DEPA 2050

Development Pathways for Aviation up to 2050

- Final Report -

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A note on Covid-19

The DEPA 2050 study was conceptualised and, to a large extent, already conducted before the full impact of the Covid-19 pandemic became apparent. Thus, the results of this study have to be regarded and interpreted in the light of a pre-Covid 19 environment. However, major changes through the Covid-19 pandemic are illustrated and discussed in the relevant sections of this report to provide additional information on potential impacts on the results and the situation of air transport as it is today.

Content

Executive Summary

The DEPA 2050 project was conducted at the German Aerospace Center (DLR) in the years 2019-2020. The project had five strategic goals:

1. Elaboration of technology roadmaps as base for a review of essential technology potentials and air transport-related vehicle concepts from an ecological, economic and societal point of view by addressing also their long-term market perspectives

2. Definition, description and assessment of two air transport technology scenarios (i.e. a conservative-evolutionary and a progressive scenario) up to the year 2050 to cover the full theoretical range of possible technological changes in the regarded time span to quantify a range of potential developments

3. Elaboration of an agreed and upgradable estimation of the possible future development in air transport to enable recommendations for the design of a future-oriented, efficient and sustainable air transport system and to evaluate corresponding impacts

4. Delivery of a pioneer study about the range of possible market development perspectives for all types of air transport vehicles in relation to their individual technology potentials

5. Development of a consistent and permanent aviation technology modelling and assessment framework within DLR for a continuous monitoring and update

The present report provides an overview of the structure and approach of the project as well as its major findings and further research needs.

Deviated from the overall objectives as outlined above, the major intention of the DEPA 2050 project was to define and estimate two air transport technology scenarios that both illustrate similarly realistic pathways for aviation's long-term development. One scenario was dealing with an accelerated diffusion of innovative technologies in the global passenger aircraft fleet. This scenario was defined as "progressive" scenario. The other one was assuming a slower market insertion of aviation technologies in general and a lower number of innovative technologies in total. This scenario was defined as "conservative-evolutionary" scenario.

The definition of both scenarios required a broad and detailed analysis of current and future aviation technologies. For this purpose, internal as well as external studies and research projects were investigated to derive from a pure description of those technologies to a robust estimation of their potential entry-into-service and a prediction of their market shares over the long-term. In combination with an estimation of the further development of framework conditions (e.g. in reference to prospects for the global economic development and population growth) the underlying analysis was used to define detailed vehicle-specific scenarios. Those were specified for established market segments (i.e. mainliner and regional aircraft, small air transport, business jets and rotorcraft) as well as for new market segments (i.e. supersonic aircraft and urban air mobility vehicles) which may enter the aviation market over the next decades. In a further step, the chosen scenario approach allowed to forecast the expected demand growth for each market segment up to the year 2050 as an initial step for the intended impact studies in the context of the DEPA

2050 project. Capacity constraints of airports have in this regard been considered to do the projection under most realistic conditions given the expected growth of passenger flights which will double until 2050.

Driven by existing objectives and initiatives to enable climate-neutrality of the aviation sector in the year 2050 the impact analysis on the further emissions development was a core part of the overall impact analysis. For this purpose, the technology roadmaps for mainliner and regional aircraft were used and embedded into specific concept vehicles for each scenario. Taking the predicted air transport demand growth and fleet renewal for those market segments into account as well as potential changes in the en-route flight efficiency and in the airport surroundings on emission inventories were prepared on this basis. A major finding in this respect is that for the conservative-evolutionary scenario total CO_2 emissions between 2014 and 2050 are expected to increase from 651 million tonnes to 1,812 million tonnes as a result of increasing overall air transport demand. For the progressive scenario CO_2 emissions are projected to rise to 1,609 million tonnes in the same time span. Meanwhile, for the relative development of CO_2 emissions in relation to the air traffic performance (measured in 100 passenger kilometres) a reduction from 10.35 kg per 100 PKM to 8.08 kg per 100 PKM is a main result of the conservative-evolutionary scenario while for the progressive scenario a reduction to 7.17 kg per 100 PKM was predicted. Both reduction rates illustrate the technological progress for the particular scenario.

A decoupling of CO_2 emissions from the projected air transport growth until 2050 is independent from political measures, which have not been regarded in this study, only possible through the consideration of sustainable aviation fuels (SAF). For this purpose, the potential impact of increasing SAF usage was assumed for both DEPA 2050 scenarios. In the conservative-evolutionary scenario a SAF usage rate of 40% throughout the global fleet was expected for 2050 while for the progressive scenario 80% was regarded as plausible as studies[1,2] estimate SAF shares of 47% to 90% in 2050. Without analysis of the availability and disregarding the influence of potential future price developments of SAF on ticket prices, especially the conservative-evolutionary values might be quite optimistic but demonstrate the relevance of SAF usage as a third pillar in the climate-neutrality strategy for aviation. In the progressive scenario SAF is the crucial factor that enables together with the predicted changes in aviation technology and ATM horizontal flight efficiency a trend reversal in the absolute growth of CO_2 emissions as outlined above. The year 2030 is the turning point in this calculation. While in this year the CO_2 emissions reach a peak with nearly 1,000 million tonnes, they reach in 2050 a level 580 million tonnes which is clearly below the value of 2014 with 651 million tonnes. In contrast, the conservative-evolutionary scenario shows an increase from 651 million tonnes CO_2 to 1,234 million tonnes in 2050 despite of increasing SAF usage. However, the curve for the overall CO_2 emissions increase is also in this scenario clearly flatter than the curve without SAF usage.

For the overall NO_x development calculations were done without the inclusion of SAF as the impact on NO_x emissions is negligible in current engines. Significant reductions of NOx could be

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[1] Cf. ATAG (2020).
[2] Cf. DESTINATION 2050 (2021).

achieved with co-optimised engines and SAF in the future, of which the impact is not evaluated yet. Within the conservative-evolutionary scenario NO_x emissions will grow from 2.9 million tonnes in 2014 to 11.8 million tonnes in 2050. Meanwhile, for the progressive scenario a rise to a level of 10 million tonnes is expected for the same time span taking technological progress and changes in the horizontal flight efficiency into account according to projections conducted in the course of the project. In relation to the subsequent climate impact modelling approach the comparisons of the DEPA 2050 scenarios was conducted in linkage to a hypothetical "Do Nothing" scenario. The latter assumed no technological progress after 2014 and no changes in the ATM efficiency. Considering solely the predicted air transport growth of additional 30 million flights between 2014 and 2050 from the DEPA 2050 flight forecast, the conservative-evolutionary scenario emission calculations including SAF usage as outlined resulted in this context in a 11% lower temperature change in 2100 than in the "Do Nothing" scenario. If the progressive scenario is compared to the "Do Nothing" scenario results, the temperature change is about 30% lower. For both calculations SAF production and usage was assumed to be CO_2-neutral by 80% over the life-cycle and soot-emissions were estimated based on fuel composition data and the SAF share for each scenario. Although aviation emissions are assumed to be constant after 2050, temperature change further increases for all analysed scenarios, as the CO_2 emissions accumulate in the atmosphere due to the long lifetime of CO_2. That means that even for constant emissions the climate impact of aviation would increase over the next decades without further mitigation measures.

Besides the focus on greenhouse gas emissions the analysis and future prediction of aircraft noise was an important part of the DEPA 2050 project in relation to the conducted environmental impact assessments. In this respect, the study focus concentrated of the reduction of noise at source. To estimate the future noise reduction potential a detailed literature study of existing and innovative noise reduction technologies and noise-optimised vehicle concepts was conducted. The findings of this research activity were used in the definition of vehicle-specific scenarios and the corresponding technology roadmaps. In-depth analyses were conducted on this basis for engine noise with a special focus on novel configurations. This included the assessment of engine noise in relation to distributed propulsion and boundary layer ingestion. Corresponding predictions concentrated on the rotor-stator interaction noise and the boundary layer ingestion noise.

