Management System	Systems	2040-2050
Wireless Flight Control System	Systems	2040-2050
Semi-Robotic Taxiing	Systems	2035-2045

Table 2: Overview of relevant aircraft technologies in the mainliner segment additional to the technologies listed in the roadmaps

Supersonic

In addition to the mainliner segment, the supersonic segment also includes additional technologies that are not reflected in detail in the vehicle roadmaps. These technologies could play a crucial role in enabling the feasibility of future supersonic travel by addressing challenges such as fuel efficiency and noise reduction. Therefore, this chapter also highlights selected technologies for the supersonic segment that are essential for achieving sustainable high-speed air transport.

The development of future supersonic aircraft heavily relies on noise reduction technologies to mitigate both landing and takeoff (LTO) noise and the sonic boom. In addition to specific aircraft technologies, operational procedures such as Variable Noise Reduction Systems (VNRS) including Programmed Thrust Lapse Rate (PLR) and High-Speed Climbout are crucial for complying with noise regulations. Furthermore, technological advancements like diverterless inlets, streamline-traced inlets, two-stage fan concepts, sound-absorbing liners in engine inlets, mixer-ejector nozzles, and targeted engine shielding offer additional noise reduction potential.

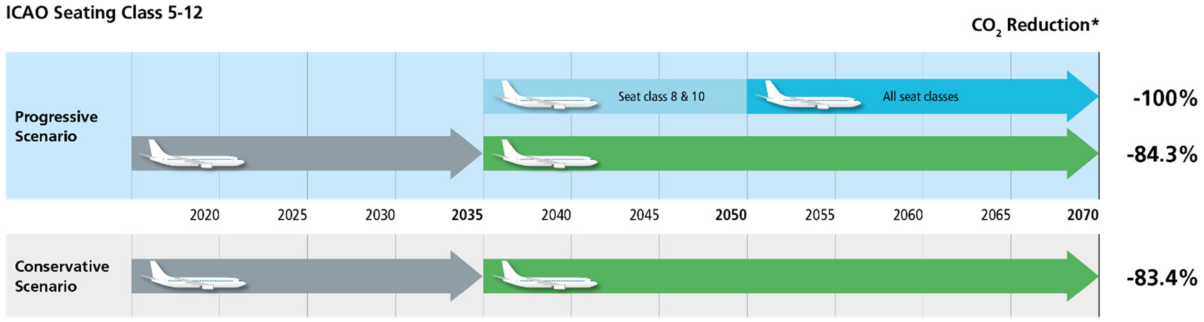
Another key aspect is the Synthetic Vision System (SVS), which is particularly relevant for low-boom concepts. The elongated nose of such aircraft significantly limits the pilot’s direct view, making an SVS necessary for safe operation. If certified, this technology could also benefit conventional supersonic designs by reducing aerodynamic drag, as direct pilot visibility would no longer dictate nose shaping. Structural considerations are also critical, especially given the high flight speeds and unconventional fuselage cross-sections dictated by area ruling constraints.

Additionally, future supersonic aircraft may benefit from advancements in landing gear technology, as the maximum allowable tire speed currently limits high-speed takeoff capabilities. In terms of emissions, the adoption of SAF remains a key strategy (cf. section 3.3). Lastly, the introduction of a real-time monitoring system for sonic boom prediction – similar to LNAS (Low Noise Augmentation System) for landing approaches – could enhance the economic feasibility of non-low-boom concepts. Such a system would allow pilots to dynamically adjust their flight paths based on real-time atmospheric conditions to minimize the impact of sonic booms over populated areas.

DEPA 2070
Vehicle Roadmaps by Fuel Type

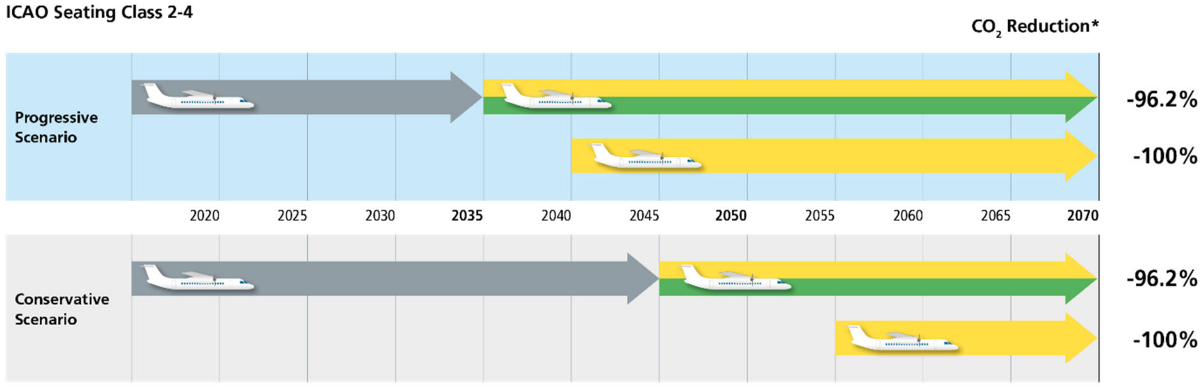
Mainliner

ICAO Seating Class 5-12



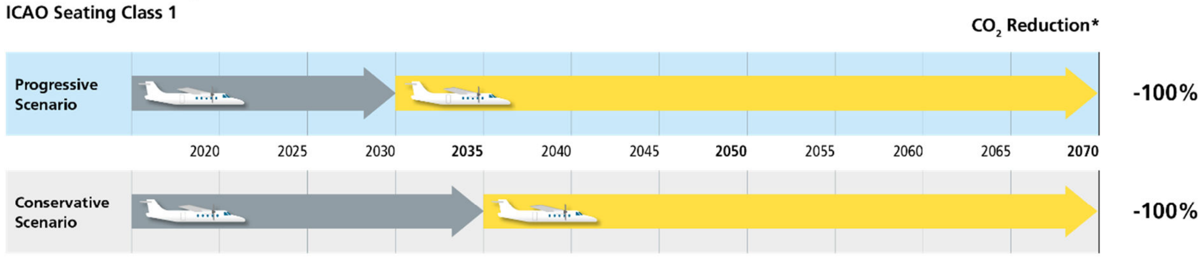
Regional

ICAO Seating Class 2-4

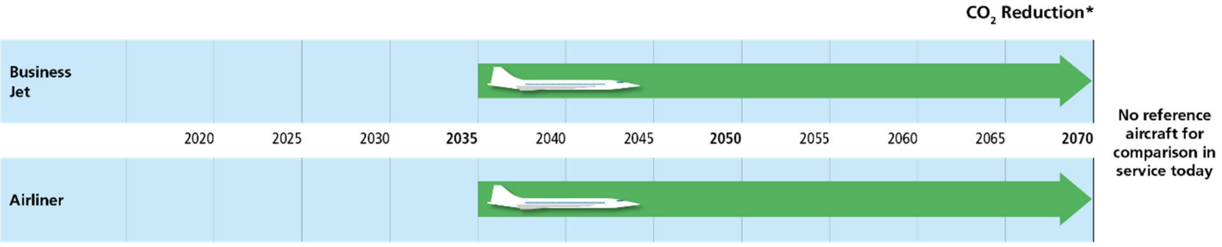


Small Air Transport (SAT)

ICAO Seating Class 1



Supersonic



* Potential Well-to-Wake Emission Reduction on Mission Level

DEPA 2070
Trendlines by Vehicle Configuration

Mainliner

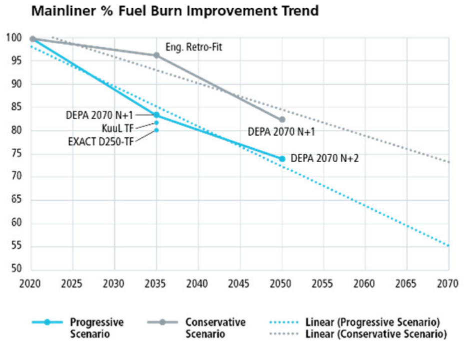
Progressive Scenario

Configuration	Fuel Type	Entry Into Service	Life Cycle Emission Intensity [kg$_{CO2}$/100km/PAX]	Compared to Current Configuration
DEPA 2070 N+1	🟢	2035	0.69	-83.4%
EXACT D250-TF	🟢	2035	0.60	-84.3%
KuuL TF	🟢	2035	1.27	-80.4%
Truss-Braced-Wing/Blended Wing Body (TBW/BWB)	🟢	2050	0.79	-82.8%
EXACT D250-TFLH2-MHEP	🔵	2035	0.0	-100%
KuuL TF	🔵	2035	0.0	-100%
DEPA 2070 N+2	🔵	2050	0.0	-100%

Conservative Scenario

DEPA 2070 Engine-Retro-Fit	🟢	2035	0.81	-80.9%
DEPA 2070 N+1	🟢	2035	0.69	-83.4%

Mainliner % Fuel Burn Improvement Trend



Regional

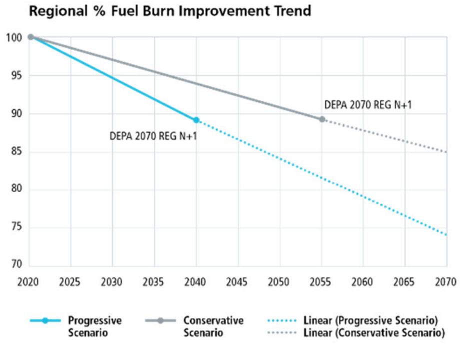
Progressive Scenario

Configuration	Fuel Type	Entry Into Service	Life Cycle Emission Intensity [kg$_{CO2}$/100km/PAX]	Compared to Current Configuration
EXACT D70-PHEA	🟢 🟡	2035	0.67	-96.2%
REG-RAD IMOTHEP	🟢 🟡	2035	1.51	-89.8%
DEPA 2070 REG N+1	🟡	2040	0.0	-100%

Conservative Scenario

EXACT D70-PHEA	🟢 🟡	2045	0.67	-96,2%
REG-RAD IMOTHEP	🟢 🟡	2045	1.51	-89,8%
DEPA 2070 REG N+1	🟡	2055	0.0	-100%

Regional % Fuel Burn Improvement Trend



Small Air Transport (SAT)

Progressive Scenario

Configuration	Fuel Type	Entry Into Service	Life Cycle Emission Intensity [kg$_{CO2}$/100km/PAX]	Compared to Current Configuration
DEPA 2070 SAT N+1	🟡	2030	0.0	-100%

Conservative Scenario

DEPA 2070 SAT N+1	🟡	2035	0.0	-100%

Supersonic

Business Jet

Concept	Incorporated Technologies
FSTB-(L)Low Boom	Low-Boom Configuration, LTO Noise Reduction: LTO Procedures and Engine Technologies, Synthetic Vision Systems (SVS), Canard Configuration, New Engine Design, SAF Combustion
FSTB-(N)Normal Boom	LTO Noise Reduction: LTO Procedures and Engine Technologies, New Engine Design, SAF Combustion

Airliner

Concept	Incorporated Technologies
FSTB-(A)Airliner	Low-Boom Configuration, LTO Noise Reduction: LTO Procedures and Engine Technologies, New Engine Concept, Synthetic Vision System (SVS), Advanced CFRP Structure, Aerodynamic Advancements, SAF Combustion

➡ **Fossil Aviation Fuel**

➡ **Electric Propulsion**
Assumption = No CO$_2$ Emissions

➡ **Hybrid-Electric Propulsion**
Assumption = -80% Life Cycle CO$_2$ Emissions

➡ **Liquid Hydrogen (LH2)**
Assumption = No CO$_2$ Emissions

➡ **Sustainable Aviation Fuel (SAF)**
Assumption = -80% Life Cycle CO$_2$ Emissions

Figure 12: DEPA 2070 Vehicle roadmaps by fuel type

4. Air Transport System Development up to 2070

4.1. Scenario Framework

With the aim of being able to make well-founded statements about the possible future development of the global air transport system up to the year 2070, vehicle-specific technology scenarios had to be developed as part of DEPA 2070. Accordingly, for each of the vehicle types - wide body, narrow body, regional aircraft, business jet, small air transport and supersonic - two different scenarios (a progressive scenario vs. a conservative scenario) were developed regarding their possible development up to the year 2070. The differentiation of these scenarios was carried out exclusively based on aviation internal influencing factors.

The first step was to carry out an analysis of the external framework developments in chapter 4.1.1. For this, all relevant external influencing factors for air transport had to be identified. After the individual factors were categorized in course of a STEEP analysis (Society, Technology, Economy, Environment, Policies), their long-term developments up to the year 2070 had to be described. For this, existing future studies and factor-specific publications were used.

The technology scenarios for each DEPA 2070 vehicle type are presented in the following chapter 4.1.2. In addition to extensive analyses of possible developments of the individual relevant influencing factors, DLR's internal expert assessments played a central role in designing these scenarios. Therefore, as part of the project, a scenario workshop was held with all DEPA 2070 project partners in which corresponding vehicle-specific scenario assumptions were discussed and defined.

Finally, in chapter 4.1.3, emission objectives of the aviation sector as well as measures and instruments for achieving these objectives are examined and a normative DEPA 2070 scenario is developed. This is also compared with other available normative aviation scenarios.

4.1.1. Framework scenarios – STEEP Analysis

Before discussing the technology senarios and the normative scenario, the expected long-term development of external aviation influencing factors up to the year 2070 had to be described. For this purpose, all external influencing factors were categorized into the categories society, technology, economy, environment and politics using a STEEP analysis. The long-term development for each category or key field is explained below. The selection of the respective influencing factors was limited to those that are particularly relevant for future air traffic development. In addition to outlining the long-term developments of the individual factors, concrete exemplary influences or effects on air traffic are also explained.

Society

In the category society a variety of factors will influence air traffic development up to the year 2070. Table 3 provides an overview of factors that are particularly relevant for air traffic in the future.

Category	Factor	Development until 2070	Predictability	Impact on Air Transport
Society	Population Development (global)	Further Increase of World Population 8,5/9,6/10,3 (2030/2050/2070)	High	Growing Demand due to increasing number of potential passengers
	Population Development (regional)	Increase in Asia & Africa vs. Decrease/Stabilisation in Europe, North America & Latin America	High	Shift to Asia as most important region for growing Air Transport Demand
	Population Growth Rates	Decline which results in peak of world population at around 2090	High	Slowdown in growth of potential passengers
	Demographic Shifts	Increasing share of older people in Society, especially in Europe, North America & East Asia	High	Adjustment of air transport supply for older people
	Migration	Increasing net interregional migration flows from Asia, Africa & Latin America to Europe, North America & Oceania	Medium	Additional demand potential for aviation in Europe, North America & Oceania
	Urbanisation	Increase of urban population from 50 percent in 2023 to 60 percent in 2070	High	Growing demand potential for Urban Air Mobility in Cities
	Mobility Patterns	Mobility-as-a-service & sharing platforms replace private ownership, Demand for convenient & flexible	Medium	Integration of new vehicles (UAM & SAT) in transport chains
	Social Trends	Environmental awareness, Individualition, More Flexibility, Experience based leisure	Medium	Growing importance of low emission air transport (SAF, electric, hydrogen)
	Pandemics & other Wildcards	Potential global crises like pandemics, conflicts, wars, economic crisis	Low	Flight bans & restrictions, Hygiene measures, Fleet grounding, Decrease of demand

Table 3: Influencing factors from the category Society

According to current forecasts, the world population will continue to grow until 2070. While there are currently 7.9 billion people in the world, this number will rise to 8.5 billion in 2030 and more than 9.6 billion in 2050. In 2070, the world population will finally consist of more than 10 billion people. Due to the continuously decreasing growth rate at the same time, the world population will reach its peak in the period after 2070 and eventually begin to decline.

A look at the individual regions of the world reveals that there are significant differences in the respective population development up to the year 2070. Accordingly, the increase in the world population originates particular from the enormous growth rates in sub-Saharan Africa, which will mean that this region will be the most populous region in the world in 2070. While today East-Southeast Asia with 2.3 billion and Central-South Asia with 2.1 billion people are the most populous regions, in 2070 Sub-Saharan Africa will be the most populous region in the world with almost 3 billion people. All other regions of the world will show a declining or stabilizing population development over the next few decades, which will gradually lead to an overall declining growth rate of the world population.

In combination with the population developments described, the increasing life expectancy worldwide and the simultaneous decline in fertility rates are leading to a demographic shift that is also described with the term "population ageing". Accordingly, the age structure of the world population will change significantly by 2070, with significantly larger proportions of older people. The proportion of people aged 65 or over worldwide will rise from just under 7.5% currently to just under 15% in 2050. There is also a significant difference between the regions of the world in this development. According to this, the proportion of people aged 65 or over will be significantly higher in the western regions of the world in the future. While in Europe and North America this proportion will be almost 25% in 2050, in sub-Saharan Africa only less than 5% of the population will be older than 65 in 2050. While by 2070 all age groups in Europe up to 65 years will have experienced a percentage age decline compared to today, there will be a significant increase in all age groups older than 65 years in 2070.

In addition to natural population growth, the distribution of the world population will also be increasingly influenced by migration in the coming decades. International migration movements will lead to a corresponding increase in population in the regions of Europe, North America and Oceania in particular. Cumulative interregional migration is forecasted to reach 66.9 million people for these three regions by 2050, while the same number of people will migrate from the other regions (Asia, Africa, Latin America).[29]

Another megatrend that will fundamentally change the world population by 2070 is increasing urbanization. According to this, the proportion of people living in cities will grow significantly faster by 2070 than the proportion of people living in rural areas. While almost 50% of the world's population currently lives in cities, by 2070 almost 60% of people will be city residents. The proportion of the global rural population will decrease from 22% to 18% in the same period. However, there are geographical differences in this development too. Urbanization is significantly more pronounced in Central/Southern Asia and sub-Saharan Africa than in other regions of the world. In these two regions, the number of cities will increase from 4,500 and 2,500 today to over 5,300 and 4,100 by 2070.

Technology

In addition to social trends and influencing factors from the social sector, technological trends also play an important role in the future development of air traffic up to the year 2070.

The diverse use of artificial intelligence (AI) will have a major impact on air traffic in the coming decades. In the future, this technology will enable autonomous flight of air taxis as part of urban air mobility.

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[29] Cf. Roland Berger (2020b).

Category	Factor	Development until 2070	Predictability	Impact on Air Transport
Technology	Artificial Intelligence	Use of AI for decision making & optimization, AGI to match or exceed human capability and intelligence	Medium	Autonomous UAM, Flight Profile Optimization, Predictive Maintenance, Digital Twins
	Battery Technologies	Substantial performance improvements, Increase of Energy density, New battery generations	Medium	Entry Into Service of all electric aircrafts for >100 seat classes
	Direct Air Capture (DAC) Technology	Increase of DAC plants around the world, Strong decrease of air capture costs, Large scale PtL production	Medium	Increase of Power-To-Liquid (PtL) Fuels for Aviation, Significant CO_2 Emission Reduction
	Advanced Biofuel Technologies	Significant production cost decrease for HEFA, FT & ATJ	Medium	Supply increase of Biofuels for Aviation, Significant CO_2 Emission Reduction
	New Materials	Technological progress of Nanomaterials, Composite materials, Advanced and lightweight composite	Medium	Weight reduction of aircrafts, Decrease of fuel consumpion
	Additive Manufacturing	Further progress and cost decrease of lightweight 3D print technology	Medium	Weight reduction of aircrafts, Efficiency increase of manufacturing and maintenance
	Robotics & IoT	Combination of both technologies and increase of Industry 4.0 and Smart Production	Medium	Predictive Maintenance, Efficiency increase, Improve reliability, Decrease DOC
	Technology of High Speed Trains & Maglevs	Improved High-Speed Train Networks in developed countries, Maglevs between agglomerations and first	Medium	Reduction of air passenger potential on these relations
	Technology of Urban Transport Concepts	Significant increase of automated/autonomous driving and shared mobility services	High	Possibility of integrating (autonomous) Urban Air Mobility in Urban Transport Concepts

Table 4: Influencing factors from the category Technology

AI will also continue to support the processes and procedures of the pilot crew in the cockpit in conventional air traffic in a variety of ways, such as in-flight profile optimization processes. AI will also play an important role in the production and maintenance of aircraft in the coming decades in order to be able to process the enormously increasing volumes of data. Applications include the development of digital twins in the aircraft design phase, the use of the Internet of Things in the production chain and the application of predictive maintenance in this context.

In addition to the applications of artificial intelligence mentioned above, other technologies will also have a decisive influence on air traffic by 2070. Accordingly, further advances in battery technologies will lead to an increased use of electric and hybrid-electric aircraft concepts. In addition, additive manufacturing, robotics and smart production will continuously increase the efficiency of aircraft production and maintenance in the coming decades. Technological advances in the field of synthetic biology and carbon capture and utilization (CCU), which are required for the production of biokerosene and synthetic kerosene, in turn lead to a further increasing share of SAF in air transport by 2070.

In the Technology Trends Outlook from Mc Kinsey (2022), future-oriented technologies for the mobility sector are also summarized under the term ACES, which stands for Autonomous, Connected, Electric and Smart. Accordingly, ACES will become increasingly important in ground and air mobility in the coming decades. For air transport, this means in particular (autonomous) urban air mobility and the increasing (hybrid) electrification of vehicle concepts in the coming decades.

In the progressive scenario, there will be greater development progress in certain technology fields than in the conservative scenario. These include in particular technologies that are necessary for the further development of specific aviation technologies to market maturity. In the progressive scenario, there will be significantly greater progress in the area of advanced energy storage technologies, which enable hybrid-electric and full electric vehicle concepts in aviation, particularly in the form of high-performance battery technologies. Major technological advances in areas such as additive manufacturing, robotics or smart manufacturing, on the other hand, allow for significant innovations and efficiency improvements in aircraft maintenance in the progressive scenario. In addition, the further development of nanomaterials is enabling great progress in aircraft construction. Examples include the integration of lightweight materials or nano-coatings on engine parts. The basic prerequisites for a larger share of SAF are the significantly greater technological advances in the progressive scenario in areas such as synthetic biology and CCU, which are used for the production of biokerosene and synthetic kerosene. Research into new SAF production processes (in which the use of waste materials also plays an important role) is already very active today. The current limit of 50% admixture as a safety buffer must be eliminated in the future through further research activities.

Economy

In addition to social and technological trends, the development of air traffic is also significantly influenced by economic developments and trends. A key factor influencing air traffic development up to 2070 from the economics category is the future development of the global economy. Global GDP will continue to increase up to 2070. However, the global GDP growth rate will decrease slightly in parallel. According to current forecasts, the GDP growth rate (PPP) will fall from 2.8% in the period 2020-2029 to 1.8% in the period 2070-2079.

At the same time, there will be a significant geographical shift in power in the global economy by 2070. The centre of gravity of the global economy will shift further and further towards the southeast in the coming decades. The reason for this is the enormous economic growth of countries such as China and India in the coming decades. This will mean that these two countries will have a higher gross domestic product in 2070 than countries such as the USA, Japan or the European Union.

Category	Factor	Development until 2070	Predictability	Impact on Air Transport
Economy	World GDP	Further increase of World GDP 1,4/2,3/3,3 (2030/2050/2070)	High	Growing Demand of potential passengers due to growing economy and disposable income
	GDP Growth Rates	Decrease of GDP growth rates 2,8/1,8 (2020-2029/2070-2079)	High	Slowing down of increasing demand for air transport
	GDP per Capita	Increase of GDP per capita of global population	High	Increase of demand for air transport due to increase of disposable income per capita
	Power Shifts	Significant power shift of global economy towards southeast; Higher GDP increase of Asian countries (esp.	High	Shift to Asia as most important region for growing Air Transport Demand
	Global Middle Class	Growth of the global middle class with highest growth rates in Asia	High	Shift to Asia as most important region for growing Air Transport Demand
	Regional disparities	Unevene moderate reductions between and within countries, Gaps in living standards will persist in 2070	High	Disparities of aviation demand within countries
	Business relations & New Work	Increase of international & intercontinental business relations, Increase of IT supported interactions	High	Continous importance of business air travel, Replacement of some business trips via IT

Table 5: Influencing factors from the category Economy

Despite the global economic developments described above, regional disparities will only be reduced to a limited extent in the coming decades. There will be a moderate reduction in regional differences in disposable income in the coming decades. In the future, however, large gaps in living standards between and within world regions will continue to exist.

Environment & Energy

Key influencing factors in the field of environment and energy can be found in Table 6. Accordingly, in addition to climate change, the increase in the share of renewable energies and the price of energy in general will have a major impact on future air traffic.

Category	Factor	Development until 2070	Predictability	Impact on Air Transport
Environment & Energy	Climate Change	Increase of global mean temperature, Environmental Degradation, Uninhabitable regions in the world	Medium	No acceptance of air transport with conventional kerosene, Increase of importance of
	Low Carbon Energy	Significant increase of share of clean energy sources for primary energy & final energy	Medium	Increase of full electric aircraft concepts and SAF share
	Energy Price	Cost decrease of renewable energy & cost increase of fossil fuels	Medium	Shift to environmental friendly aviation with electric & SAF

Table 6: Influencing factors from the category Environment & Energy

Global climate change will have serious consequences for the environment and society in the coming decades without far-reaching political countermeasures. The global average temperature is expected to rise by 4 degrees in 2100 compared to pre-industrial times if no significant countermeasures are taken.

This development is also described by the Intergovernmental Panel on Climate Change (IPCC) with the so-called Shared Socioeconomic Pathway 2 (SSP 2), which is a business-as-usual scenario. In this scenario, no major changes in social, economic and technological trends are assumed. Such a global temperature increase would mean that, for example, many regions in South America would no longer be inhabitable by 2070.

The availability of sustainable energy sources will play a crucial role in the future development of air traffic and the successful reduction of emissions considering the climate change.

In order to be able to plausibly justify the scenario-specific factor assumptions for the individual vehicle types in the DEPA 2070 technology scenarios outlined later, it was necessary to make different assumptions in the area of energy in addition to the area of technology. For this reason, this outlook up to 2070 was based on the Energy Technology Perspectives of the International Energy Agency (IEA). These represent two possible global energy technology developments up to 2070 and are therefore particularly suitable for creating a scenario-specific outlook on this topic. The progressive DEPA 2070 scenario is based on the so-called Sustainable Development Scenario (SDS) and the conservative scenario on the so-called Stated Policies Scenario (SPS). Energy demand in 2070 will be significantly lower in the progressive scenario at around 15,000 million tonnes of oil equivalent (Mtoe) than in the conservative scenario at just under 20,000 Mtoe. This is mainly due to the significantly greater progress in the progressive scenario in the area of energy and material efficiency. There are also clear differences between the two scenarios in the share of renewable energies in 2070. Accordingly, the share of renewable energies is significantly higher with 65% than in the conservative scenario with 30%. Here, non-sustainable energy sources such as coal (16%), oil (24%), gas (24%) and nuclear energy (6%) will still play an important role in 2070.

Policies

Finally, political framework developments will have a significant impact on future air traffic. In order to limit the predicted effects of climate change described above, it is particularly important to reduce global emissions in the coming decades.

Category	Factor	Development until 2070	Predictability	Impact on Air Transport
Policies	General policy development	Increased importance of climate policy	Medium	Increase of SAF blending mandates in Europe & other world regions
	Research & Development	Political support of innovative technologies for climate friendly solutions	Medium	Increase of performance of electric vehicle concepts & SAF use
	Marked based measures	Increased internalisation of external costs of carbon emissions	Medium	ETS & CORSIA, landing charges & fuel tax etc.
	Regulations & Restrictions	Further political actions & laws to transform global transport system to climate friendly	Medium	Ban of short-haul kerosene flights, certification of autonomous UAM flights

Table 7: Influencing factors from the category Policies

Therefore, a wide range of political measures are being used to further reduce the economy's emissions.

The results of the regularly published status reports of the IPCC on the state of scientific knowledge on global warming have led to climate policy becoming increasingly relevant worldwide in recent decades. For example, with the Paris Agreement, 195 countries have committed themselves to reduce climate change and transforming the global economy in a climate-friendly way. The main objectives of this agreement are to limit the increase in the global average temperature, reduce emissions and adapt to climate change, and direct financial resources in line with climate protection goals.

In addition to these overarching agreements, entire sectors of the economy have also committed themselves to specific emission reduction targets over the years. In the air traffic sector, "Zero CO_2 emissions in 2050" is currently considered as the key goal. All key players in air traffic (ICAO, IATA, ATAG, One World Airline Alliance, European Union, United States, etc.) have now committed to a zero CO_2 emission target for air traffic by 2050. For achieving CO_2 neutrality by 2050, a wide range of political instruments and measures are necessary.

The three major political areas of influence for future air traffic development can be divided into the promotion of research programs, regulations and restrictions, and market-based measures. The political initiation and promotion of programs in the field of research and development for air traffic is primarily focused on technological development and optimization of the air traffic system. This is intended to reduce emissions in air traffic primarily with the help of technological innovations. The most prominent example of such a program is "Clean Aviation" with its predecessor project "Clean Sky 2". There are also many other research programs funded by the EU that deal specifically with the topics of SAF, electrified vehicle concepts or air traffic management. The political initiation and promotion of programs in the field of research and development will therefore continue to play a decisive role in the further development of air traffic in the future.

Regulations and restrictions represent the second major area of political influence on air traffic. Examples include mandates for the use of SAF in air traffic (e.g. Refuel EU) or fuel efficiency standards for new aircraft. In the future, the certification of UAM vehicles or a ban on kerosene-powered flights over very short distances could be possible political influences in air traffic. These are just four examples from this political influence category.

Finally, market-based measures represent the third major area of political influence. These can be divided into the instruments of emissions trading (EU ETS), offsetting (CORSIA) and Levies (e.g. kerosene tax).

For air transport, this means a medium- and long-term switch to hybrid and full electric vehicle concepts as well as an increasing share of SAF or hydrogen in the coming decades in order to be able to achieve the respective objectives.

4.1.2. DEPA 2070 Technology Scenarios

As a basis for the development of vehicle-specific technology scenarios for all DEPA 2070 vehicle types, it was first necessary to develop trend analyses or rather future outlooks for the individual impact categories. This enables the creation of plausible assumptions for the individual factors for the respective vehicle-specific scenarios, which are within the scope of possible future developments.

Figure 13 provides an overview of future possible shares of SAF in aviation based on various scenarios in aviation from different institutions. It can be seen that the SAF share will increase significantly in the future. At the same time, there is great uncertainty in the assumed future SAF shares, which can be clearly seen in the wide range in 2050. This is primarily due to the different assumptions made in the individual scenarios regarding technological development, availability and production, regulatory framework conditions and market and infrastructure development. This results in different projections of SAF shares in aviation up to 2070, from moderate admixtures to complete substitution of fossil fuels.

Figure 14 provides an overview of the possible market entry and planned seating capacity of hydrogen-powered aircraft concepts, based on information from available studies and from the respective manufacturers. Future hydrogen aircraft will have different passenger capacities and ranges depending on their concept. As can be seen, a differentiation was made between Direct Hydrogen Combustion and Hydrogen Fuel Cell. The figure shows that the future seating capacities for hydrogen combustion aircraft concepts will be significantly larger than for hydrogen fuel cell aircraft concepts. However, the introduction of hydrogen aircraft requires significant investments in new infrastructure devices, such as special tanks for storing liquid hydrogen at airports. In addition, availability and costs, technology development (safe aircraft integration) and logistics are further challenges in establishing hydrogen-powered air transport. However, hydrogen offers enormous potential to significantly reduce emissions in aviation and to promote the decarbonization of air traffic.

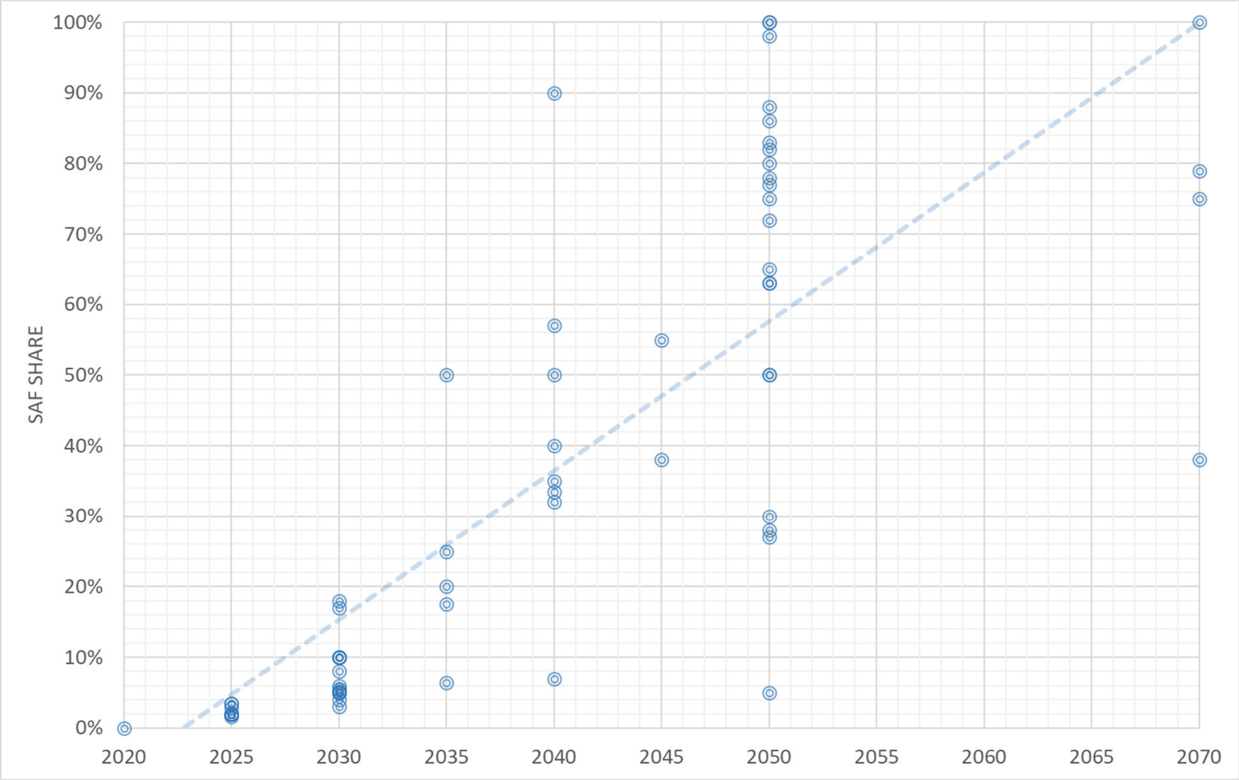


Figure 13: SAF shares based on literature research

An analysis of currently planned electric vehicle concepts illustrates the range of possible performance data for future full electric and hybrid-electric aircraft. Only conventional vehicle concepts - electrical conventional take off & landing (eCTOL) - were considered, which require a runway and in which the vehicles cannot take off and land vertically, like eVTOL's (electric vertical take-off and landing aircraft). Figure 15 summarizes the EIS planned by the relevant manufacturers and the passenger capacities of the vehicle concepts currently in development. It is noticeable that the performance data of purely electrically powered small aircraft (full electric eCTOL) are lower than for hybrid electric vehicle concepts (hybrid electric eCTOL). In addition to the ES-19 design with 19 passenger seats from Heart Aerospace - which has now been replaced by the hybrid electric ES-30 vehicle concept - and the Echolon One (Maeve 1) vehicle concept from Venturi with 44 passenger seats, the range of full electric vehicle concepts currently in development is limited to an average of around 400 kilometres and a passenger capacity of 9 seats.

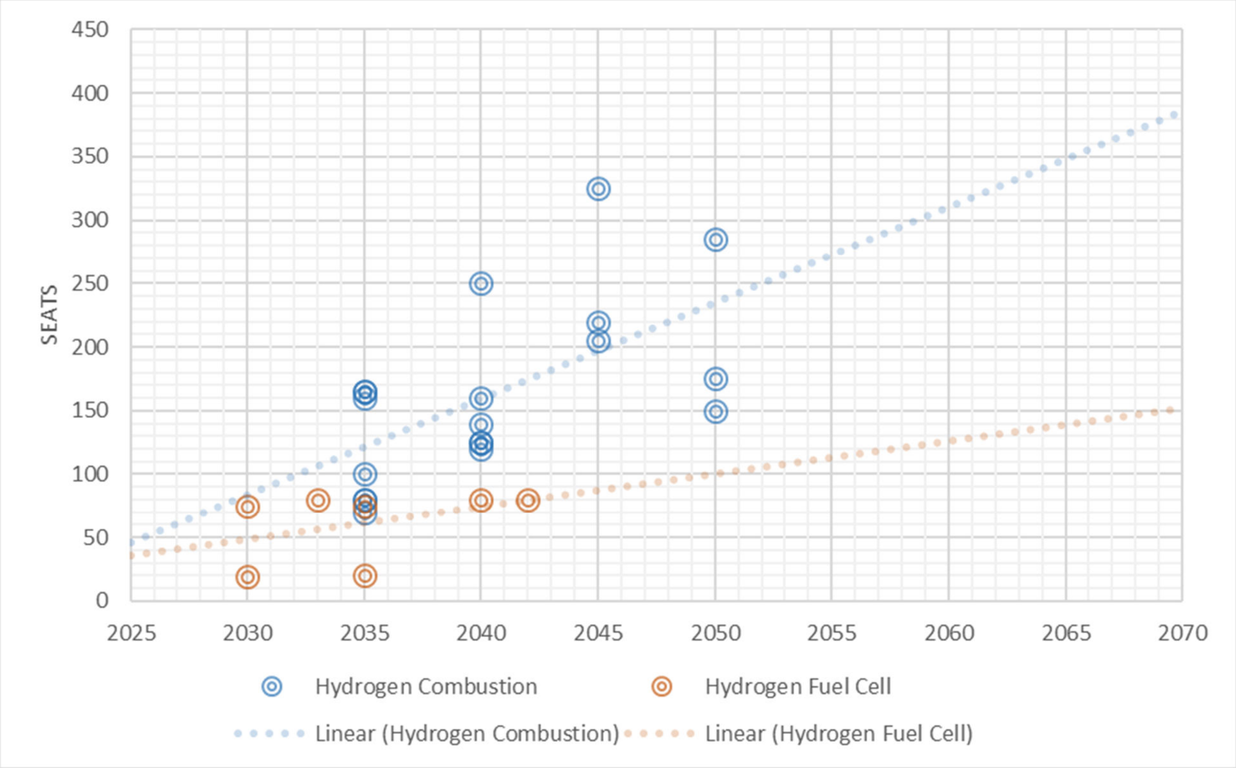


Figure 14: Announced EIS and seat capacity of hydrogen aircraft

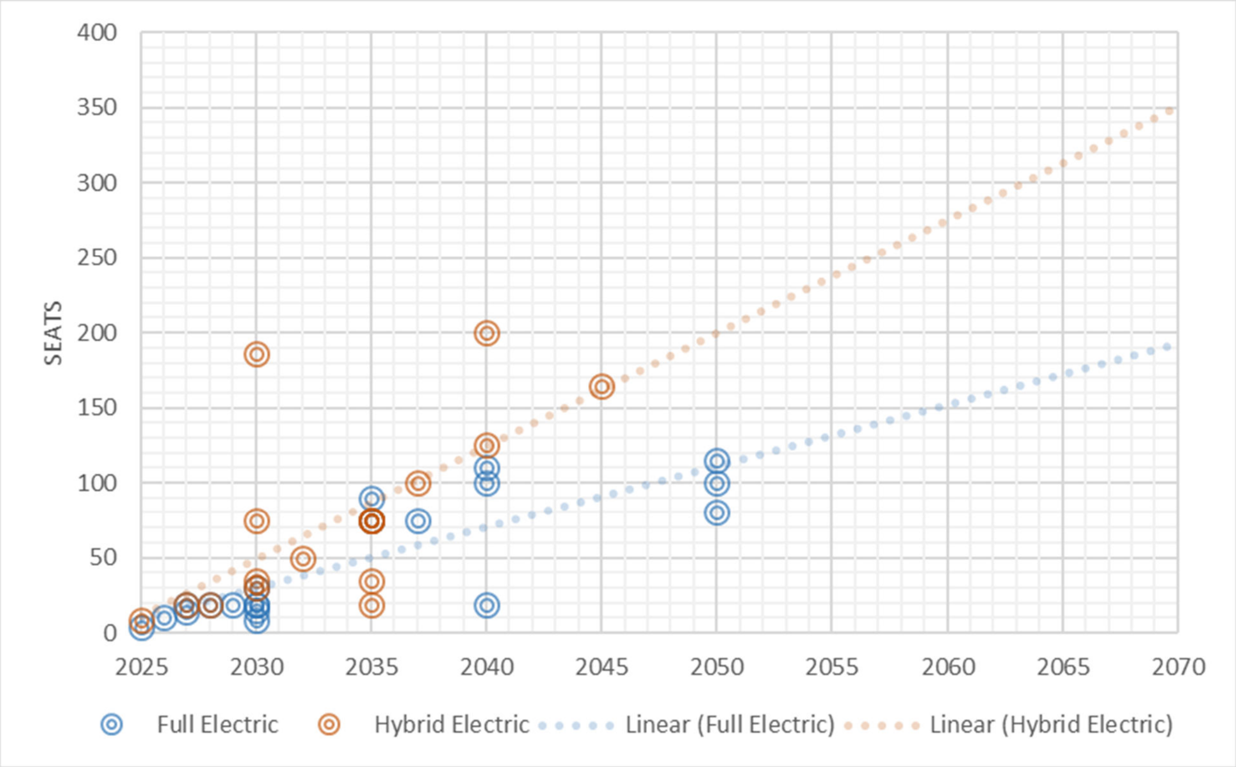


Figure 15: Announced EIS and seat capacity of electric aircraft

The trend analyses outlined above for SAF, electric aircraft and hydrogen aircraft were finally discussed together with preliminary analyses of possible market entries and market maturity of technologies from other influencing factor categories (aerodynamics, propulsion, concepts, etc.) in a DEPA 2070 scenario workshop with the other DEPA 2070 project partners. In the workshop, the central assumptions for influencing factors for each vehicle type and scenario were finally defined. The following two tables summarise the central assumptions regarding market entry of electrified aircraft and hydrogen-powered aircraft concepts for all DEPA 2070 vehicle types and both technology scenarios.