As a further part of the conducted impact analyses in the DEPA 2050 project mobility and vehicle productivity impacts were analysed. Those can also be assorted to the social domain of sustainability and play an important role for society including potential benefits like connectivity and travel time savings. For instance, the ACARE four-hour-goal goals postulates that by 2050 "90% of travellers within Europe are able to complete their journey, door-to-door within 4 hours." As no concrete definition for the measurement of this goal exists, the DEPA 2050 study used a two-step approach. The first approach analysed the percentage of accessible population in the European Economic Area that can theoretically by reached within four hours by usage of existing air connections in combination with a car as airport access and egress mode. In this

respect, one major finding was that only 10.2% of population can be reached in four hours. If more than 90% should be reached, a total travel time of nine hours is needed.

As a second approach real demand data was used to analyse the travel choices of intra-European air passengers. The corresponding analysis showed that a large share of those passengers travels typically to final destinations where the 4-hour-goal cannot be achieved realistically. Even if non-stop flights exist, the resulting distances are too far to accomplish a trip within four hours. Taking those conditions into account, connectivity improvement potentials for the future exist to a large extent for new or advanced vehicle concepts. For instance, smaller aircraft that might be designed for longer-distance travel in the future might conquer specific niche markets in the European aviation network where demand is given but actually too low to operate these routes economically with regional or mainliner aircraft. As a further finding from the DEPA 2050 vehicle-specific scenarios air taxis will certainly play a more important role over the next decades. They will become a major player in urban air mobility, but might also be used for feeder flights to and from airports. Similar changes within the global aviation network can also be expected from the return of supersonic aircraft which enables travel time savings especially over long distances. For supersonic aircraft the conservative-evolutionary scenario predicts a start of supersonic flights in 2025 with 17,191 flights in total and a growth up to 84,797 flights in 2050. The fleet is expected to grow from 49 aircraft in 2025 to 221 in 2050. In contrast, the progressive development pathway assumes an increase of supersonic flights from 53,182 in 2025 to 220,815 in 2050. Appropriate fleet growth to handle the predicted demand would require 152 supersonic aircraft in 2025 and 538 in 2050 within the global aircraft fleet.

For the future market segment of urban air mobility, the demand estimates covered passenger-related trips per day and movements per day. In terms of trips a growth from 0.03 million trips per day in 2030 and 1.08 million trips per day in 2050 was forecasted in the conservative-evolutionary scenario. For the progressive scenario a rise from 0.32 million trips per day to 3.51 million trips per day was forecasted for the same time span. Correspondingly, the movements per day are expected to increase from 0.03 million in 2030 to around 1.25 million in 2050 in the conservative-evolutionary scenario. The progressive scenario predicts about 0.27 million movements per day in 2030 and 2.04 million movements per day in 2050 within the same time span. Following these demand estimates the UAM fleet is expected to grow from around 3,700 UAM vehicles in 2030 to around 138,000 in operation in 2050. For the progressive scenario 30,000 UAM vehicles in operation are assumed for 2030 and 170,000 vehicles in 2050. Despite of growing demand a stagnation in the fleet growth was furthermore calculated in this case based on the assumption that the seat capacity of the respective UAM vehicles increases over time.

Finally, as the third pillar of sustainability an economic impact analysis was conducted in the scope of the DEPA 2050 project to estimate the long-term impact of air transport activities from an economical point of view. In relation to the predicted air transport demand growth of the DEPA 2050 scenarios from around 31 million flights in 2014 to 60.5 million flights in 2050 and 3.3 billion passengers to 12.6 billion passengers in 2050, the added value generated by air

transport related activities will increase from 587 billion euro to 1,215 billion euro on global scale. For the EU-28 member states[3] it will grow from 157 billion euro to 231 billion euro over the next three decades. All of these values cover direct, indirect and induced effects of air transport's economic outcome.

The further economic footprint in relation to air transport-related employment shows that aviation has supported around 19 million jobs on global scale and 2.4 million jobs within EU-28 in the year 2014. Again, these values include direct, indirect and induced employment. For the year 2050 around 39.2 million jobs on global scale are estimated as an effect of air transport growth while 3.7 million jobs could be supported by aviation on EU level.

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[3] As the DEPA 2050 reference year is 2014 the United Kingdom is still included in the analysis.

1. Introduction

1.1. Motivation for the Project

Driven by continuous and strong growth the air transport sector has become one of the most important industries throughout the world. Diverse forecasts indicate that this trend will continue in the future[4] supporting economic development of industrial as well as developing economies, cultural exchange and technological progress. Especially the latter point has gained increasing importance over the last years by intensified research activities dedicated to advanced air transportation and vehicle concepts including fast rotorcraft, electric aircraft, supersonic air transport and urban air mobility (UAM).[5] As essential component of all these research initiatives environmental sustainability has become a major requirement in the design stage of aircraft manufacturing. In parallel, the highly competitive environment in the air transport market has led to a shift of power towards the customers over the last decades. Requests for connectivity improvements and customer requirements in terms of service quality have to be balanced with higher price sensitivity among all passenger groups. On the other hand, stakeholders from politics and society expect a positive indirect outcome of air transport in form of employment, value creation and taxes.

Initiated by these developments and diverse long-term trends (e.g. population and economic growth, digitalisation and artificial intelligence as well as climate change and the peak oil restriction) it is quite clear that the air transport sector will face significant changes over the next decades.[6] Many research studies indicate that those changes will be of disruptive nature leaving the evolutionary path from the past by shifts in technology (e.g. from combustion engines to alternative propulsion), the introduction of new transportation concepts (e.g. UAM) as well as changes in the day-to-day business with regard to air transport operations (concerning air traffic management and further management concepts). While there is consensus that those trends will shape the future a system-oriented coherent analysis of the impact of those trends is missing. Uncertainty about the state of single technologies as well as about their market perspectives complicate a future outlook as views of air transport experts about the scope, depth and timeframe of the expected technology shifts differ.

As a result, consistent statements relating to the entry-into-service (EIS) of technologies and their individual technology-readiness levels (TRL) represent a gap in the current state of research. As consequence a system- and fleet-wide estimation of the impact of introducing a broad range of promising aircraft technologies and new air transportation concepts has not been conducted yet. Taking this base case into account the research project "**DE**velopment **P**athways for **A**viation up

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[4] Cf. ICAO (2018a).

[5] Cf. e.g. Roland Berger (2018b).

[6] Those trends are furthermore accelerated through political objectives and agenda setting. For instance, the European Commission has just launched the "Sustainable and Smart Mobility Strategy" (cf. European Commission (2020b)).

to **2050**" (**DEPA 2050**) of DLR, which run from 2019 to 2020 aimed at delivering a first approach to analyse the potentials of new technologies in air transport up to the year 2050. For this purpose, promising technologies were selected for an incorporation into future aircraft concept models via technology factors to populate the future global fleet. In a second step, a scenario-based analysis presuming two probable pathways for the technological development allowed to quantify and describe the overall impact of the scenario-specific aviation development with regard to the three pillars of sustainability (i.e. environment, economy and society).