Scenario	Type of Electric Propulsion	Entry Into Service (EIS)					
		Mainliner (wide body)	Mainliner (narrow body)	Regional	SAT	Business Jet	Supersonic
Conservative	Full Electric (Battery)	-	-	2055	2035	-	-
	Hybrid Electric (Fuel & Battery)	2060	2050	2045	2030	2045	-
Progressive	Full Electric (Battery)	-	-	2040	2030	-	-
	Hybrid Electric (Fuel & Battery)	2040	2035	2035	2025	2030	-

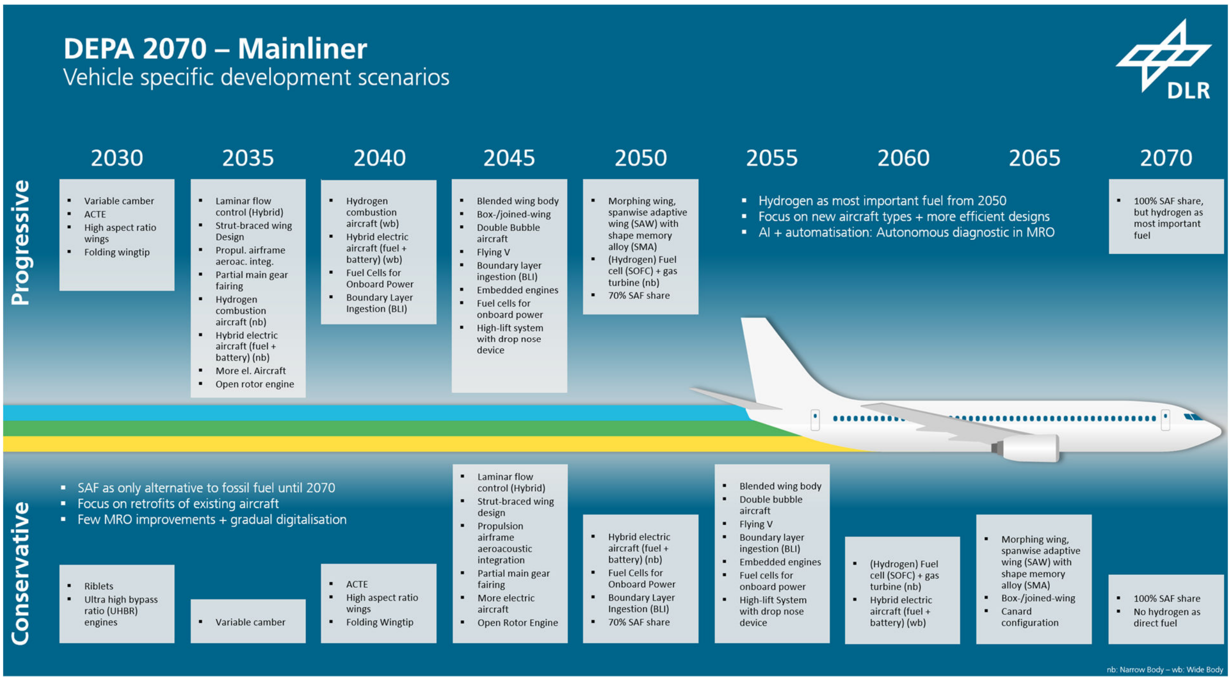
Table 8: EIS assumptions for electric aircraft, scenario specific and vehicle specific

Scenario	Type of Hydrogen Propulsion	Entry Into Service (EIS)					
		Mainliner (wide body)	Mainliner (narrow body)	Regional	SAT	Business Jet	Supersonic
Conservative	Hydrogen Combustion	-	-	-	-	-	-
	Hydrogen Fuel Cell (PEM)	-	-	2055	2040	-	-
	(Hydrogen) Fuel Cell (SOFC)+Gas Turbine Hybrid	-	2060	2060	-	-	
Progressive	Hydrogen Combustion	2040	2035	2035	-	2040	-
	Hydrogen Fuel Cell (PEM)	-	-	2035	2030	-	-
	(Hydrogen) Fuel Cell (SOFC)+Gas Turbine Hybrid	-	2050	2050	-	-	-

Table 9: EIS assumptions for hydrogen aircraft, scenario specific and vehicle specific

The following figures provide a summarised overview of the technology scenarios for each DEPA 2070 vehicle type. In the mainliner vehicle segment, which includes wide-body and narrow-body aircraft types, hydrogen-powered vehicle concepts will increasingly play an important role in the progressive scenario. Hydrogen-powered narrow-body vehicle types are expected from 2035 and hydrogen-powered wide body vehicle types from 2040. At the same time, the share of sustainable aviation fuels will increase to 70% by 2050 and to 100% by 2070. However, with the increasing proportion of hydrogen-powered aircraft concepts in the progressive scenario, the importance of SAF for mainliners is becoming less. A different picture emerges when looking at the conservative scenario, in which no market entry of hydrogen-powered vehicle concepts is assumed. Accordingly, the increasing SAF share, which will also rise to 100% in 2070, represents the primary alternative to fossil kerosene. Individual technologies such as Laminar Flow Control or Open Rotor Engine have a market entry in 2035 in the progressive scenario and 10 years later in 2045 in the conservative scenario. Very innovative technologies such as a spanwise adaptive wing with shape memory alloy are planned for 2050 in the progressive scenario and in the conservative scenario for the year 2060.

While in the progressive scenario various completely new vehicle types such as a Blended Wing Body or Double Bubble aircraft are possible from the year 2045, in the conservative scenario the focus is on retrofits of existing aircraft or the entry into service of such completely new vehicle types is much later from the year 2055.



DEPA 2070 – Mainliner
Vehicle specific development scenarios

Progressive

2030
- Variable camber
- ACTE
- High aspect ratio wings
- Folding wingtip

2035
- Laminar flow control (Hybrid)
- Strut-braced wing Design
- Propul. airframe aeroac. integ.
- Partial main gear fairing
- Hydrogen combustion aircraft (nb)
- Hybrid electric aircraft (fuel + battery) (nb)
- More el. Aircraft
- Open rotor engine

2040
- Hydrogen combustion aircraft (wb)
- Hybrid electric aircraft (fuel + battery) (wb)
- Fuel Cells for Onboard Power
- Boundary Layer Ingestion (BLI)

2045
- Blended wing body
- Box-/joined-wing
- Double Bubble aircraft
- Flying V
- Boundary layer ingestion (BLI)
- Embedded engines
- Fuel cells for onboard power
- High-lift system with drop nose device

2050
- Morphing wing, spanwise adaptive wing (SAW) with shape memory alloy (SMA)
- (Hydrogen) Fuel cell (SOFC) + gas turbine (nb)
- 70% SAF share

2055 **2060** **2065**
- Hydrogen as most important fuel from 2050
- Focus on new aircraft types + more efficient designs
- AI + automatisation: Autonomous diagnostic in MRO

2070
- 100% SAF share, but hydrogen as most important fuel

Conservative

- SAF as only alternative to fossil fuel until 2070
- Focus on retrofits of existing aircraft
- Few MRO improvements + gradual digitalisation

2030
- Riblets
- Ultra high bypass ratio (UHBR) engines

2035
- Variable camber

2040
- ACTE
- High aspect ratio wings
- Folding Wingtip

2045
- Laminar flow control (Hybrid)
- Strut-braced wing design
- Propulsion airframe aeroacoustic integration
- Partial main gear fairing
- More electric aircraft
- Open Rotor Engine

2050
- Hybrid electric aircraft (fuel + battery) (nb)
- Fuel Cells for Onboard Power
- Boundary Layer Ingestion (BLI)
- 70% SAF share

2055
- Blended wing body
- Double bubble aircraft
- Flying V
- Boundary layer ingestion (BLI)
- Embedded engines
- Fuel cells for onboard power
- High-lift System with drop nose device

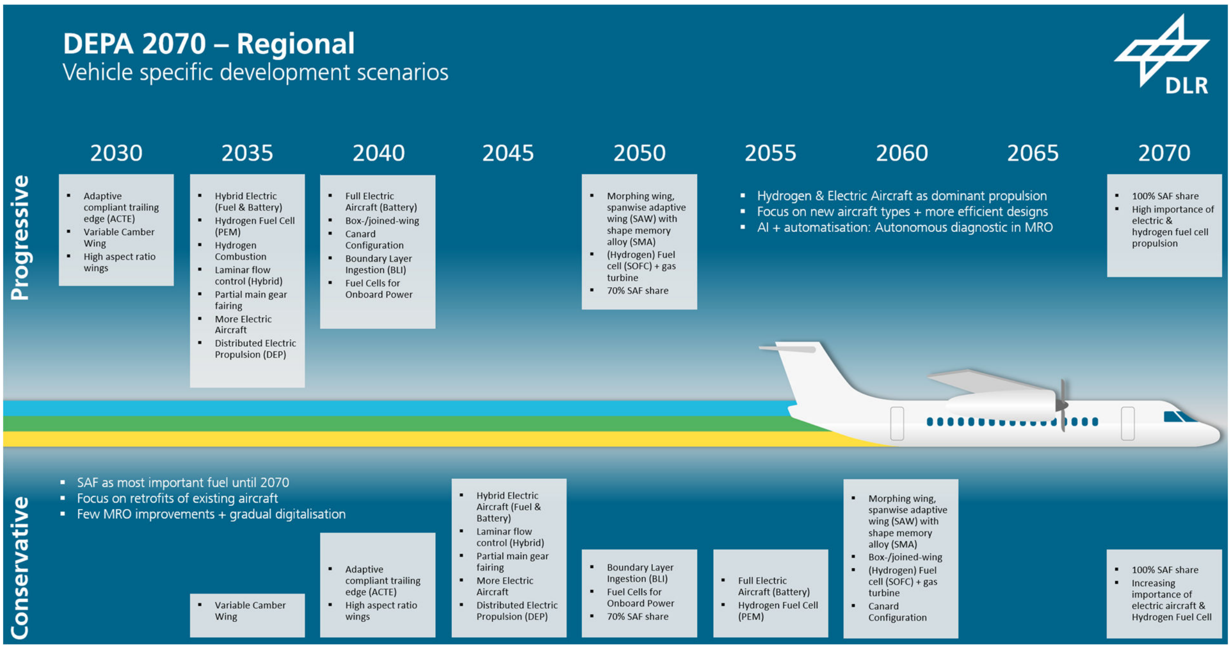
2060
- (Hydrogen) Fuel cell (SOFC) + gas turbine (nb)
- Hybrid electric aircraft (fuel + battery) (wb)

2065
- Morphing wing, spanwise adaptive wing (SAW) with shape memory alloy (SMA)
- Box-/joined-wing
- Canard configuration

2070
- 100% SAF share
- No hydrogen as direct fuel

nb: Narrow Body – wb: Wide Body

Figure 16: DEPA 2070 technology scenario for mainliner aircraft



DEPA 2070 – Regional
Vehicle specific development scenarios

Progressive

2030
- Adaptive compliant trailing edge (ACTE)
- Variable Camber Wing
- High aspect ratio wings

2035
- Hybrid Electric (Fuel & Battery)
- Hydrogen Fuel Cell (PEM)
- Hydrogen Combustion
- Laminar flow control (Hybrid)
- Partial main gear fairing
- More Electric Aircraft
- Distributed Electric Propulsion (DEP)

2040
- Full Electric Aircraft (Battery)
- Box-/joined-wing
- Canard Configuration
- Boundary Layer Ingestion (BLI)
- Fuel Cells for Onboard Power

2045

2050
- Morphing wing, spanwise adaptive wing (SAW) with shape memory alloy (SMA)
- (Hydrogen) Fuel cell (SOFC) + gas turbine
- 70% SAF share

2055 **2060** **2065**
- Hydrogen & Electric Aircraft as dominant propulsion
- Focus on new aircraft types + more efficient designs
- AI + automatisation: Autonomous diagnostic in MRO

2070
- 100% SAF share
- High importance of electric & hydrogen fuel cell propulsion

Conservative

- SAF as most important fuel until 2070
- Focus on retrofits of existing aircraft
- Few MRO improvements + gradual digitalisation

2035
- Variable Camber Wing

2040
- Adaptive compliant trailing edge (ACTE)
- High aspect ratio wings

2045
- Hybrid Electric Aircraft (Fuel & Battery)
- Laminar flow control (Hybrid)
- Partial main gear fairing
- More Electric Aircraft
- Distributed Electric Propulsion (DEP)

2050
- Boundary Layer Ingestion (BLI)
- Fuel Cells for Onboard Power
- 70% SAF share

2055
- Full Electric Aircraft (Battery)
- Hydrogen Fuel Cell (PEM)

2060
- Morphing wing, spanwise adaptive wing (SAW) with shape memory alloy (SMA)
- Box-/joined-wing
- (Hydrogen) Fuel cell (SOFC) + gas turbine
- Canard Configuration

2070
- 100% SAF share
- Increasing importance of electric aircraft & Hydrogen Fuel Cell

Figure 17: DEPA 2070 technology scenario for regional aircraft

A look at the technology scenarios for the regional vehicle segment, which includes, for example, an ATR 72 with 90 seats, shows the increasing importance of electrified aircraft concepts as the size of the aircraft becomes smaller. Accordingly, in the progressive scenario, a full electric vehicle concept in the regional segment is possible from 2040 onwards. In the conservative scenario, the market entry is planned 15 years later in 2055. In addition to electrified vehicle concepts, hydrogen can also play an important role as a power source for regional aircraft. From 2035 onwards, hydrogen combustion aircraft and hydrogen fuel cell aircraft will be possible in the progressive scenario. In the conservative scenario, hydrogen fuel cell aircraft are only expected to enter the market in 2055. The share of sustainable aviation fuels will increase to 70% by 2050 and to 100% by 2070, although, especially in the progressive scenario with hydrogen and batteries, there will be enough alternative propulsion types available and will make up the lion's share by 2070. The market entry date of technologies such as boundary layer ingestion and fuel cells for onboard power is assumed to be 2040 in the progressive scenario and 10 years later in 2050 in the conservative scenario.

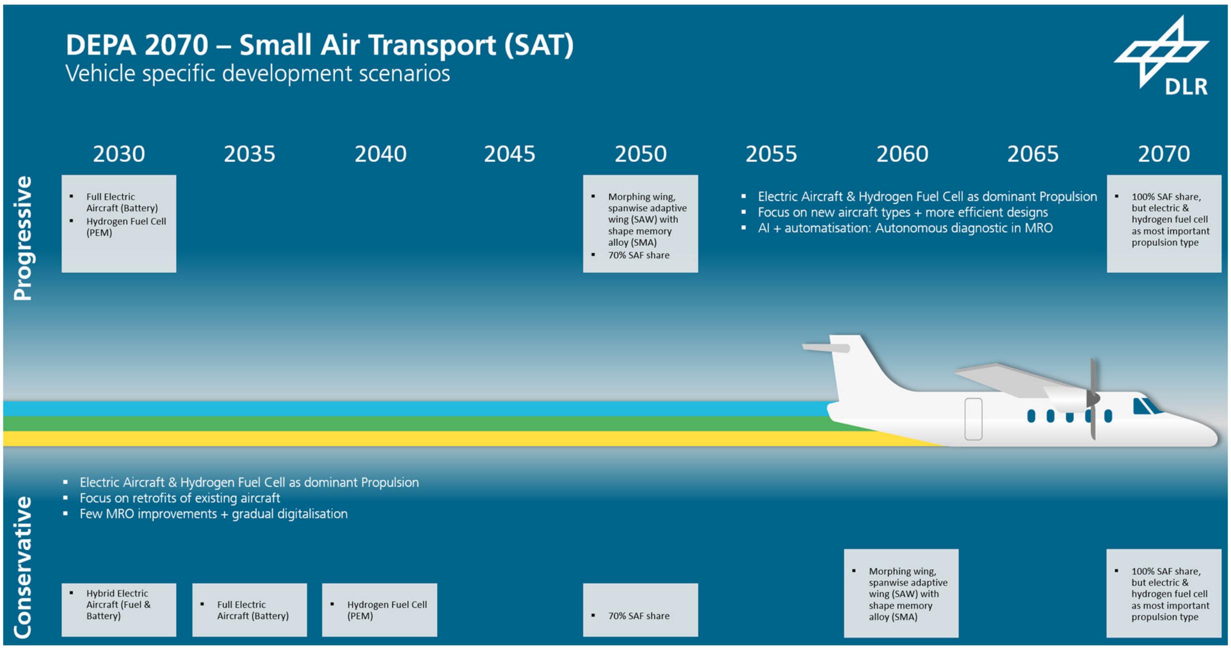


Figure 18: DEPA 2070 technology scenario for small air transport

The technology scenarios for SAT, which includes aircraft types such as a Dornier 228 with 19 seats, show an even greater importance of electrified vehicle concepts. In the progressive scenario, full electric vehicle concepts are expected to enter the market in 2030. In the conservative scenario, the market entry is planned 5 years later in 2035. Hydrogen fuel cell vehicle concepts will come into the market from 2035 in the progressive scenario and from 2040 in the conservative scenario. The share of sustainable aviation fuels will rise to 70% in 2050 and to 100% in 2070. However, due to the early market entry of full electric vehicle concepts in both scenarios, SAF will no longer play a significant role in this vehicle segment by 2070. Due to the lower operational range and passenger seats, SAT is an excellent vehicle segment for a complete electrification. Market entry of individual technologies such as adaptive compliant trailing edge (ACTE) in 2030 or Laminar Flow Control in 2035 will take place earlier in the progressive scenario than in the conservative scenario (2040 or rather 2045).

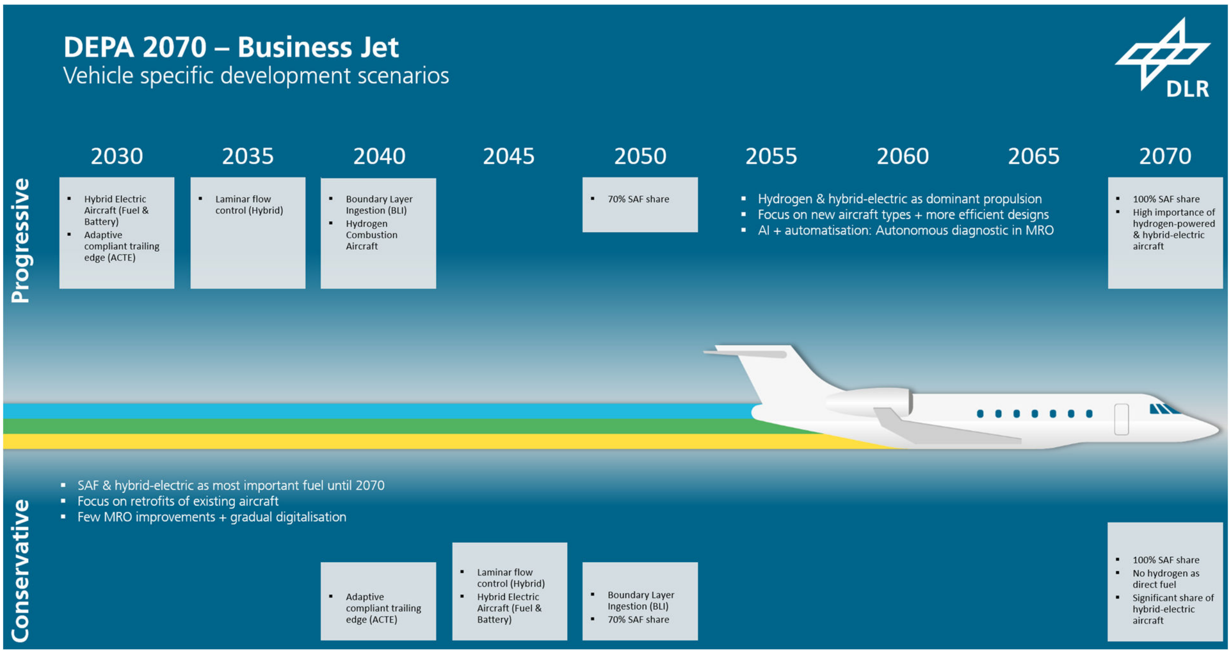


Figure 19: DEPA 2070 technology scenario for business jets

The technology scenarios for business jets are represented in the figure above. While in the progressive scenario hydrogen-powered vehicle concepts are possible from 2040, in the conservative scenario there are no market entries for hydrogen-based vehicle concepts. Hybrid-electric vehicle concepts (combination of fuel and battery) are possible from the year 2030 in the progressive scenario and only 15 years later from 2045 in the conservative scenario. These assumptions mean that sustainable aviation fuels will be the most important power source for business jets in the conservative scenario by 2070. The share of SAF will increase to 70% in 2050 and to 100% in 2070. The market entry of hydrogen-powered vehicle concepts in the progressive scenario will lead to a correspondingly lower dependence on SAF by 2070.

A look at the technology scenarios of supersonic shows that neither in the progressive scenario nor in the conservative scenario an entry into service of hydrogen-powered or electric vehicle concepts are assumed. Due to the very long ranges and enormous speeds, supersonic only considers sustainable aviation fuels as an alternative to fossil fuels. The share of SAF will increase to 70% by 2050 and to a total of 100% by 2070 for both scenarios. Individual technologies such as laminar flow control, partial main gear fairing or riblets will come into the market for supersonic in 2035 in the progressive scenario. In the conservative scenario, the introduction of these technologies for supersonic will take place 10 years later in 2045.

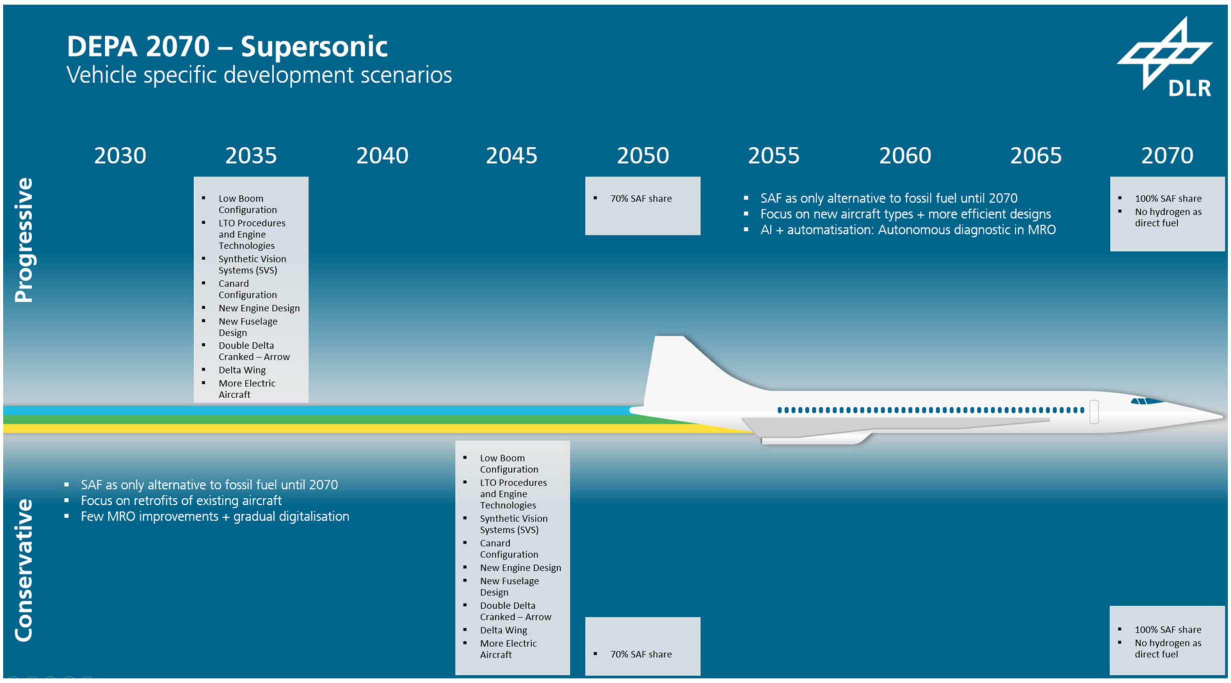


Figure 20: DEPA 2070 technology scenario for supersonic aircraft

4.1.3. DEPA 2070 Normative Scenario

In addition to the vehicle-specific technology scenarios outlined in the previous chapter, a normative DEPA 2070 scenario had to be developed. Normative scenarios examine how a specific defined future goal can be achieved. They are characterized by a goal-oriented approach in which a desired end state is defined and then retrospectively analysed to determine which measures are necessary to achieve this state. Normative scenarios are therefore often referred to as backcasting.

In the aviation sector “Zero CO_2 emissions in 2050” is now considered as the decisive objective. Accordingly, central institutions and organizations such as IATA, ICAO or ATAG as well as regions such as the European Union or the United States have agreed on a corresponding objective by 2050. In order to achieve such a goal in aviation and to be able to further reduce CO_2 emissions, various measures and instruments are required. Through various optimizations and technological innovations for the aircraft (sub-areas aerodynamics, propulsion, systems, new aircraft concepts), fuel savings can be further increased and thus emissions reduced. Sustainable aviation fuels are another option to further reduce emissions in aviation. A differentiation can be made between four different types of SAF (HEFA, gasification/FT, alcohol to jet, power to liquid), with PtL being seen as the best long-term solution, as 100% emission reductions can be achieved here. Zero emission planes are another option for significantly reducing emissions in aviation. These include completely new types of vehicles that are either full electric or powered by hydrogen (hydrogen combustion or hydrogen fuel cell). Innovations and optimizations in the areas of air traffic management and operations also contribute to reducing fuel consumption in aviation. A wide variety of approaches and technologies such as sectorless ATM, airport congestion management, flexible use of military airspace, formation flights or trajectory-based operations can help to increase efficiency in aviation. Finally, economic measures with their three main approaches offsetting (e.g. CORSIA), emission trading (e.g. EU ETS) and levies (direct pricing of aviation CO_2 emissions) represent a way to further reduce future emissions in aviation.

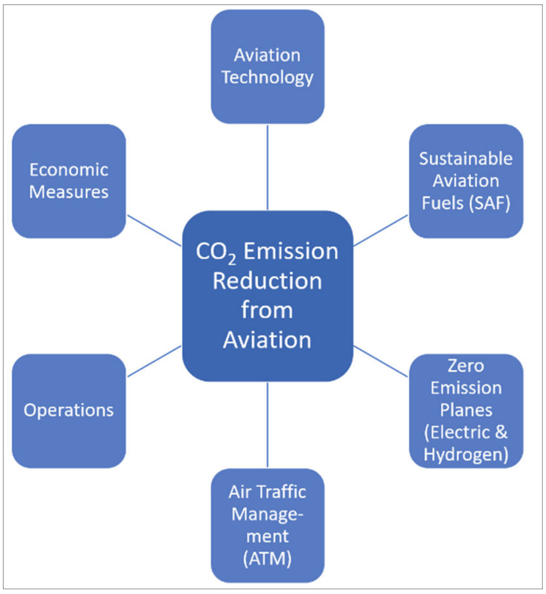


Figure 21: Measures and instruments for emission reduction in aviation

An analysis of various normative aviation scenarios with a Net Zero CO_2 Emission Goal by 2050 reveals the high uncertainty regarding future emission reduction potential of the aviation industry until 2050. For this analysis, the five aviation scenarios from ATAG, which were part of the "Waypoint 2050" study,[30] were selected. These scenarios represent global outlooks on emission reductions in aviation under different assumptions. In addition to these scenarios, the global "Net Zero Carbon 2050 Resolution" from IATA was also considered in this normative aviation scenario comparison. At the European level, the "Base Scenario" from EUROCONTROL, the "Destination 2050 Roadmap" from NLR, and the "Breakthrough Scenario" from ICCT were included in this comparative analysis.

These normative aviation scenarios with a Net Zero CO_2 Emission Goal by 2050 were finally also compared with the global so-called "Integrated Scenarios" from ICAO, which, unlike the normative scenarios, do not consider any market-based measures for emission reductions. These Integrated Scenarios demonstrate the emission reduction potential of aviation by 2050 under pessimistic assumptions (IS I), medium assumptions (IS II), and maximum possible assumptions (IS III).

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[30] Cf. ATAG (2021).

Figure 22 shows the emission reduction potentials for aviation in 2050 for the mentioned normative scenarios and integrated scenarios subdivided between the four following different emission reduction categories: Aviation Technology, Air Traffic Management & Operations, Sustainable Aviation Fuels and Market Based Measures.

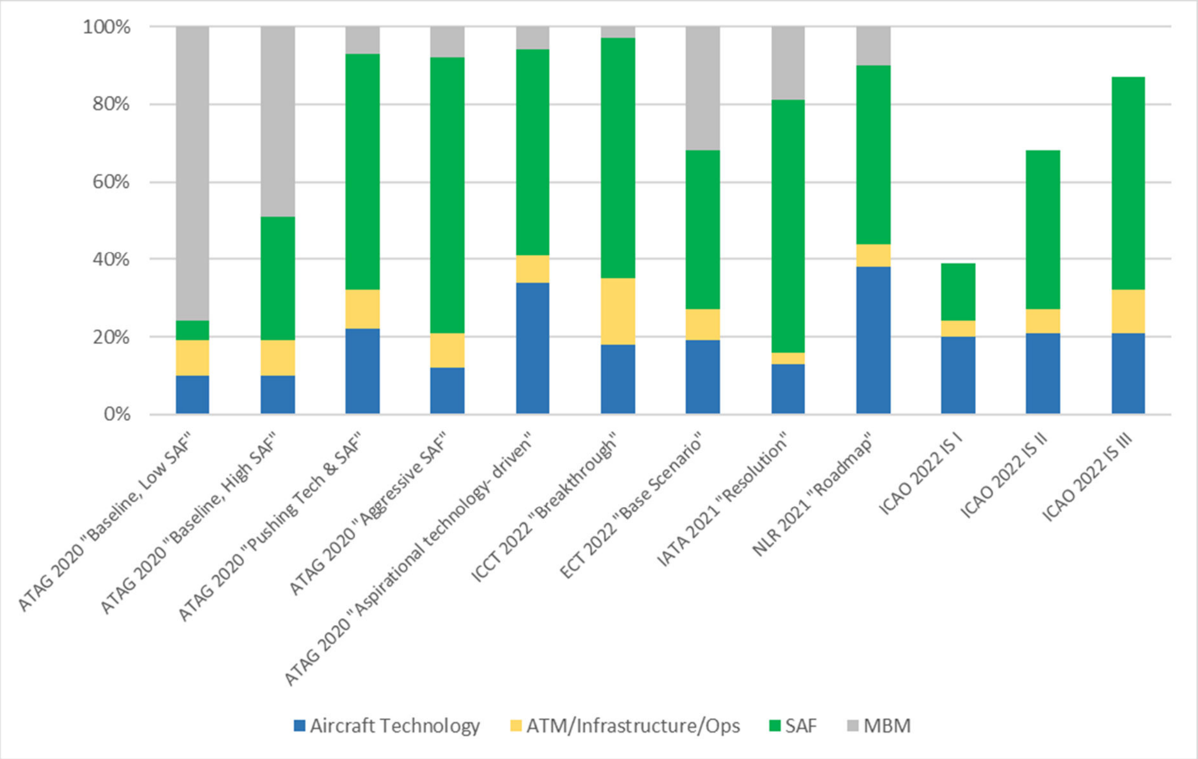

Figure 22: Comparison analysis of different normative aviation scenarios and ICAO-IS scenarios regarding emission reduction potential in the year 2050

On the one hand it can clearly be seen that SAF play in almost all scenarios by far the most important role for reducing the CO_2 emissions from aviation in 2050. Secondly, in all normative aviation scenarios the need of market-based measures for theoretically reaching a net zero CO_2 emission goal in 2050 can be seen. Thirdly, a comparison with the Integrated Scenarios from ICAO show that the emission reduction assumptions in the normative aviation scenarios are quite optimistic. Thus, some normative scenarios show even higher emission reduction potentials than the Integrated Scenario III with maximum possible emission reduction potentials of in total 87% in 2050.

Based on a comparative analysis of the respective external normative aviation scenarios (see Figure 22), the contributions of the individual categories for a normative DEPA 2070 scenario with a "Net Zero CO_2 Emission" objective were defined. Accordingly, 20% of emissions in aviation will be reduced in 2050 by Aircraft Technology. With the help of Sustainable Aviation Fuels, 58% of emissions can be reduced in 2050. Improvements in the category ATM, Operations and

Infrastructure enables a further 7% emission reduction in aviation in 2050. The remaining 15% of required emission reductions will finally be achieved through Economic Measures.

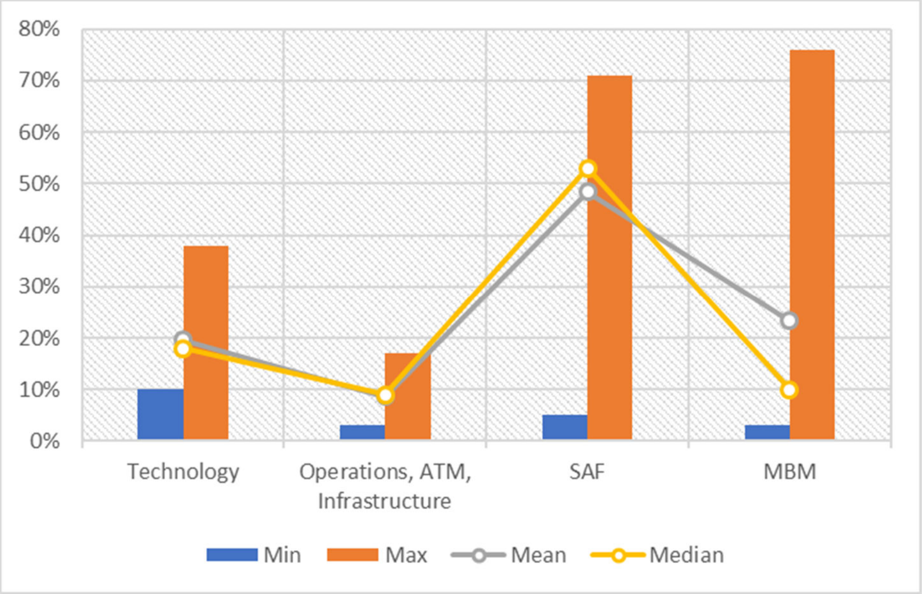

Figure 23: Contribution values of individual categories to the achievement of Zero CO_2 emissions in 2050 from the comparative studies

In order to achieve the defined contributions of the individual categories to emission reduction in 2050, an interactive table was created in which quantitative assumptions about the individual factor categories for each vehicle type can be assumed. First, the share of total emissions in aviation was allocated to the individual vehicle types in a no-action forecast and then extrapolated for the next decades. Using the respective assumptions, the emission savings for each vehicle type and for each factor category can finally be determined.

The assumed share of zero emission planes in 2050 varies depending on the vehicle type from 1% (wide-body) and 3% (narrow-body) to 15% (regional & business jet) and 30% (SAT). The assumed fuel efficiency improvements in 2050 for all vehicle types are 20% (compared to 2018 reference aircraft). The share of sustainable aviation fuels in air transport in 2050 is 75% overall, of which 35% are synthetic fuels. The assumed efficiency improvements through ATM and operations in 2050 are 7% (compared to 2018).

With these assumptions, a total of 85% of emissions in air transport can be reduced in 2050. At the same time, the contributions to emission reduction per category defined for the normative scenario are considered. With the help of economic measures, the remaining 15% of emissions will be reduced in 2050 and a net zero CO_2 emission target would theoretically be achieved.

4.2. Demand Forecast

4.2.1. Traffic Forecast for established Vehicle Concepts: Methodology

The DLR passenger and fleet forecast model operates on the airport pair level, so that passenger and flight volume as well as the aircraft fleet are modelled for each flight route. Based on the forecasted passenger volume the model calculates the flights and corresponding aircraft fleet to serve the passenger demand. The figure below illustrates the model approach in more detail. In the first step, an unconstrained passenger and flight volume forecast is generated. This includes new nonstop flights, which become viable due to the increase in origin-destination demand. There is, for example, some potential for new nonstop flights in the long-haul market, i.e., on routes that are currently served only by stopover flights. The same is true regarding short and medium distance air travel, where origin-destination demand rises above a threshold, and a nonstop flight with smaller aircraft becomes viable. In figure 24, boxes with blue frames refer to un-constrained models, while boxes with red frames refer to constrained models that include the effects of limited airport capacity and related aircraft up-gauging, i.e., more seats per aircraft. The box with blue and red frames (aircraft up-gauging and aircraft fleet) refers to both categories. Passenger and flight volume per airport pair is modelled by a gravity model. The three major drivers of passenger demand are:

- Real gross domestic product (GDP) per capita: the use of the term “real” means that it is inflation-adjusted to reflect actual purchasing power and is a measure of the wealth or income of the population per capita that can, for example, be spent on air travel. It is split into GDP per capita for the origin and the destination of a journey, to allow for more complex relationships.
- Population: the larger the population, the larger the potential for air travel demand at a particular wealth or income level (i.e. real GDP per capita). Real GDP per capita and population taken together regarding origin and destination, is the typical real GDP variable that appears in many air transport demand models.
- Real airfare development: the development of real, i.e. inflation-adjusted, airfares have a direct effect on passenger demand volume. Increasing real airfares reduce demand volume, while decreasing real airfares have a positive effect on passenger demand volume. In the past, real airfares declined by about 1.5% per year on average on a global level due to organisational and technological innovations, i.e., due to better organisation, and the employment of more efficient aircraft. It is difficult to assess if this assumption will hold for the future, especially in the light of increases in kerosene and SAF prices. Fuel costs make up about 15% to 30% of the ticket price.

The elasticities of these major drivers determine the overall unconstrained passenger volume development. Real GDP, i.e. real GDP per capita times population, has an elasticity of 1.31, so that an increase of 1% of real GDP increases passenger volume by 1.31%. Real airfares have an elasticity of -1.11, so that a decrease of 1% increases passenger volume by 1.11%. Both real GDP and airfares are thus elastic, so that passenger volume reacts over-proportionally to changes in real GDP. However, there is one caveat: these drivers are measured in real terms, so the effects of inflation need to be considered. One could argue that inflation reduces real airfares (given nominal airfares remain the same or rise more slowly than inflation), which is positive for demand development, but GDP also needs to be considered. Inflation burns purchasing power, i.e. real GDP (given that nominal GDP remains the same, or rises more slowly than inflation), which is negative in terms of demand development. Real GDP has a greater impact on passenger volume than real airfares (1.31 compared to 1.11 in absolute values), so the total effect on demand is negative.