The main motivation for the corresponding study was in this context to elaborate and test a coherent approach that allows examining the impact of new aviation technologies on fleet level to estimate their global impact over the long-term. This hold especially for the analysis of effects on mobility/vehicle productivity, emissions and climate impact as well as on noise and economy to evaluate the aviation development also from a sustainable point of view. Furthermore, a consistent assessment framework was also requested from DLR side as continuous platform to predict and estimate benefits of internally developed aviation technologies regularly. Although uncertainties in long-term projections may remain, the concept enabled this way a first delivery of a robust modelling framework that can serve as starting point for regular updates (i.e. for 5-10 years) addressing progress in technology and changing framework conditions.[7] In addition, the further scope of the analysis concentrated on the current state of technological potentials in air transport research and development in order to project the market perspectives for single technologies in consideration of the resulting impact on environment, mobility and society including linked chances and challenges. The latter point is in most technology roadmaps and outlooks not appropriately addressed as pointed out in section 1.2 and represents therefore an important research gap to be closed. This was also one major driver for the research activities that have been conducted in the scope of the DEPA 2050 project.

Furthermore, findings from the project as described in this study should serve as starting point to provide recommendations for industry and politics in relation to the further air transport system design and development. The research intended to deliver additional input for discussions about future strategic research agendas and visions linked to aviation's long-term development. This holds for national stakeholders from politics and industry but also for important stakeholders on European level like the "Advisory Council for Aviation Research and Innovation in Europe" (ACARE) and on global level the "International Civil Aviation Organization" (ICAO).

1.2. State of Research

As described in section 1.1 the main intention for running the DEPA 2050 project was to close the gap between the analysis of individual technology potentials on component level and an extended impact analysis of those technologies on fleet level to estimate their overall impact on

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[7] Especially the unforeseeable Covid-19 pandemic demonstrates the need for such adaptable assessment frameworks that can be run several times in relation to changing framework conditions.

global scale and with a special focus on the long-term. In contrast, many studies in research typically concentrate mainly on the analysis of individual technologies.[8] A further type of studies and projects presents more detailed investigations of a broader set of technologies by embedding them into technology roadmaps.[9] In some of those analyses the respective technology roadmaps are also combined with estimations on the market perspectives for new vehicle types by incorporating the technologies under discussion or by providing at least an estimation on global or world regional demand for new vehicle concepts based on assumed manufacturing costs and/or expert surveys. However, the concrete air transport demand development over time and the distribution of demand on local scale is often not considered in such a study framework. This holds especially for the consideration of interdependencies between single technologies, resulting infrastructure requirements, intermodal competition and future network development in air transport (e.g. regarding capacity constraints). Thus, realistic market insertion and penetration of technologies is not reflected in a needed degree to evaluate the full potential of technology streams. Similarly, methodological approaches in many studies are often not made transparent.

Facing these conditions, the starting point for the DEPA 2050 project was to analyse external studies with a corresponding approach as well as DLR's internal projects to choose the most promising technologies for consideration in the qualitative description of two different technology scenarios. Those scenarios served as base for a concluding quantitative and qualitative estimation of the overall impact of the selected technologies by embedding them into aircraft concept models. A more progressive technology pathway in a more ambitious scenario ("progressive scenario") was defined in the scope of this approach together with a more evolutionary technology pathway ("conservative-evolutionary scenario") as counterpart assuming a less progressive development relying on historical development steps as observed in the past. Besides this, the further intention of the project was to regard new types of air transportation and advanced vehicle configurations (i.e. UAM and supersonic aircraft).

Following this approach, the set-up of the DEPA 2050 project aimed at contributing to a system-wide impact analysis of new technologies and air transportation concepts. A similar objective is currently only addressed by a few studies and initiatives of air transport actors on European and global scale. In relation to gaseous emissions, local air quality (LAQ) and noise the "Committee on Aviation Environmental Protection" of ICAO (ICAO CAEP) regularly monitors the progress in relation to the ICAO goals for the medium-term up to 2050.[10] Predictions on the long-term development of CO_2, NO_x and noise of international aviation have correspondingly been given in ICAO's "Environmental Report" in 2019 but with an exclusive focus on business jets, regional

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[8] Cf. e.g. Roland Berger (2018a, 2018b).

[9] Cf. BDLI (2020a, 2020b).

[10] Within all existing goal frameworks for aviation the issue of climate change has the highest priority. Correspondingly in 2019, ICAO approved the resolution A40-18 announcing the goal of a 2% annual fuel efficiency improvement up to 2050 for international aviation and carbon neutral growth from 2020 onwards. Within this goal framework technology development is one pillar to reach the goals.

jets, single-aisle and twin-aisle aircraft and a time frame up to 2037.[11] Additional estimations for reaching the ICAO goals in 2050 were also provided in this report by the definition of different scenarios incorporating different levels of technological and operational improvements as well as certain levels of alternative fuels usage in the air transport sector over the long-term. Although those scenarios provide a good orientation on the realistic perspectives to reach the ICAO goals in the environmental domain the potential of additional technologies and vehicle types (e.g. electric aircraft, supersonic aircraft) as well as their corresponding benefits for other pillars of sustainability is currently not completely addressed. Another difference to the DEPA 2050 project is given by the shorter time horizon. Similarly, the "European Aviation Environmental Report" from the "European Aviation Safety Agency" has a broad perspective on aviation technologies and their contribution to mitigate the impact of aviation on climate change, noise and air quality.[12] Here, the perspective is partially also a long-term (on average up to the year 2040) but this does not refer to all elements of the aviation system (e.g. ATM) and parts of the analysis refer stronger on the European level.

A wider perspective in terms of a more coherent system-wide analysis is provided by the Clean Sky 2 project.[13] With the objective to develop innovative aviation technologies and to embed and test them by incorporation into vehicle demonstrators the main intention is to reduce CO_2 emissions, NO_x and noise up to the year 2050 and to strengthen the competitiveness of the European aviation system. These objectives are similar to the DEPA 2050 study. However, the final results of the project will not be available before the year 2024 and the focus in Clean Sky 2 is mainly concentrated on the optimisation of existing vehicle concepts (i.e. large passenger aircraft, regional aircraft, small air transport, rotorcraft and business jets). UAM and supersonic aircraft are not primarily in the focus of research. Innovative concepts such as hydrogen-powered vehicles, electric aircraft or the usage of sustainable aviation fuels (SAF) are not investigated in depth, too.

However, the mentioned aviation stakeholders' activities and studies provided important information which was reviewed in the scope of the DEPA 2050 project. Based on the mentioned reference studies and further publications the project concentrated on the provision of an initial estimate of additional benefits to be expected by progress in aviation technologies and improved vehicle types as well as in ATM over the long-term. To deliver also more adequate information on the overall benefits to be expected the corresponding impact studies concentrated also on the economic and social domain of sustainability. Although it was not possible to perform a complete impact analysis mainly driven by gaps of information and partially higher levels of uncertainty with regard to different assumed developments the project was able to identify major trends that can be used as starting point for further analyses in the described field of research.

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[11] Cf. ICAO (2019). IATA has also delivered a similar projection with an own technology roadmap and scenario elaboration for a primary estimation of the future development of CO_2 emissions and fuel consumption (cf. IATA 2013). Another study based on state-of-the-art aircraft with an assumed EIS of 2020 the latest was published by Ploetner et al. (2017).

[12] Cf. EASA (2019).

[13] Cf. https://www.cleansky.eu/.