After obtaining the unconstrained passenger and flight volume forecast for each airport pair, airport capacity constraints and aircraft up-gauging are applied. The airport capacity constraints model contains an element that calculates current airport capacity for each airport using data envelopment analysis (DEA) and regression models and is based on discrete choice theory. This offers a model that estimates the probability of airport capacity expansion if capacity is not sufficient to handle the forecast demand. Based on this probability, an expected delay regarding the realisation of a new runway can be derived, if indeed it is possible at all.

Aircraft up-gauging depends not only on the level of airport capacity constraints but also on various other factors such as passenger demand volume, flight distance, and more. It affects constrained as well as unconstrained airports because of interdependencies in the global air traffic network.[31] The up-gauging model belongs to both the unconstrained and constrained models. The model is implemented using DEA and regression models, and incorporates factors such as passenger volume, flight distance and the constraints' situation at airports. The forecast result is the average number of passengers per flight ("aircraft size") for each airport pair. Combining future airport capacity and aircraft size per airport pair with the unconstrained passenger forecast, yields the constrained forecast model. The forecast results are the constrained passenger and flight volume, as well as lost passenger demand and restricted flight volume due to limited airport capacity.

Passenger and flight volume per airport pair, either from the constrained or unconstrained forecast, are passed to the fleet model. Input into the fleet model are the base year fleet, the specifications of current and future aircraft, which can also be concept aircraft. For future aircraft, information regarding entry into service is needed. The model is based upon up to 14 ICAO seat class categories but not limited to these. Furthermore, the seat classes are not limited to one type of aircraft. Multiple aircraft per seat class are possible to permit a more detailed fleet modelling. Examples include the simulation of multiple concept aircraft in a particular seat class, such as liquid hydrogen- and SAF-powered aircraft. The assignment of different aircraft of a seat class to airport pairs can

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[31] Cf. Gelhausen, M. C. et al. (2021), Gelhausen, M. C. et al (2019).

be based on factors such as minimum and maximum flight ranges, cost-based rules, or any other rule such as an equal market share approach.

Passengers and flights are assigned to seat classes with the use of an optimisation model. Thus, for each airport pair the average number of passengers per flight can be calculated. If a load factor is applied then, the average number of seats per airport pair can be obtained. In a next step, two seat classes neighbouring the average seat per flight value are chosen and mixed share-wise, so that they match the average seat per flight value. This results in a rather compact distribution around the mean value. Aircraft types are assigned to the flights of each seat class as already described.

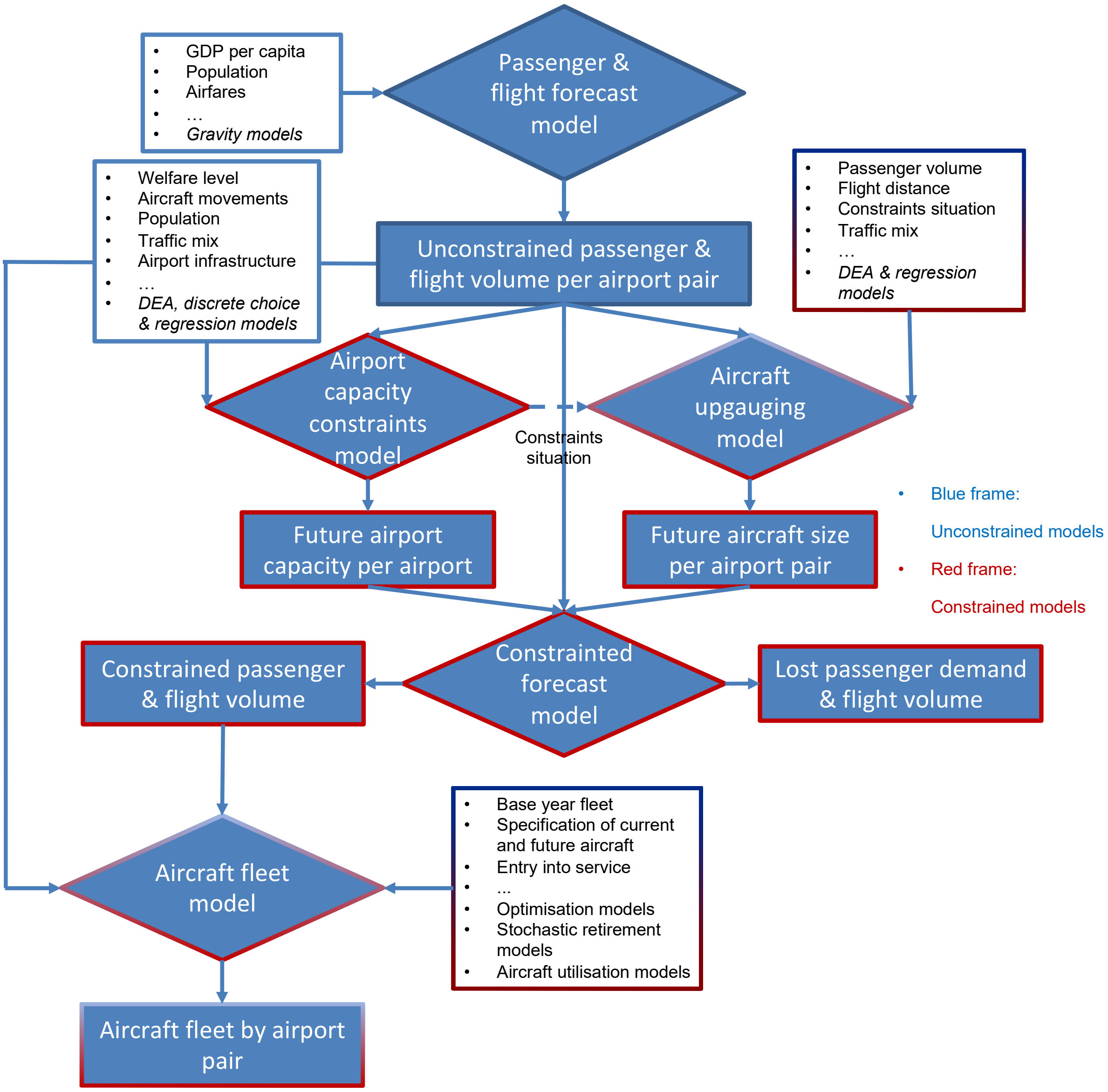


Figure 24: Overview of the DLR passenger and fleet forecast model

4.2.2. Traffic Forecast for established Vehicle Concepts: Results

In this section the forecast results up to 2070 for scheduled passenger traffic, which is typically operated by regional and mainliner aircraft, is presented. Values up to 2023 are actual values and thereafter the forecast is provided in five-years-steps.

Figure 25 displays the forecast global passenger volume up to 2070. The number of passengers increases from 4.4 billion in 2019 to more than 21 billion in 2070, which corresponds to a compound annual growth rate (CAGR) of 3.1%.

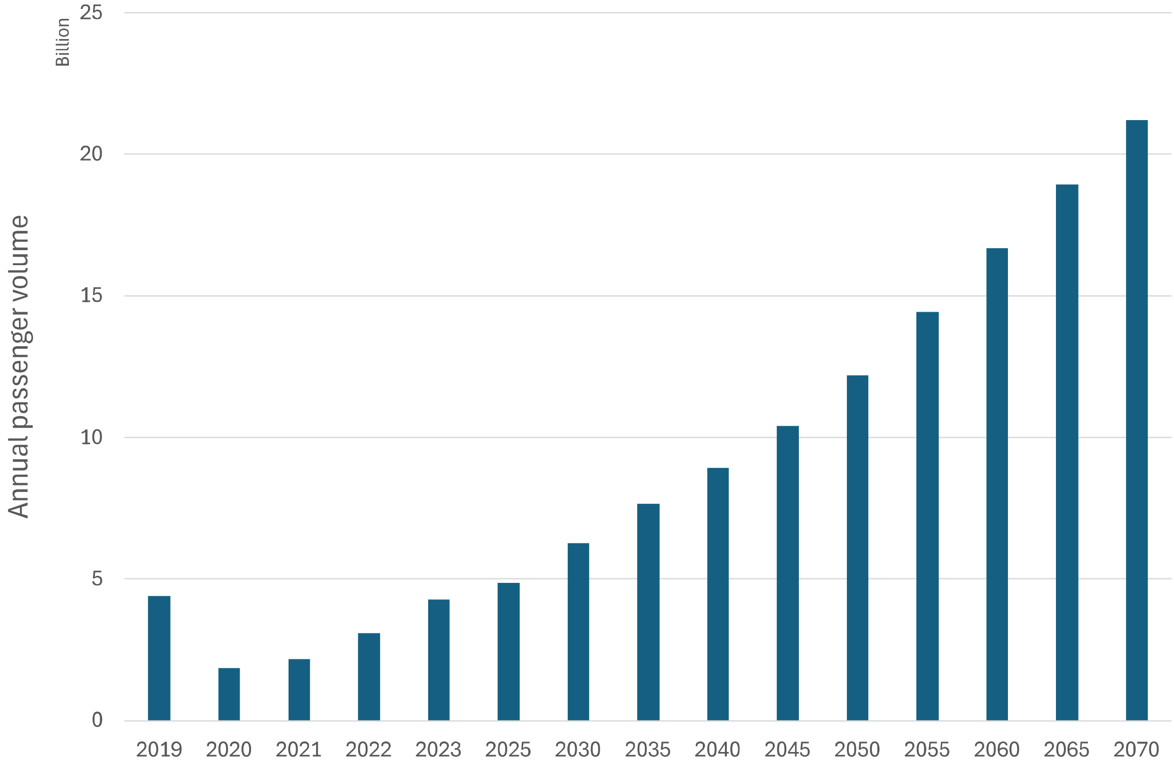


Figure 25: Global passenger volume forecast up to 2070

The global revenue passenger kilometres (RPK) volume displayed in Figure 26 increases in a similar fashion: There are 8.2 trillion RPK in 2019 which quadrupel to almost 34 trillion in 2070. This equals a CAGR of 2.8%.

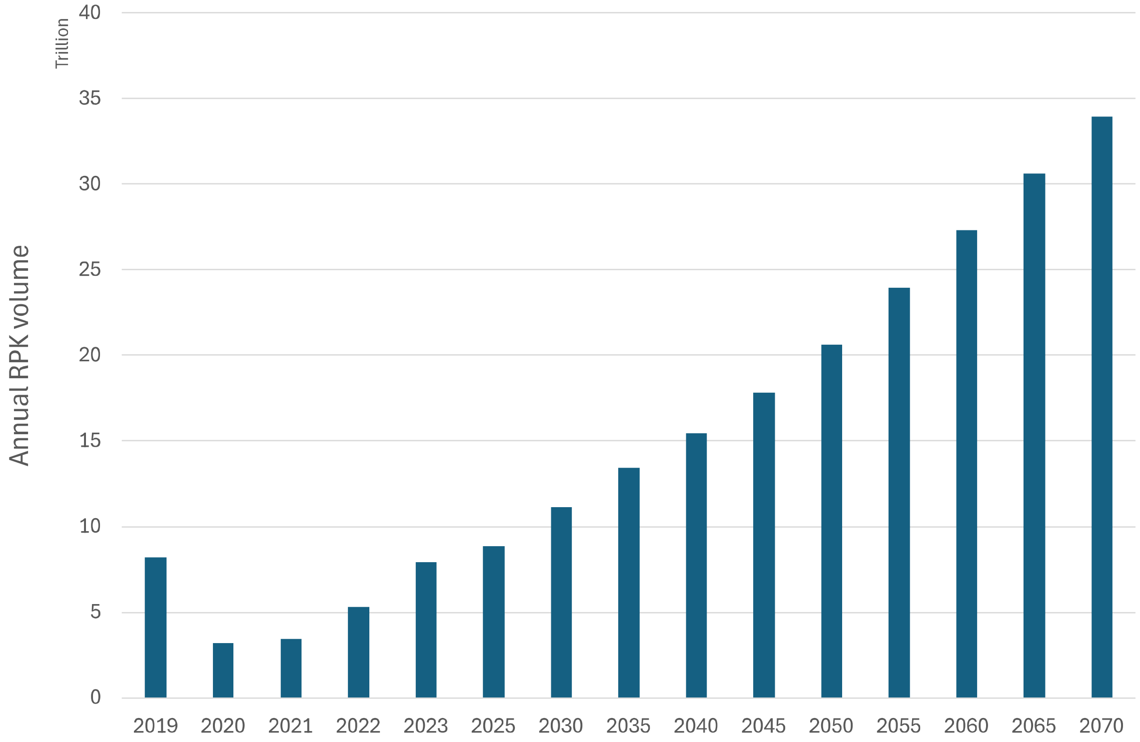


Figure 26: Global RPK volume forecast up to 2070

The number of flights increases globally from 36 million to over 76 million between 2019 and 2070 as Figure 27 shows. This equals a CAGR of 1.5%.

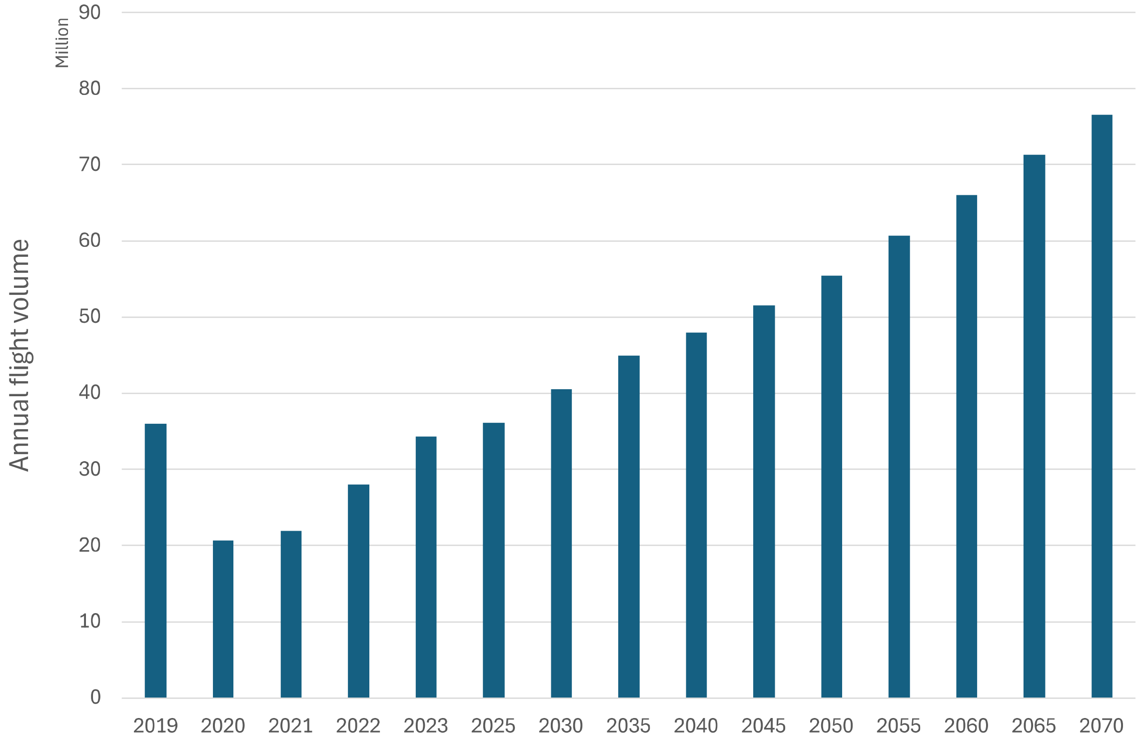


Figure 27: Global flight volume forecast up to 2070

The development of passenger and flight volume is different: passenger volume increases considerably faster than the number of flights. This is mainly a result of scarce airport capacity and the inability to enlarge it according to passenger volume development. As a result, more and more passengers are transported per flight, so that an increasing share of high-capacity aircraft will be employed. The figure below illustrates the forecast results up to 2070: the number of passengers per flight increases from 122 in 2019 to 277 in the year 2070, which corresponds to a CAGR of 1.6%. Increasing number of passengers per flight does not only mean that many more very large aircraft with high seating capacity are needed, but that more passengers per flight are transported across the whole spectrum of aircraft size. Nevertheless, average seating capacity will be rather high and the availability of high-capacity aircraft is crucial for serving the forecast demand.

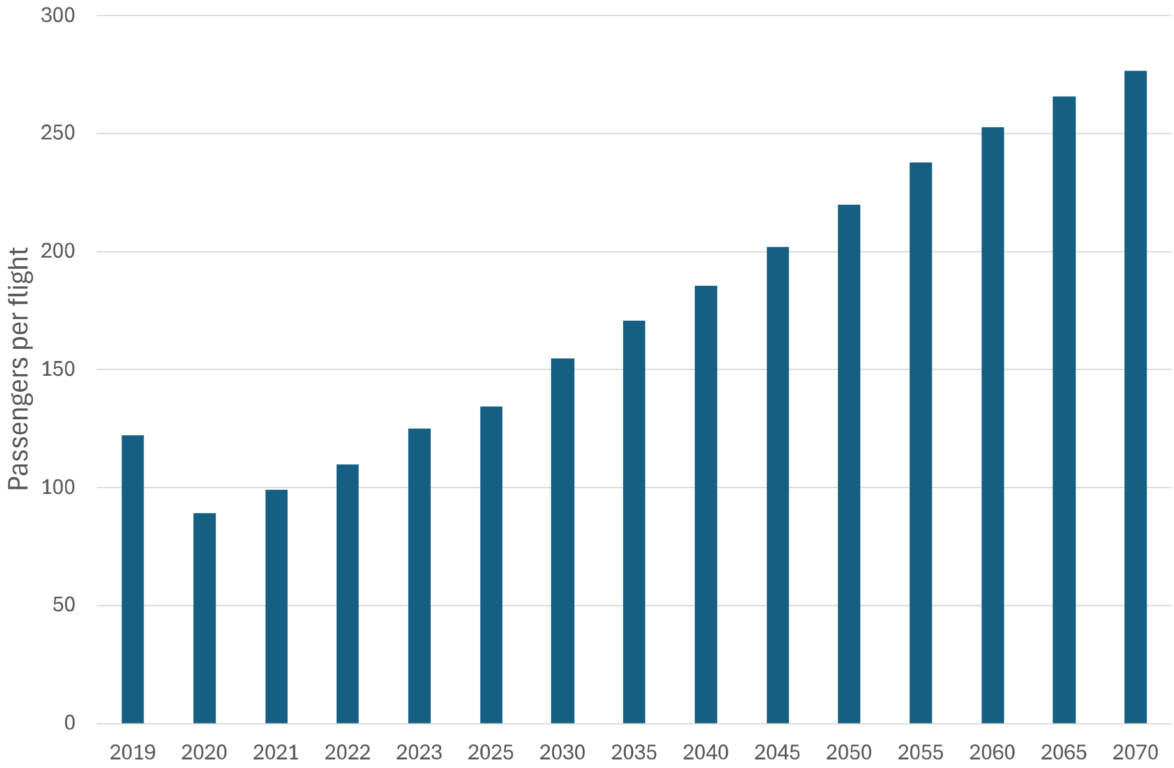


Figure 28: Development of passengers per flight up to 2070

Figure 29 illustrates the number of passengers that cannot be served due to a capacity shortage at airports. Lost demand is a little bit above 2 million in 2050 and increases to more than 18 billion in 2070, which is almost the number of passengers served. Lost demand is therefore nearly 50% of the unconstrained passenger demand in 2070. It increases exponentially, because it becomes increasingly difficult to enlarge airport capacity and additional runways increase capacity less and less because of interdependencies between runways. Aircraft size, on the other hand cannot grow indefinitely and is already quite high in 2070 as the preceding figure shows.

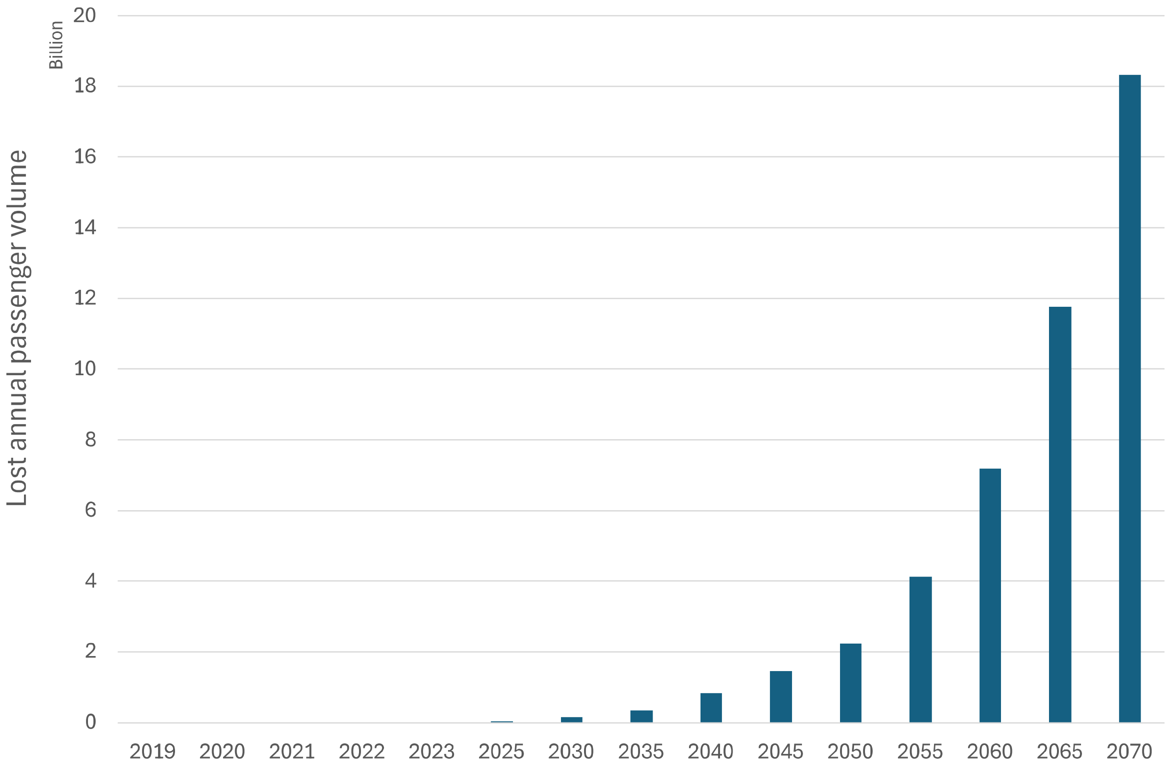


Figure 29: Lost passenger volume up to 2070

To assess the forecast results established forecasts of Airbus, Boeing, IATA and ICAO were used for comparison. The comparison was done on base of the unconstrained DLR forecast (DLR UC), because the other forecasts assume always sufficient airport capacity. However, this also allows to put the constrained forecast (DLR CON) into perspective. As Figure 30 illustrates the DLR UC forecast correspond quite well with the forecasts of Airbus, Boeing as well as with those of IATA and ICAO. Airbus and Boeing respectively forecast 3.6% and 3.7% RPK volume growth per year for the period 2019 to 2042. The IATA forecast is a bit lower with 3.3% p.a. for the period 2019 to 2040. The ICAO Post-Covid Long-Term Forecasts range between 2.9% and 4.2% p.a., with the mid-version forecasting 3.6% p.a. RPK volume growth. The difference between DLR UC and DLR CON reflects the impact of limited airport capacity on future passenger volume development. This will be even more important for forecasts up to 2070, which are not covered by established forecasts: while forecast RPK growth is 3.0% p.a. from 2019 to 2050, it declines to 2.8% for the whole forecast period 2019 to 2070. It is certainly no surprise that passenger demand volume cannot grow indefinitely.

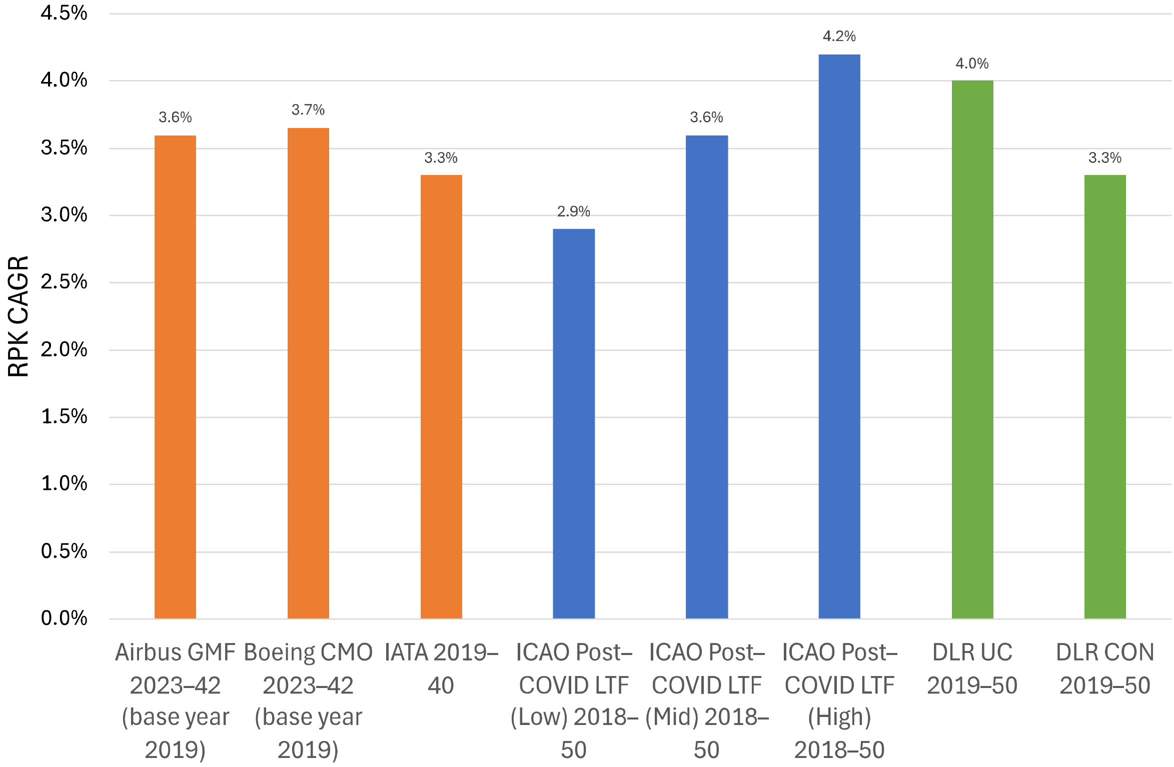


Figure 30: Comparion of different RPK volume forecasts

Figure 31 displays a comparison of the DLR forecasts with current aircraft delivery forecasts of Airbus and Boeing. Comparing aircraft delivery forecasts is always difficult, because of assumptions regarding aircraft retirement and aircraft productivity, i.e. how many aircraft are needed to serve a given flight schedule.

The DLR model is based on ICAO CAEP retirement curves which are currently the gold standard and aircraft productivity has been calculated from data such as Cirium Fleets Analyzer, OAG, and Sabre MI. Nevertheless, the results presented in Figure 31 show that the DLR fleet results fit very well with that of the established industry forecasts.

Compared to Airbus and Boeing total deliveries and the split between narrow-body and wide-body aircraft is about same as in the DLR UC. Airbus and Boeing forecast 40,840 and 39,860 aircraft with 100+ seats until 2042, of which 8,220 and 7,440 are wide-bodies. The corresponding DLR forecast values are 38,388 aircraft with 100+ seats until 2042, of which 6,775 are wide-bodies.

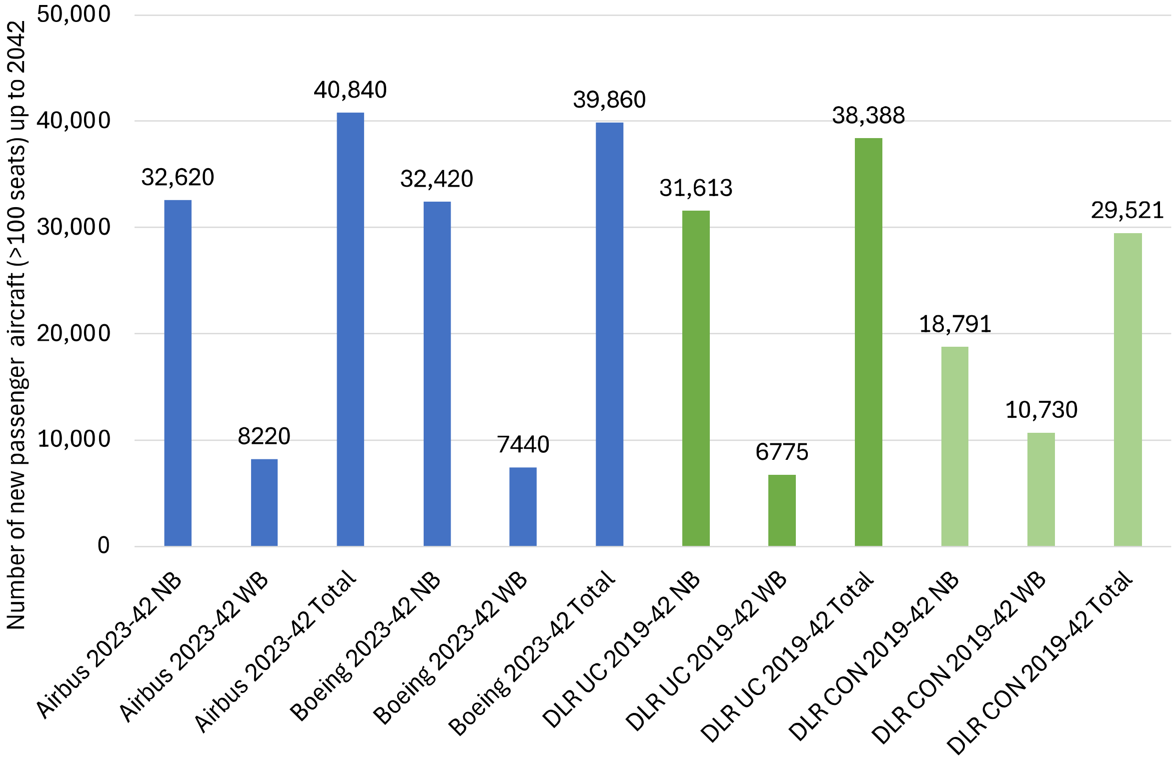


Figure 31: Comparison of the DLR UC aircraft delivery forecast with Airbus and Boeing forecasts (NB: narrow-body aircraft, WB: wide-body aircraft)

The constrained DLR forecast (DLR CON) in the figure above is significantly different because of the inclusion of limited airport capacity and thus leaning towards less but larger aircraft across the whole spectrum of aircraft sizes, not only the top end of very large aircraft, especially not on short distances. Airport capacity is forecasted according to the demand pressure for more airport capacity and the opposition of the population surrounding the airport against such plans. However, compared to the unconstrained Airbus, Boeing and DLR (DLR UC) forecasts, the results of the constrained DLR forecast make sense: There is a shift towards more wide-body aircraft and overall less aircraft are delivered until 2042. In the DLR CON 29,521 new 100+ seats aircraft up to 2042 are forecasted. Out of these 10,730 are wide-bodies.

Figure 32 presents the forecasted number of business jet flights up to the year 2070. The CAGR is very similar to the mainliners and regionals segment, with economic growth being the main driver. The number of global business jet flights grows from 6.5 million to almost 14 million in 2070. The business jet operations do not depend as much as the scheduled passenger service on larger airports with scarce capacity, but more on smaller airports with ample capacity reserves.

Like the business jet segment (cf. Figure 32) Figure 33 illustrates the development of the number of flights of small air transport up to the year 2070.

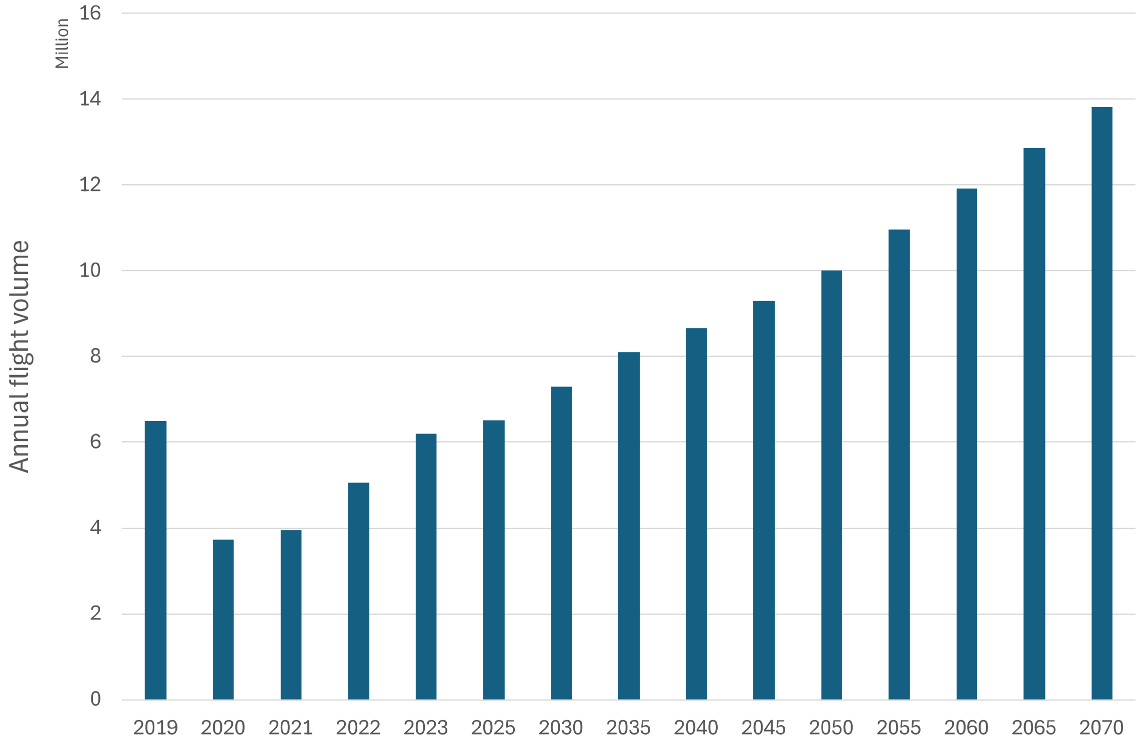


Figure 32: Development of business jet flights up to 2070

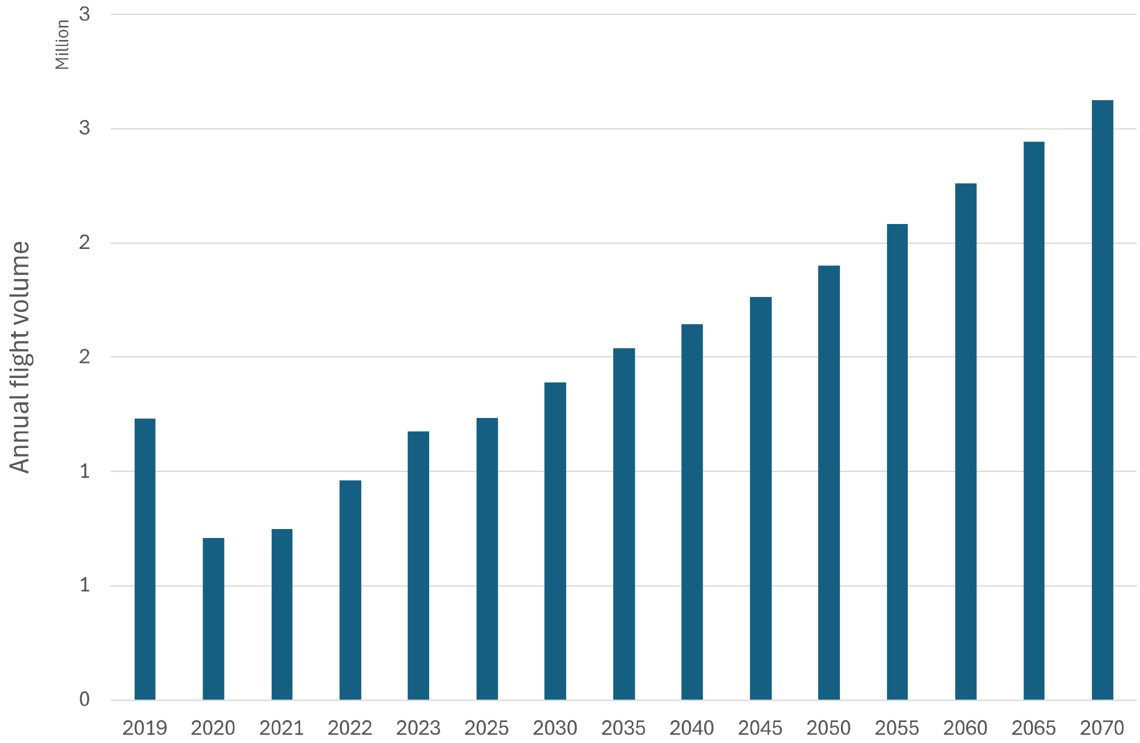


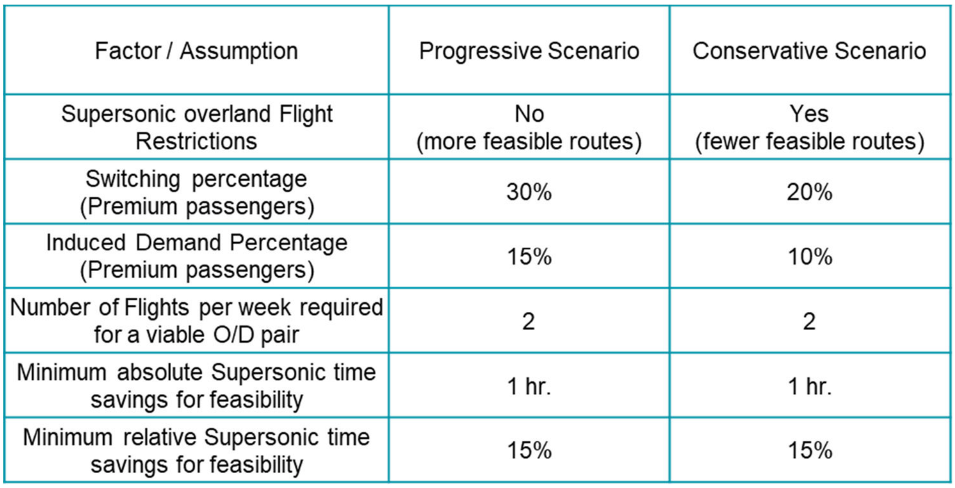
Figure 33: Development of SAT flights up to 2070

This segment is rather small, and flight volume increases from 1.2 million in 2019 to 2.6 million in 2070. Like business aviation, SAT focuses more on small airports without limiting capacity.

4.2.3. Traffic Forecast for Supersonic Aircraft

In this section the future market potential for supersonic flights as a new market segment is described. Supersonic flight in civil aviation has the potential to significantly reduce travel times and to create a new era of air transport supply. Companies such as Boom Supersonic have been working for several years on aircraft that can reach speeds of over Mach 2 which would drastically reduce travel time between continents.

With the aim of being able to make a traffic forecast for supersonics up to the year 2070, the supersonic forecast of the predecessor project DEPA 2050 was updated and extended up to the year 2070. For this purpose, the latest forecast data from the mainliner forecast (cf. the preceding section) was used as basis data and the Covid recovery was considered. The key supersonic vehicle parameters assumed were a passenger capacity of 55, a maximum speed of Mach 2.2 and a range of 8,334 kilometres. As can be seen in Table 10, no restrictions on supersonic overland flights were assumed in the progressive scenario. In the conservative scenario, supersonic speeds are only permitted over seas. In addition, the assumptions regarding switching percentage age of premium passengers differ between the two scenarios (30% vs. 20%) as well as the induced demand percentage age (15% vs. 10%).