1.3. Research Objectives

From a strategic perspective the main intention of the DEPA 2050 project was to contribute to the closure of existing research gaps as described in section 1.2 of this report. While the operational goals of the project are outlined in section 2.1 the high-level targets of the project were defined as follows:

1. Elaboration of technology roadmaps as base for a review of essential technology potentials and air transport-related vehicle concepts from an ecological, economic and societal point of view by addressing also their long-term market perspectives
2. Definition, description and assessment of two air transport technology scenarios (i.e. a conservative-evolutionary and a progressive scenario) up to the year 2050 to cover the full theoretical range of possible technological changes in the regarded time span to quantify a range of potential developments
3. Elaboration of an agreed and upgradable estimation of the possible future development in air transport to enable recommendations for the design of a future-oriented, efficient and sustainable air transport system and to evaluate corresponding impacts
4. Delivery of a pioneer study about the range of possible market development perspectives for all types of air transport vehicles in relation to their individual technology potentials
5. Development of a consistent and permanent aviation technology modelling and assessment framework within DLR for a continuous monitoring and update

During the course of the DEPA 2050 project those strategic and high-level objectives served as guideline to define concrete goals on the operational level (cf. section 2.1) and to prioritise the necessary research activities and working steps. In alignment with objective no. 3 special emphasis was put during the whole project also on the identification of recommendations for science, politics and industry to support the goal of a more efficient and sustainable air transport system. Corresponding conclusions are presented in section 6 of this report. The relation of the findings to external goals are also discussed in this section.

2. Project DEPA 2050

2.1. Objectives

As pointed out in the preceding sections, long-term forecasts and scenarios for the overall air transport development consider new technologies and vehicle concepts in most cases not in a sufficient manner. This holds for quantitative as well as qualitative analyses. Furthermore, the methodology is often not transparent and the connection to the broad portfolio of DLR's internal research activities is not necessarily given.

If pure technology scenarios are regarded, market developments (including e.g. competitiveness, business models of airlines) and political conditions have often a lower priority and are not presented in detail. This limits the significance of the corresponding scenarios as the technical feasibility remains in this case the only requirement to identify potential break-through technologies and to conclude on their potential success in a very dynamic market environment as it is the case for air transportation. Thus, the high degree of competitiveness, ongoing cost pressure, long-term manufacturing processes and requirements from the highly diversified customer segments in air transport are typically not addressed sufficiently.

Based on this situation the DEPA 2050 project aimed at answering the following research questions to contribute to an extended status quo analysis of system-wide technology potentials and air transport development perspectives up to 2050:

- How does the most probable development of the air transport system up to 2050 look alike? Which major trends can be identified? Which role play external developments?
- Which development would be the most preferable one in terms of overall system performance and sustainability considering existing goals for the long-term air transport development (e.g. with regard to the scope of ACARE's "Flightpath 2050")?
- Which drivers and which limitations exist with regard to this most preferable development that can be used to provide recommendations for science, politics and industry?
- Which positive effects and development tendencies can be enforced?
- How and to what extent do innovative air transport technologies and vehicle concepts contribute to emissions reduction, climate-neutral growth, economic prosperity and connectivity improvements? Which contribution is given by operational improvements of the current air transport system (e.g. with regard to ATM and airport operations)?
- Which market penetration rates for different vehicle concepts and which market segments can be expected over the long-term? Which changes in the structure of the air transport system and which general consequences will be the outcome of corresponding shifts in air transport demand and supply?
- What is the general contribution DLR can make with regard to the design of a more efficient and more sustainable future air transport system?

Furthermore, with regard to dissemination the main intention of the project was to demonstrate the added value of DLR's air transport research activities for politics, industry and society. The corresponding objectives are given in the following figure. The dissemination strategy was differentiated by an internal and an external perspective to appeal to an extended group of potential users of the project results and to address the benefits they can expect from the project's outcome.

Distribution Strategy – Internally

- Generation and extension of knowledge/competencies
- Establishing cross-linkages between DLR research institutes
- Elaboration of a standardised and persistent „storyline" and a consistent modelling and evaluation framework for the continuous assessment of new aviation technologies and vehicle concepts
- Positioning of DLR's institutes, projects and guiding concepts with regard to a coherent view on the air transport system as of 2050
- Deduction of main recommendations for an ambitious, innovative and sustainability-oriented air transport development over the long-term
- Contribution to the strengthening and update of DLR's research agenda

Distribution Strategy – Externally

- Stressing the high importance of integrated technology assessments in the field of politics, industry and society
- Strengthening of the external perception of DLR and its research agenda
- Delivering a useful completion of the research activities of Clean Sky 2, ACARE, ICAO CAEP, SESAR 2020,…
- Fostering an persistent and coherent impact assessment of aviation technologies
- Providing easily accessible and easily understandable information of the outcome of DLR's air transport research activities to the public by showing the practical relevance of the topics under consideration

Figure 1: DEPA 2050 – Dissemination strategy

Following this argumentation, the DEPA 2050 operational project goals were derived from the strategic goals and were defined as follows:

1. Elaboration of future-oriented technology roadmaps to develop an agreed perspective on the essential potentials and market perspectives of aviation technology components and vehicle concepts in consideration of resulting environmental, economic and social implications
2. Definition, description and calculation of two air transport technology scenarios up to the year 2050 to cover the full theoretical range of possible technological developments in the regarded time span and to assess the expected results
3. Generation of a first holistic overview of the range of possible market perspectives for all air transport vehicle types in relation to their individual technology potentials

2.2.   Structure

The structure of the DEPA 2050 project is given in the following figure.

WP 0 Project Management				
WP 1 Air Transport System – Market Development and Scenarios	**WP 2** Technology Development – Component Level	**WP 3** Technology Development Vehicles and ATM	**WP 4** Szenario Quantification and Impact Assessment	**WP 5** "DLR Air Transport Vision 2050" – Concept and Dissemination
WP 1.1 Conceptual Design Impact Assessment	**WP 2.1** Analysis Technology Development Propulsion	**WP 3.1** Analysis Technology Development Vehicle Level/Roadmapping	**WP 4.1** Scenario Quantification Air Transport Development	**WP 5.1** Concept and Dissemination Strategy
WP 1.2 Scenario Definition	**WP 2.2** Analysis Technology Development Flight Systems	**WP 3.2** Technology Integration, Vehicle Design and Assessment	**WP 4.2** Impact Analysis Emissions	**WP 5.2** Elaboration "DLR Air Transport Vision 2050"
WP 1.3 Air Transport Development and Impact Analysis – Reference Year 2014	**WP 2.3** Analysis Technology Development MRO	**WP 3.3** Analysis Technology/System Development ATM	**WP 4.3** Impact Analysis Noise	**WP 5.3** Marketing Measures "DLR Air Transport Vision 2050"
			WP 4.4 Impact Analysis Economy	
			WP 4.5 Impact Analysis Mobility/Vehicle Productivity	
			WP 4.6 Final Assessment Air Transport Development	

* With regard to WP 5 the title and sub-titles are outdated. Due to a priority shift during the course of the project it was decided to focus more on air transport development pathways than on the creation of a vision for air transport.

Figure 2: DEPA 2050 – Work breakdown structure

The DEPA 2050 project was led by DLR's Institute of Air Transport and Airport Research. In total, seven DLR institutes were part of the project:

- Institute of Propulsion Technology (Departments "Engine" and "Engine Acoustics")
- Institute of Flight Guidance
- Institute of Maintenance, Repair and Overhaul
- Institute of Atmospheric Physics
- Institute of System Architecture in Aeronautics
- Institute of Engineering Thermodynamics
- Institute of Combustion Technology

2.3. Methodology

The following figure provides an overview of the DEPA 2050 modelling and assessment framework.
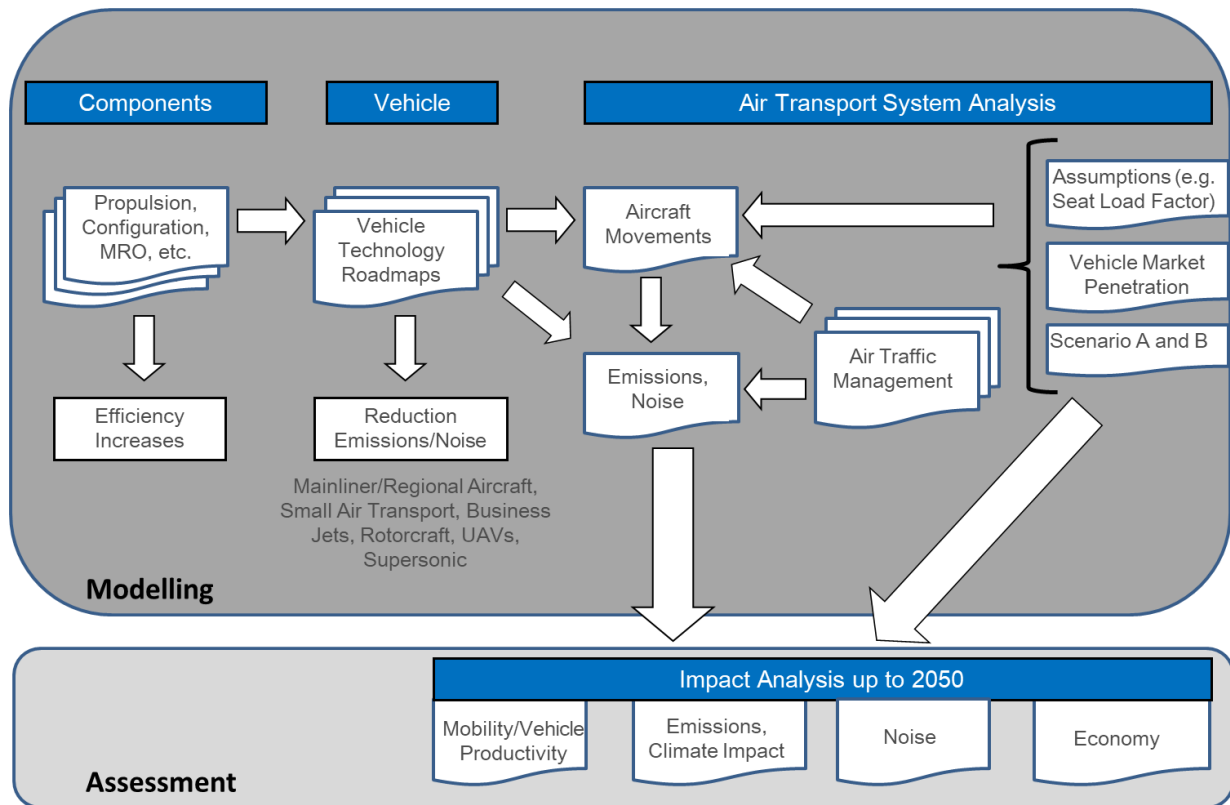

Figure 3: DEPA 2050 – Modelling and assessment framework

The starting point for the methodological approach of the DEPA 2050 project consisted of the qualitative definition of vehicle-specific technology scenarios as explained in section 3.1. In order to describe and estimate the potential development of the overall air transport system up to 2050 those scenarios were also extended by an overall system perspective addressing potential changes in air transport demand and optional ATM efficiency improvements up to 2050. This process formed the base for the subsequent detection and choice of suitable technologies for the two DEPA 2050 scenarios. Considering differing assumptions on "technology-readiness-levels" (TRL), resulting efficiencies and market entry dates for both scenarios those technologies were then inserted into specific vehicle technology roadmaps. In a further step, technology factors were used to derive from the roadmaps to quantitative estimates on fuel consumption and emissions (CO_2 and NO_x) per vehicle seat category. For more advanced vehicle concepts (e.g. in the field of UAM and with regard to supersonic aircraft) only partially estimates could be given due to the higher level of uncertainty with regard to market entries and vehicle performance. However, it was also tried to present the current state of research in those innovative fields and to draw further conclusions from the current status as adequate as possible.

In parallel to the modelling steps on component and vehicle level a system-wide analysis of the potential air transport system development up to 2050 covering demand development and potential ATM efficiency improvements was conducted. For this purpose, a high-scaled air transport demand forecast was elaborated for both scenarios to estimate the full impact of new technologies and advanced vehicle concepts by incorporating them into the global fleet. This process allowed to assess full technology potentials under realistic conditions in line with future passenger and flight development as well as fleet retirement. In addition, possible ATM improvements en-route and in the airport surrounding area were investigated during this working step to prepare the overall impact analysis. This analysis was done in 10-year steps between 2020 and 2050 to track changes over time in relation to the continuous market insertion of new aircraft technologies and vehicle concepts.[14] As a final step, the overall impact analysis was done for the two DEPA 2050 scenarios and the resulting air transport development pathways with a predefined assessment scheme as starting point. This assessment scheme is presented in the following table.

Table 1: Indicators and metrics for the impact assessment within the DEPA 2050 study

Assessment Category	Indicator	Explanation
Mobility/Vehicle Productivity	Number of flights (millions)	Number of flights means the total number of scheduled passenger flights in a specific time span. Each flight - which means also a transfer flight - is counted separately.
	Actual distance flown (billion km)	Actual distance flown is calculated out of the total number of scheduled passenger flights in a specific time span.
	Average distance per flight (km)	Average distance per flight is calculated out of the total number of scheduled passenger flights in a specific time span.
	Passengers (millions)	Passenger figures refer to scheduled services in a specific time span and can further be differentiated in domestic and international passengers. Transfer passengers are separately counted for each flight leg.
	Passenger load factor (%)	Passenger load factor measures the capacity utilization of airlines. Ratio of passenger-kilometres travelled to seat-kilometres available
	Passengers per flight (average number)	Passengers per flight refers to the total number of passengers on scheduled services divided by the total number of scheduled passenger flights in a specific year.
	Passenger kilometres (billion)	Revenue passenger kilometres (RPKs) refer to scheduled services (international and domestic). Transfer passengers are separately counted for each flight leg.
	Average aircraft age (years)	The average aircraft age refers to passenger and combi aircraft in service at a certain date.
	Fuel burn (billion gallons of fuel)	Fuel burn means the total fuel consumption (including taxiing).
	Success level of the ACARE 4h goal (%)	This indicator analyses the share of air transport in reaching the ACARE 4h-goal which says that 90% of travellers within Europe should be able to complete their journey, door-to-door within 4 hours. Most probably this might be conducted by case studies.
	Travel time savings	For specific use cases (regional case studies) travel time improvements in form of time savings through higher flight speed and/or other vehicle innovations are to be addressed.

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[14] Partially, estimations in 5-year steps have also been added if more robust data was available.

Emissions	CO_2 (million tonnes)	CO2 emissions as estimated to be emitted per single flight.
	NO_x (million tonnes)	NOx emissions as estimated to be emitted per single flight.
Aircraft Noise	Noise level (global fleet)	Average value based on EASA's certification noise levels database which might be differentiated further for separate airports/regions for the base year 2014. For 2050 rough estimates on improvement potential on vehicle category level or global level might be given.
Economy	Air transport related direct employment (number)	Air transport related direct employment refers to all employees that are directly employed by an airline in a specific country.
	Air transport related indirect employment (number)	Air transport related indirect employment includes all employees whose job is indirectly supported by the demand of the air transport industry for intermediate supplies.
	Air transport related direct gross value added (billion €)	Air transport's direct gross value added (GVA) means the grand total of all revenues in the air transport sector including sales and subsidies, while taxes are subtracted as well as the intermediate consumption (input from other sectors to the specific sector under investigation).
	Air transport related indirect gross value added (billion €)	Air transport's indirect gross value added (GVA) refers to the grand total of revenues of all other industries that is originating from the air transport sector's demand for intermediate deliveries from these industries.