Factor / Assumption	Progressive Scenario	Conservative Scenario
Supersonic overland Flight Restrictions	No (more feasible routes)	Yes (fewer feasible routes)
Switching percentage (Premium passengers)	30%	20%
Induced Demand Percentage (Premium passengers)	15%	10%
Number of Flights per week required for a viable O/D pair	2	2
Minimum absolute Supersonic time savings for feasibility	1 hr.	1 hr.
Minimum relative Supersonic time savings for feasibility	15%	15%

Table 10: Supersonic scenario assumptions

Figure 34 shows the development of global supersonic routes for both scenarios. In the conservative scenario, the number of supersonic transport (SST) routes increases from 300 in 2030 to over 800 in 2070. In the progressive scenario, the number is significantly higher, with 600 in 2030 and over 1,700 in 2070. It is important to note that these results or number of routes represent the pure demand potential if there is a sufficient number of supersonic vehicles on the market in the respective years. The results are therefore to be seen independently of the supply. The realisation of the theoretical demand potential is uncertain. In the past, there have been some postponements of announced supersonic market entries.

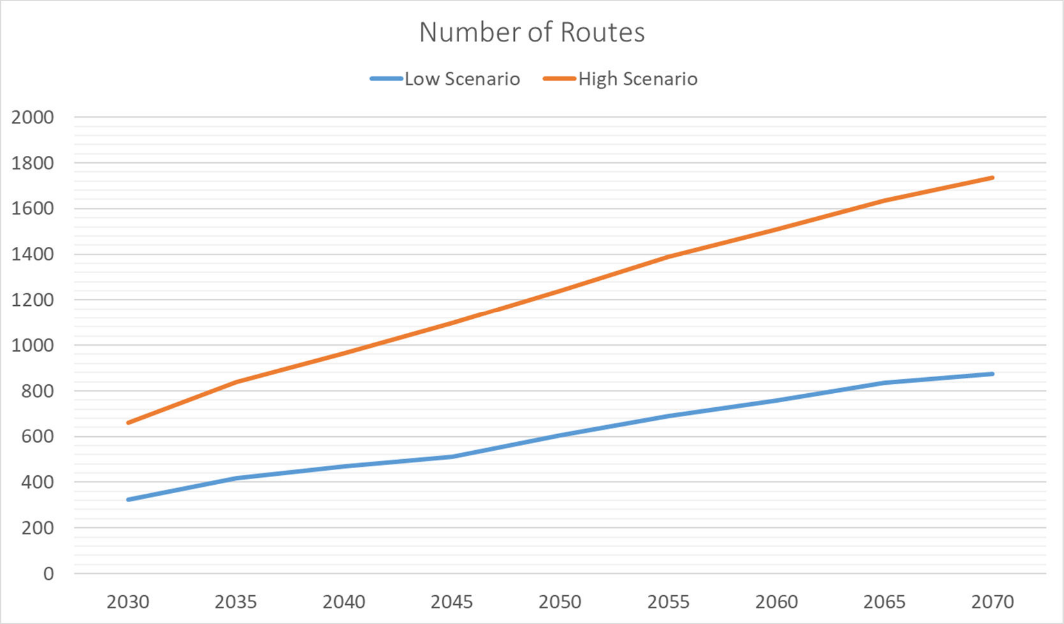


Figure 34: Number of supersonic routes in both DEPA 2070 scenarios

5. Vehicle and Fleet Development up to 2070

5.1. Concept and Reference Vehicles for the DEPA 2070 Scenarios

The assessment of future aircraft technologies, which are described in chapter 3, requires their application on specific reference aircraft to evaluate their impact on future aircraft performance. In this subchapter, these reference aircraft, which are based on existing commercial aircraft models, are listed as they serve as a baseline for the aircraft design process. Additionally, DEPA 2070 includes future aircraft concepts expected to enter a global fleet with specified EIS. These concepts have been derived from relevant DLR aircraft design projects and represent a diverse range of technological advancements and operational capabilities. The combination of reference aircraft and future concepts is essential to capture the full spectrum of fleet evolution, allowing a comprehensive assessment of technology transitions, emissions reductions, and operational feasibility across different market segments.

To provide a structured overview, Table 11 lists all considered reference aircraft and future aircraft concepts in the project DEPA 2070. Additionally, the aircraft type in the project DEPA 2070 is described.

Aircraft	**Aircraft Type**
Dornier 228	Reference
ATR42-500	Reference
ATR72-600	Reference
DashQ8-400	Reference
Embraer E190-E2	Reference
Embraer E195-E2	Reference
Airbus A220-300	Reference
Airbus A320neo	Reference
Airbus A321neo	Reference
Boeing 787-900	Reference
Airbus A350-900/1000	Reference
Boeing 777-300ER	Reference
Airbus A380-800	Reference
Boeing 777-9	Reference

Aircraft	**Aircraft Type**
REG-RAD	Regional Concept from the Project IMOTHEP[32]
EXACT D70-PHEP	Regional Concept from the Project EXACT[33]
EXACT D250-TF	Narrow-Body Concept from the Project EXACT[34]
EXACT D250-TFLH2-MHEP	Narrow-Body Concept from the Project EXACT[35]
SIAM A320neo Baseline	Narrow-Body Concept from the Project SIAM[36]
KuuL TF Kerosene / LH2	Wide-Body Concepts from the Project KuuL[37]
Truss-Braced Wing (TBW)	Narrow-Body Concept retrived from a DLR Study[38]

Table 11: DEPA 2070 reference and concept aircraft

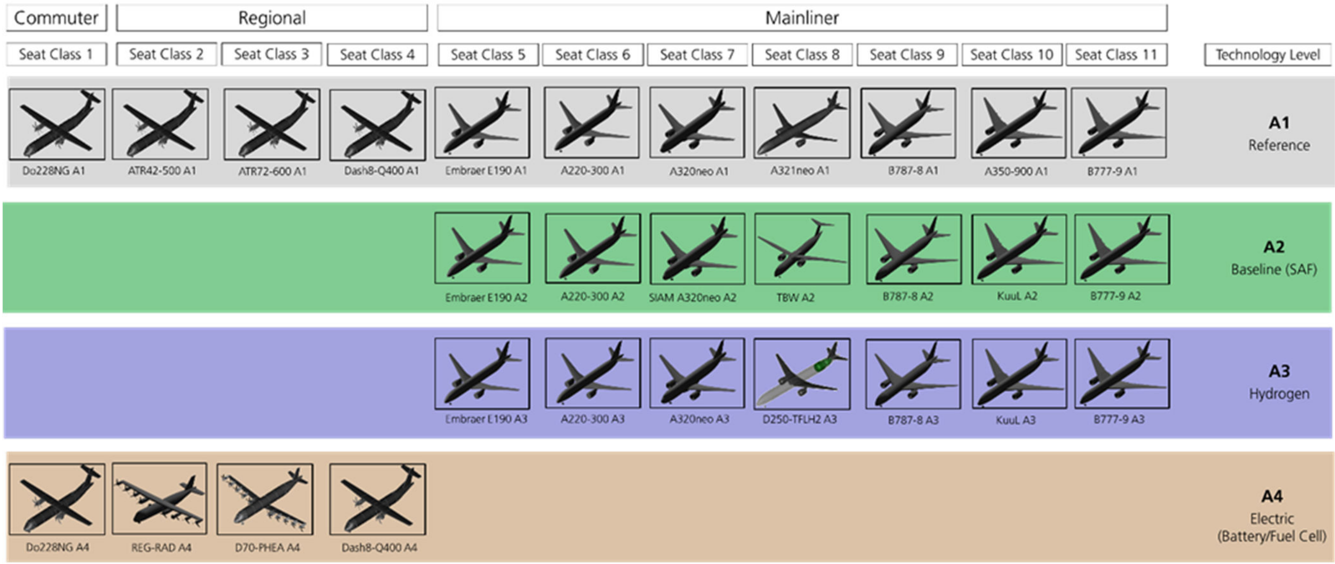


Figure 35: Overview of relevant aircraft concepts in DEPA 2070

In addition to the reference aircraft and future aircraft concepts derived from existing DLR projects, DEPA 2070 also includes a set of future aircraft concepts modelled through a systematic trend analysis of upcoming aircraft technologies, which are described in chapter 3. These concepts were developed using a stepwise approach, modelling Engine Retro-Fit, N+1 and N+2 aircraft

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[32] Cf. European Union (2022).
[33] Cf. Atanasov, G. (2022).
[34] Cf. Atanasov et al. (2021).
[35] Cf. Atanasov, G., Silberhorn, D. (2024).
[36] Cf. Mößner, M. (2024), Wienke et al. (2023).
[37] Cf. Wöhler et al. (2024).
[38] Cf. Kugler, L. (2024).

configurations by utilising reference aircraft for the most relevant aircraft segments: ATR72-600 (regional segment), A321neo (narrow-body segment) and A350-1000 (wide-body segment). The calculated technological advancements and their associated reduction potentials were then applied to all reference aircraft within the same market segment, enabling a broader assessment of future fleet evolution. This process led to the identification of additional aircraft concepts, which were integrated into the fleet modelling framework. For consistency in the upcoming chapters of this report, these concepts are referenced using a standardized naming convention:

- "A1" represents configurations utilising conventional kerosene fuel,
- "A2" for aircraft using SAF,
- "A3" corresponds to hydrogen-powered combustion, and
- A4 refers to vehicle with electric propulsion.

Additionally, the EIS year is included in the designation to indicate the market introduction for each concept.

To account for different pathways of technological progression, two distinct fleet evolution scenarios were considered as described in the previous chapters: a conservative scenario and a progressive scenario. In the conservative scenario, only Engine-Retro Fit and N+1 aircraft configurations are introduced, reflecting a more incremental technological adoption. The progressive scenario includes both N+1 and N+2 concepts, representing a more ambitious transition toward advanced aircraft architectures. The naming convention is extended to incorporate scenario differentiation, using the format: *ReferenceAircraftName FuelType EIS ScenarioName*. For example, Airbus A320neo A3 2050 progressive denotes a hydrogen-powered (A3) N+2 aircraft expected to enter service in 2050 as part of the progressive scenario.

The methodology used to determine the reduction potentials applied to the fleet modeling process is described in detail in the following chapter.

5.1.1. Vehicle Design

The structured aircraft design methodology applied in this project ensures a systematic assessment of future aircraft concepts by integrating key technological advancements utilising an aircraft design tool. As described in Weber (2024)[39] this approach establishes a consistent framework for evaluating the impact of future technologies on aircraft performance. Especially technology factors for the narrow-body and wide-body segments have been derived by considering advancements in aerodynamics, propulsion, structures, and systems. These technology factors serve as fundamental input parameters, allowing for a quantitative assessment of performance improvements over time.

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[39] Cf. Weber (2024), chapter 5.

To maintain methodological consistency across the different aircraft categories, the derived technology factors have been applied to all reference aircraft identified in the project. The reference vehicles, which are based on existing commercial aircraft models, serve as a reference for assessing the technological progression of regional, narrow-body and wide-body aircraft. By applying the same structured methodology across all vehicle classes, a consistent comparison of technological advancements becomes possible. The DEPA 2070 future aircraft concepts, developed through trend analysis, were modelled using this approach to ensure a realistic representation of future concepts. The derived technology factors from Weber (2024)[40] are displayed again in Table 12 including the reduction potential of the N+1 concepts in the regional segment which is not described in Weber (2024) but follows the same design methodology.

Aircraft Configuration	Fuel Burn Reduction Potential on Mission Level
SAT N+1	-8.9%
Business Jet N+1	-11.9%
Regional N+1	-11.9%
Narrow-Body N+1	-17.1%
Narrow-Body N+2	-21.8%
Wide-Body N+1	-17.2%
Wide-Body N+2	-25.8%

Table 12: Fuel burn reduction potentials for all aircraft segments based on studies to one reference aircraft concept per segment

5.1.2. Vehicle Performance Evaluation

This chapter focuses on the trend lines for the regional and mainliner segment (see the following figures). The DEPA 2070 trend lines for the mainliner segment, covering both narrow-body and wide-body aircraft, are displayed in detail in Weber (2024).[41] This report presents trend lines for the whole mainliner segment, extrapolated linearly to 2070. The impact on fuel burn, as discussed in the previous chapter, is summarised in the table above. A linear projection until 2070 indicates that, in the conservative scenario, a mission-level fuel burn reduction of 28.4% is achievable by 2070, while a progressive scenario indicates a reduction of 44.9% (see Figure 36). These improvements result solely from advancements in aircraft technologies. The integrated technologies considered in this study are detailed in Weber (2024).[42]

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[40] Cf. Ibid.
[41] Cf. Ibid.
[42] Cf. Ibid.

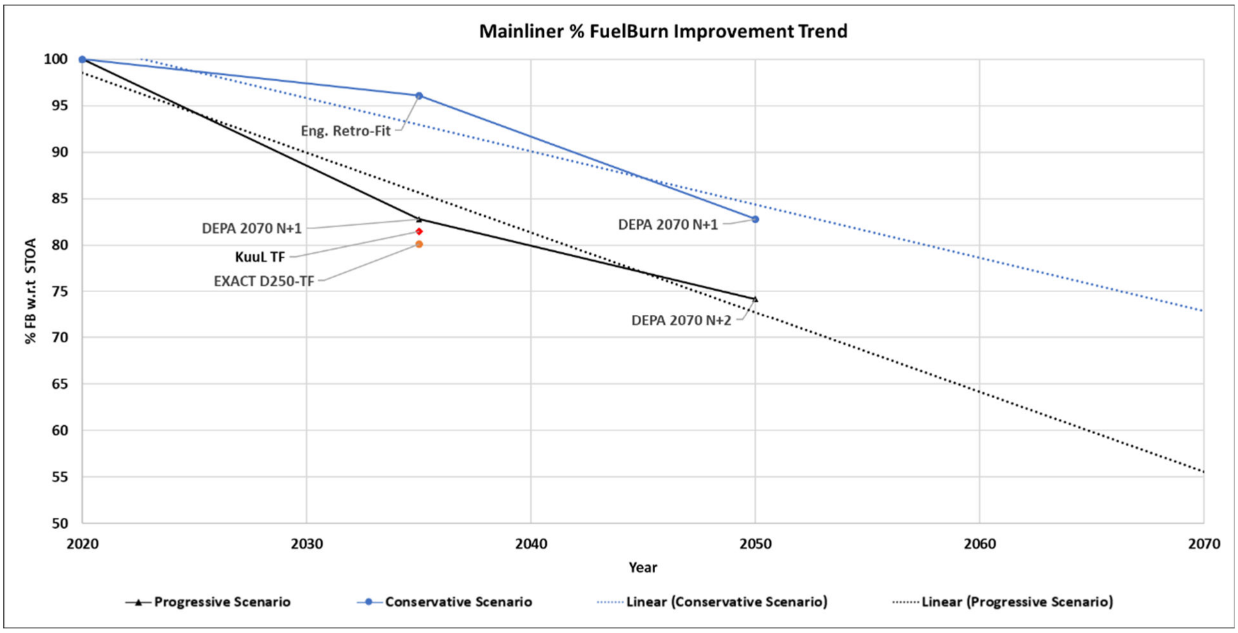

Figure 36: DEPA 2070 mainliner aircraft fuel improvement trendline

The analysis of the regional segment reveals that in both assessed scenarios, a fuel burn reduction of 11.9% is achievable through efficiency improvements in conventional propulsion and airframe technologies. Furthermore, the long-term trend toward 2070 indicates that in the progressive scenario, advancements in novel technologies could lead to a total fuel burn improvement exceeding 25%. As outlined in previous chapters, the regional segment will potentially adapt a fully electric flight at an earlier stage, with a potential transition starting in 2035. This shift could impact the long-term development of fuel-based efficiency improvements in this category.

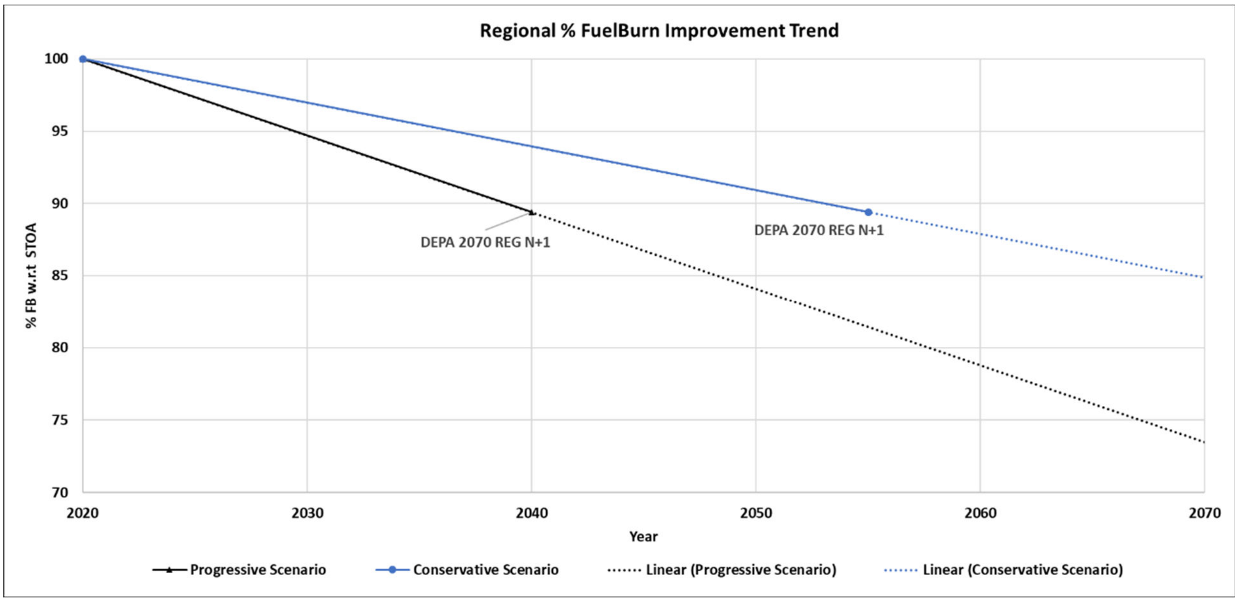

Figure 37: DEPA 2070 regional aircraft fuel improvement trendline

5.1.3. Economic Vehicle Evaluation

A Direct Operating Cost (DOC) based methodology was used to evaluate the vehicles presented. The regression-based methodology was developed specifically to enable the evaluation of alternative propulsion technologies such as SAF, hydrogen and electric systems. The methodology, embedded in the software environment LYFE, has been used in other internal DLR projects in the past, but the wide variety of aircraft designs in the DEPA 2070 project made its application a first of its kind. Existing automated interfaces to the vehicle design could be used for fast and precise evaluation.

The DOC method distinguishes between the categories of capital costs, fees, crew, maintenance and fuel. Fuel costs are usually the most significant part of direct operating costs, but cannot be compared between all aircraft models as it is not possible to define a comparable design mission applicable to all aircraft categories. Nonetheless, three scenarios, which are also used in the DLR projects “EXACT” and “EXACT2”, were assumed as input for the energy prices (cf. also Figure 38). This enables comparability of the vehicle evaluation across different projects.

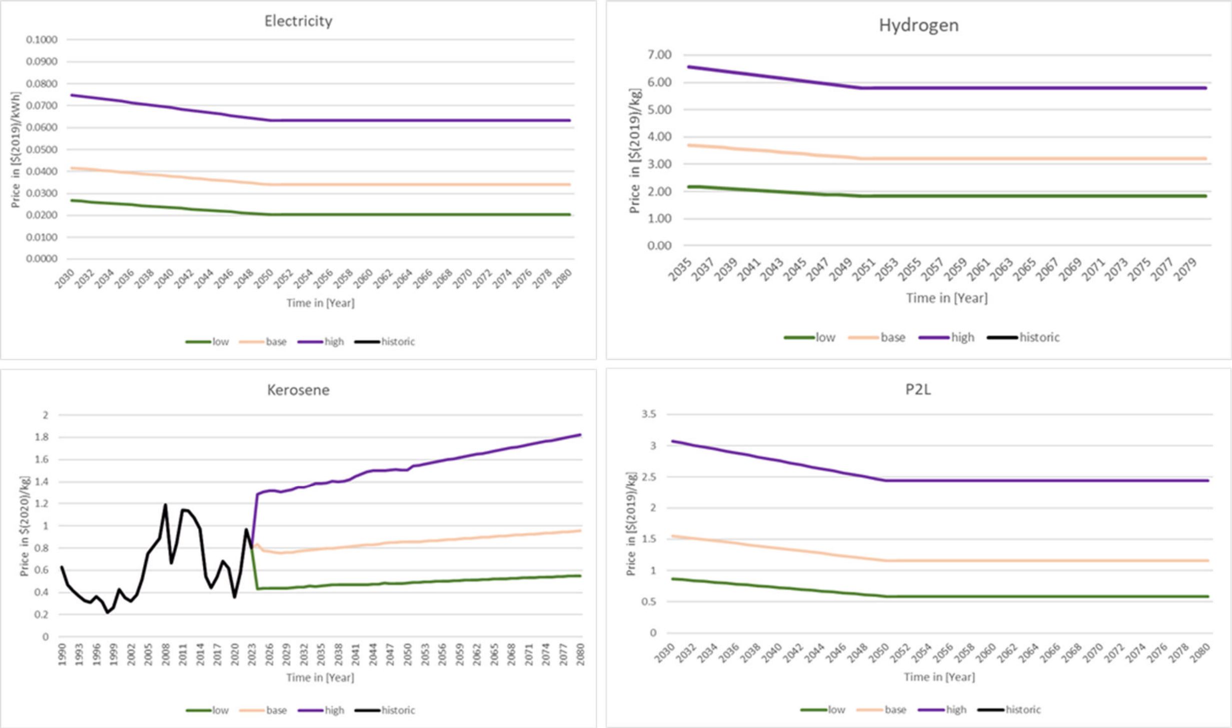

Figure 38: Energy price scenarios

From the results as presented in the next two figures several interesting aspects can be derived. In the smaller seat categories, full electric aircraft designs show a massive increase in capital costs, which is mostly due to the costs of battery packs procurement. These costs cannot be offset by slightly lower fuel and maintenance costs that, resulting in a significant increase in DOCs (e.g. of more than 25% in seat category 3). Hybrid vehicles such as in seat category 4 are less affected by this as they require substantially less battery capacity. Therefore, they are a realistic alternative to the conservatively kerosene-powered reference aircraft.

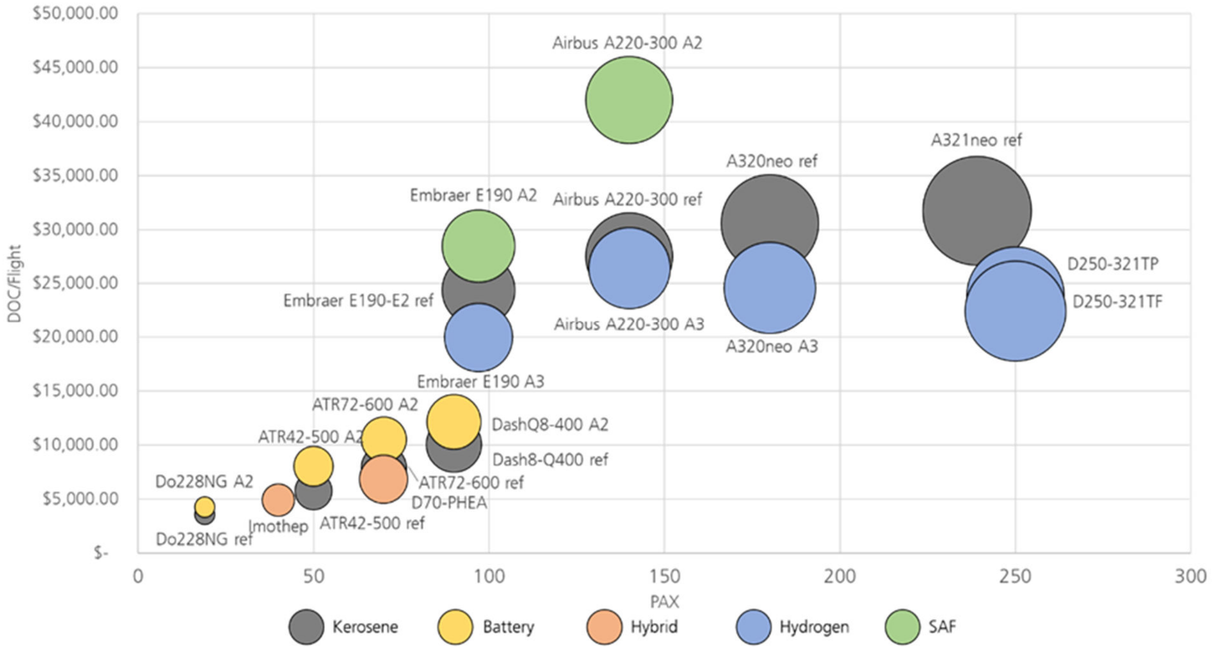

Figure 39: Overview DOCs DEPA 2070 short- and medium-range aircraft[43]

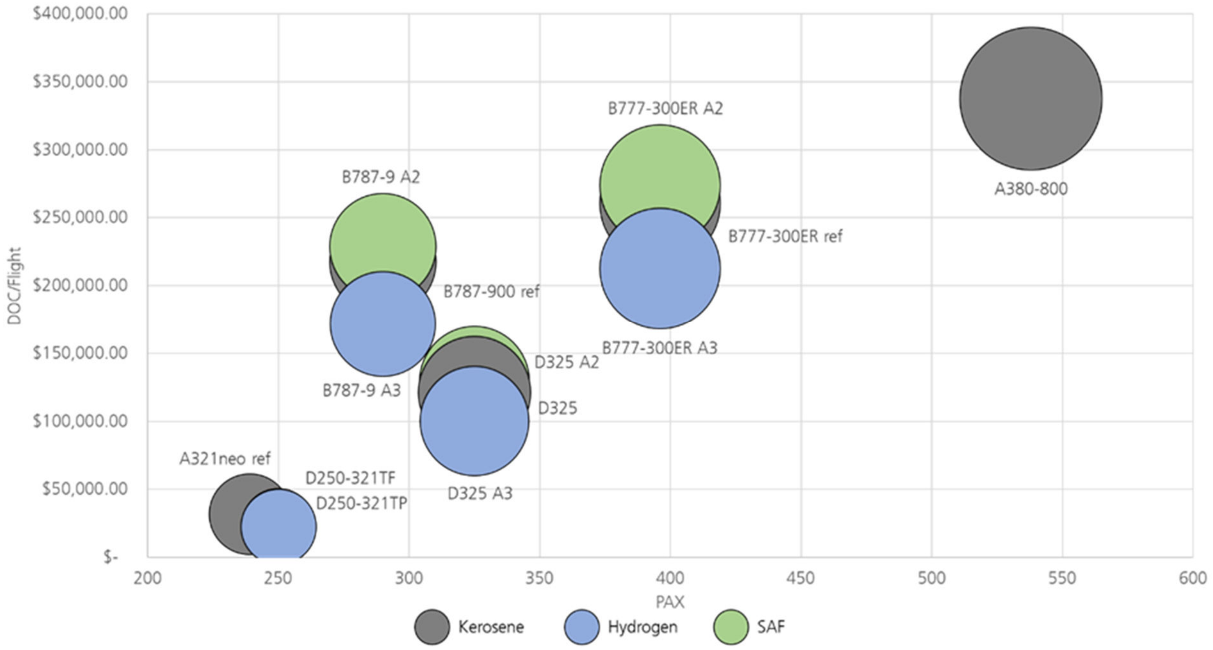

Figure 40: Overview DOCs for DEPA 2070 long-range aircraft[44]

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[43] The size of the circles represents the ASKs.
[44] The size of the circles represents the ASKs.

The results of seat category 5 (designs based on the Embraer E190) demonstrate the effects of the introduction of SAF and LH2 designs in a smaller aircraft segment perfectly. While capital costs and crew costs remain constant, there are slight reductions in fees for most of the new models. Only a small proportion of the costs are related to maintenance, which are also not subjected to significant changes. However, the increase in fuel due to the operation with SAF (assuming a 100% SAF quota in the base price scenario) overcompensates for the slight cost reductions in the other DOC categories and thus prevents an overall reduction in DOC. On the contrary, there is a moderate increase in costs under the given conditions. The 2050 advanced aircraft powered by hydrogen has lower fuel costs compared to the SAF models, but does not reach the level of the kerosene reference aircraft.

This effect is not seen in the larger seat categories, where all new aircraft designs are also SAF- or LH2-fuelled. Due to the higher fuel cost of the reference, the 2050 designs can achieve lower DOCs, demonstrating the potential of alternative fuels. However, to understand this result in detail, it is important to note that the comparatively high fuel costs of the reference aircraft are strongly influenced by the year of entry into service. As the historical cost of kerosene varies significantly, this dynamic also results in the great dependence of the vehicle evaluation on the assumed energy price scenarios. While the remaining DOC categories are reduced in an evolutionary and expected manner, high uncertainties are reflected in the energy prices in particular. Nevertheless, it has been demonstrated that hydrogen-powered aircraft are generally evaluated as being advantageous in terms of DOC due to lower fuel costs when compared to SAF-powered designs. Hybrid-powered aircraft appear to be advantageous in comparison to full electric aircraft, which appear to be unable to meet the cost efficiency of the kerosene-powered reference aircraft.

5.2. Fleet Development for the DEPA 2070 Scenarios

5.2.1. Fleet Evolution

The fleet evolution research structures and analyses the current (reference) and future (concept) aircraft and thus conceptualizes the whole range of available- and potential innovative aircraft for research purpose. Reference aircraft are being eased to represent (technical) averages across the 13 ICAO seating categories (or seating classes, SC). Concept aircraft are evaluated from vehicle design with regards to performance and (direct) operating cost and distinguished between propulsion technology and SC as well. In order to utilise concept aircraft in the DEPA 2070 fleet modelling, production windows for anticipated entry into service and thus technology readiness levels of aircraft are needed. Those were derived from the technology and scenario evaluation activities within the project. In Figure 41 the main drivers of fleet development are being displayed, which are considered in the fleet evolution modelling step.

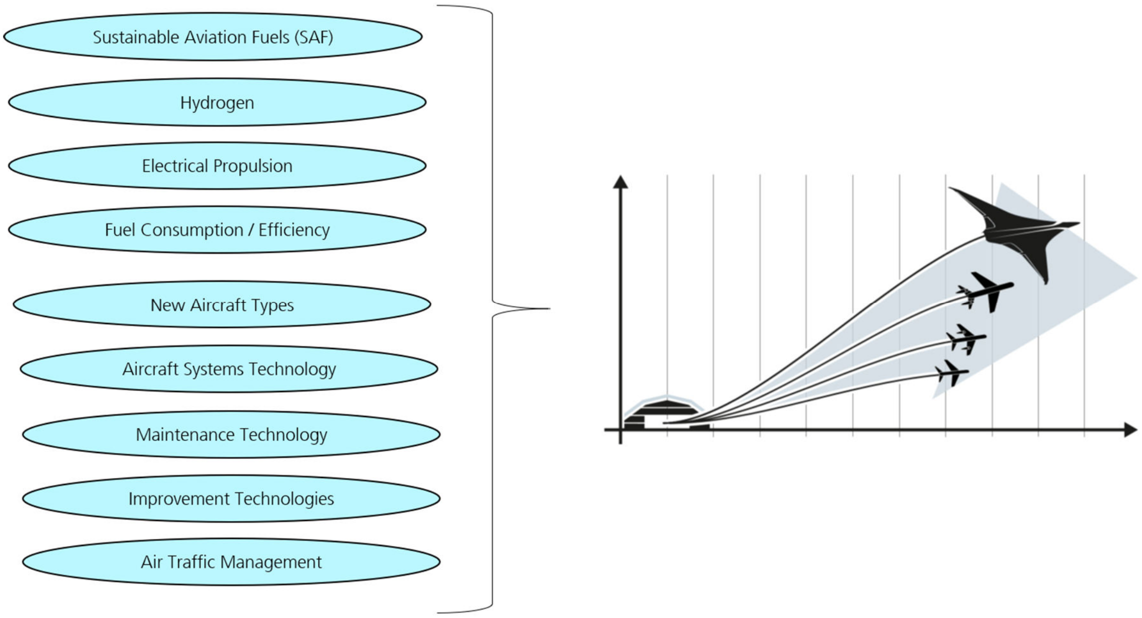

Figure 41: Drivers of fleet development

As indicated in table 8 from chapter 4.1.2 the conservative scenario is defined to implement full electric aircraft for the regional sector in 2055 whereby in 2045 hybrid-electric concepts become reasonable for regional aircraft, in 2050 for narrow-body- and 2060 for wide-body aircraft. Hyrogen fuel cell combustion is conservatively described to be market-ready in 2055 for regional aircraft, and hybrid gas-turbine concepts in 2060 for regional- and narrow-body aircraft (see table 9; chapter 4.1.2).

The progressive scenario takes more optimistic approaches, entering full electric battery regional concepts in 2040 and hybrid-electric concepts (with kerosene/SAF) already 2035 for regional- and narrow-body aircraft, and 2040 for wide-body aircraft. Hydrogen direct combustion and PEM are dated to be marked ready by 2035 for the regional aircraft market. Narrow- and wide-body aircraft with direct hydrogen combustion enter 2035- and 2040 respectively. Checking with technical aircraft designs in section 5.1.1/5.1.2 and economic and life cycle evaluation in 5.1.3 the most promising technologies are implemented in the production window scheme for concept aircraft. We however lose out on battery-hybrid concepts for the narrow- and wide-body segment, as electrified aircraft are seen to perform best (including DOC and life cycle) in the “smaller” aircraft categories with up to 85 seats. Compiling all previous work and information scenario specific production windows were then constructed with reference- and concept aircraft respectively, as seen in Table 13.

DEPA 2070 Aircraft in-production window (progressive scenario)

AO seat catego	pax	ICAO seating class	Aircraft	Aircraft Type	Energy Carrier	Max. Range (nmi)	Entry into service	Out of production
1-19	19	1	Do228NG A1	Commuter Turboprop	Kerosene	690	2015	2029
1-19	19	1	Do228NG A2 2030 progressive	Commuter Turboprop	Full electric	690	2030	2070
20-50	50	2	ATR42-500 A1	Regional Turboprop	Kerosene	726	2015	2034
20-50	50	2	ATR42-500 A1	Regional Turboprop	Kerosene	726	2035	2039
20-50	40	2	IMOTHEP REG_RAD A3 2035 progressive	Regional Turboprop	Hybrid-Electric	650	2035	2070
20-50	50	2	ATR42-500 A2 2040 progressive	Regional Turboprop	Full electric	1000	2040	2070
51-70	70	3	ATR72-600 A1	Regional Turboprop	Kerosene	740	2015	2034
51-70	70	3	EXACT Regional A3 2035 progressive	Regional Turboprop	Hybrid-Electric	1000	2035	2039
51-70	70	3	EXACT Regional A3 2035 progressive	Regional Turboprop	Hybrid-Electric	1000	2040	2070
51-70	70	3	ATR72-600 A2 2040 progressive	Regional Turboprop	Full electric	300	2040	2070
71-85	85	4	DashQ8-400 A1	Regional Turboprop	Kerosene	1100	2015	2039
71-85	85	4	DashQ8-400 A1	Regional Turboprop	Kerosene	1100	2040	2070
71-85	85	4	DashQ8-400 A2 2040 progressive	Regional Turboprop	Full electric	1000	2040	2070
86-100	97	5	Embraer E190-E2 A1	Narrowbody Jet	Kerosene	2850	2018	2034
86-100	97	5	Embraer E190 A2 2035 progressive	Narrowbody Jet	SAF	2850	2035	2049
86-100	97	5	Embraer E190 A2 2035 progressive	Narrowbody Jet	SAF	2850	2050	2070
86-100	97	5	Embraer E190 A3 2050 progressive	Narrowbody Jet	LH2	2000	2050	2070
101-125	120	6	Embraer E195-E2 A1	Narrowbody Jet	Kerosene	2850	2018	2034
101-125	120	6	Embraer E195 A2 2035 progressive	Narrowbody Jet	SAF	2850	2035	2049
101-125	120	6	Embraer E195 A2 2035 progressive	Narrowbody Jet	SAF	2850	2050	2070
101-125	120	6	Embraer E195 A3 2050 progressive	Narrowbody Jet	LH2	2000	2050	2070
126-150	140	7	Airbus A220-300 A1	Narrowbody Jet	Kerosene	3080	2016	2034
126-150	140	7	Airbus A220-300 A2 2035 progressive	Narrowbody Jet	SAF	3080	2035	2049
126-150	140	7	Airbus A220-300 A2 2035 progressive	Narrowbody Jet	SAF	3080	2050	2070
126-150	140	7	Airbus A220-300 A3 2050 progressive	Narrowbody Jet	LH2	2000	2050	2070
151-175	175	8	Airbus A320neo A1	Narrowbody Jet	Kerosene	3400	2016	2034
151-175	175	8	SIAM A320neo Baseline A2	Narrowbody Jet	SAF	3400	2035	2070
151-175	175	8	SIAM A320neo Baseline A2	Narrowbody Jet	SAF	3400	2035	2070
151-175	175	8	Airbus A320neo A3 2050 progressive	Narrowbody Jet	LH2	2000	2050	2070
176-235	235	9	Airbus A321neo A1	Narrowbody Jet	Kerosene	2500	2017	2034
176-235	235	9	Truss-Braced Wing A2 2035 progressive	Narrowbody Jet	SAF	2500	2035	2070
176-235	235	9	EXACT TF A3 2035 progressive	Narrowbody Jet	LH2	1500	2035	2070
236-300	290	10	Boeing 787-900 A1	Widebody Jet	Kerosene	8000	2011	2039
236-300	290	10	Boeing 787-8 A2 2035 progressive	Widebody Jet	SAF	8000	2040	2054
236-300	290	10	Boeing 787-8 A3 2050 progressive	Widebody Jet	LH2	8000	2055	2070
301-400	325	11	Airbus A350-900 A1	Widebody Jet	Kerosene	8000	2015	2034
301-400	325	11	KuuL Concept A2 2040 progressive	Widebody Jet	SAF	8000	2040	2070
301-400	325	11	KuuL Concept A3 2040 progressive	Widebody Jet	LH2	6200	2040	2070
401-500	401	12	Boeing 777-300ER	Widebody Jet	Kerosene	7750	2005	2025
401-500	401	12	Boeing 777-9 A1	Widebody Jet	Kerosene	7750	2026	2039
401-500	401	12	Boeing 777-9 A2 2035 progressive	Widebody Jet	SAF	7750	2040	2054
401-500	401	12	Boeing 777-9 A3 2050 progressive	Widebody Jet	LH2	8000	2055	2070
501-600	575	13	Airbus A380-800 A1	Widebody Jet	Kerosene	8000	2007	2021

Table 13: Production window for the progressive DEPA 2070 scenario

An aircraft concept mix from several DLR projects is applied.

It shall be noted that several new development steps within DEPA 2070 research have been translated into practice: we have up to three different propulsion technologies in single seating categories, competing with each other for market shares. Worth noting is as well that not all competing aircraft have same range, so e.g. the long-range market might be under less competitive pressure than medium- or shorter ranges where liquid hydrogen concepts are more present. For SC 13 we do not have successor aircraft in production post-A 380 and therefore this aircraft type will fade out within the “natural” retirement phase and be non-existent at some point in the future.

5.2.2. Methodological Concepts

The competition between propulsion technologies in single SCs can be processed in several ways within the fleet model:

- Equal share: new aircraft which enter the market are split 50/50 (or 3x1/3) to each respective technology; e.g. if 200 SC 10 aircraft (reference Boeing 787) are needed to be produced and thus enter the market within a future year, 50 % of those will have a liquid hydrogen propulsion system and the other 50 % will be specialised SAF aircraft.

- Winner-takes-all: one propulsion technology is seen to be superior over the other (due to cost, infrastructure, safety,…); in that case all new aircraft entering the market will be of the superior technology, presupposed the flight ranges do not (negatively) deviate. In the latter case we have a natural split as certain technologies are only suitable and thus specialised for the long-range-market.

- (Direct) operating cost: implementing cost-curves with respect to propulsion technology and operational area/distance specialisation; depending on the route profile and individual aircraft utilisation, the model selects the cheapest option. Additional information with regards to cost (DOC as well as life cycle) is then needed to a higher degree of detail, which has been modelled in the wider context of the fleet modelling as well (averaging about 60% pro-liquid-hydrogen, without considering infrastructural cost).

The current in-service fleet (reference aircraft plus all other current aircraft in use) is analysed with regards to their retirement-, utilisation- and seat load properties. We stochastically derive individual retirement rates as functions which we can vary in future, e.g. if future aircraft differ in their life-cycle properties and are prone to deviances in retirement. For utilisation, e.g. how many flight kilometres and number of operations can be operated within a certain period of time (in this case: utilisation per year) we proceed a similar way to calculate the current average and transfer an individually chosen growth rate on-top. This depicts more efficient aircraft handling in future (runway- and ground traffic optimisation, turnaround times, (un)loading, gains through digitalisation etc.). Utilisation is as well designed as variable, and thus prone to change in the fleet model (e.g. if certain aircraft types need longer re-fuel times). The seat load factor is designed respectively.

The fleet forecasting process starts from a (current) base year using in-service aircraft on route level globally (CIRIUM Fleet-Analyzer, former ASCEND). For each of the following years, at first the number of retiring aircraft is estimated (according to each aircraft (AC) individual retirement curve; dependent on AC type regional [business] jet, turboprop, narrow-body, wide-body and AC age) via probability function. Those aircraft then a) need to be replaced and b) growing passenger demand on-route needs to be satisfied with additional vehicles. How many (and which) aircraft are needed on each individual route also depends on the aircraft utilisation function (which converges over time to an "optimal measure" for each AC type) in order to calculate how efficient aircraft handle passengers.

All origin-destination routes globally with more than 1,000 passengers are analysed, resulting in 83,100 routes for the base year 2019 (the last stable pre-Covid year was taken as base year, from the Sabre market intelligence database). For each route, the demand- and capacity forecast estimates then an optimal aircraft size in order not to violate capacity constraints.

The aircraft assigned on respective routes are either that pre-determined optimal size or a mixture of +/- one seating class to it, according to a linear solve function (lp_solve). Figure 42 shows CAEP 13 calibrated survival- and thus retirement rates, whereby the figure after next illustrates aircraft utilisation.

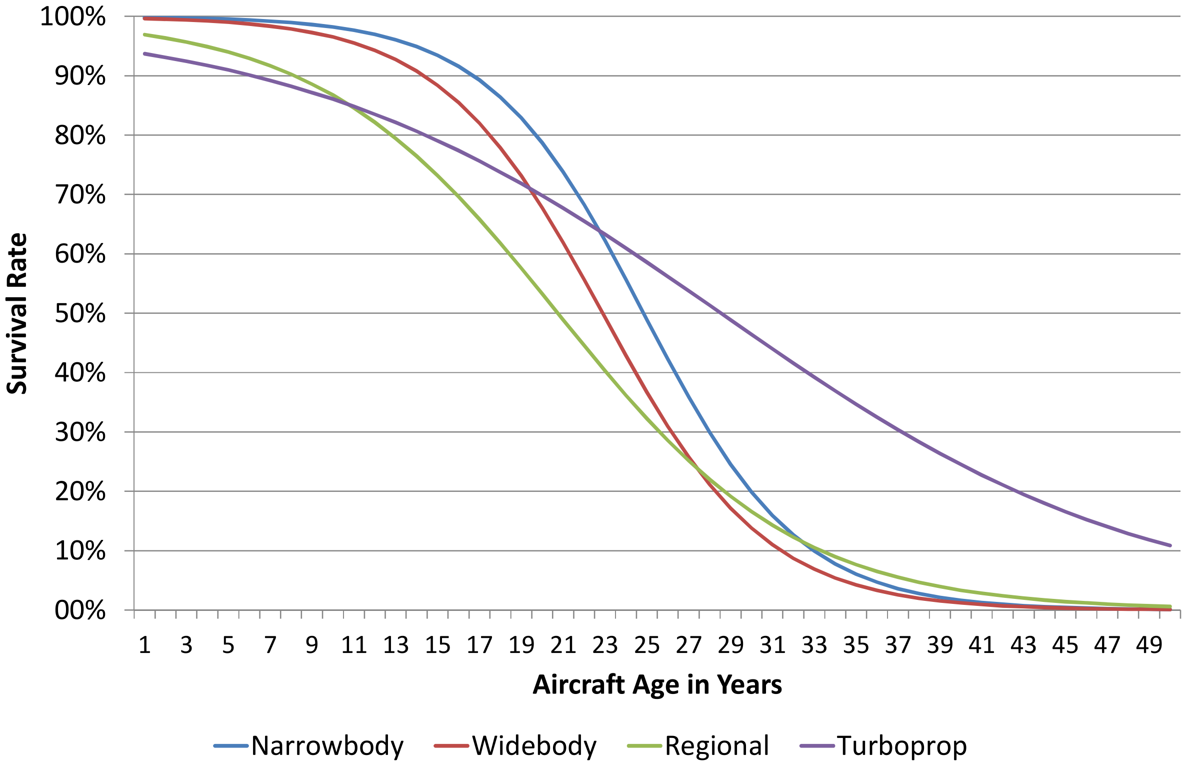

Figure 42: Aircraft retirement according to aircraft type

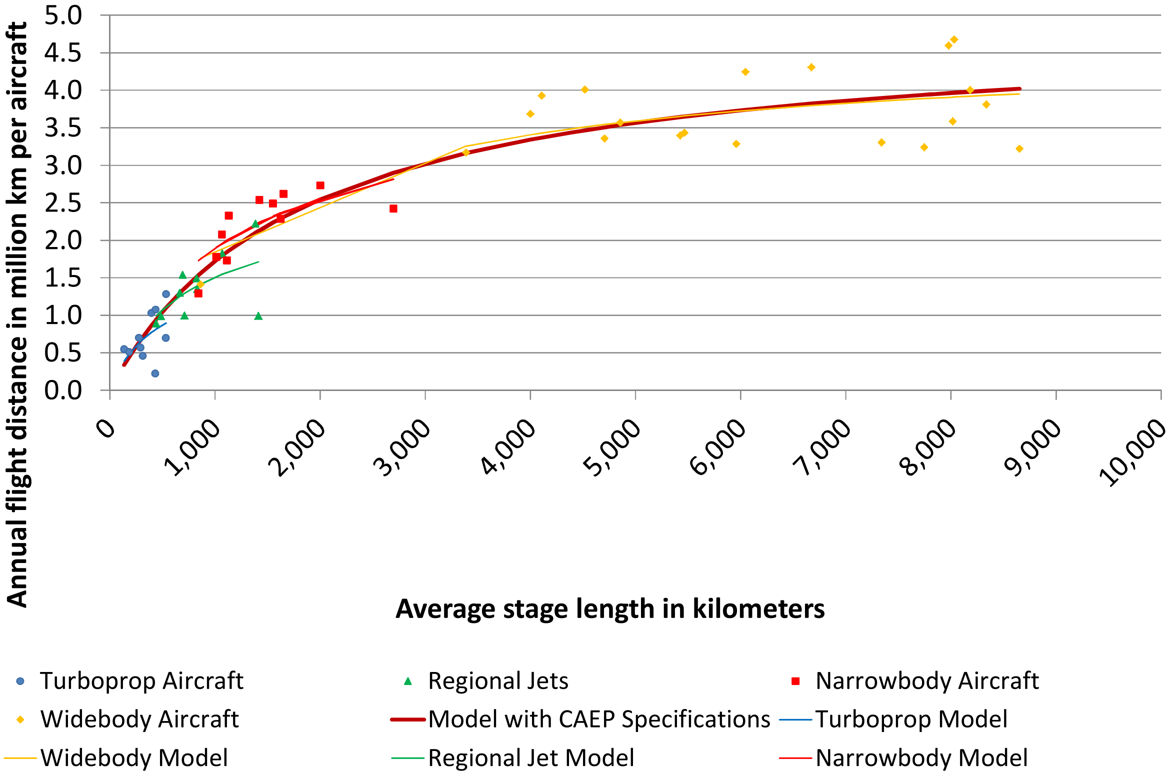

Figure 43: Aircraft utilisation according to aircraft type

After calculating the total amount of new aircraft needed (fleet growth) and thus the total fleet for each year respectively, the aircraft are distributed across all routes under the premise of "optimal aircraft size on route". This leads to global airport-to-airport aggregated schedules, e.g. the type and amount of aircraft on each route.

5.2.3. Final Results

For the final fleet calculation within the DEPA 2070 project CAEP calibrated coefficients for the utilisation-, retirement- and seat load factor functions were utilised in order for comparability and evaluation of results in comparison to other forecasts, e.g. from Airbus and Boeing. Utilising CAEP coefficients also minimised the vulnerability of the fleet model used in DEPA 2070 and enabled to focus on the actual methodological differences compared to other state-of-the-art forecast models. With regards to the choice of concept aircraft for competitive (business) aircraft, it was strategically decided to go "winner-takes-all" pro liquid hydrogen in order to be in line with other current DLR projects like EXACT, THOR and ALICIA.

Figure 44 illustrates the global flight volume by seat class for all aircraft; we estimate that flight volumes in larger SC grow rapidly, driven by fleet replacement on existing routes which experience steady passenger growth but underlie airport capacities to some extent. In order to handle the amount of growing passenger numbers, the average AC size needs to grow in the absence of other alternatives to increase the amount of operations. For detailed analysis on passenger growth and airport capacities, see also the preceding 4.2.

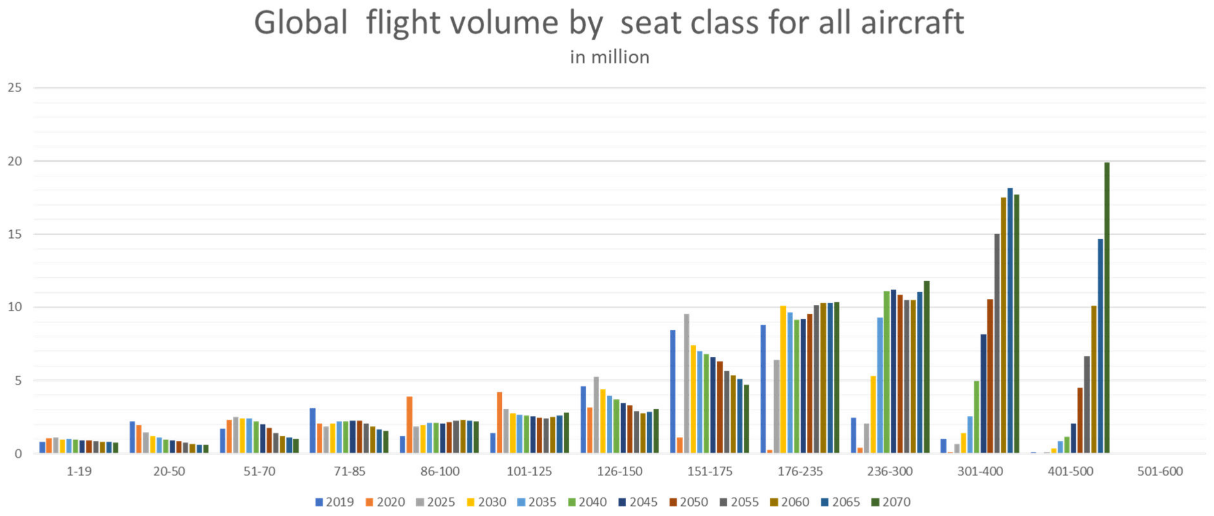

Figure 44: Flight volume by seat class

The passenger volume per SC shows an even more dedicated picture in Figure 45 with respective to larger classes, due to the fact that larger aircraft naturally carry more passengers. In 2070 the majority of all passengers are seen to be travelling with wide-body aircraft, e.g. SC 11 and 12, whereas SC 1-4 – so up to 85 seats – do actually barely evolve. This is due to the fact that less-frequented routes grow over time into “more” or “medium” frequented routes and thus acquiring larger AC.

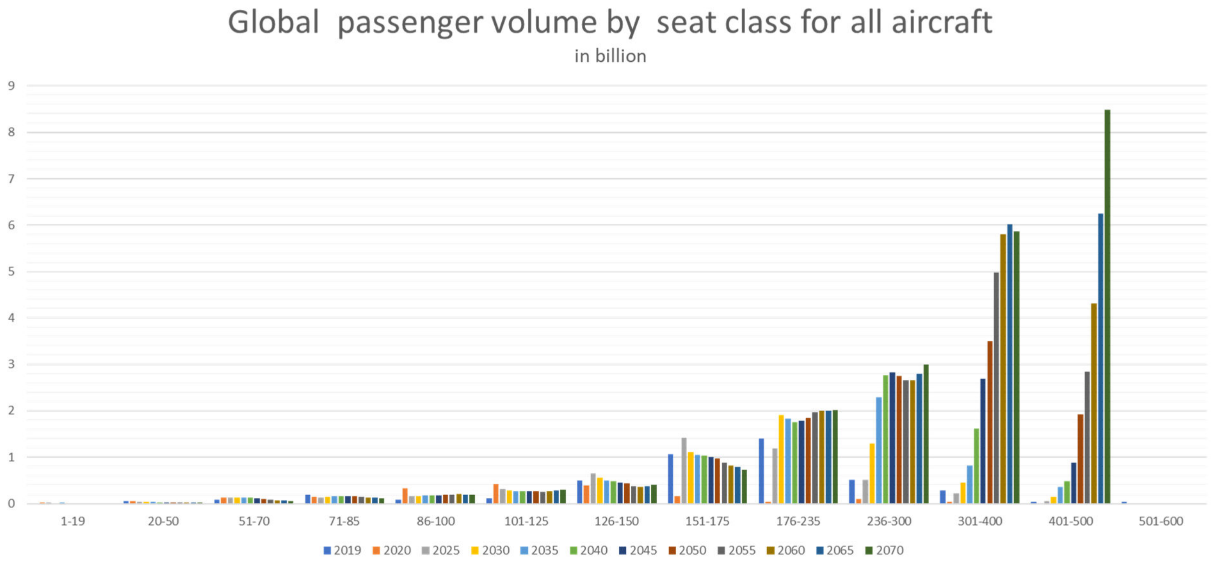

Figure 45: Passenger volume by seat class

When looking at the fleet mix from a technical perspective, comparing AC with respect to propulsion technologies, we find in Figure 46 that especially in the progressive scenario the market will be taken over by mainly liquid hydrogen narrow- and wide-body concepts, as those dominate in the SC 9-12 according to our assumptions in 5.2.2. In the progressive scenario, there is still a significant amount of SAF aircraft in SC 11 due to range advantages over hydrogen and "leftover" AC 2040–2054, which serve as carry-over technology before introducing liquid hydrogen aircraft for SC 10 and 12, respectively. Kerosene is not produced anymore but fading out of market via natural retirement (which could in general be varied by forced retirement e.g. scrapping bonus). The hybrid-electric and full electric segment is rather small, as they are mainly present in the short-distance sector which globally has (and will have) low market shares in general. The conservative scenario is defined without liquid hydrogen aircraft, thus SAF would be the way to go for narrow- and wide-body aircraft. We would still have more kerosene AC in the market, as the EIS windows are as well shifted some years backwards.

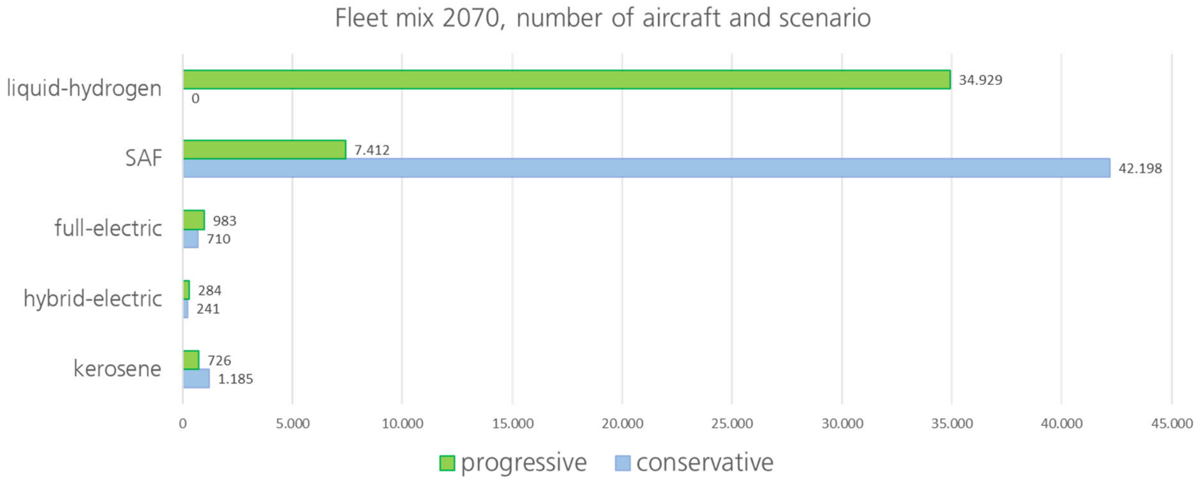

Figure 46: Fleet mix according to propulsion technology and scenario

Summing up, the findings show that average AC size grows and explicitly the share of wide-bodies is accelerating between 2050 and 2070, which leads to several further implications:

- A large fraction of growth occurs on short- and short-medium routes up to 2,000 km; those are subsequently filled with wide-body aircraft in order to handle the amount of passengers;
- Reference- and concept wide-body aircraft are designed to perform on long- instead of short distance and thus are not optimal to serve duty on most of the routes they currently are assigned to (with respect to DOC and life-cycle assumptions; large weight and many operations lead to faster material erosion and thus steeper retirement curves);
- Thus, high potential for 400+ seats on short-range aircraft design is seen (e.g. a "People Mover" concept);

- Starting 2050, wide-body-production with 500+ per year is estimated, while by 2070 it will increase to 1,000+; a huge number comparing to current production (in 2023: 64 AC of the A350 family have been produced); It is questionable whether production can ramp up this fast and if such AC would even sell, with regards to market risks (new technology, energy carrier, less flexibility, retail market);
- Supply-chain and feedstock issues have not been considered in the fleet modelling, but were investigated in relation to the trend analyses conducted for the DEPA 2070 scenarios; they could become an issue especially for wide-body-production; estimates in that regard are rather sketchy, as the current wide-body-production is in a niche, specialised and globally produced in low numbers only.

6. Impact Analysis

6.1. Impact on CO_2 Emissions

6.1.1. Methodology of the Emisssions Calculation

An advanced emissions tool was utilised to calculate the hydrocarbon-based-fuel burn as well as the CO_2 emissions for the future air traffic demand scenarios. A bottom-up approach was used and the flight plans from the demand forecast and fleet assignment (see chapter 4.2 and 5.2) were linked with the fuel burn from the vehicle designs (see chapter 5.1). To consider the effect of detours on the flight distance, great circle distance dependent formulas were derived from a set of one million real aircraft trajectories. The data was clustered in flights below a great circle distance of 2,000 km, between the latter and 6,000 km and above 6,000 km, whereby flights over 6,000 km have a constant increase of 3.2 %. Effects due to inefficient cruise altitudes or wind effects were not considered. The life cycle impact effects of sustainable aviation fuel were finally considered in a post-processing step. The ReFuel EU mandate was applied on a global level without consideration of possible inavailabilities or differences between countries and especially developing nations. For the time horizon between 2050 and 2070 a linear increase of SAF usage from 70 % to 100 % was assumed. The reduction of life-cycle CO_2 emissions due to SAF were considered with 80 % in contrast to normal Jet A-1 kerosene. SAF was treated equally in the conservative and progressive scenario. The year 2019 was taken as common reference. The corresponding flight plan was obtained by Sabre Market Intelligence. It is important to note that in line with the DEPA 2070 project only scheduled commercial air traffic was considered for the fuel burn and emission calculation.[45]

6.1.2. Results of the CO_2 Emissions Calculation

The consumption of hydrocarbon-based fuel (Jet A-1 and SAF) is displayed in the figure below. The fuel consumption is projected to reach pre-Covid levels in 2029 which is in line with IEAs estimate that the level will not be reached prior 2027. In the conservative scenario the fuel demand is going to increase by 249% until 2070 to about 630 megatons. The annual growth rate is 2.41% whereby the available seat kilometres (ASK) increase with 2.93% p.a. In the progressive fleet scenario on the other hand, the fuel consumption will have its peak in 2035 (313 megatons) with an increase of 22% compared to 2019 levels. Due to the introduction of liquid hydrogen- and electrical propulsion the fuel demand remains almost constant until 2050 and decreases by 69% to 94 megatons in 2070.

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[45] Correspondingly, military- and governmental aviation, cargo- and business aviation is not included in the assessment figures.

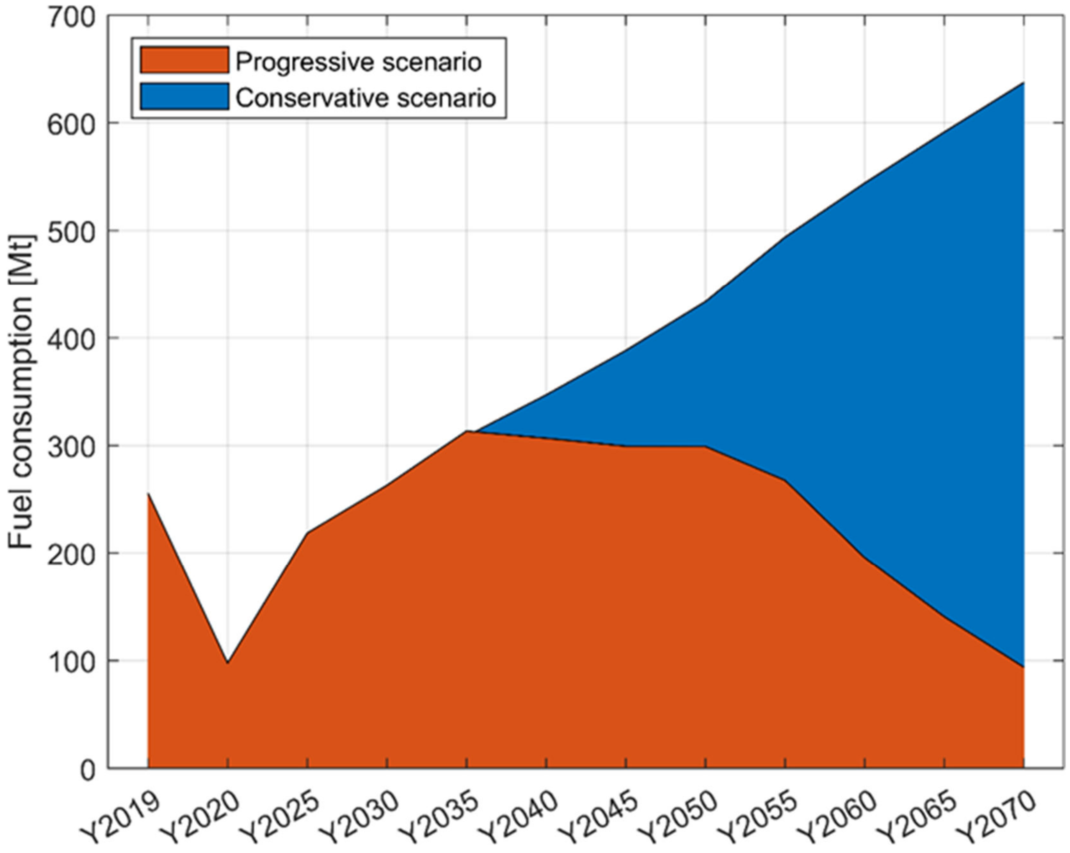

Figure 47: Consumption of hydrocarbon-based-fuel for the conservative and progressive scenario

The specific consumption of hydrocarbon-based-fuels is displayed in Figure 48.

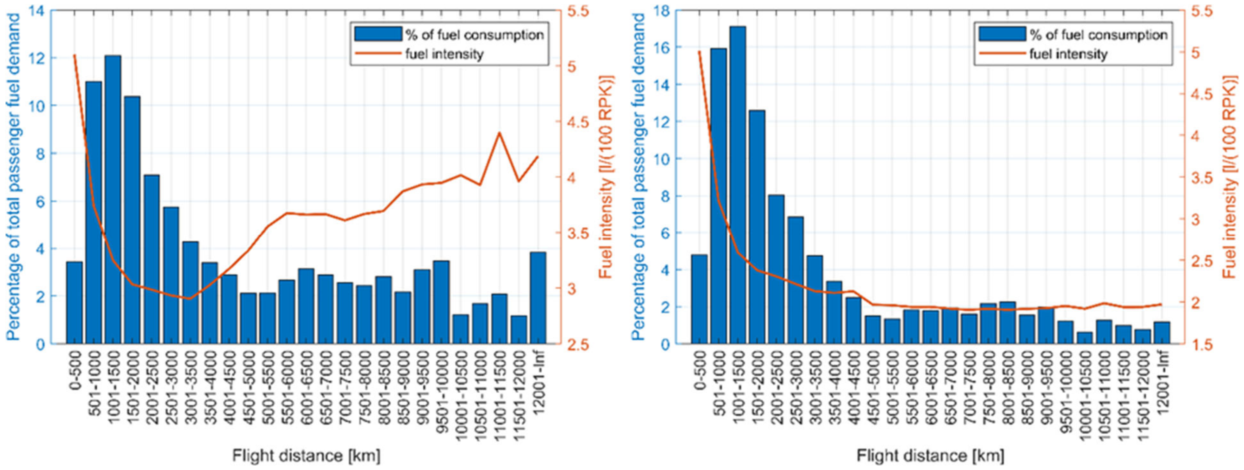

Figure 48: Fuel demand per flight distance and specific fuel consumption for the conservative scenario (on the left for 2019 and on the right for 2070)

The specific consumption of hydrocarbon-based fuel decreases from about 3.4 liter per 100 RPK in 2019 by 30% to 2.37 liter per RPK in 2070 in the conservative scenario. This is due to improved aircraft technology, an increased load factor and an increase in the average seat capacity per aircraft. If only considering hydrocarbon-based fuels there is no meaningful difference between the conservative and progressive scenario. However, if considering non-hydrocarbon-based fuels (hydrogen and electric), the average fuel consumption decreases by 90% to 0.35 liter per 100 RPK. This is mainly due to the introduction of liquid hydrogen propulsion in all seat classes.

Figure 49 shows that in 2019 flights under 2,000 km accounted for 37% all CO_2 emissions.

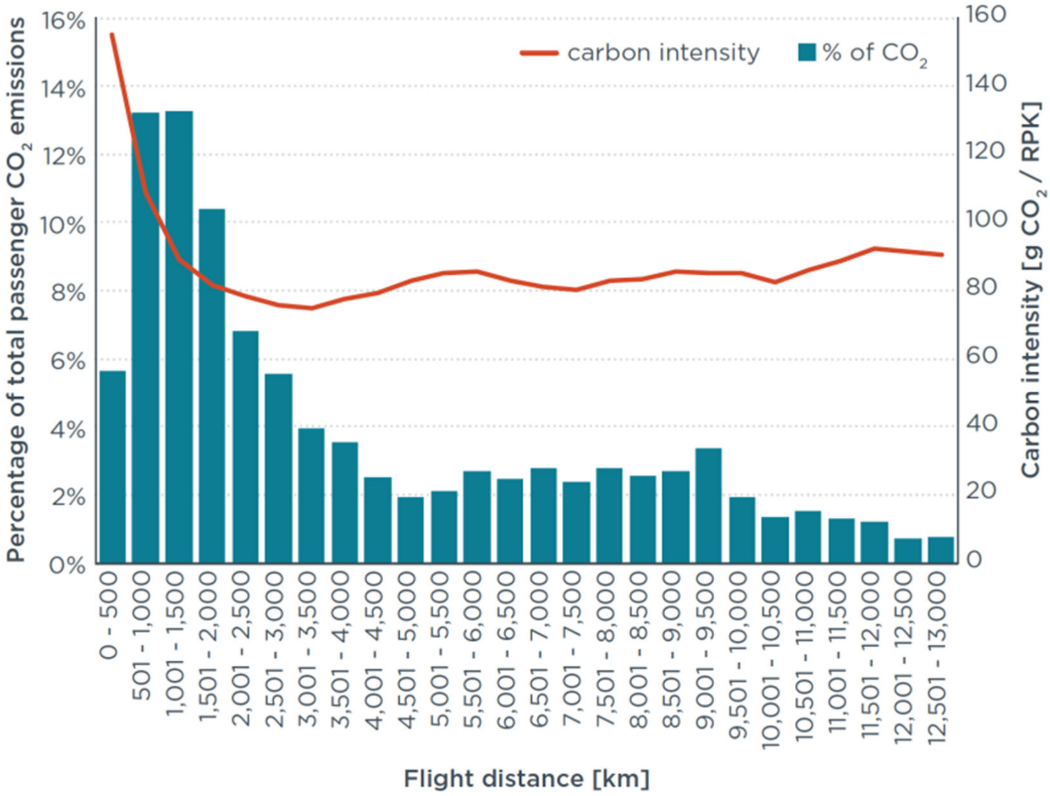

Figure 49: Flights under 2000 km are accountable for 43% of CO_2 emissions[46]

In the conservative fleet scenario this share increases to 50.5% in 2070. The specific fuel consumption decreases with an increasing flight distance while increasing again after a certain threshold. This is very visible in 2019. Due to the demand forecast, the average seating per aircraft increases significantly. The ASK per fuel type in the progressive scenario are displayed in Figure 50.

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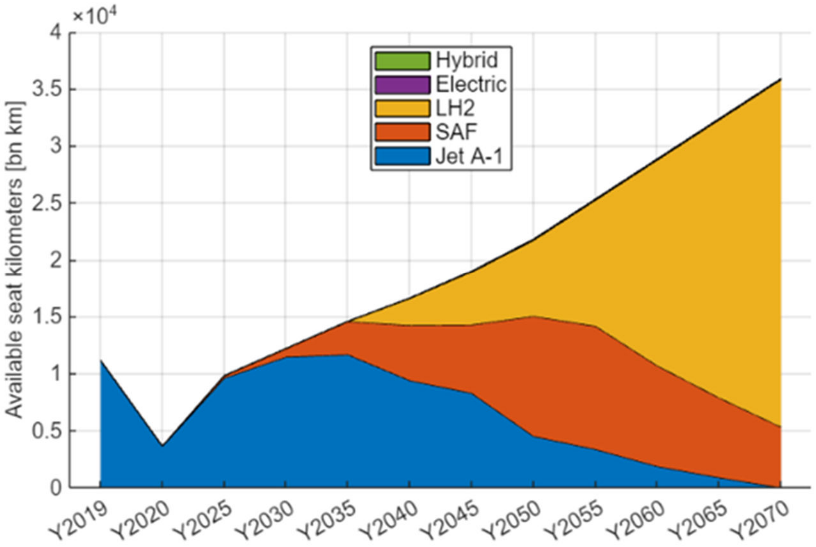
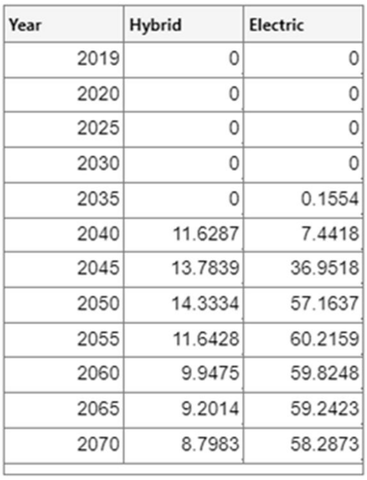
[46] Cf. Graver, B. et al (2019).





Year	Hybrid	Electric
2019	0	0
2020	0	0
2025	0	0
2030	0	0
2035	0	0.1554
2040	11.6287	7.4418
2045	13.7839	36.9518
2050	14.3334	57.1637
2055	11.6428	60.2159
2060	9.9475	59.8248
2065	9.2014	59.2423
2070	8.7983	58.2873

Figure 50: Provided ASK per fuel type[47]

The share of electric- und hybrid-electric propelled aircraft has its peak in 2050 with a market share of 0.325% and a total available transport capacity of about 71.5 bn ASK. The share of SAF is equivalent to the ReFuel EU quotas which increase up to 70% in 2050.

It is important to note that the quota is applied to all flights, flying with hydrocarbon-based fuels. Liquid hydrogen aircraft have their EIS in 2035 with the EXACT TF A3 (an A321 derivative). A wide-body aircraft, the KuuL Concept A3, follows in 2040 (A359 derivative). In 2050 an E190, E195, A223 and A320 derivative will join the market. With the EIS of a B787 and B777X successor in 2055 all ICAO seat classes greater than five have a liquid hydrogen propulsion alternative (except seat class 13 with only the A388). This leads not only to a carbon-neutral growth of aviation but also to a reduction of ASK performed by hydrocarbon-based aircraft.

Although SAF only has a minor impact on the fuel demand and direct combustion CO_2 emissions, it has major impacts on the life-cycle CO_2 emissions of aviation. The life-cycle CO_2 emissions, with and without consideration of SAF, are displayed in Figure 51.

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[47] The table shows the flown ASK for hybrid- and electric aircraft in bn km for the progressive fleet scenario.

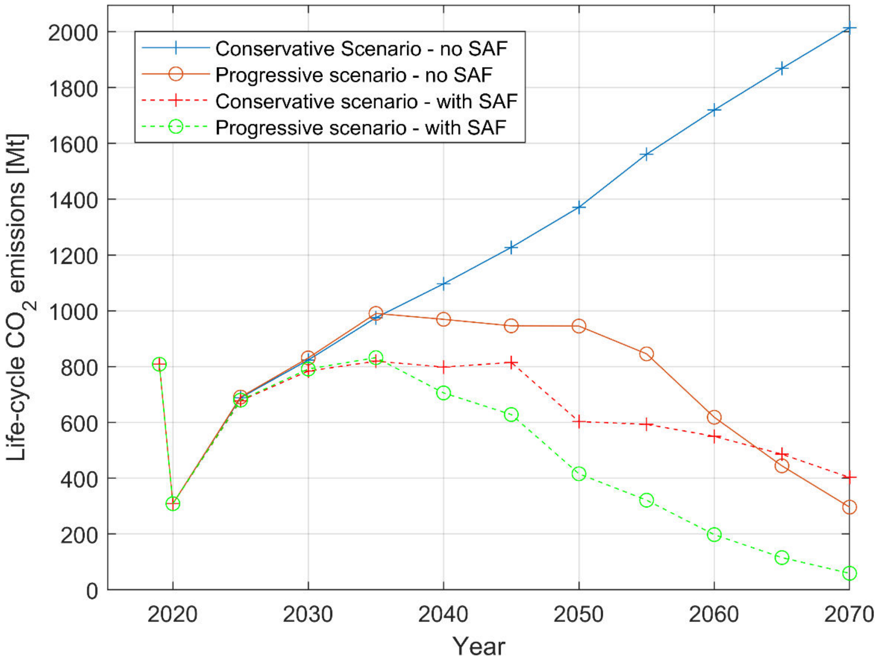


Figure 51: Life-cycle CO₂ emissions for the DEPA 2070 scenarios with and without consideration of SAF

With consideration of SAF, the life-cycle CO_2 emission levels of 2019 will never be reached again. Neither in the conservative nor in the progressive scenario. From 2030 to 2045 the increasing share of SAF is compensating the higher demand and thus higher CO_2 emissions. Because of the large increase of SAF share between 2045 and 2050 (32% to 70%), the life-cycle CO_2 emissions decrease rapidly. Also, the life-cycle emissions per 100 RPK decrease in all DEPA 2070 scenarios and are displayed in Figure 52.

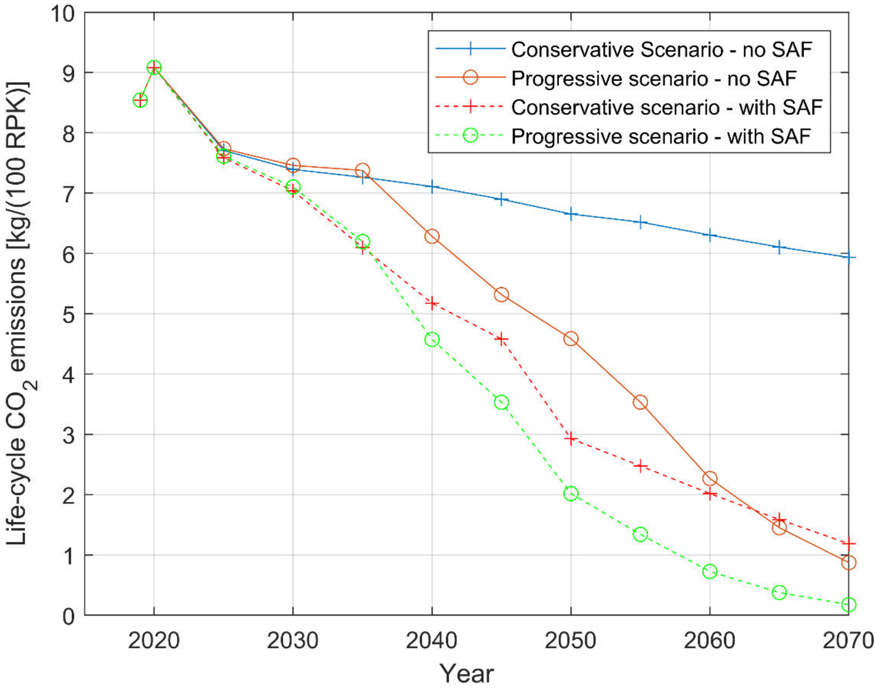
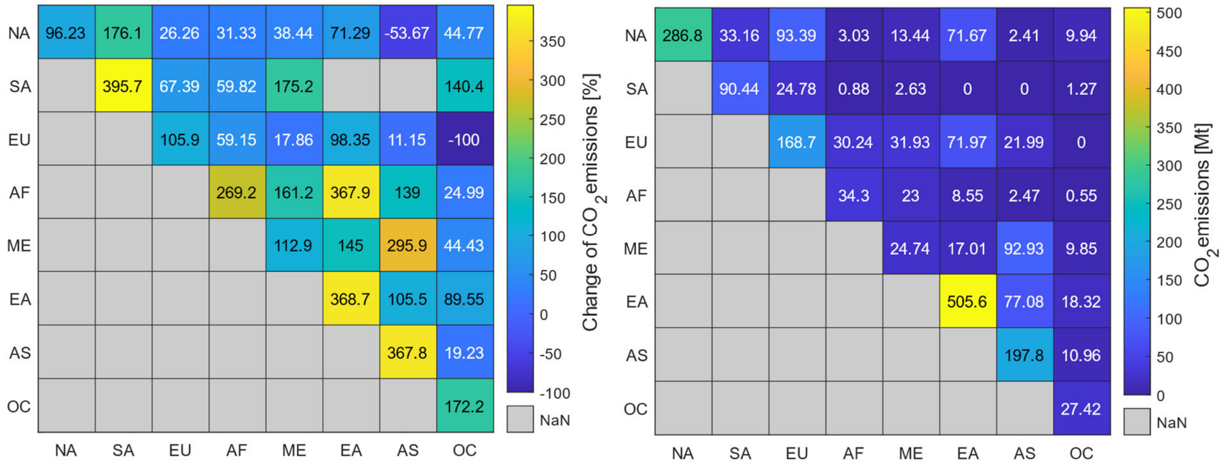


Figure 52: Life-cycle CO₂ emissions per 100 RPK for the DEPA 2070 scenarios with and without consideration of SAF

In the conservative scenario, without consideration of SAF, they decrease by 30.5% until 2070 due to improved aircraft technology as well as a higher seat load factor and aircraft seating capacity. The introduction of SAF is further reducing the life-cycle impact up to 86% compared to 2019. The improvement due to the introduction of carbon neutral energy carriers in the progressive scenario is 90% without the consideration of SAF. With, it increases to 98%. However, it should be noted that the life-cycle reduction of SAF is dependent on multiple factors such as SAF-type, feed stock, carbon intensity of the electricity used to produce SAF and much more. In further studies these variables should be factored into the life-cycle assessment although especially the future energy mix is difficult to predict precisely.

The regional distribution of the emissions, based on their departure and arrival airport, is displayed in Figure 53.