The basic idea was to cover and describe the long-term development of the aviation sector in relation to four different assessment categories that are all oriented on the three pillars of sustainability. In this respect, the assessment in the category of "mobility/vehicle productivity" focuses on the social dimension of sustainability by analysing potential efficiency gains and improvements in the overall air transport performance from different perspectives. Meanwhile, the environmental pillar is addressed by the categories on "emissions" and "noise". Both categories are separately listed in the table above as also the corresponding analyses and outcomes in the scope of the DEPA 2050 study differ from each other. Finally, a further category on "economy" was dedicated to the purpose to estimate the economic impact of air transport activities that can be expected over the long-term.

The separate impact analyses in the different categories were mainly done on a quantitative level. However, due to data lacks, existing research gaps or a higher level of uncertainty in some fields of analysis the impact assessment was partially conducted on base of a qualitative approach instead. For example, for advanced vehicle types like supersonic aircraft or UAM vehicles only limited knowledge exists with regard to the outcome and benefits of their practical usage. In such cases the resulting restrictions have been outlined in detail in the corresponding sections of this report. The following table provides in this respect a first basic overview of the regarded vehicle types in the scope of this study, the corresponding scenario assumptions, the reliability of the related demand forecasts and the types and uncertainty levels of the conducted impact analyses.

Table 2: Overview of main vehicle categories and related scenario, demand and impact assessments within the DEPA 2050 study

Vehicle category	Main vehicle assumptions in the DEPA 2050 conservative-evolutionary scenario	Main vehicle assumptions in the DEPA 2050 progressive scenario	Demand forecast model[1]	Considered impact assessment category[2] and assessment type	Level of uncertainty of the results[3]
Mainliner Aircraft	- Medium increase in fuel efficiency and conservative market environment for SAF, electric propulsion and hydrogen - Retrofits of existing aircrafts	- High fuel efficiency improvements and positive market environment for SAF, electric propulsion and hydrogen - Partially new aircraft types	Level 2	Quantitative: 1, 2, 3, 4	Low
Regional Aircraft	- Medium increase in fuel efficiency and conservative market environment for SAF, electric propulsion and hydrogen - Retrofits of existing aircrafts	- High fuel efficiency improvements and positive market environment for SAF, electric propulsion and hydrogen - Partially new aircraft types	Level 1	Quantitative: 1, 2, 3, 4	Low
Business Jets	- Medium increase in fuel efficiency and conservative market environment for SAF - Retrofits of existing aircrafts	- High fuel efficiency improvements and positive market environment for SAF - Partially new aircraft types	Level 1	Quantitative: 4	Medium
Small Air Transport	- Medium increase in fuel efficiency and conservative market environment for SAF and electric propulsion - Retrofits of existing aircrafts	- High fuel efficiency improvements and positive market environment for SAF and electric propulsion - Partially new aircraft types	Level 1	Qualitative: 3 Quantitative: 4	Medium
Rotorcraft	- Medium increase in fuel efficiency and conservative market environment for SAF and electric propulsion - Retrofits of existing rotorcraft - Medium speed improvements	- High improvements in fuel efficiency and positive market environment for SAF and electric propulsion - Partially new rotorcraft types - Significant speed improvements	Level 1	-	Medium

Vehicle category	Main vehicle assumptions in the DEPA 2050 conservative-evolutionary scenario	Main vehicle assumptions in the DEPA 2050 progressive scenario	Demand forecast model[1]	Considered impact assessment category[2] and assessment type	Level of uncertainty of the results[3]
UAM	- Medium battery efficiency improvements, but very positive market environment for electric propulsion + fuel cell battery hybrid - Less advances in noise reduction - Medium range/capacity improvements	- High battery efficiency improvements and positive market environment for electric propulsion + fuel cell battery hybrid + hydrogen - Significant reduction of noise - Significant range/capacity improvements	Level 1	Quantitative: 2 Qualitative: 3	High
Supersonic Aircraft	- Medium increase in fuel efficiency and conservative market environment for SAF - Less advances in noise reduction; no reduction of sonic boom effect; Medium speed improvement	- High fuel efficiency improvements and positive market environment for SAF - Significant reduction of noise and sonic boom effect; overland flights allowed; significant speed improvement	Level 1	Quantitative: 2 Qualitative: 3	High

[1] To provide a rough orientation we differentiated the forecast demand model reliability according to the following classification scheme with level 1 being the highest reliable level: -Driver identified via system-wide analysis (à Level 0); -Data on drivers available, weight/influence estimated/assumed, reference methods applied (à Level 1); -Drivers influence/weight validated and model calibrated (à Level 2)

[2] Impact assessment categories: 1. Mobility/Vehicle Productivity 2. Emissions 3. Noise 4. Economy. (Due to data gaps and methodological uncertainties complete impact assessments for all assessment categories could not be conducted for each vehicle segment. However, it was tried to perform qualitative analyses whenever possible. Assessments that could not be conducted by a qualitative approach at least mean finally an identified research gap to be eventually covered in a follow-up project.

[3] The estimation refers to the scenario and forecast outcome as well as to the results of the conducted impact assessments. Especially for the innovative vehicle concepts "supersonic aircraft" and "UAVs/air taxis the category "high uncertainty" was chosen as those are not operating in the aviation market yet and many uncertain factors will finally influence their EIS and market diffusion over the long-term. However, the scenario approach in the DEPA 2050 project was chosen to compensate this uncertainty to a large extent by defining, describing and assessing two alternative probabilities of future developments in reference to a progressive and a conservative-evolutionary development pathway.

3. Air Transport System Development up to 2050

3.1. DEPA 2050 Scenario Assumptions

3.1.1. Methodological Approach

As an important basis for answering the central research questions outlined in section 2.1, in a first step vehicle-specific scenarios had to be developed in course of DEPA 2050.

Accordingly, for each of the vehicle types which had to be considered - mainliner, regional aircraft, business jets, small air transport, rotorcraft, supersonics and UAM vehicles - two different scenarios (progressive scenario vs. conservative-evolutionary scenario) were created to describe their possible development after 2030. As pointed out before, the two scenarios differ from each other by assuming different technological pathways for the further air transport technology development in relation to vehicle components and the development of air traffic management. This basic characteristic is outlined in the following figure.

Progressive scenario	Conservative-evolutionary scenario
• Substantial technological progress with regard to the aviation sector • Partially faster development cycles/market entries	• Technological progress as in the past with regard to the aviation sector • No disruptive developments • „Business as usual" assumption

Figure 4: Basic characteristics and differences between the progressive scenario and the conservative-evolutionary scenario

Although the progressive and the conservative-evolutionary scenarios differ in terms of the technological development significantly both scenarios are regarded as similarly probable in the future in order to perform a corresponding impact analysis that provides also a realistic overview of resulting consequences. Based on this general approach the differentiations of the vehicle-specific scenarios were carried out mainly based on aviation internal factors (aviation technology + aviation market development). The external framework developments in both scenarios were kept as similar as possible.

For the development of the scenarios generally the following steps were undertaken:

- A comprehensive influencing factor analysis was carried out, which aimed to identify any fields and factors that could influence the future development of air traffic (external factors + aviation internal factors) → section 3.1.2.
- After categorising these influencing factors into different key fields, the taxonomy - underlying the two scenarios - and the scenario structure was defined → section 3.1.3.
- The external framework developments underlying the two scenarios were described by storylines and summarised figures and tables about the factor assumptions → section 3.1.4.
- Vehicle-specific scenarios were finally developed and described by storylines and summarised figures and tables of the respective assumptions → section 3.1.5.