	NA	SA	EU	AF	ME	EA	AS	OC
NA	96.23	176.1	26.26	31.33	38.44	71.29	-53.67	44.77
SA		395.7	67.39	59.82	175.2			140.4
EU			105.9	59.15	17.86	98.35	11.15	-100
AF				269.2	161.2	367.9	139	24.99
ME					112.9	145	295.9	44.43
EA						368.7	105.5	89.55
AS							367.8	19.23
OC								172.2

	NA	SA	EU	AF	ME	EA	AS	OC
NA	286.8	33.16	93.39	3.03	13.44	71.67	2.41	9.94
SA		90.44	24.78	0.88	2.63	0	0	1.27
EU			168.7	30.24	31.93	71.97	21.99	0
AF				34.3	23	8.55	2.47	0.55
ME					24.74	17.01	92.93	9.85
EA						505.6	77.08	18.32
AS							197.8	10.96
OC								27.42

Figure 53: CO_2 emissions for the intra- and interregional air traffic development[48].[49]

The intra-North-American traffic was the most relevant in 2019 with 146 Mt. This will change due to the higher demand growth in East-Asia until 2070 (369% compared to 96%). The intra-East-Asian traffic will account for approximately 20% of all CO_2 emissions in 2070. It can be observed that the trans-atlantic emissions are almost saturated and will increase only moderately by 26%. The same applies to international travel involving Europe and North-America which shows a smaller growth. Emissions will increase in almost all regions and significantly in developing and emerging nations.

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[48] On the left is the change of CO_2 emissions in 2070 to the reference year 2019 for the conservative scenario. On the right are the absolute emissions for the intra- and interregional traffic between geographical regions in 2070. The regional assignment is in the annex.

[49] The emission amount in 2019 is 822 megatons and in 2070 2,014 megatons. There is scheduled passenger traffic between Asia and South Africa as well as Europe and the Oceanic region. However, it is so little that the relevance is zero.

The life-cycle CO_2 emissions will rise significantly if only technology improvements as well as higher seat load factors and seating capacity are considered. Thus, achieving the climate targets is not possible without additional efforts in other fields. Furthermore, SAF is a gamechanger in reducing the life-cycle CO_2 emissions in special regard of the conservative scenario. With a global application of the ReFuelEU SAF mandate, the life-cycle CO_2 emissions of 2019 will be the highest ever occurred and despite of growing air traffic demand the life-cycle emissions will not exceed the 2019 peak in the long-term. Nevertheless, in general significant offsetting is necessary to achieve the current emission goals. In regard of the long-term perspective introducing new aircraft designs is, however, also needed to contribute to a consistent overall CO_2 emissions reduction but as technology is not ready yet to propel aircraft without hydrocarbon-based fuels SAF should be given the highest priority.

As outlined in this report, from 2035/2040[50] onwards technology will then also contribute with a rising share to the CO_2 emissions reduction and further efforts should be put in parallel in corresponding R&D to prepare the exploitation of the expectable benefits in consideration of the generally longer development and life cycles in the aviation industry. To prepare the best conditions for fleet renewal is in this case essential as already today the fleet renewal process is a major driver of efficiency improvements, helping to partially offset the increase in CO_2 emissions resulting from growing demand. Lastly, it has to be considered that aviation's climate impact is not only CO_2 but also nitrogen oxide, soot, water and contrails effects which may contribute significantly to the overall climate impact of aviation. These aspects were not regarded in this report.

6.2. Impact on Aircraft Noise

In the vicinity of airports, aircraft noise is the most significant environmental problem. The problem is exacerbated by the fact that forecasts assume an annual increase in air traffic of approx. 3 to 5%,[51] which corresponds to an average increase in aircraft movements of approx. 1.5%,[52] but also an increase in aircraft weights (i.e. larger aircraft on average). For the development of the aircraft noise situation, it is of decisive importance whether the increase in aircraft movements and aircraft weights, which leads to an increase in noise, can be (over)compensated by technical innovations in order to achieve political goals (e.g. Flightpath 2050.[53])

In order to be able to analyse the development of the aircraft noise situation globally, national and international airports must be considered. Decisive for the development of the aircraft noise

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[50] Cf. https://www.reuters.com/business/aerospace-defense/airbus-postpones-development-new-hydrogen-aircraft-2025-02-07. The postponement of the ZEROe aircraft of Airbus indicates that 2040 is more likely to have a first hydrogn-powered aircraft available for the aviation market.

[51] Cf. Airbus (2024); Boeing (2024); Schmid et al. (2023).

[52] Cf. Schmid, R. et al. (2023).

[53] Cf. European Commission (2011).

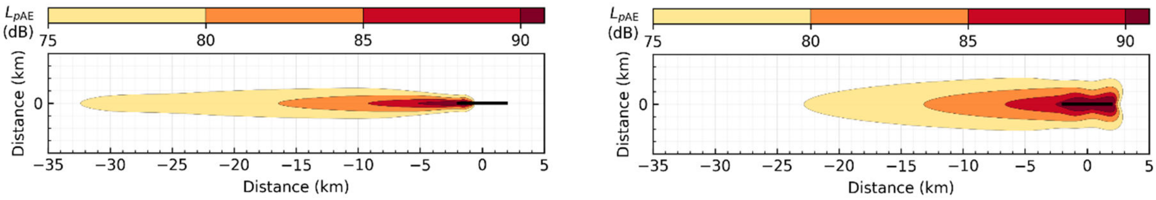
situation is the development of the number of aircraft operations and the composition of the types of aircraft operating at each airport. Local details (e.g. route structure or distribution of movements on routes) play a subordinate role in analyses of the global noise development.

For this reason, it makes sense to evaluate the development of the global aircraft noise situation using the concept of so-called noise points. With this concept, each aircraft type is assigned a noise point that adequately describes its noise immission. If the noise points are summed according to the number of operations at an airport, this noise point sum provides a measure of the aircraft noise situation and its development at an airport. This concept is also related to the "Quota Count"-system applied (amongst others) at London's airports Heathrow, Gatwick, and Stansted to limit noise at night time.[54] In this system, each aircraft is assigned a "Quota Count" based on its certification levels. The British department of transport limits the allowed quotas per night and also reduces the quotas periodically in order to achieve noise reductions.

In this report, the determination of noise points is based on the "Instructions for the calculation of noise protection zones" (AzB[55]), which is implemented in the Aircraft Noise Analyses Framework (AIRNAF) at the Institute of Aerodynamics and Flow Technology at DLR. In order to be able to adequately consider more modern aircraft types, a proposed revised data basis (known as AzB21[56]) is used as data basis. Nonetheless, the procedure presented in this report for determining noise points also works using other data bases and calculation methods. The noise points determined here are primarily aimed to achieve an equivalence to the 60dB L_{Aeq}-contour area for most German airports, but can also be regarded as general representatives of the noise immissions of the aircraft types.

6.2.1. Methodology of Determining Noise Points

In a first step of determining noise points, the behavior of contour areas is analysed for a single event.Figure 54 shows the L_{AE} contours of AzB-group S3_M130_T2_N7 for approach (left-hand figure) and departure (right-hand figure).



(a) Approach (b) Departure

Figure 54: L_{AE} contours of group S3_M130_T2_N7 for approach (class "-L") and for departure (class "-SB")

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[54] Cf. Ollerhead & Hopewell (2003).

[55] Cf. Der Bundesminister für Umwelt Naturschutz und Reaktorsicherheit (2008).

[56] Cf. Blinstrub et al. (2020).

For the contours above Figure 55 shows how the 80dB L_{AE} contour area changes if noise levels change for both approach (blue line) and departure (red line). In addition, an exponential function determined by regression analysis according to the following equation is shown for departure and approach. In the case shown, the base q determined for departure is[57] $q = 1.212$ and for approach $q = 1.289$. As a rule of thumb, a noise level increase by 1dB leads to an increase of a contour area of about 20%.

$$\frac{A_{L_{AE}}}{A_{L_{AE,ref}}} \approx q^{L_{AE}-L_{AE,ref}}$$

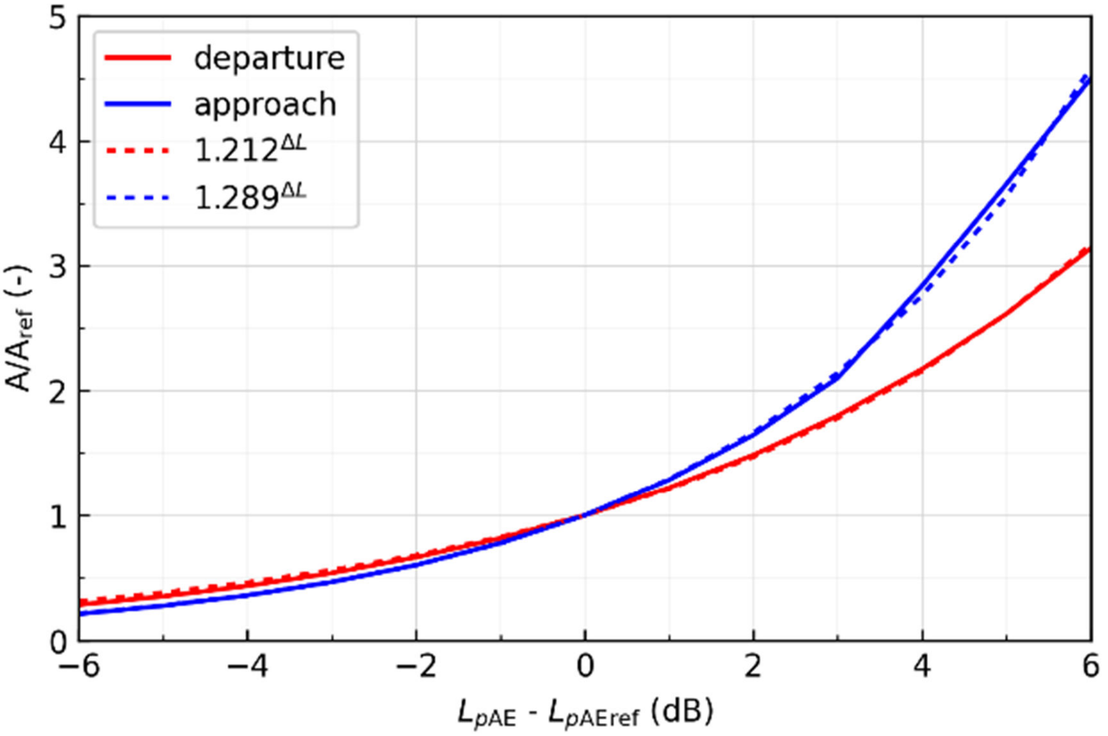

Figure 55: Dependence of the change in area of the 80dB L_{AE} contour area on a change in noise level for the group S3_M130_T2_N7 (-L for approach and -SB departure)[58]

In the previous figures, departure and approach were considered separately. In a traffic scenario, however, there is inevitably a departure for every approach. In this second step, it is therefore analysed how a L_{Aeq} contour area behaves in a highly simplified traffic scenario. For this highly simplified traffic scenario, only movements of group S3_M130_T2_N7 on an east/west aligned runway of 4km length are considered. For the operating direction distribution, 70% west and 30% east are selected, as this corresponds to a typical distribution in Germany. For the selection of the number of operations per year, it makes sense in this case to select these in such a way that the

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[57] Note that with a base of $q = 10^{0.1} = 1.259$, a doubling of the sound exposure, i.e. $L_{AE} - L_{AE,ref} = 10lg(2)$, leads to a doubling of the contour area.

[58] The dashed line shows the exponential functions determined by regression analyses.

60dB L_{Aeq} contour area mathematically corresponds to the 80dB L_{AE} contour area, which is the case for $N = 315360$ (since a year has 31536000 seconds). The resulting L_{Aeq} contour is shown in Figure 56.

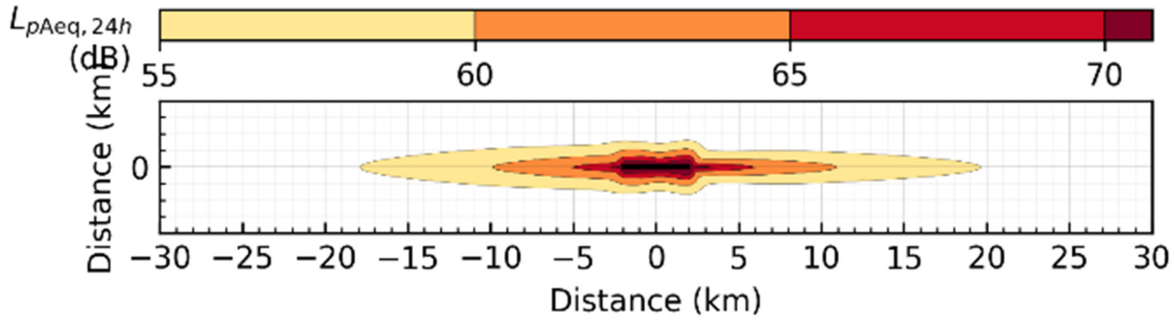

Figure 56: L_{Aeq} contour of group S3_M130_T2_N7 for 315360 operations per year (70% west, 30% east)

As with the single flight, the dependency of the 60dB L_{Aeq} contour area can now be visualised as a function of a level change. Here, too, a regression analysis can be carried out in which the basis of an exponential function is determined, i.e.

$$\frac{A_{L_{eq}}}{A_{L_{eq,ref}}} \approx m^{L_{Aeq}-L_{Aeq,ref}}$$

Both, the area dependency and the exponential function, are shown in Figure 57. In this case, the basis for the exponential function was determined to be $m = 1.266$.

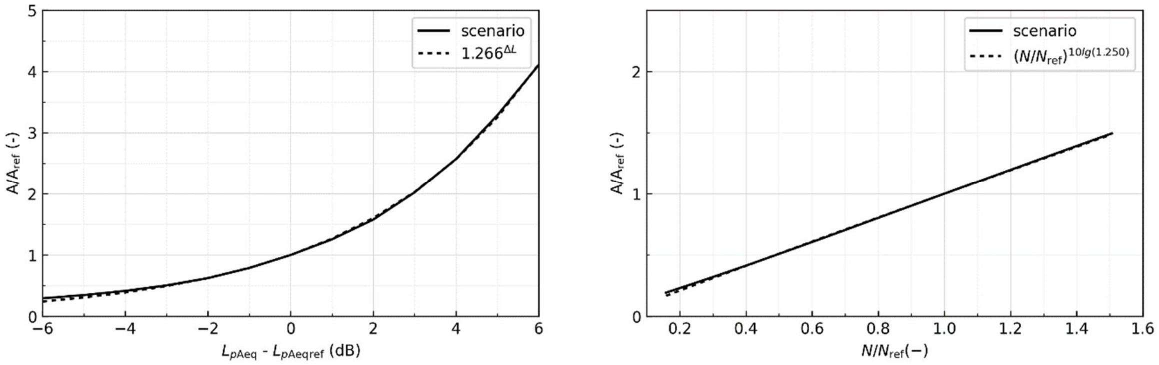

Figure 57: Dependence of the change in area of the 60dB L_{Aeq} contour area on a change in noise level (left) and on a change in number of operations (right) for the group S3_M130_T2_N7[59]

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[59] The dashed lines show the exponential function determined by a regression analysis.

The dependence of the contour area on the number of operations, is also of interest. For this, the previous equation can be transformed into

$$\frac{A_{L_{eq}}}{A_{L_{eq,ref}}} \approx m^{10\, lg(N/N_{ref})} = \left(N/N_{ref}\right)^{10lg(m)}$$

which is only valid for the highly simplified traffic scenario, i.e. if only a single aircraft group is operating. The problem remains, however, that in a typical traffic scenario, different aircraft types travel on different routes, so that this equation no longer applies.[60] A simple way to still be able to use this equation is to convert the number of operations of any aircraft group into an equivalent number of operations of a selected reference aircraft group N_{equ}. Then, the total equivalent number of operations for a traffic scenario is calculated by summing the number of operations for each aircraft group N_g multiplied by its equivalent number of movements $N_{equ,g}$. In combination with the previous equation, this results in

$$\frac{A_{L_{eq}}}{A_{L_{eq,ref}}} \approx \left(\sum_g N_g \cdot \frac{N_{equ,g}}{N_{ref}}\right)^{10lg(m)} = \left(\sum_g \frac{N_g \cdot P_g}{N_{ref}}\right)^{10lg(m)} = \left(\frac{P_{sum}}{N_{ref}}\right)^{10lg(m)}$$

In this equation, it is already shown that one can consider the equivalent number of operations $N_{equ,g}$ as a noise point P_g and the summation of those noise points multiplied by the respective number of operations as the noise point sum P_{sum}. The noise point, or the equivalent number of operations, can be determined in various ways, e.g. based on single microphone positions, such as certification levels, using

$$P_g = 10^{\frac{L_{AE,g} - L_{AE,refgruppe}}{10}}$$

or on calculated contour areas using

$$P_g = \left(\frac{A_g}{A_{\mathrm{ref}gruppe}}\right)^{\frac{1}{10lg(q)}}$$

The selection also depends on the available data. Four different approaches have been analysed thoroughly within the project.[61] Here, only the most promising approach is presented.

As shown in Figure 57 (right), the relationship between the L_{Aeq} contour area and the noise point sum is almost linear. Therefore, for a simple practical application, the influence of the parameter m is usually negligible, i.e., it can be set to $m = 10^{0.1} = 1.259$. For detailed analyses, however, it may be relevant to take this parameter into account.

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[60] Unless the number of operations would change evenly across all aircraft types and routes.

[61] Cf. DEPA 2070 internal project-report „Lärmpunkte als Mittel zur Beurteilung zukünftiger Fluglärmsituationen“.

6.2.2. Determination of the Final Noise Points

The noise points presented and analysed here are determined using the AzB-group S3_M130_T2_N7 (A320, B737 etc.) as a reference. Most aircraft operations at German commercial airports are carried out with aircraft from this group. At many airports, it is the dominant and also noise-dominant aircraft group. The advantage of this choice is that the resulting noise point sum at an airport is comparable with the number of aircraft operations. If the noise point total at an airport is higher than the number of movements, this can be referred to as a noisy aircraft mix and vice versa as a quiet aircraft mix.

The noise points are determined such that a simplified traffic as in Figure 56 is created for each aircraft group. The L_{Aeq} contour area is then determined accordingly and converted into a noise point using

$$P_g = \left(\frac{A_g}{A_{\mathrm{ref}gruppe}}\right)^{\frac{1}{10lg(q)}}$$

In this equation, a value of q=1.23 is used for across all aircraft groups, since this value produced good results in the context of preliminary investigations. This noise point can be further subdivided into individual noise points for approach and departure using the ratios of individually determined departure and approach areas[61]. The final noise points used for the impact analyses are summarised in the following table.

AzB class	Noise Points	AzB class	Noise Points
P3_M015_TU-S	0.101	S3_M320_T2_N7-SA	3.36
P3_M015_TU-L	0.145	S3_M320_T2_N7-SB	3.95
P3_MXXX_TU-S	0.187	S3_M320_T2_N7-L	1.482
P3_MXXX_TU-L	0.395	S3_M320_T2_NX-SA	1.061
S3_M020_TU_NU-S	0.564	S3_M320_T2_NX-SB	1.268
S3_M020_TU_NU-L	0.138	S3_M320_T2_NX-L	0.928
S3_M050_TU_N7-S	0.623	S3_M320_T3_N7-SA	4.991
S3_M050_TU_N7-L	0.313	S3_M320_T3_N7-SB	7.025
S3_M050_TU_NX-S	0.238	S3_M320_T3_N7-L	2.344
S3_M050_TU_NX-L	0.266	S3_M320_T4_N7-SA	5.978
S3_M070_TU_N7-S	1.36	S3_M320_T4_N7-SB	7.29
S3_M070_TU_N7-L	0.586	S3_M320_T4_N7-L	1.114
S3_M070_TU_NX-S	0.379	S3_M500_T2_NX-SA	2.504
S3_M070_TU_NX-L	0.445	S3_M500_T2_NX-SB	3.058
S3_M100_TU_N2-S	7.904	S3_M500_T2_NX-L	1.396
S3_M100_TU_N2-L	0.842	S3_M500_T4_N7-SA	10.054
S3_M130_T2_N7-SA	1.269	S3_M500_T4_N7-SB	12.635

AzB class	Noise Points	AzB class	Noise Points
S3_M130_T2_N7-SB	1.494	S3_M500_T4_N7-L	2.808
S3_M130_T2_N7-L	0.668	S3_M500_T4_NX-SA	6.337
S3_M130_T2_NX-SA	0.581	S3_M500_T4_NX-SB	7.601
S3_M130_T2_NX-SB	0.673	S3_M500_T4_NX-L	2.819
S3_M130_T2_NX-L	0.41	S3_MXXX_T4_NX-SA	4.23
S3_M220_T2_N7-SA	2.801	S3_MXXX_T4_NX-SB	5.051
S3_M220_T2_N7-SB	3.294	S3_MXXX_T4_NX-L	2.454
S3_M220_T2_N7-L	1.05		
S3_M220_T4_N7-S	6.226		
S3_M220_T4_N7-L	3.385		

Table 14: Selected noise points for AzB21 aircraft classes

6.2.3. Verification of the Determined Noise Points

The noise points are verified on the basis of available airports and traffic from the previous DLR projects FluiD21[62] and ELK[63]. Firstly, the aim is to check whether the noise point sum is consistent with the 60dB L_{Aeq} contour area across several airports. Secondly, and more importantly, the aim is to check whether the temporal development of the 60dB L_{Aeq} contour area can be adequately represented by the noise point sum. The following airports and traffic volumes are available from the FluiD21 and ELK projects:

- Generic traffic volumes at an airport with one (referred to as ONE) and at an airport with two (referred to as TWO) runways from the DLR FluiD21 project for the years 2020, 2025, 2030, 2035, 2040, 2045 and 2050.
- Simulated traffic from the DLR impulse project ELK for 2019 for the airports at Berlin Brandenburg (BER), Cologne (CGN), Düsseldorf (DUS), Frankfurt (FRA), Hannover (HAJ), Hamburg (HAM), Leipzip (LEJ), Munich (MUC), Nuremberg (NUE), Stuttgart (STR).

In order to check the consistency of the noise point sum, the 60dB L_{Aeq} contour areas of the ten airports available from the DLR project ELK are plotted against their corresponding noise point sum in Figure 58 as colored points. Additionally, a linear regression is shown as solid black line and an approximated area using the noise point sum is shown as dashed line. It can be seen that the noise point sum provides a good approximation of the 60dB L_{Aeq} contour area for several airports and thus provides consistent results.

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[62] Cf. Schmid et al. (2023)

[63] Cf. Righi et al. (2022)

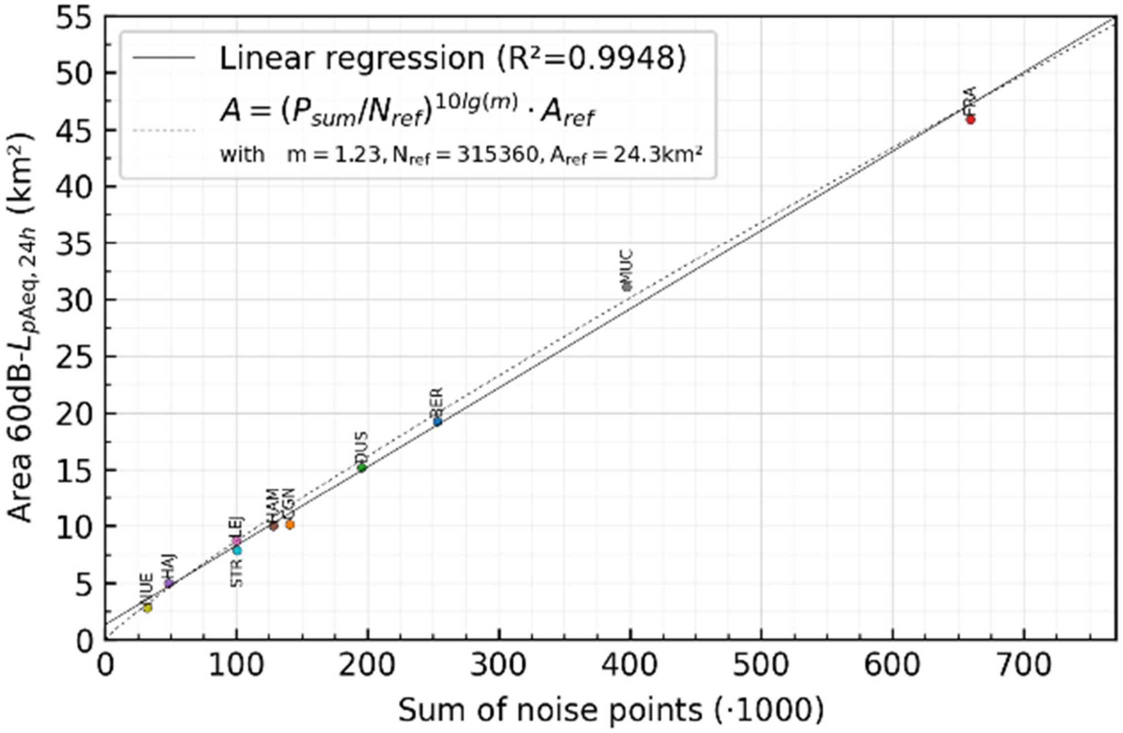
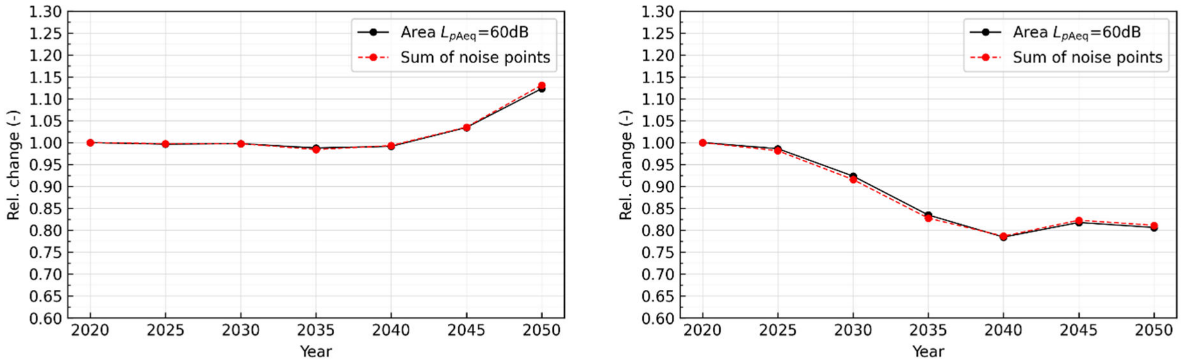


Figure 58: 60dB L_{Aeq} contour area plotted over the noise point sum for each airport (coloured dots)[64]

To check the temporal development of a 60dB L_{Aeq} contour area, the traffic volumes available from the FluiD21-project are used. The relative change in the contour area (black line) and the noise point sum (red line) is shown in Figure 59. It can be seen that the development of the contour area is well represented by the development of the noise point sum.



(a) airport ONE (b) airport TWO

Figure 59: Relative development of the 60dB L_{Aeq} contour area and the noise point sum normalised to the reference year

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[64] A linear regression is shown as solid black line and an approximated area is shown as dashed line.

6.2.4. Summary and Outlook

As shown in this study, noise points can be a suitable means of analysing the (relative) development of the aircraft noise situation in the form of the 60dB L_{Aeq} contour area. One of the key advantages of the concept is that no details of the airport, the route structure, or operation are required. Additionally, the noise points can be applied without profound aircraft noise expertise or the need to run detailed noise calculations. Thus, it is advantageous for the analyses of what-if scenarios considering multiple airports at once and to study the effect of noise mitigation measures (e.g. new technologies, aircraft, or political control measures) on the global aircraft noise situation. Naturally, however, local details cannot be analysed with this concept. Therefore, a detailed noise calculation is still required to evaluate local effects.

Considering the concept of noise points, future research should focus on further fine-tuning the noise point concept by applying and checking the concept against the temporal development of contour areas at more complex airport structures. A possible way to improve the concept is to determine the equivalent number of operations directly based on the contour area, i.e., find the number of operations of an aircraft that results in the exact same contour area as one operation of the reference aircraft. Furthermore, the relevance of the parameter m should be further investigated since it may enable to fine-tune the concept to the complexity of the airport or the shape of the contour respectively. Finally, it should be analysed which steps need to be performed in order to determine a noise point based on single event calculations of new aircraft concepts.

For the follow-up project “DEPA-extended” (DEPA-ext.) an extended usage of the concept is also planned to apply the concept with regard to a set of airports and to perform more detailed analyses on the potential future noise situation addressing also technological improvements in aircraft design.

6.3. Impact on Economy

6.3.1. Methodology of the Economic Impact Assessment

Air transport is an important driver of global economic growth and prosperity. It provides fast, reliable, and safe transportation of people and goods over long distances thereby contributing significantly to global connectivity. By connecting regions across borders, air transport fosters international trade, tourism, and foreign direct investment. However, air transport not only contributes to economic growth through its benefits for other sectors of the economy, but also the production of air transport services itself creates income and employment.

The following analysis assesses the current and potential future economic impact of the air transport industry in the European Union and the world. The indicators used to measure the socio-economic impact are the gross value added (GVA) and the employment created by the industry. GVA describes the value of goods and services produced as output minus the value of inputs used in the process. The GVA of an industry is therefore a measure of its contribution to gross domestic product (GDP). While the GVA impact is measured in monetary terms, its employment impact is measured in the number of jobs created.

The air transport industry impacts GVA and employment are measured through three main types of effects: (1) direct effects stemming from the economic activity within the industry itself (i.e. the airlines), (2) indirect effects arising from the economic activity of upstream suppliers (e.g. aircraft manufacturers, suppliers of aircraft fuel), and (3) induced effects resulting from the spending of labor income by those directly and indirectly employed, as their consumption of goods and services further stimulates economic activity.

Figure 60: Economic impacts of air transport activities

For most European countries and the United States, data on direct GVA and employment are obtained for the reference year 2019 from official statistics for the air transport industry. Data sources are Eurostat for Europe, and the US Bureau of Labor Statistics (BLS) and the US Bureau of Economic Analysis (BEA) for the United States.[65]. For countries in the rest of the world, direct GVA and employment are estimated for the year 2019 using a regression model and data on the number of flights per country and year from the Sabre Market Intelligence (MI) database.[66]

Indirect and induced effects have to be estimated using an input-output model and an input-output table. Input-output models link the gross output of an industry with the intermediate demand of other industries and the final demand of consumers. Input-output tables provide data on transactions of goods and services between industries.

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[65] Cf. Eurostat (2024); US BLS (2024); US BEA (2024).

[66] Cf. Sabre (2024).

The input-output table used is the OECD Inter-Country Input-Output (ICIO) table for the year 2019.[67] The OECD ICIO table covers 45 industry sectors in 76 countries and the rest of the world. The input-output model produces multipliers that link the direct employment/GVA with indirect and induced employment/GVA.[68] The direct effects are then multiplied with the corresponding multipliers to obtain the indirect and induced effects.

Based on the economic effects in the reference year 2019, projections were made for the long-term development of air transport's direct, indirect, and induced economic impacts. The effects are projected up to the year 2070 based on the DEPA 2070 air traffic forecast. It is assumed that the economic effects will grow in proportion to the number of aircraft movements in each country, effectively assuming a stable structure of the overall economy. While it can be argued that potential future disruptions (e.g. autonomous flight, electric propulsion) could alter the economic structure of the air transport industry, the impact and timing of such fundamental technological changes remains highly uncertain and are therefore excluded from the projections.

6.3.2. Global Economic Impact

Aviation plays an important role with respect to employment as illustrated in Figure 61.

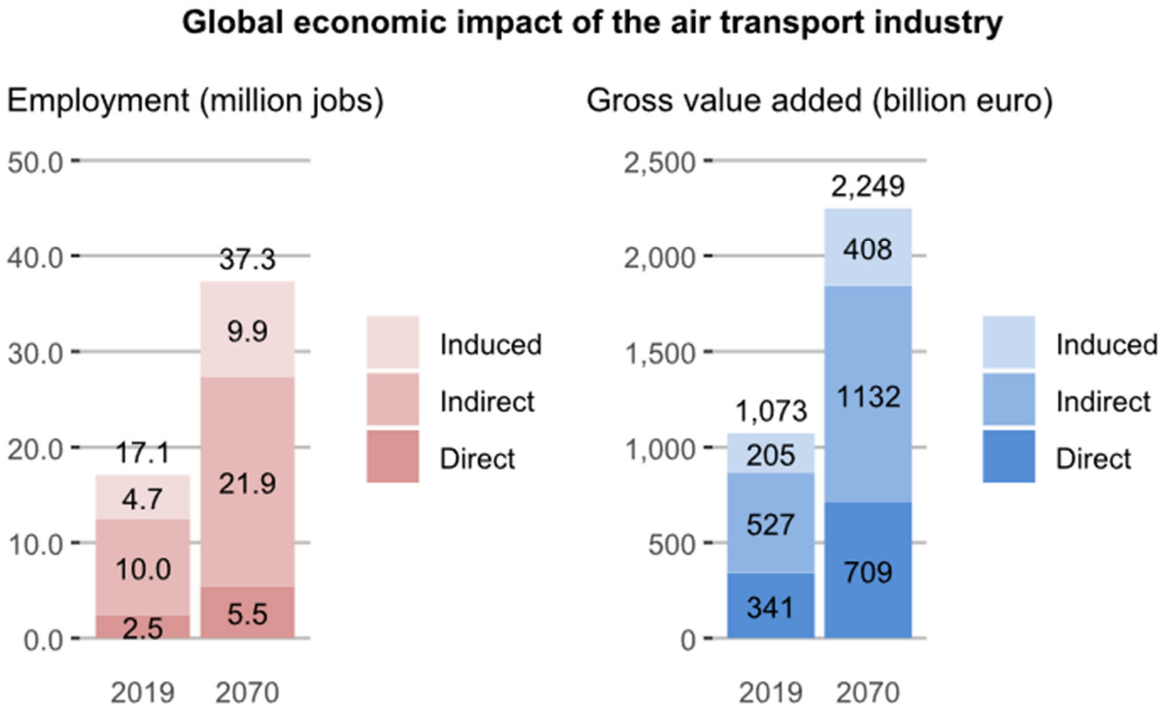

Figure 61: Long-term global economic impact of air transport – direct, indirect and induced employment effects

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[67] Cf. OECD (2023).
[68] Cf. Miller, R. E., Blair, P. D. (2009).

On the global scale, around 2.5 million direct jobs at airlines could be reported for the year 2019. Also important are the indirect jobs created via air transport. It can be observed that 10 million indirect jobs related to the purchase of goods and services in the aviation supply chain were reported in the year 2019. As the direct and indirect jobs reported have further spending in air transport, this has resulted in a further 4.7 million induced jobs in the year 2019. This equals a total of 17.1 million jobs which depend directly or indirectly on air transport activities in the year 2019. The total jobs on a global scale in 2019 equals 3.46 billion. This means that air transport related jobs equal 0.5% of all jobs on the global scale. As air transport is a growing industry fuelled by a rapid growth in developing countries, these values are expected to significantly increase over the next decades. Direct employment is expected to more than double to 5.5 million jobs in 2070. This is also the case with indirect jobs which are expected to reach the level of 21.9 million jobs in 2070. The same trend can be observed for induced jobs which will rise to 9.9 million in 2070. Given that air transport is a part of a globalised supply chain, this industry will play a major role for all major economies in the world with developing countries benefitting from this industry due to a rapid growth of air transport in their respective economies.

Taking account of all of the jobs together, the employment generated by air transport activities will grow from 17.1 million jobs in 2019 to 37.3 million jobs in 2070. The trend observed is in accordance with the estimated growth of flights. We also expect a change in the employment landscape in the future with air transport employees being skilled and equipped with the necessary tools like digitalisation, automation and artificial intelligence. While some jobs may be replaced because of these developments, air transport is estimated to continue to be a job creation engine in the global economy.

Besides this, the gross value added created by aviation is an important factor to consider in economic impact assessments. The development of this metric in the long-term is also given in the figure above.

In 2019, air transport was responsible for 1.36% of global GDP. The direct gross value added by air transport in 2019 amounted to a value of 341 billion Euros in the same year. This value is expected to increase to 709 billion Euros in 2070, which is more than double the value in 2019. The indirect gross value added by stakeholders in the aviation supply chain is also expected to more than double from 527 billion Euros in 2019 to 1,132 billion Euros in 2070. The induced gross value added to the global economy is also expected to rise from 205 billion Euros in 2019 to 408 billion Euros in 2070. Putting all these gross value added figures together, the air transport industry will have a total gross value added of 2,249 billion Euros in 2070 which is more than double the value of 1,073 billion Euros in 2019. All of these figures in relation to employment and gross value added show that air transport contributes significantly to economic development and social welfare on a global scale. This fact can also be observed in Figure 62 which shows how employment and gross value added will increase over time in some of the major global economies. However, we expect some long-term changes such as developing countries playing a bigger role in the coming decades. This is mainly the case in Asia. Countries such as China and India will take up a larger share of employment and gross value added in the coming decades.

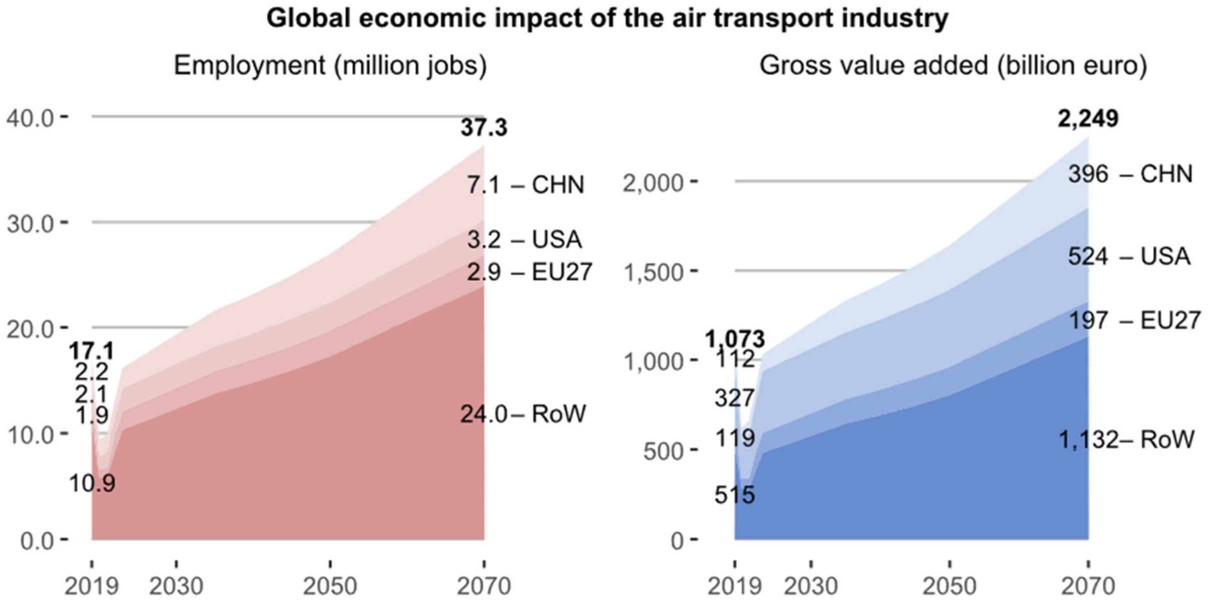


Figure 62: Long-term global economic impact of air transport – direct, indirect and induced gross value added

A closer look at the regionally differentiated figures reveals some more interesting details. China, USA and the EU-27 had almost the same number of people employed in aviation in 2019 with some minor differences. However, this is expected to change significantly in the coming decades. For example, in 2070, while USA and the EU-27 will still have almost the same number of people employed, the aviation employment in China will greatly rise and it will employ more than double the number of people employed in USA and the EU-27.

The question that naturally arises from this fact is whether China will gain from this rise in employment. The right panel of the figure above gives an indication. The gross value added in the USA is still going to be higher than that of China in 2070. What this reveals is that while USA may have a highly paid base of employees in the aviation sector, China will have access to cheap labour that is also highly skilled, which could give it a competitive advantage. This is a clear indication that China will benefit from the rise of the aviation sector in the global economy.

6.3.3. Economic Impact in the European Union

As shown in Figure 63 the air transport industry also plays a vital role for the EU-27 countries, which will be explained further below.