At this point it should be mentioned that the DEPA 2050 scenarios are not normative scenarios ("desirable future") which, for example, are oriented towards the successful achievement of ACARE's "Flightpath 2050" goals in regard of the factor assumptions. The DEPA 2050 scenarios therefore represent exploratory scenarios ("possible future") for a possible future aviation development.

3.1.2. Relevant Drivers and Factors

For the development of the scenarios, a comprehensive influencing factor analysis was first carried out, which aimed to identify any fields and factors that could influence future aviation development. For this purpose, a large number of scenario publications were analysed. All of them had a thematical focus on aviation, were not older than 20 years and included scenarios with a time horizon of at least until the year 2030. In addition to concrete air traffic scenario publications, also scenario studies with a thematic focus on the fields of "Transport, Mobility, Logistics", "Economy" or "Environment, Energy" were analysed, because they are closely linked to aviation.

Appendix A provides an overview of the considered influencing factors that were identified as most important during the review of the selected scenario publications. In this process, especially pure aviation-specific studies - even if none of these publications address such a large number of different vehicle types as in DEPA 2050 - played an important role.

Through further DLR internal expert interviews, an extensive collection of relevant factors could be created that have to be considered when developing air traffic scenarios.

STEEP-A categorization

In order to structure the extensive collection of relevant influencing factors on the future aviation development and to create an adequate taxonomy for the scenarios, a "STEEP" categorization approach was chosen (see the following figure).
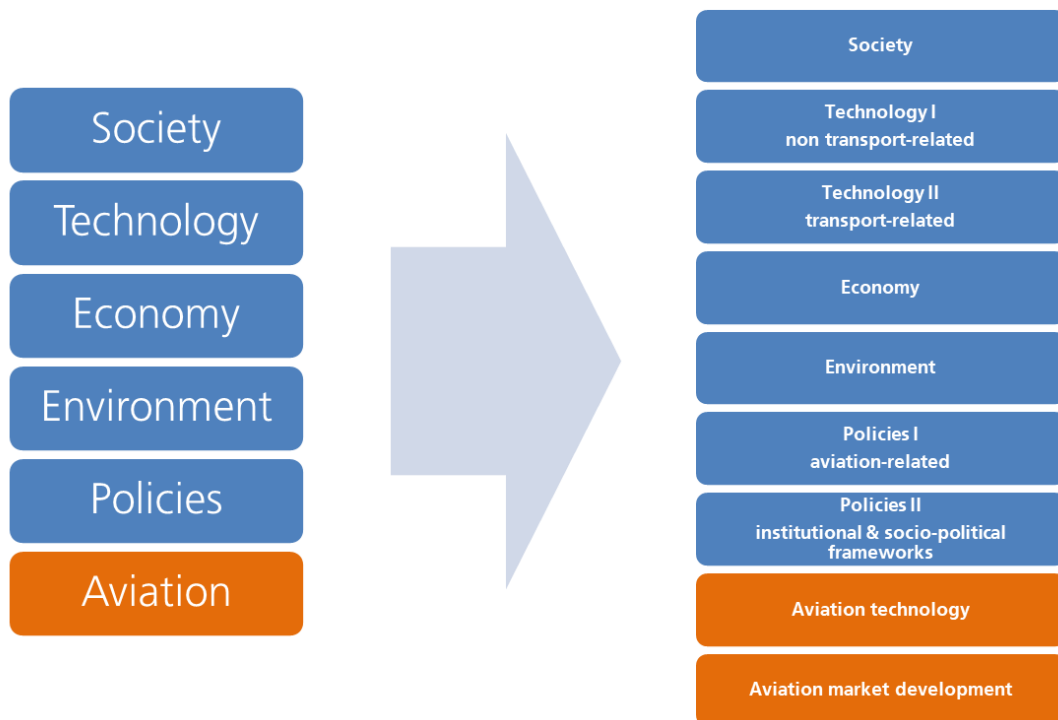
Figure 5: STEEP-A categorization structure of DEPA 2050

All identified influencing factors are assigned to the five overarching key fields "Society", "Technology", "Economy", "Environment" and "Policies". The key field "Technology" was further divided into transport-related technology and non-transport-related technology.

Table 3: Influencing factors on the future aviation development and assignment to STEEP categories

Key Field	Factor
Society	Population development
	World population
	Population growth rates
	Age distribution
	Migration
	Urbanization
	Global population growth driven by Asia and Africa
	Development of the global middle class
	Middle class growth in China and the Asia Pacific region
	Social trends
	Mobility patterns
	Level of education and prosperity
	Environmental awareness in society
Technology I (non transport-related)	Technology development in general
	Level of telecommunication / information technology
	Level of computer technology / virtual reality
Technology II (transport-related)	Technology development of high-speed trains
	Technology development of maglev
	Technology development of hyperloop
	Technology development of urban transport concepts
Economy	World GDP
	Real GDP growth rates
	GDP per capita
	Development of the global economy
	Economic development of emerging markets (esp. BRIC)
	Regional disparities
	Openness of international markets
	World trade development
	Stability of the financial sector
Environment	Environmental condition
	Resources consumption
	Energy demand
	Share of low-carbon energy
	Energy price
	Fuel costs
Policies I institutional & socio-political frameworks	Governance
	General level of environmental policy
	Political influence on mobility
	Dominant scale of decision making
	General nature and level of international cooperation
	Actions related to international migration
Policies II aviation-related	Regulations
	Restrictions
	Fuel tax
	Landing charges
	Emission trading costs
	Certain ban of flights
	Subsidization

Also, in the key field "Policies" a corresponding further separation into the subsections aviation-related and institutional & social-political frameworks was made. Finally, the STEEP categorization key fields have been expanded by the key fields aviation technology and aviation market development, which are central for the definition of the vehicle specific aviation scenarios.

Table 3 and table 4 show the assignment of the influencing factors to the superordinate STEEP-A key fields. Thus, a large number of influencing factors from the respective STEEP key fields have to be considered when defining and describing the framework developments. In addition to concrete quantitative influencing parameters, such as the future growth rates of the world population and the world economy, qualitative factors also play an important role, which are used particularly in the course of the storylines and have a major function to improve plausibility and consistency of the aviation scenarios.

Table 4: Aviation-internal influencing factors for the vehicle-specific scenario differentiation

Key Field	Factor
Aviation technology	Sustainable aviation fuels (SAF)
	Electrical propulsion
	Hydrogen
	Fuel consumption/ efficiency
	New aircraft types
	Aircraft system technology
	Maintenance technology
	Improvement technologies (propulsion, noise etc.)
	Air traffic management
Aviation market development	Supply
	Demand
	Competition in aviation industry / between airlines
	Business models
	Network connectivity
	Competition with other modes of transport

Table 4 provides an overview of the central influencing factors from the key fields aviation technology and aviation market development. In course of the scenario development it was necessary to create scenario-specific and vehicle type-specific assumptions for each of these influencing factors. The developed scenarios (progressive + conservative-evolutionary) for each vehicle type had to meet certain conditions regarding consistency and plausibility.

On the one hand, it was important to make internally consistent and plausible assumptions that do not conflict with the technological assumptions and market-related assumptions of the respective vehicle type. On the other hand, consistency and plausibility to the external framework

developments had to be guaranteed. Thus, the vehicle-specific aviation scenarios (progressive & conservative-evolutionary) had to be "within the bounds of possibility".