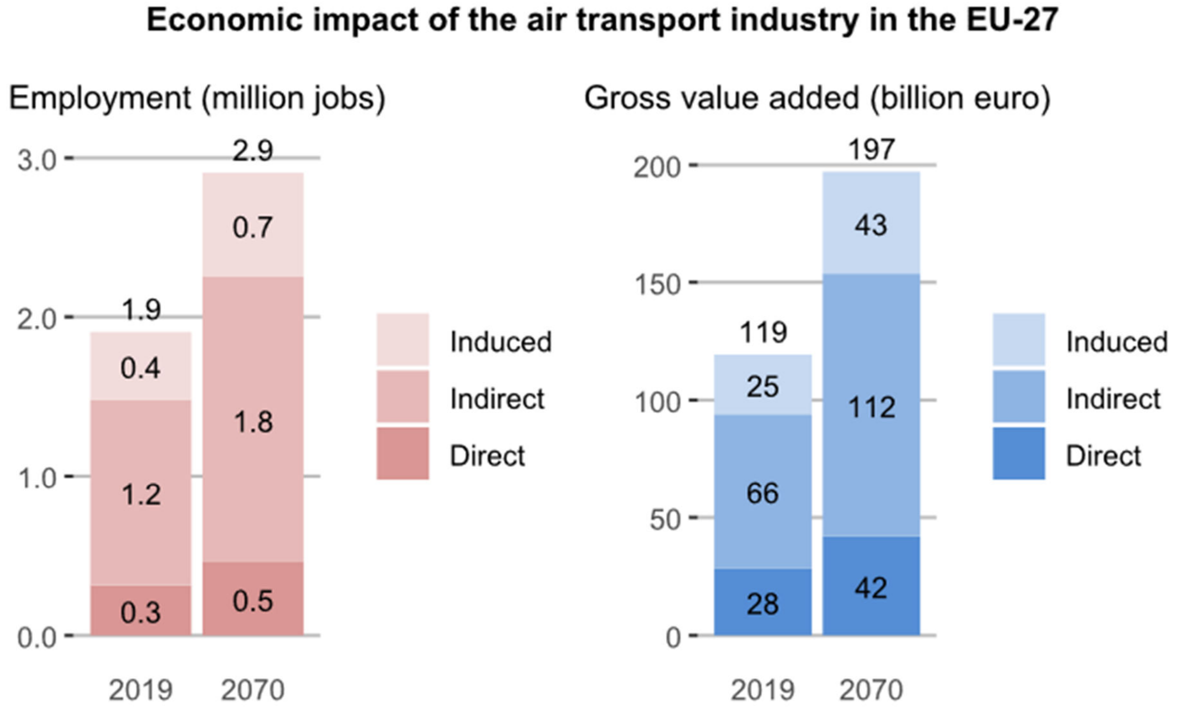


Figure 63: Economic impact of air transport in the EU-27

In 2019, the air transport industry generated approximately 300,000 direct jobs and 1.2 million indirect jobs in the EU-27 economy. This is expected to grow in the future with 500,000 direct jobs generated in 2070 and 1.8 million indirect jobs generated in 2070. The induced jobs will increase from 400,000 jobs in 2019 to 700,000 jobs in 2070. In total, the employment generated from air transport will rise from 1.9 million jobs in 2019 to 2.9 million jobs in 2070 in the EU-27 economy. As air transport already supports about 1% of all employment in the EU, this share is expected to rise until 2070.

The right panel of the figure above shows the gross value added by the aviation sector in the EU-27 countries. The direct gross value added by the aviation sector is expected to increase from 28 billion Euros in 2019 to 42 billion Euros in 2070. The indirect gross value added will also increase from 66 billion Euros in 2019 to 112 billion Euros in 2070. Furthermore, the induced gross value added will increase from 25 billion Euros in 2019 to 43 billion Euros in 2070. Put together, the total gross value added from aviation is expected to increase from 119 billion Euros in 2019 to 197 billion Euros in 2070 in the EU-27 countries. This makes it evident that the air transport sector plays a vital role in relation to the creation of benefits to the economy and the society. This is mainly because aviation is a creator of employment and a catalyst of value creation. A good indicator is the Covid-19 pandemic which led to job and financial losses in the aviation sector. As this is a structural break in the economy, aviation's rebound after the pandemic shows how the sector is resilient and that there is scope for long-term development when air transport demand recovers. This is also an indicator of the causality between air transport growth and its economic impact. It is also worthwhile to note that developments such as digitalisation, automation and artificial intelligence may in fact prove to be an advantage to the air transport sector in relation to employment and gross value added because it employs highly-skilled employees. As this sector consists of an employee base with a highly diversified set of skills and higher education levels, we expect the entire air transport supply chain to have major advancements in relation to safety, efficiency and innovation in the coming decades until 2070 and beyond.

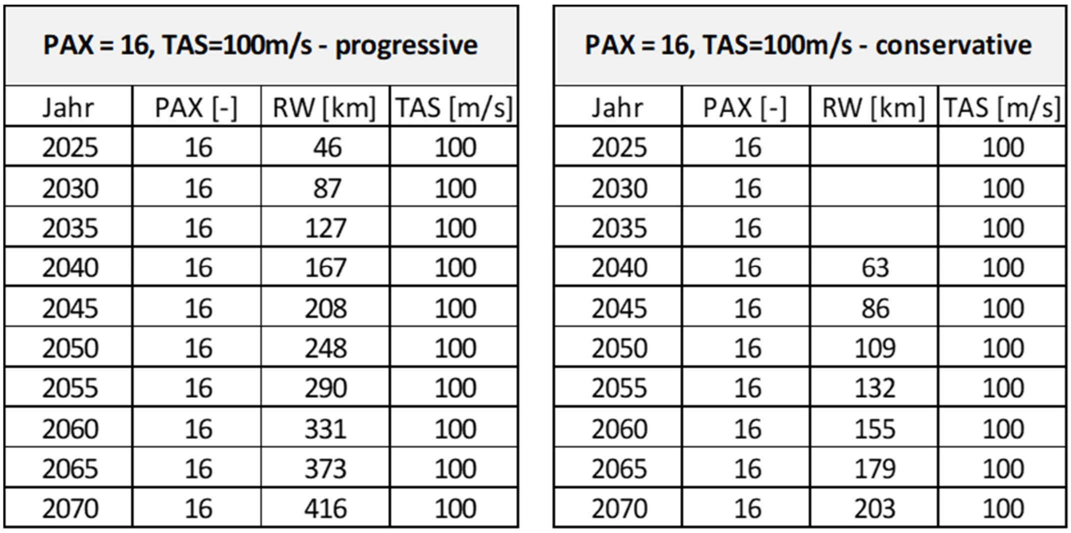
6.4. Impact on Mobility

The objective of this chapter is to analyse possible future mobility and connectivity gains as well as related societal impacts through the further development of the air transport network and the use of new or optimized vehicle types and transport concepts. The main focus is on analysing the potential of full electric small air transport in Europe as an interesting new market segment. A further objective was to investigate possible mobility gains of an innovative transport chain consisting of fully electric SAT as feeder transport and supersonic flight connections.

The ETISplus transport matrix from the European Commission was used as a central data basis within this context. It contains detailed traffic data on ground-based transport in Europe. In addition to differentiating between the means of transport (car, rail), the traffic data is also differentiated between transport purposes (business, private). Accordingly, data is available about the annual number of passengers between all 1,576 NUTS 3 regions (district level) in Europe. In addition, the data set includes the actual road distance travelled and the duration of the trip for all transport relations. Since not all European traffic relations (~2.5 million) are suitable for a full electric SAT vehicle with only a limited range, it was necessary to further narrow down the relevant routes.

The first step was to define the central scenario-specific SAT parameter assumptions (range, speed, passenger capacity) up to the year 2070. For this purpose, an assessment of possible technological performance data for full electric SAT vehicles for a progressive technology scenario and for a conservative technology scenario was done (see also chapter 3.2).

With the objective of being able to compare the two scenarios in terms of their potential impact on mobility, the range was defined as the primary parameter for differentiating the scenarios. A speed of 360 km/h (TAS 100 m/s) and a passenger capacity of 16 people were defined as a constant parameter - not changing over time - for both scenarios. The range of the full electric SAT vehicle increases to 416 kilometres in 2070 in the progressive scenario; In the conservative scenario, however, the maximum range in 2070 is only 203 kilometres. The development of the SAT ranges between 2025 and 2070 for both scenarios can be seen in Table 15.

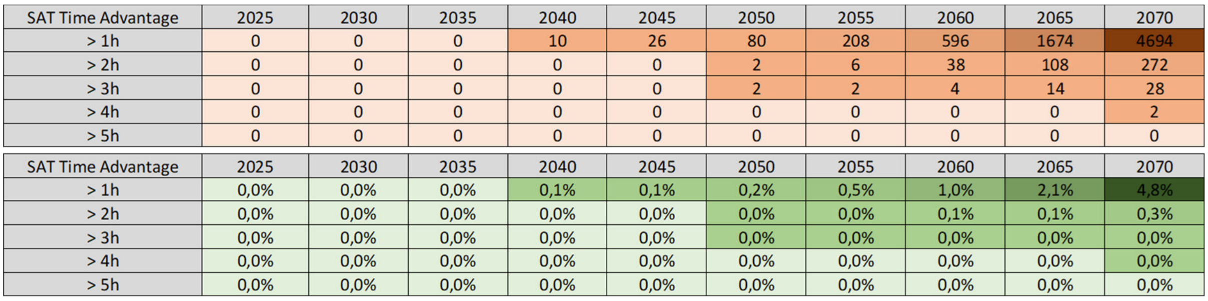


PAX = 16, TAS=100m/s - progressive			
Jahr	PAX [-]	RW [km]	TAS [m/s]
2025	16	46	100
2030	16	87	100
2035	16	127	100
2040	16	167	100
2045	16	208	100
2050	16	248	100
2055	16	290	100
2060	16	331	100
2065	16	373	100
2070	16	416	100

PAX = 16, TAS=100m/s - conservative			
Jahr	PAX [-]	RW [km]	TAS [m/s]
2025	16		100
2030	16		100
2035	16		100
2040	16	63	100
2045	16	86	100
2050	16	109	100
2055	16	132	100
2060	16	155	100
2065	16	179	100
2070	16	203	100

Table 15: Scenario specific parameter assumptions for full electric SAT vehicles in the time span 2025-2070 for the DEPA 2070 mobility study

Table 16 provides an overview of the number of routes in Europe in the conservative scenario on which a SAT vehicle with the corresponding speed and assumed range would have a time advantage over passenger car traffic. It is important to note that this evaluation is not based on any actual passenger movements, so only the purely theoretical time advantage of SAT over cars between European NUTS 3 regions is shown. It can be seen that only from the year 2040 - in which the market entry of a full electric SAT vehicle with a range of only 63 kilometres is assumed - there will be a small number of routes in Europe (10) on which a SAT time advantage of at least 1 hour exists compared to car traffic.

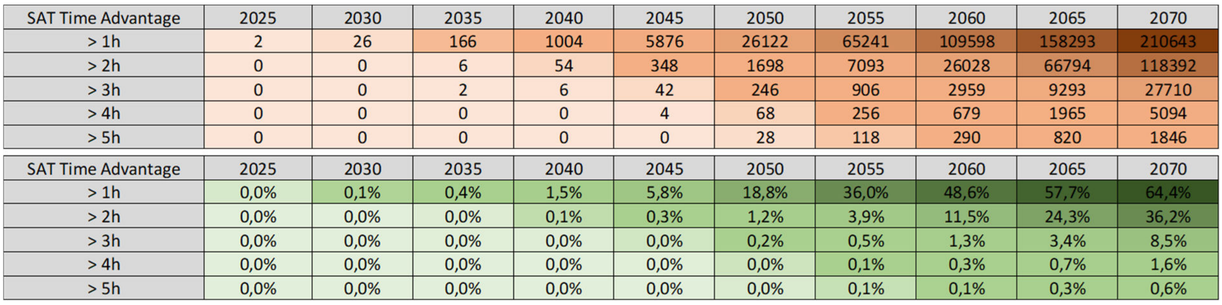


SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0	0	0	10	26	80	208	596	1674	4694
> 2h	0	0	0	0	0	2	6	38	108	272
> 3h	0	0	0	0	0	2	2	4	14	28
> 4h	0	0	0	0	0	0	0	0	0	2
> 5h	0	0	0	0	0	0	0	0	0	0

SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0,0%	0,0%	0,0%	0,1%	0,1%	0,2%	0,5%	1,0%	2,1%	4,8%
> 2h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,1%	0,1%	0,3%
> 3h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
> 4h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
> 5h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%

Table 16: Number of NUTS 3 relations in Europe with SAT time advantages in the conservative scenario, absolute and relative, without consideration of current passenger demand

This corresponds to only 0.1% of all routes in Europe that have a maximum distance of 63 kilometres. Over the years, the number of routes in Europe with SAT time advantages continues to increase due to the increasing range. In 2070, the number of routes with SAT time advantages will be 4,694, some will even have time advantages of more than 3 hours and 4 hours. In 2070, 4.8% of all European routes with a maximum distance of 203 kilometres will therefore have theoretical SAT time advantages of at least 1 hour compared to road traffic. The direct comparison with the progressive scenario shows significantly greater dynamics and connectivity potential. While in 2025 there will be SAT time advantages of at least 1 hour on only two routes in Europe, in 2040 - in which in the conservative scenario only 10 connections with SAT time advantages exist - there will already be over 1,000 routes in Europe on which SAT vehicles with the corresponding range theoretically have time advantages of at least 1 hour; 54 of these connections even have a time advantage of at least 2 hours. This corresponds to a share of 1.5% of all routes in Europe with a maximum distance of 167 kilometres on which the fully electric SAT vehicle has a time advantage of at least 1 hour.



SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	2	26	166	1004	5876	26122	65241	109598	158293	210643
> 2h	0	0	6	54	348	1698	7093	26028	66794	118392
> 3h	0	0	2	6	42	246	906	2959	9293	27710
> 4h	0	0	0	0	4	68	256	679	1965	5094
> 5h	0	0	0	0	0	28	118	290	820	1846

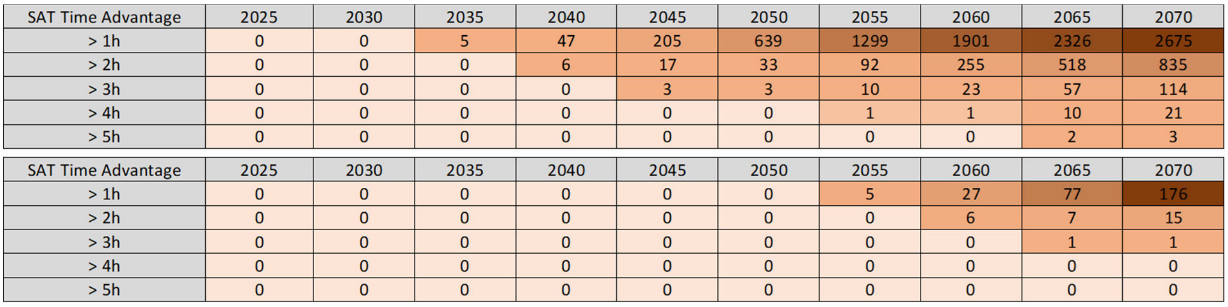
SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0,0%	0,1%	0,4%	1,5%	5,8%	18,8%	36,0%	48,6%	57,7%	64,4%
> 2h	0,0%	0,0%	0,0%	0,1%	0,3%	1,2%	3,9%	11,5%	24,3%	36,2%
> 3h	0,0%	0,0%	0,0%	0,0%	0,0%	0,2%	0,5%	1,3%	3,4%	8,5%
> 4h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,1%	0,3%	0,7%	1,6%
> 5h	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,1%	0,1%	0,3%	0,6%

Table 17: Number of NUTS 3 relations in Europe with SAT time advantages in the progressive scenario, absolute and relative, without consideration of current passenger demand

In 2070, the number of routes in Europe on which the full electric SAT vehicle with a range of 416 kilometres has a theoretical time advantage of at least 1 hour compared to a car will be over 200,000, of which many connections have time advantages of over 3 hours and over 4 hours. This results in a share of over 64% of all routes in Europe with a maximum distance of 416 kilometres on which a full electric SAT vehicle has a time advantage of at least 1 hour compared to car traffic.

Analyses of mobility and connectivity improvements through full electric SAT vehicles while considering current passenger flows in ground-based transport lead to significantly lower numbers in both scenarios. When determining routes in Europe with time savings through SAT, now only transport connections are considered on which business travellers also travel (cf. Table 18) or on which at least 5,000 business trips take place per year.

The number of European routes with time advantages of at least 1 hour in 2050 is thus reduced from 26,000 (not taking business travelers into account) to 3,342 (> 0 business travelers/year) or 639 (> 5,000 business travelers/year). In the conservative scenario, all 80 connections in 2050 on which time advantages of at least 1 hour existed are eliminated, if only routes on which business trips take place are taken into account. The enormous number of European routes in 2070 in the progressive scenario on which a full electric SAT vehicle theoretically has time advantages of at least 1 hour compared to ground-based transport is reduced from over 200,000 to 14,726 (> 0 business travelers/year) or 2,675 (> 5,000 business travelers/year). In the conservative scenario in the same year from 4,694 to 816 (> 0 business travelers/year) or 176 (> 5,000 business travelers/year).

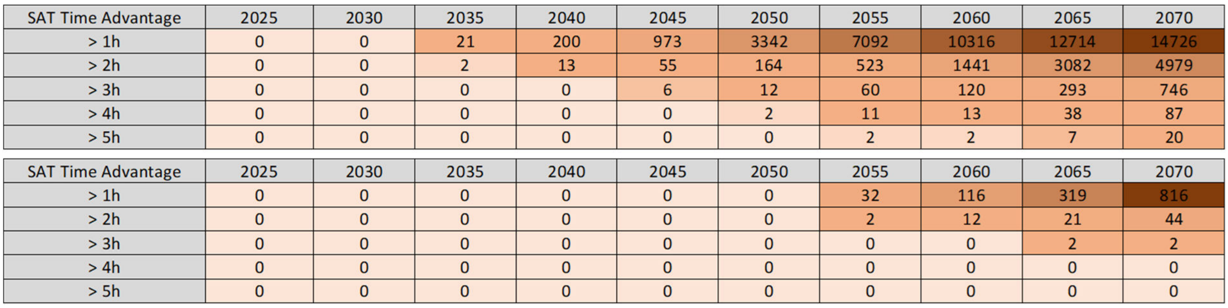


SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0	0	5	47	205	639	1299	1901	2326	2675
> 2h	0	0	0	6	17	33	92	255	518	835
> 3h	0	0	0	0	3	3	10	23	57	114
> 4h	0	0	0	0	0	0	1	1	10	21
> 5h	0	0	0	0	0	0	0	0	2	3

SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0	0	0	0	0	0	5	27	77	176
> 2h	0	0	0	0	0	0	0	6	7	15
> 3h	0	0	0	0	0	0	0	0	1	1
> 4h	0	0	0	0	0	0	0	0	0	0
> 5h	0	0	0	0	0	0	0	0	0	0

Table 18: Number of NUTS 3 relations in Europe with SAT time advantages in the progressive scenario (top) and conservative scenario (below), >0 car business trips per year

It can be stated that, even if only European transport routes on which business trips already take place in ground-based transport are considered, many of these connections can be served significantly faster with a full electric SAT vehicle than with ground-based transport.



SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0	0	21	200	973	3342	7092	10316	12714	14726
> 2h	0	0	2	13	55	164	523	1441	3082	4979
> 3h	0	0	0	0	6	12	60	120	293	746
> 4h	0	0	0	0	0	2	11	13	38	87
> 5h	0	0	0	0	0	0	2	2	7	20

SAT Time Advantage	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
> 1h	0	0	0	0	0	0	32	116	319	816
> 2h	0	0	0	0	0	0	2	12	21	44
> 3h	0	0	0	0	0	0	0	0	2	2
> 4h	0	0	0	0	0	0	0	0	0	0
> 5h	0	0	0	0	0	0	0	0	0	0

Table 19: Number of NUTS 3 Relations in Europe with SAT time advantages in the progressive scenario (top) and conservative scenario (below), >5,000 car business trips per year

The geographical distribution of the identified routes that have the greatest SAT time advantages compared to ground-based transport is shown below. The focus is on the routes in the progressive scenario in 2060 and 2070, which have a time advantage of more than 3 hours compared to ground-based transport.

It can be seen that especially regions with physical barriers (mountains, lakes, sea, etc.) have relations on which a corresponding full electric SAT vehicle has significant time advantages compared to ground-based transport. Examples include routes in Scandinavia (especially Norway) and Southern Europe (e.g. Southern France, Italy, Greece).

In such regions, there are connections where you have to take relatively long detours by car due to mountains or bodies of water. With a full electric SAT vehicle with direct air distance, the greatest time savings can be achieved here.

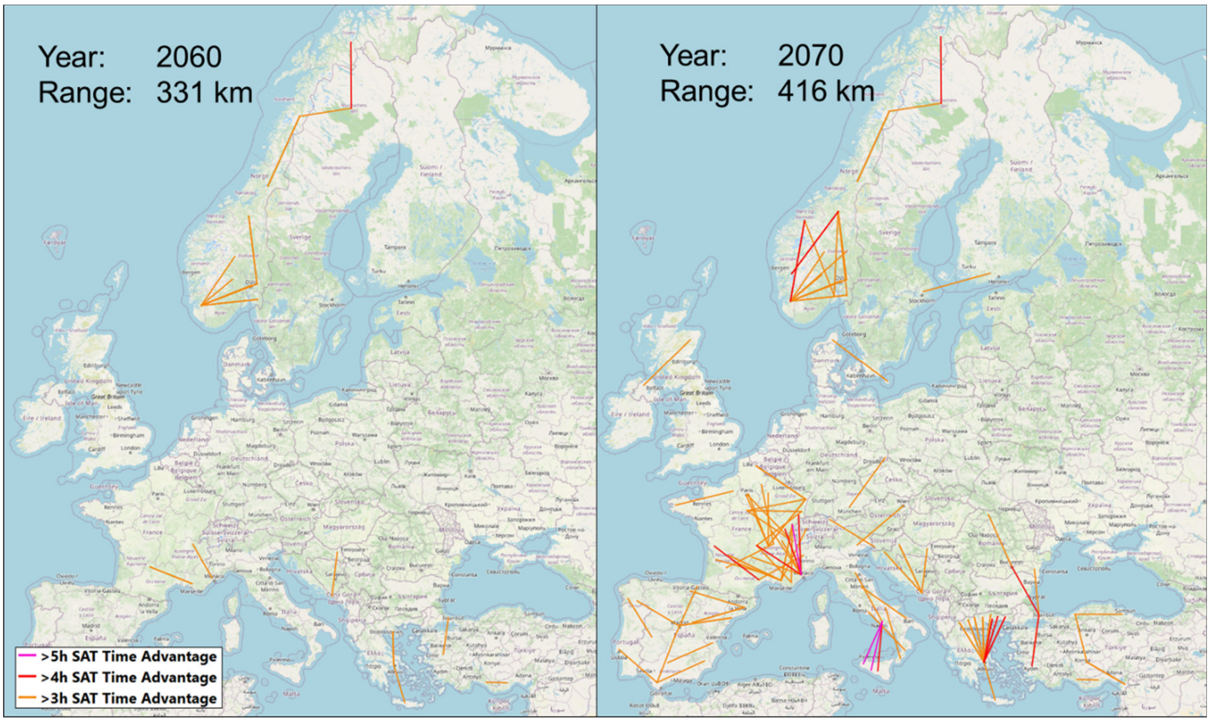


Figure 64: Relations in Europe in the progressive scenario with minimum 3 h time advantages of full electric SAT compared to car, Minimum 5,000 Business Trips per year

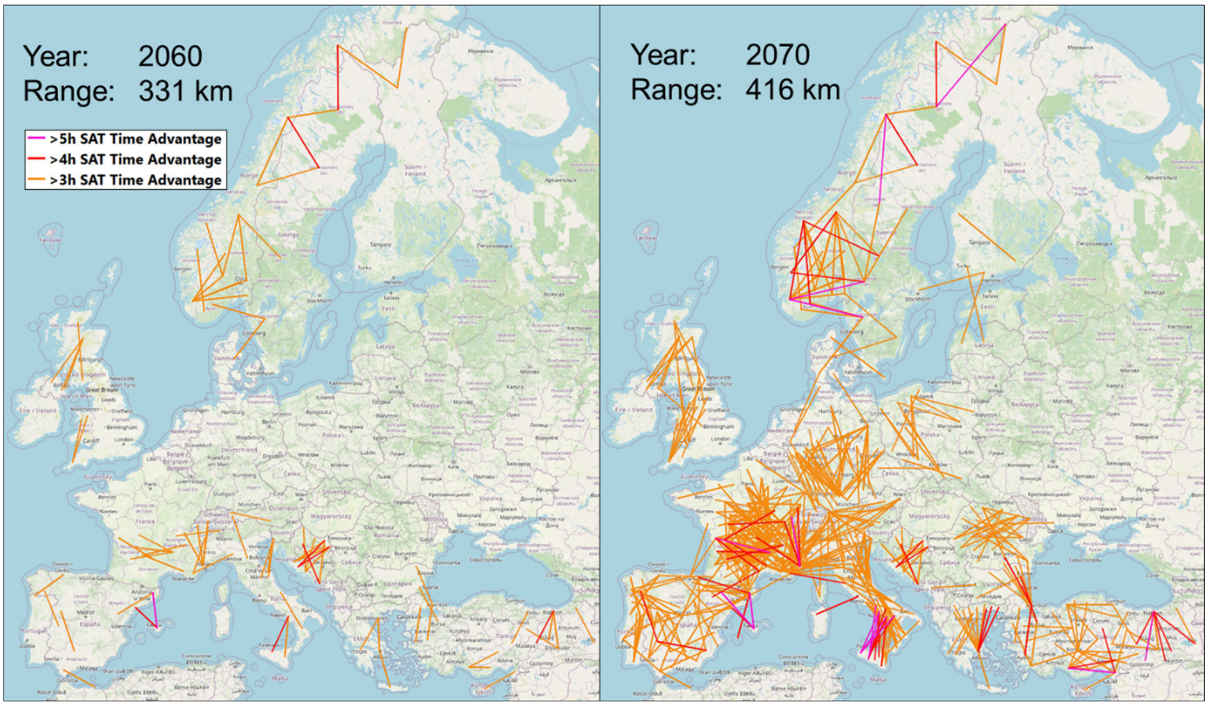


Figure 65: Relations in Europe in the progressive scenario with minimum 3 h time advantages of full electric SAT compared to car, >0 Business Trips per year

In addition to these physical barriers that have to be bypassed by road (sea, lakes, mountains, etc.), administrative borders can also represent a certain barrier. One example is the identified SAT connections in Croatia, which arise due to the national border of Bosnia and Herzegovina that has to be bypassed by car.

In addition to presenting mobility and connectivity improvements through the introduction of full electric SAT vehicles and analysing routes on which the greatest time savings exist, the following section will look at determining the specific SAT demand and potential CO_2 emission savings that would theoretically result in the two scenarios. In order to determine the specific SAT demand, it was first necessary to make certain further demand-specific assumptions. The proportion of car passengers switching to SAT increases, as can be seen in Table 20 depending on the time savings and the transport purpose.[69]

SAT Time Advantages	Switching Percentage	
	Private	Business
>1 Std.	2,5%	10,0%
>2 Std.	5,0%	15,0%
>3 Std.	7,5%	20,0%
>4 Std.	10,0%	25,0%
>5 Std.	12,5%	30,0%

Table 20: Assumptions regarding switching shares of car passengers to SAT vehicles

Furthermore, only routes are taken into account on which at least 1 flight per day and a maximum of 5 flights per day would arise due to the switching car passengers. If there is demand for more than 5 SAT flights per day, a larger aircraft would make more sense. If there is demand for less than 1 SAT flight per day, the introduction of a SAT connection would tend not to be profitable. For the emission savings calculation, 112.2 g/km is assumed for car traffic. At this point, however, it can be noted that the calculated car emissions saved by replacing it by full electric SAT will be lower, as car traffic will also be increasingly electrified in the future. The results are presented in the figures 65-67. The number of identified European SAT routes in the progressive scenario increases from 1 in 2035 to 60 in 2050 and to 179 in 2070. In the conservative scenario, there will not be a SAT relation that meets the relevant minimum requirements until 2055. In 2070, there will be 25 SAT connections in the conservative scenario. A similar dynamic or development can be seen in the number of SAT flights per day for both scenarios. In the progressive scenario, the number of daily flights increases to over 300 per day in 2070, and in the conservative scenario, the number of daily SAT flights is more than 20 per day in 2070. The theoretically saved CO_2 emissions that would result from switching from car passengers to SAT aircraft can be seen in figure 68.

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[69] It has to be stated that the shares in table 20 are rather a conservative estimation. A general increase of the switching share assumptions would lead to a significant increase of the general SAT demand potential.

Accordingly, the emissions saved in the progressive scenario in 2070 would total almost 1.2 million tons of CO_2. In the conservative scenario, the emission savings in 2070 are significantly lower with 0.2 million tons.

As already mentioned, this does not take into account the fact that car traffic will also have a significant proportion of electric cars in the future. Depending on the proportion, the emissions savings mentioned would be significantly reduced by shifting to full electric SAT connections.

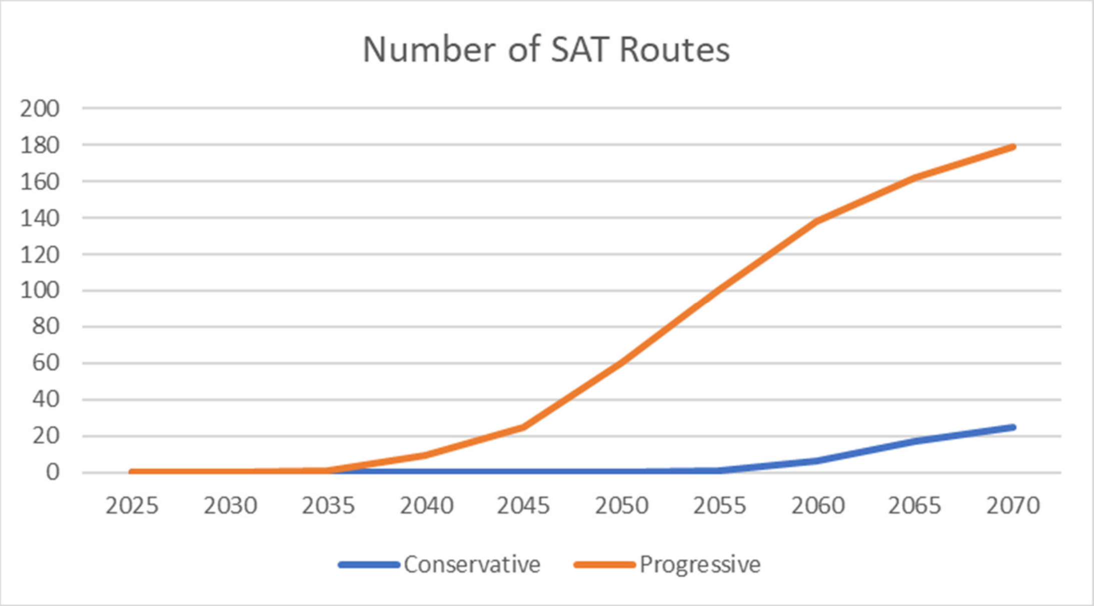

Figure 66: Number of SAT connections in Europe for both DEPA 2070 scenarios

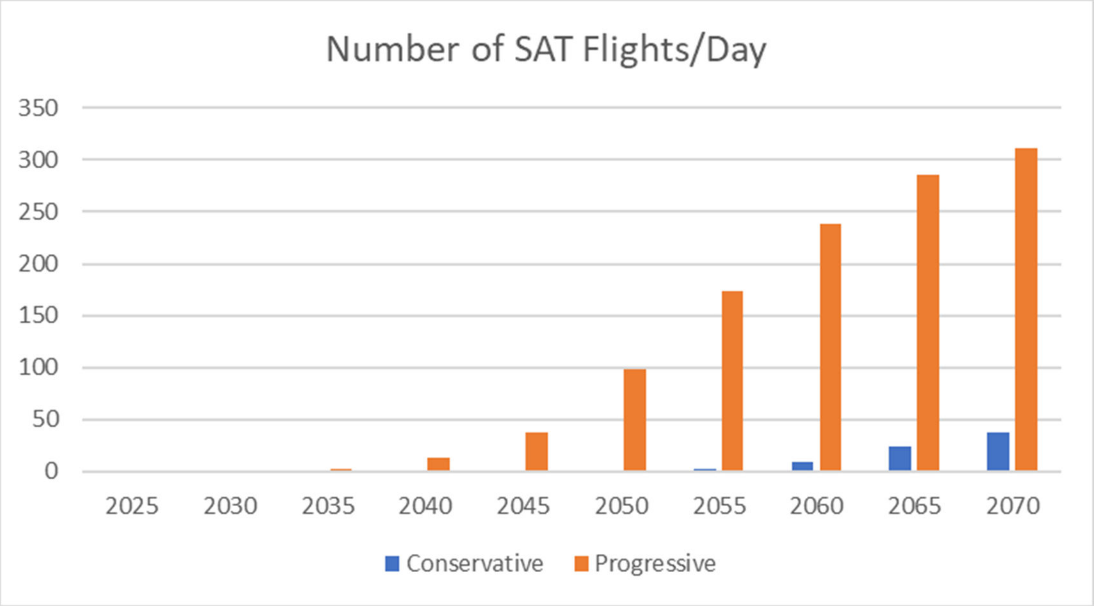

Figure 67: Number of SAT Flights per day in Europe for both DEPA 2070 scenarios

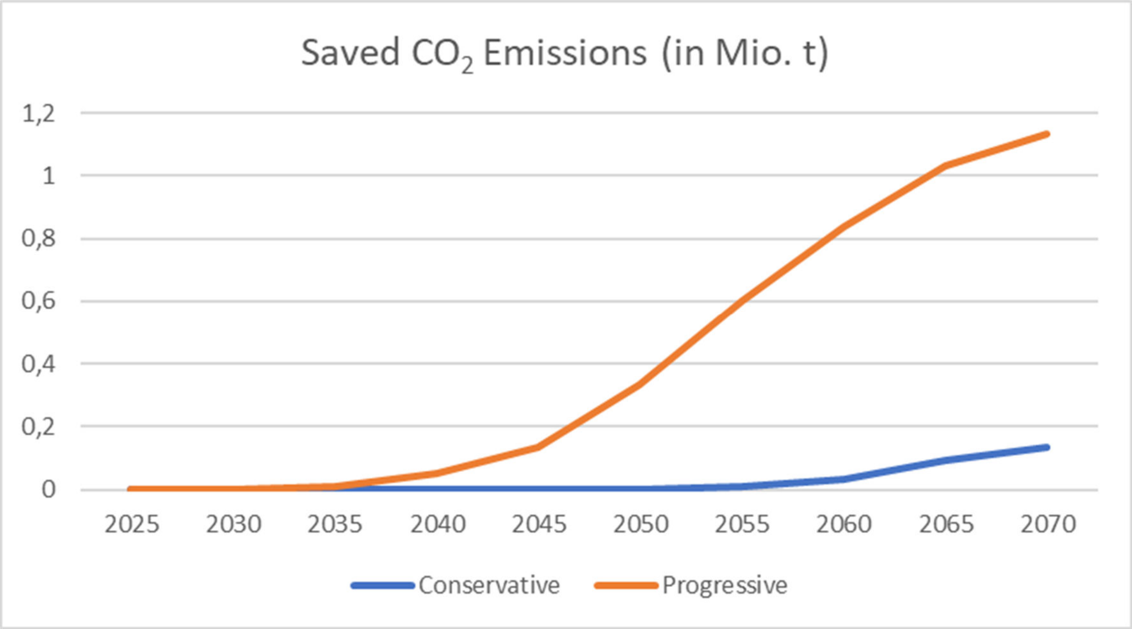

Figure 68: Saved CO_2 emissions through switching car passengers to full electric SAT vehicles[70]

The greatest time advantages of full electric SAT vehicles compared to car traffic arise primarily over long distances. This is illustrated in the following table, which shows the average travel time (in hours) of car traffic and SAT traffic between NUTS 3 regions in Europe. It is noticeable that SAT vehicles have significant time advantages compared to cars from around 150 kilometres of air distance, which continue to increase sharply as the distance increases. On shorter distances of less than 100 kilometres, cars usually have time advantages compared to SAT vehicles, as no trips to and from the airport and no boarding and deboarding times need to be considered.

Air Distance	Road	SAT	Time Advantage
50-100	1,18	1,71	-0,53
100-150	1,85	1,85	0,00
150-200	2,52	1,99	0,53
200-250	3,21	2,13	1,08
250-300	3,90	2,27	1,63
300-350	4,59	2,40	2,19

Table 21: Average travel time (in hours) between NUTS 3 regions in Europe for car traffic and for SAT traffic

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[70] Assumption: 112,2 g/km CO_2 in car traffic, No consideration of electric car shares.

Finally, a mobility analysis of possible future innovative transport chains with a combination of supersonic to and from Europe and SAT feeder traffic within Europe was carried out. For this purpose, the supersonic forecast from the previous project DEPA 2050 was extended to the year 2070 (see also Chapter 4.2.2). In the progressive scenario without overland flight restrictions, a total of 39 destination airports for supersonic traffic would therefore be in Europe in 2070. The number of incoming SST routes varies greatly between airports in Europe. While large hubs have a very high number of SST routes (for example 37 SST routes to London Heathrow (LHR), 23 SST routes to Frankfurt am Main (FRA), 19 SST routes to Amsterdam Schiphol (AMS), there is only one SST route to Oslo (OSL) and Riga (RIX) in 2070.

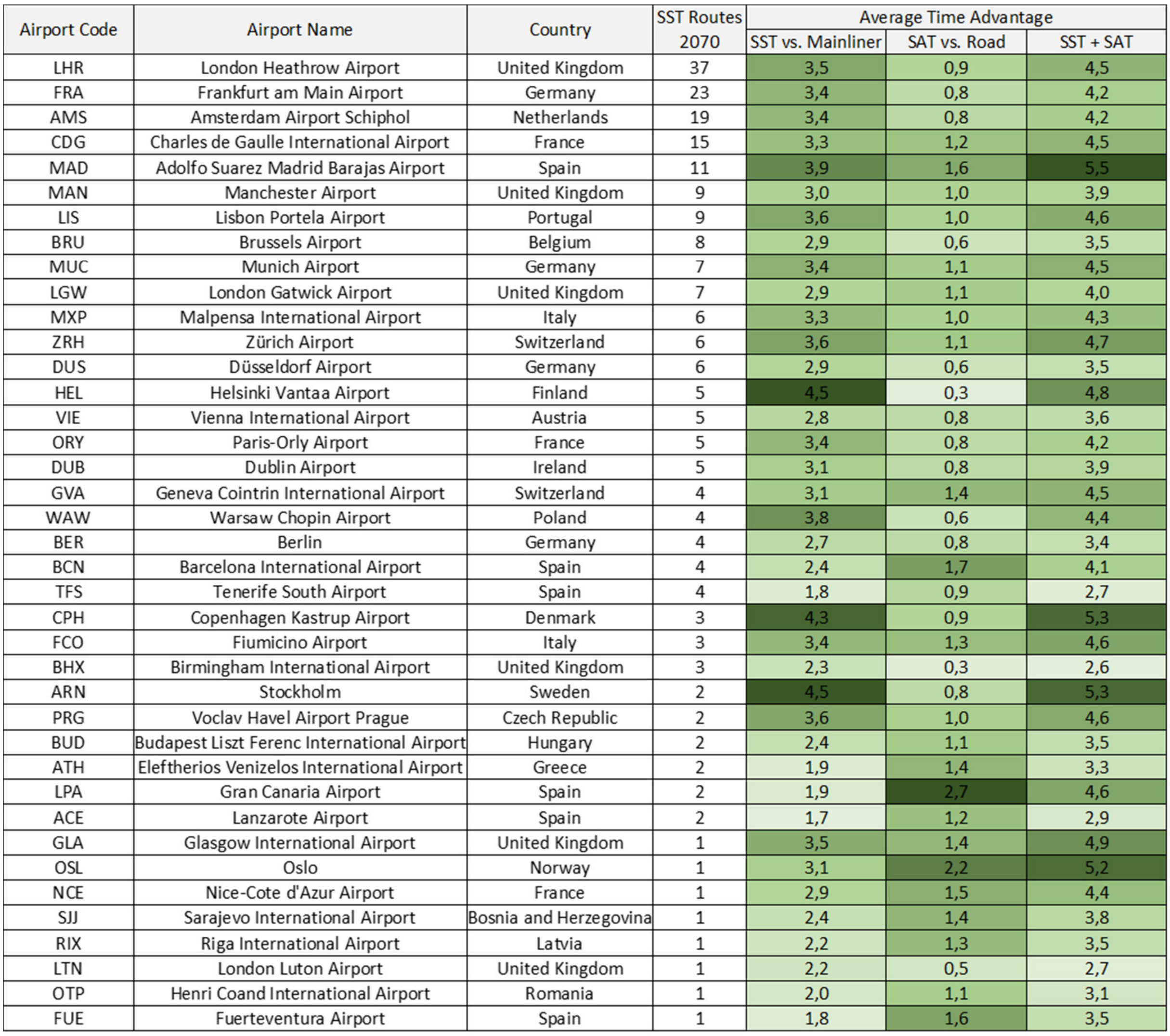
	Min	Average	Max
SST	1,7	3,0	4,5
SAT	0,3	1,1	2,7
SST+SAT	2,6	4,1	5,5

Table 22: Time advantage (in hours) of SST in comparison to mainliner, SAT in comparison to car traffic and total time advantages of SST+SAT in comparison to car+mainliner aircraft

With regard to SAT feeder services, a SAT range of 300 kilometres and a speed of 360 km/h are assumed. For the time comparison calculation for SAT, only relations from the 39 airports to NUTS 3 regions that are at least 100 kilometres away are considered, since SAT as feeder services would not make sense over short distances.

The table above provides in this context a summary overview of the resulting average time advantages of supersonic services compared to conventional mainliner services.

It is noticeable that the time advantages vary - depending on the route - from 1.7 hours to a maximum of 4.5 hours and are on average 3.0 hours. The time advantages of SAT as feeder traffic compared to car traffic vary - depending on the airport - between a minimum of 0.3 hours and a maximum of 2.7 hours. On average, the time advantage of SAT as feeder traffic is 1.1 hours compared to car traffic. The total time savings of SST in combination with SAT vary between a minimum of 2.6 hours and a maximum of 5.5 hours. On average, the time savings of SST in combination with SAT compared to mainliner in combination with road traffic is 4.1 hours.



Airport Code	Airport Name	Country	SST Routes 2070	Average Time Advantage		
				SST vs. Mainliner	SAT vs. Road	SST + SAT
LHR	London Heathrow Airport	United Kingdom	37	3,5	0,9	4,5
FRA	Frankfurt am Main Airport	Germany	23	3,4	0,8	4,2
AMS	Amsterdam Airport Schiphol	Netherlands	19	3,4	0,8	4,2
CDG	Charles de Gaulle International Airport	France	15	3,3	1,2	4,5
MAD	Adolfo Suarez Madrid Barajas Airport	Spain	11	3,9	1,6	5,5
MAN	Manchester Airport	United Kingdom	9	3,0	1,0	3,9
LIS	Lisbon Portela Airport	Portugal	9	3,6	1,0	4,6
BRU	Brussels Airport	Belgium	8	2,9	0,6	3,5
MUC	Munich Airport	Germany	7	3,4	1,1	4,5
LGW	London Gatwick Airport	United Kingdom	7	2,9	1,1	4,0
MXP	Malpensa International Airport	Italy	6	3,3	1,0	4,3
ZRH	Zürich Airport	Switzerland	6	3,6	1,1	4,7
DUS	Düsseldorf Airport	Germany	6	2,9	0,6	3,5
HEL	Helsinki Vantaa Airport	Finland	5	4,5	0,3	4,8
VIE	Vienna International Airport	Austria	5	2,8	0,8	3,6
ORY	Paris-Orly Airport	France	5	3,4	0,8	4,2
DUB	Dublin Airport	Ireland	5	3,1	0,8	3,9
GVA	Geneva Cointrin International Airport	Switzerland	4	3,1	1,4	4,5
WAW	Warsaw Chopin Airport	Poland	4	3,8	0,6	4,4
BER	Berlin	Germany	4	2,7	0,8	3,4
BCN	Barcelona International Airport	Spain	4	2,4	1,7	4,1
TFS	Tenerife South Airport	Spain	4	1,8	0,9	2,7
CPH	Copenhagen Kastrup Airport	Denmark	3	4,3	0,9	5,3
FCO	Fiumicino Airport	Italy	3	3,4	1,3	4,6
BHX	Birmingham International Airport	United Kingdom	3	2,3	0,3	2,6
ARN	Stockholm	Sweden	2	4,5	0,8	5,3
PRG	Voclav Havel Airport Prague	Czech Republic	2	3,6	1,0	4,6
BUD	Budapest Liszt Ferenc International Airport	Hungary	2	2,4	1,1	3,5
ATH	Eleftherios Venizelos International Airport	Greece	2	1,9	1,4	3,3
LPA	Gran Canaria Airport	Spain	2	1,9	2,7	4,6
ACE	Lanzarote Airport	Spain	2	1,7	1,2	2,9
GLA	Glasgow International Airport	United Kingdom	1	3,5	1,4	4,9
OSL	Oslo	Norway	1	3,1	2,2	5,2
NCE	Nice-Cote d'Azur Airport	France	1	2,9	1,5	4,4
SJJ	Sarajevo International Airport	Bosnia and Herzegovina	1	2,4	1,4	3,8
RIX	Riga International Airport	Latvia	1	2,2	1,3	3,5
LTN	London Luton Airport	United Kingdom	1	2,2	0,5	2,7
OTP	Henri Coand International Airport	Romania	1	2,0	1,1	3,1
FUE	Fuerteventura Airport	Spain	1	1,8	1,6	3,5

Table 23: Time advantage of SST and SAT from airports with SST traffic in 2070

A more detailed overview at airport level is provided in the table above which shows the average resulting time advantages of SST and SAT in 2070. The greatest theoretical time advantages of such a transport chain consisting of SST and SAT at airport level therefore exist in Madrid (5.5 hours), Copenhagen (5.3 hours), Stockholm (5.3 hours), Oslo (5.2 hours), Glasgow (4.9 hours) and Helsinki (4.8 hours).

The analyses have shown that full electric small air transport has significant time advantages compared to ground-based transport, especially over longer distances. Accordingly, range plays a crucial role in improving the connectivity and mobility of the population in Europe through the use of SAT vehicles. This became clear in the comparison of the two DEPA 2070 technology scenarios. The number of European transport routes on which SAT has time advantages compared to ground-based transport is significantly greater in the progressive scenario with larger assumed ranges than in the conservative scenario. Even if only European transport routes on which business trips already take place in ground-based transport are taken into account, many of these connections can be served much faster with a full electric SAT vehicle than with ground-based transport.

A further look at the identified transport routes with the greatest potential for SAT transport in Europe shows that especially regions with physical barriers (mountains, lakes, sea, etc.) have relations on which a corresponding full electric SAT vehicle has significantly large time advantages compared to ground-based transport. Examples include routes in Scandinavia (especially Norway) and Southern Europe (e.g. Southern France, Italy, Greece). In these regions there are connections on which you have to take relatively long detours by car due to mountains or bodies of water. With a full electric SAT vehicle with a direct air distance, the greatest time savings can be achieved here. In addition to these physical barriers that must be bypassed (sea, lakes, mountains, etc.), administrative borders can also represent a certain barrier. One example is the identified SAT connections in Croatia, which arise because the country border of Bosnia and Herzegovina must be bypassed by car. It can be stated that SAT vehicles have significant time advantages compared to cars for air distances of around 150 kilometres and above, and this time advantage increases significantly as the distance increases. For shorter distances of less than 100 kilometres, cars usually have time advantages over SAT vehicles, as there is no need to plan for trips to and from the airport and no boarding and deboarding times. The mobility analysis of future possible innovative transport chains in the combination of supersonic to and from Europe and SAT feeder traffic within Europe has shown that there are significant time advantages with an average (across all SST airports) of 3 hours time saving through SST compared to mainliner and an average of 1-hour time saving through SAT compared to car.

To conclude, there is a relevant market potential in the long-term that can be exploited if the adequate technologies and transportation concepts are realised in the time span up to 2070. This goes hand in hand with significant benefits with regard to society and mobility as the analyses show.

6.5. Impact on Infrastructure Development

In the course of the DEPA 2070 project the role of aviation infrastructure was investigated with a special focus on airport infrastructure development as this is an important requirement for the sustainable transformation of the whole air transport sector. For this purpose, related key challenges were categorised into short-, medium-, and long-term perspectives. In the short-term (three to five years), the focus is on the need for airports to start making concrete plans for future scenarios (which are currently still highly uncertain). Regional differentiation, cooperation, capacity bottlenecks and the potential expansion of infrastructure, especially with regard to the use of new energy sources such as SAF and hydrogen, play a central role. In the medium-term (five to fifteen years), significant investments will be required in production and distribution infrastructure for alternative fuels, alongside the preparation of airport operations to new aircraft types. In the long-term (> fifteen years), availability and capacity take centre stage. The increasing demand for air transport requires the large-scale expansion of airports and the ramp up of sufficient production capacities for alternative fuels.

In regard to battery electric or hybrid aircraft the key issue is the provision of reliable and sufficient charging infrastructure at airports. This goes hand in hand with a standardised battery charging infrastructure which includes the management of heat emissions during fast charging. Battery swapping and storage, as well as charging turnaround times play a key role in operational planning. While at large airports the impact on operations may be minimal, at smaller airports it may be necessary to extend runways to accommodate electric aircraft which are heavier compared to conversional counterparts.

The introduction of hydrogen-powered aircraft as analysed in the progressive DEPA 2070 scenario would pose a number of additional challenges for airports and the wider aviation infrastructure. A key issue is the supply of hydrogen, which requires careful planning based on demand and the geographical location of the individual airport. In particular, the infrastructure will require significant investment to provide the necessary storage and distribution facilities and to comply with safety regulations. For large airports wishing to offer hydrogen-powered flights, the provision of suitable storage facilities for liquid hydrogen will require a considerable amount of space and energy. In the medium-term perspective (up to 2035), delivery of hydrogen by rail or road could be a temporary solution, as pipelines and distribution networks cannot be developed/extended extensively in this time span. The cost of providing the infrastructure, especially in remote regions, will be a key issue, that requires political support. In addition, airports will need to make technical adjustments as existing fuel systems and processes are not designed for hydrogen. It seems plausible that these challenges result in the introduction of hubs where hydrogen flights are concentrated to increase network efficiency.

The introduction of SAF will have different effects on the airport infrastructure, but they depend on the type of product. If it is a "drop-in" product that is mixed with the existing kerosene, no significant changes to the infrastructure are required. In this case, SAF will be seamlessly integrated into the existing logistics and no additional storage space or tanks will be required.

However, if it is a "non-drop-in" product that is not blended with kerosene, significant expansions are necessary. This applies in particular to the storage and handling of two different types of fuel, which requires additional tanks, infrastructure and processes at the airports. The reason for the latter option would be that it would be possible to refuel aircraft flying routes with a high probability of contrails with pure SAF and thus reduce emissions through non-CO_2 effects.

Other non-fuel related impacts include the growth of larger aircraft classes, especially those with longer wingspans, which can lead to space problems at airports. This affects not only flight operations, but also taxiing, runways, general occupancy and approach procedures. Changes in the global network structure and increasing digitalisation (e.g. cyber security) are also important issues that airports will need to address in the future. Finally, multimodal connections (road, rail, air) and zero-emission technologies in passenger and ground handling will play an increasingly important role in the operation of future airports.

Figure 69 summarises the pre-mentioned issues in relation to their complexity and their relevance with regard to the DEPA 2070 time horizon.

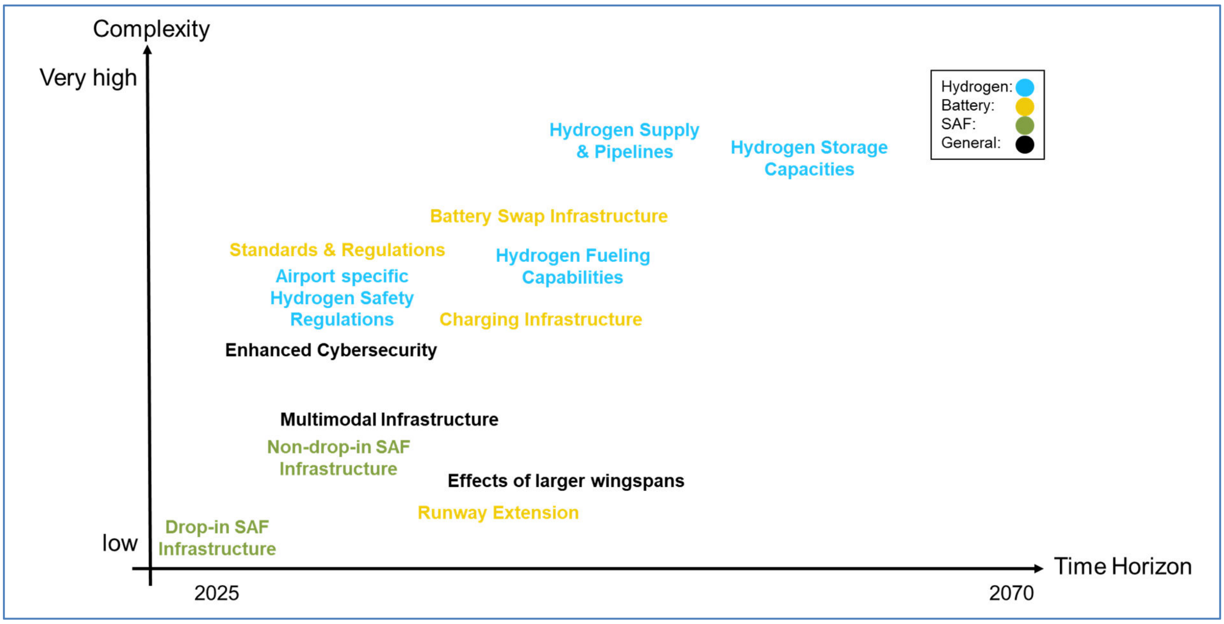


Figure 69: Infrastructure requirements in relation to the DEPA 2070 scenarios

As a result, it can be concluded that the challenges for the future are manifold and depend significantly on the size and individual position of each airport in the global air transportation network. Nevertheless, a coordinated approach and continuous exchange between all involved air transportation stakeholders is required in order to make the right decisions for the future in this context. The broad coverage of the DEPA 2070 scenarios with regard to the time horizon and the resulting impacts of the forecasted pathways for aviation development can in this respect deliver some hints for strategic planning in order to provide the best conditions for the intended sustainable transformation of the whole aviation system.

7. Conclusion

7.1. Scenario Comparison for CO_2 Emissions

This chapter summarises the results of the DEPA 2070 study in relation to the CO_2 emissions results (cf. also section 6.1.2) and compares them with other external aviation scenarios.

The results of DEPA 2070 project show that a significant emission reduction potential is possible in future aviation development. At the same time, it becomes clear that the aviation industry's goal of achieving net CO_2 neutrality by 2050 is extremely ambitious and unlikely to be met; primarily due to continued strong growth in air transport demand.

Figure 70 provides an overview of the development of CO_2 emissions from global aviation in the progressive technology scenario. It can be seen that enormous emission savings can be achieved, especially by considering hydrogen-powered aircraft. Accordingly, 484 MT of emissions can be saved in 2050 through aviation technology alone (including hydrogen-powered aircraft concepts), which corresponds to 33% of total emissions (1,429 MT) from aviation. The amount of saved emissions finally increases to 1,998 MT in 2070, which corresponds to 87% of total emissions (2,294 MT). With the additional use of sustainable aviation fuels, a total of 70% (1,014 MT) of all emissions from global aviation can be reduced in the progressive scenario in 2050 and finally 97% (2,235 MT) in 2070.

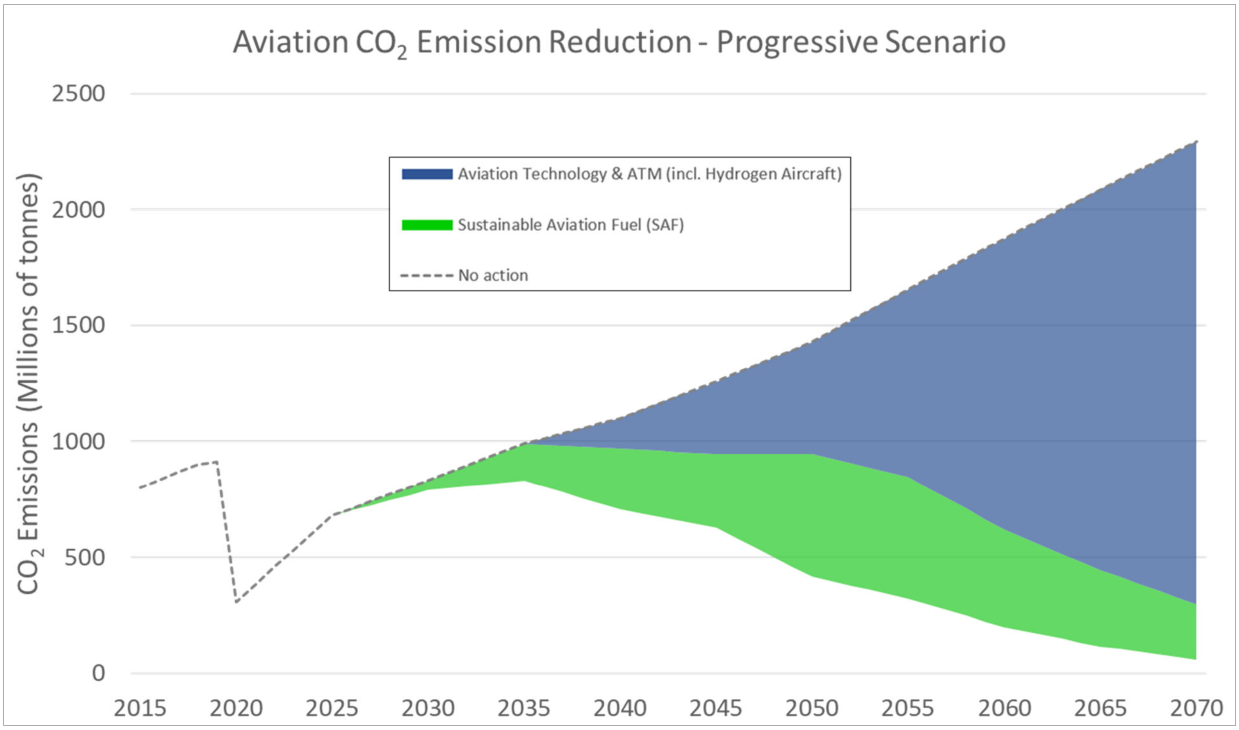


Figure 70: CO_2 emission reductions in the progressive DEPA 2070 scenario

A different picture emerges by looking at the conservative scenario in Figure 71. Here, the future CO_2 emission savings potential through aviation technology is significantly lower, as no market entry of hydrogen-powered aircraft concepts is assumed. Consequently, sustainable aviation fuels are of significantly greater importance. In 2050, only 4% of emissions savings are achieved through aviation technology in the conservative scenario, which corresponds to a quantity of 58 MT. This share increases to 12% (280 MT) in 2070. Over the same period, the emission savings in aviation through sustainable aviation fuels are significantly greater. Accordingly, 768 MT (53%) will be saved in 2050 and a total of 1,611 MT (70%) in 2070 through the use of SAF. Finally, the comparison with the progressive scenario shows that significantly more emissions can be saved in 2070 in the progressive scenario (97%) than in the conservative scenario (82%).

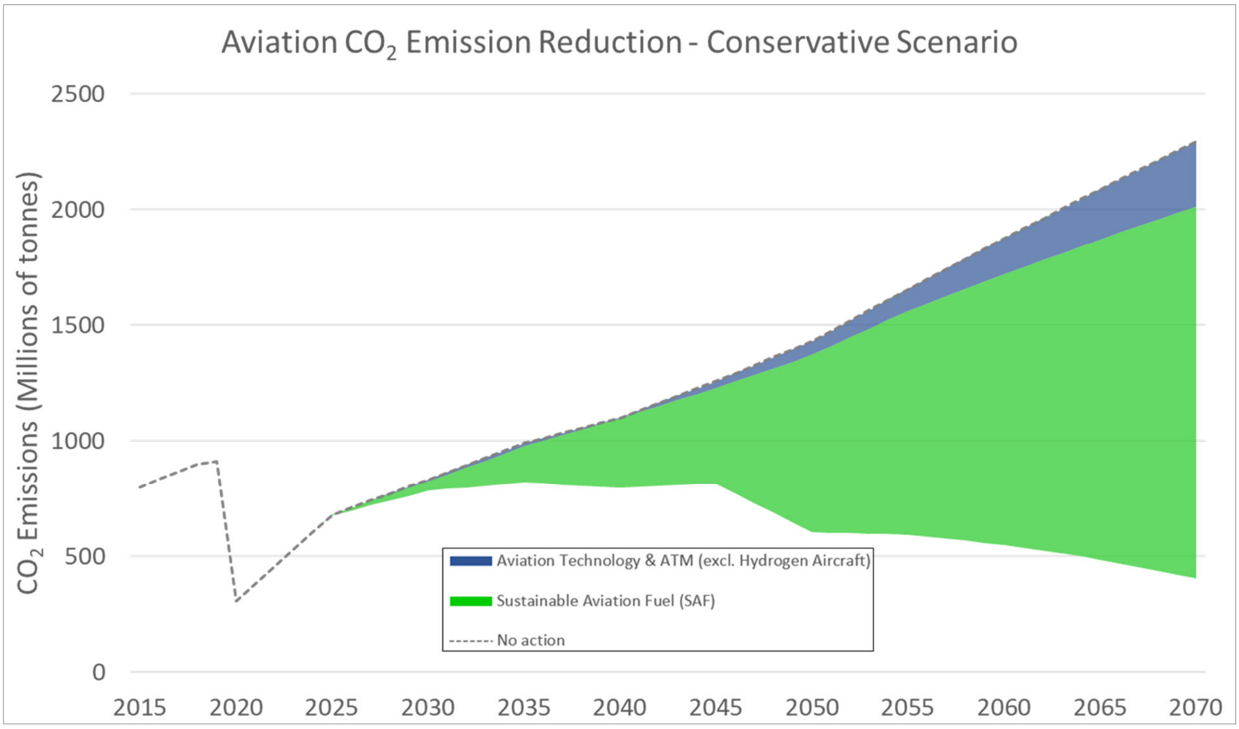


Figure 71: CO_2 emission reductions in the conservative DEPA 2070 scenario

A comparison with other external aviation scenarios (cf. Figure 72) places the results of DEPA 2070 in the context of the aviation sector's objective of achieving net CO_2 neutrality by 2050. In addition to DEPA 2070, the calculated emission savings potentials of the DEPA 2050 scenarios and various external scenarios (ATAG, Eurocontrol, IATA, NLR, ICCT) are considered. The total emission savings potentials of the progressive DEPA 2070 scenario are slightly higher than the progressive DEPA 2050 scenario. Furthermore, the emission savings potentials of the progressive DEPA 2070 scenario are comparable to the Eurocontrol "Base Scenario". Other external normative scenarios (with a target of zero CO_2 emissions in 2050) assume even greater potential emission savings in 2050 by the nature of their normative character. The emission savings of the conservative DEPA 2070 scenario are comparable to ATAG's "Baseline High SAF" scenario. The conservative DEPA 2050 scenario, however, is most comparable to ATAG's "Baseline Low SAF" scenario in terms of assumed emission savings in 2050.

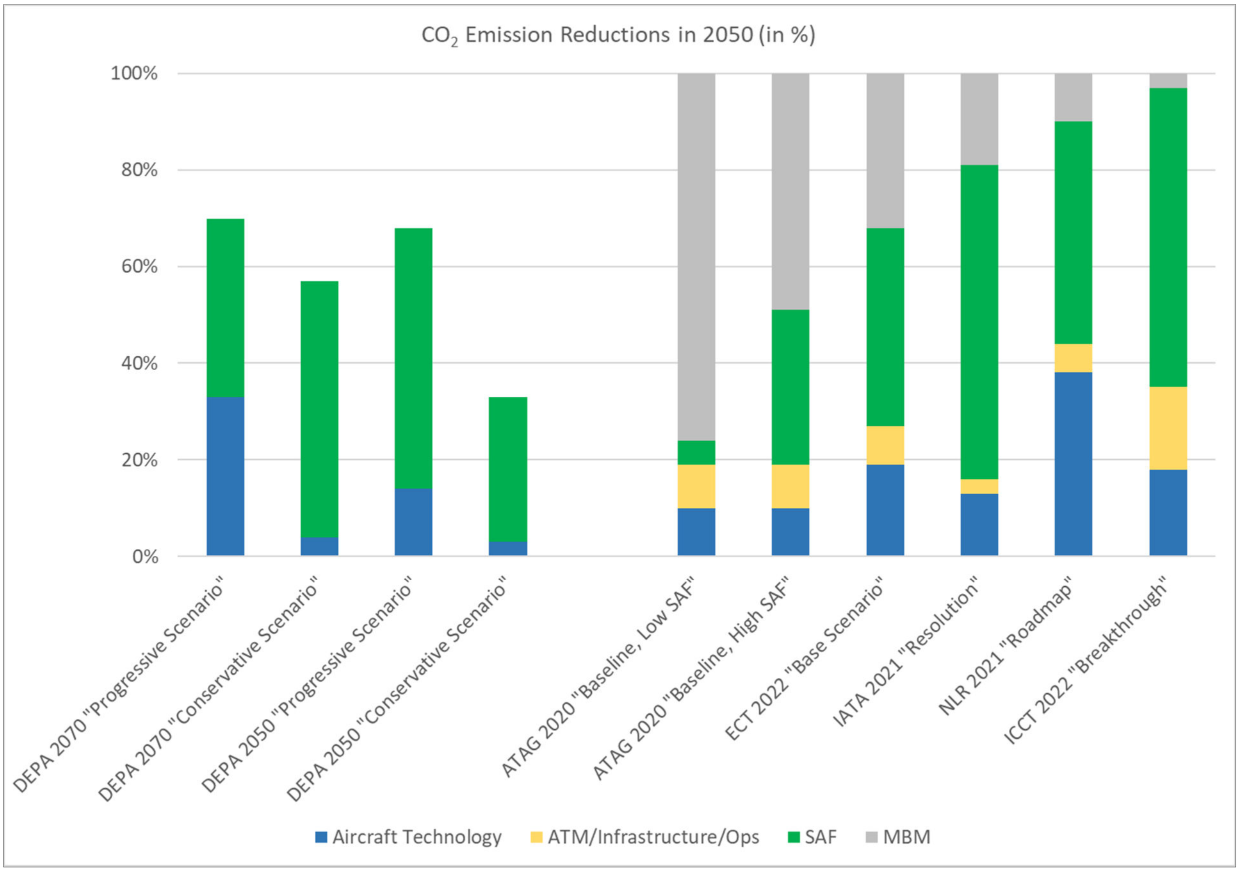


Figure 72: Comparison of aviation CO_2 emission reductions in 2050 of DEPA 2070 & DEPA 2050 scenarios with external scenarios

As a result of the comparison it can be stated that the DEPA 2070 scenarios successfully met the objective to show the broadest possible range of future development pathways for aviation. As pointed out before, the progressive DEPA 2070 is in this respect very optimistic with regard to the technological development in aviation and is dependent on optimal framework conditions. Nevertheless, it successfully demonstrates what could be achieved in terms of CO_2 emissions savings from the aviation technology point of view if significant effort is put in this field. On the other side, the conservative scenario is more in line with a business-as-usual development and from this perspective it illustrates the crucial role of SAF over the next decades. In this respect, the conservative scenario could be the starting point for setting priorities and to decide what has to be done to develop the aviation sector into the direction of the progressive scenario. It is also clear, that all the categories mentioned (aircraft technology, ATM/infrastructure/operations, SAF and market-based measures) will play a role in this respect.

7.2. Overall Conclusion

The DEPA 2070 study was conducted to analyse and evaluate aviation development pathways up to the year 2070 with a special focus on the development of the time span 2050+. With regard to the overall project objectives as described in section 1.3 it can be concluded that the study fulfilled the requirements that were identified at the beginning.

With regard to the trend analysis as outlined in section 3 of this report it became clear that especially the future energy mix of aviation and the new and innovative air transportation concepts (like supersonic aircraft and UAM) are highly uncertain. In order to address this uncertainty, the technology scenarios for DEPA 2070 were defined in a more extreme way by describing a progressive scenario that assumes very optimistic conditions for future technology development in aviation and a conservative scenario that is rather oriented on a business-as-usual development. This allowed to analyse the impact on CO_2 emissions for the "best case" (progressive) development with a higher share of hydrogen aircraft and (hybrid-)electric aircraft in the fleet and a more moderate (conservative) development without hydrogen carriers and less (hybrid-)electric aircraft. As a result, the CO_2 emissions reduction potential in the conservative scenario is significantly lower than in the progressive scenario.

For both scenarios, SAF plays a crucial role when life-cycle CO_2 emissions are regarded. Given the aviation demand growth that is expected up to the year 2070 SAF will be the game changer to compensate the resulting CO_2 emissions growth out of this development. Thus, by an increased usage of SAF in the global fleet together with improved aviation technology climate-neutrality can be reached from 2030 onwards.

For the other impacts positive results can be reported, too. Aircraft noise might further be reduced through improved aviation technology. However, the situation might differ from one airport to another depending on traffic volumes and the respective fleet mix. To enable a quick evaluation of the individual airport situation now and in the future a new method for noise assessment was developed within the DEPA 2070 project. As outlined in section 6.2.4 this method should be used in follow-up projects in combination with noise-optimised aircraft concepts to analyse some specific airport use cases to contribute to a global picture on aircraft noise impacts.

With regard to the economic impact analysis, which was also a part of this study, it can be concluded that the projected air transport growth until the year 2070 will have very positive results on the global and European economy. The employment generated by air transport activities will grow from 17.1 million jobs in 2019 to 37.3 million jobs in 2070 on global scale and from 1.9 to 2.9 million jobs in the European Union within the same time span. Correspondingly, gross value added generated by air transport will grow from 1,073 billion Euros to 2,249 billion globally and in the European Union from 119 billion Euros in 2019 to 197 billion Euros in 2070.

Concerning the societal impacts aviation will contribute to an increased mobility of the global society by offering an extended network and a growing number of connections and frequencies in response to aviation demand. In addition, advanced types of air transportation (e.g. supersonic air transport as outlined in section 4.2.3) will create opportunities for faster transportation. The same holds for (hybrid-)electric air transport which might especially improve connectivity and travel times on shorter routes and includes also the opportunity to substitute car travel up to a certain extent as outlined in section 6.4.

The critical bottleneck remains the air transport infrastructure as described in the corresponding impact analysis in section 6.5. As especially with regard to new energy sources in aviation infrastructure has to be extended and processes have to be optimised, investment costs for these changes are rather high and the current geo-political climate is signified by a high uncertainty. In addition, as outlined in relation to the trend analysis of the aviation market in this study many actors are involved. Thus, a coordinated effort is needed which is not so easy to realise due to the heterogeneity of the different stakeholders and their individual interests. Further research on improvement options and continuous exchange between all stakeholders is therefore crucial to improve strategic planning in this field.

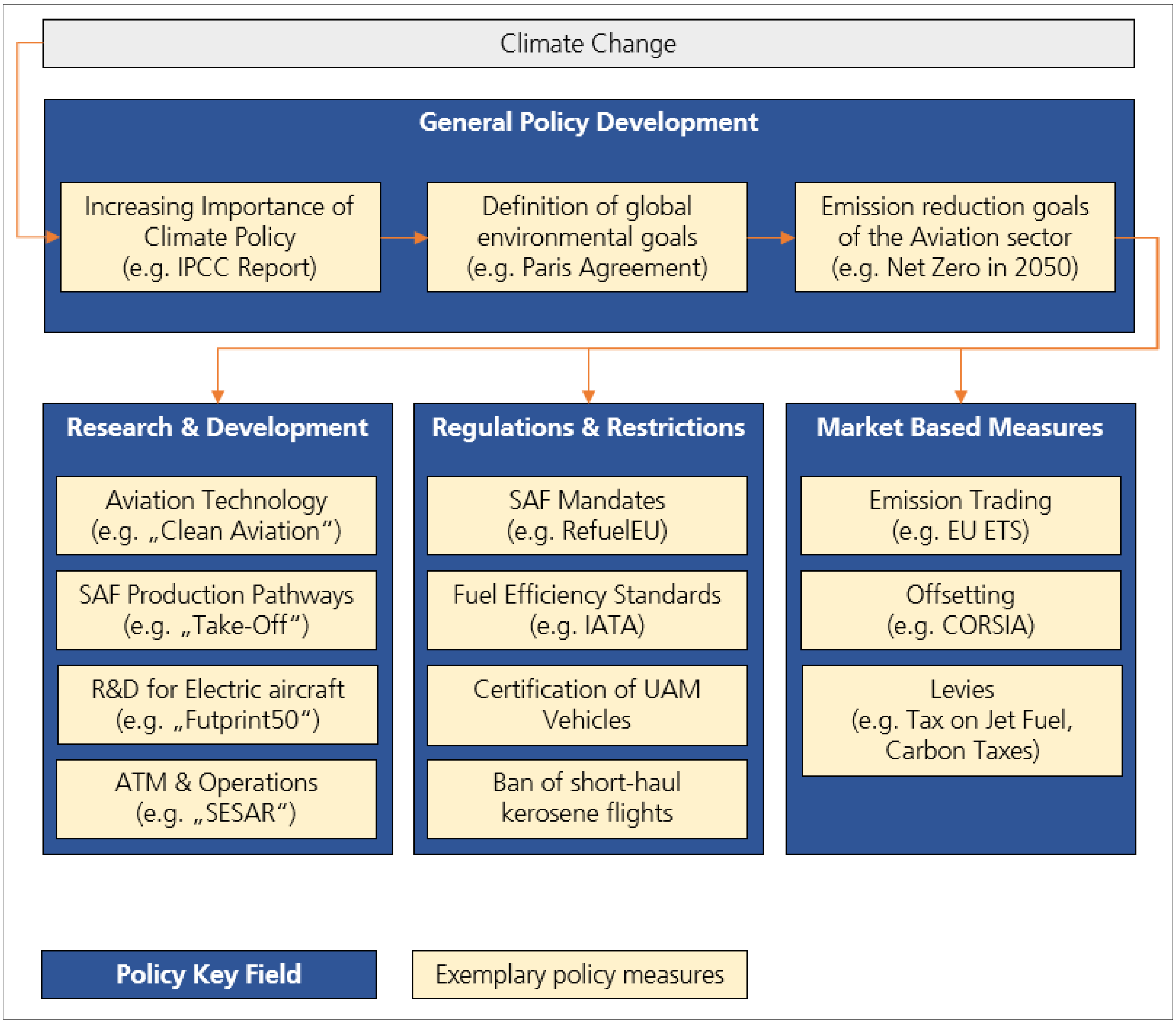
To conclude, the purpose of this study was to explore what could be possible in relation to the planned transition of the aviation sector over the next 50 years. The progressive DEPA 2070 scenario illustrates in detail the potential improvements that could be reached in this respect in the field of CO_2 emissions reduction under optimal conditions. Although the conservative scenario outlined in this study is in contrast more realistic in the end the progressive scenario provides this way an important orientation for the next steps in the right direction. Nevertheless, this requires also over the long-term a coordinated effort of all relevant aviation stakeholders in order to set the right priorities for future of air transportation.

8. Annex

Aviation Technologies	Category	**Potential** (Fuel savings)	**Market Maturity** (TRL)
Active load alleviation	Aerodynamics	~3%	High
Adaptive compliant trailing edge (ACTE)	Aerodynamics	~7,5%	Medium
Variable Camber	Aerodynamics	~1,5%	High
High-aspect ratio wings, Increased span	Aerodynamics	n.a.	Medium
Laminar flow control (Hybrid)	Aerodynamics	~12,5%	Medium
Laminar flow control (Natural)	Aerodynamics	~7,5%	Medium
More efficient fuselage structure	Aerodynamics	n.a.	Medium
Morphing wing, Spanwise Adaptive Wing (SAW), Active smart wing	Aerodynamics	~5%	Low
Riblets	Aerodynamics	~1%	High
Spiroid Winglets	Aerodynamics	~4%	Medium
Blended Wing Body	New Aircraft Concept	~20%	Low
Box-/Joined-Wing	New Aircraft Concept	~7,5%	Low
Canard configuration	New Aircraft Concept	~4%	Low
Double Bubble aircraft	New Aircraft Concept	~20%	Low
Flying V	New Aircraft Concept	~20%	Low
Strut-braced wing design (SBW)	New Aircraft Concept	~9%	Medium
Boundary Layer Ingestion (BLI)	Propulsion	~8%	Medium
Distributed propulsion	Propulsion	n.a.	Medium
Open rotor engine, Counter rotating open rotor (CROR)	Propulsion	~30%	Medium
Ultra high bypass ratio (UHBR) engines	Propulsion	~25%	Medium
Advanced fly-by wire systems	Systems	~2%	High
Fuel cells for onboard power	Systems	~3%	Medium
Structural health monitoring	Systems	~2,5%	High
Electric taxiing	Systems	~3%	High

Measure	**Potential** (CO$_2$ Emision Savings)	**Market Maturity** (TRL)	Relevance/Applicability
Airport Collaborative Decision-Making (A-CDM)	High	High	Airports, ATM, Airlines
Continuous Descent & Climb	High	High	ATM, Airports, Airlines
Flexible Use of Military Airspace	High	High	ATM
Sectorless ATM	High	Medium	ATM
Advanced air traffic management for formation flying	Medium	Low	ATM
Airport congestion management	High	Low	Airports, ATM, Airlines
Reduced Extra Fuel Onboard	Low	Medium	Airlines
In Trail Procedere (ITP)	Low	Medium	ATM, Airline
More flexible tracks	High	Low	ATM, Airports, Airlines
Performance-based Navigation (PBN)	High	Medium	ATM, Airports, Airlines
Reducing the laps between aircraft at takeoff	High	Medium	Airport, ATM
Required Navigation Performance (RNP)	High	Medium	ATM, Airports, Airlines
Space-based navigation	Medium	Medium	ATM, Airports, Airlines
Trajectory-based operations (TBO)	High	Low	ATM, Airports, Airlines
Optimization of Aircraft Trajectories	Medium	High	Airlines, ATM, Airports
Flight Planning	Medium	High	Airlines
Formation Flights	Medium	Low	Airlines, ATM, Airports
Reduced use of engines when driving	Low	High	Airlines
Pre-Conditioned Air (PCA) system at parking position	Medium	Low	Airports
Electrical Tug Detachable Aircraft Towing Equipment	Low	Low	Airports
Airline Fuel Management System	Medium	Low	Airlines
Optimized Runway Delivery (ORD)	Low	Medium	ATM
Reduced vertical separation minimum (RVSM)	Medium	Low	ATM, Airlines
Global Air Traffic Flow Management	Low	Medium	ATM

Economic Measure	Concept	Explanation
Offsetting (Offset Scheme)	Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)	Offsetting of Emissions by purchasing carbon credits or investing in CO$_2$ Emission Reduction Projects
Emission Trading (Cap & Trade Scheme)	European Union Emission Trading System (EU ETS)	Acquisition of Emission Allowances (Certificates) where total number of allowances capped at specific level (Emission Target)
Levies	Direct pricing of Aviation CO$_2$ Emissions	Tax on Jet Fuel, Carbon Taxes


Climate Change
General Policy Development
Increasing Importance of Climate Policy (e.g. IPCC Report)
Definition of global environmental goals (e.g. Paris Agreement)
Emission reduction goals of the Aviation sector (e.g. Net Zero in 2050)
Research & Development
Aviation Technology (e.g. „Clean Aviation")
SAF Production Pathways (e.g. „Take-Off")
R&D for Electric aircraft (e.g. „Futprint50")
ATM & Operations (e.g. „SESAR")
Regulations & Restrictions
SAF Mandates (e.g. RefuelEU)
Fuel Efficiency Standards (e.g. IATA)
Certification of UAM Vehicles
Ban of short-haul kerosene flights
Market Based Measures
Emission Trading (e.g. EU ETS)
Offsetting (e.g. CORSIA)
Levies (e.g. Tax on Jet Fuel, Carbon Taxes)
Policy Key Field
Exemplary policy measures

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