3.1.3. Scenario Taxonomy

Based on the identification and categorisation of the influencing factors an appropriate scenario taxonomy was developed. The aviation scenarios should meet four key requirements:

- Period of time: 2030 – 2050
- Definition of two basic scenarios (progressive & conservative-evolutionary) for every DEPA 2050 vehicle type (mainliner, regional aircraft, business jet, small air transport, rotorcraft, supersonics, UAM)
- Further scenario differentiation mainly based on aviation internal influencing factors
- External framework developments should be kept as similar as possible

Based on these requirements, the structure of the taxonomy could be derived. It is shown in the following table. Accordingly, all influencing factors from the fields of aviation technology and aviation market development had to be defined and described separately for each vehicle type and for each of the two scenarios (progressive + conservative-evolutionary).

Table 5: Scenario taxonomy*

Key Field	Vehicle-specific	Scenario-specific	Constant assumptions*
Aviation technology	●	●	
Aviation market development	●	●	
Aviation infrastructure			●
Society			●
Technology I non-transport related			●
Technology II transport-related			●
Economy			●
Environment			●
Policies I aviation-related			●
Policies II Institutional & socio-political frameworks			●

*partly some differentiations to justify vehicle specific scenario differentiations

Mainly based on these two key fields, the primary scenario differentiation was made. The central external framework developments, in particular quantitative assumptions such as GDP or world population, were not varied in the two scenarios. Although slight differentiations were indispensable in some areas, especially with regard to technology and energy-related assumptions, in order to justify the aviation-specific and scenario-specific developments. In general, however, the external framework developments in both scenarios were kept as similar as possible. This provides an adequate basis for assessing the success and impact of new aviation technologies and aviation markets in both scenarios without differentiating the external framework developments.

At this point, certain limitations in the scenario development should also be pointed out, which result from the defined scenario taxonomy. For example, in a future market diffusion of electrified or hydrogen-based vehicle types, the scenario categories aviation infrastructure or aviation-related policies will of course also play a central role. Higher market shares of these vehicle types can only be achieved through existing adequate infrastructures and/or concrete political regulations, which do not yet exist today. However, these two categories are not primary scenario-spreading categories in the DEPA 2050 scenarios. It is therefore assumed that these categories adapt accordingly to the various assumptions of aviation technology scenarios.
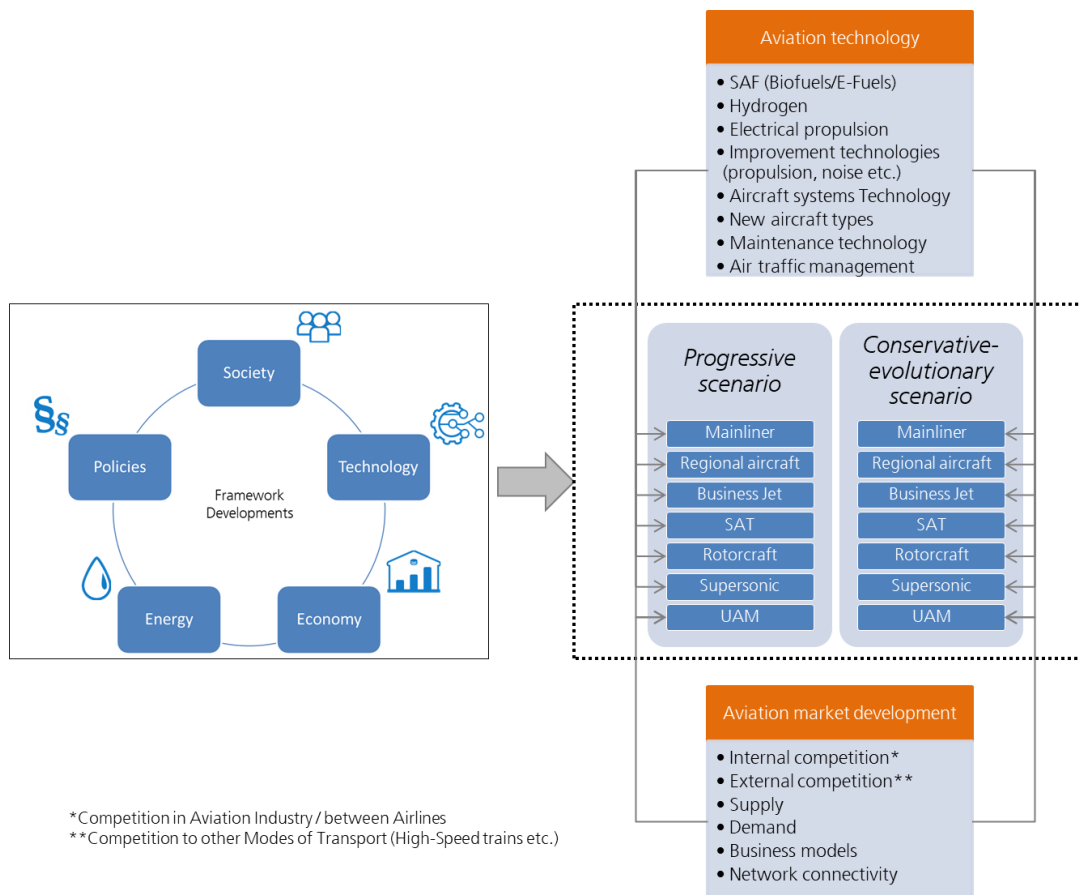
Figure 6: General structure and concept of the DEPA 2050 scenarios

Various approaches were used in the development of the assumptions for the individual factors influencing future aviation development. While concrete forecasted quantitative values for the identified factors from the external framework developments (esp. GDP & population) were easily defined based on adequate data sources, for the qualitative assumptions of the external framework developments different studies and publications were analysed. In addition to extensive literature research, especially an internal DLR scenario workshop was conducted to define assumptions about how aviation technology and aviation market development could develop in each of the two scenarios. Here - in discussion with various DLR institutes - specific aviation technology assumptions for the various types of vehicles were discussed and defined. In addition to general technological developments, possible entry-into-service dates for individual aviation technologies were discussed and defined in the respective scenarios in regard of the different vehicle types.

In order to make appropriate assumptions about how the influencing factors of the external framework developments could develop in the period 2030-2050, representative future studies and publications on the most probable future development of the respective factors were analysed. Figure 6 shows the final scenario structure for the DEPA 2050 study. It can be seen that the external framework developments with their key fields "Society", "Technology", "Economy", "Energy" and "Policies" were held constant for the progressive as well as for the conservative-evolutionary 2030-2050 vehicle scenarios. The primary differentiation was made by the vehicle-specific factor assumptions from the two key fields aviation technology and aviation market development.

3.1.4. Framework Developments

The external framework developments are all based on the most probable future development of the individual key fields and factors and are underlying both scenarios. They can be subdivided into the key fields "Society", "Technology", "Economy", "Environment" and "Policies", and in turn comprise various factors.

Society

For the future development of air traffic, the development of the society is of crucial importance (Figure 7). Thus, the demand characteristics of future passengers and the total potential size of the aviation passenger market are strongly influenced by social and demographic changes.

The world population is expected to grow until 2050. While 7.7 billion people live on Earth in 2019, by the middle of the century the global population will exceed 9.7 billion.

SOCIETY

	PROGRESSIVE	CONSERVATIVE-EVOLUTIONARY
Population development	Increase of world population until 2100 but growth rate continues to fall	
World population (in billion)	8.5 | 9.2 | 9.7 (2030 | 2040 | 2050)	
Population growth rates (p.a. in %, from 2014)	1.05 | 0.93 | 0.86 (2030 | 2040 | 2050)	
Social trends	• Move towards more active and healty lifestyles • Individualisation, more flexibility & acceleration of social life (*liquid modernity*) • Experienced-based leisure (inter-cultural understanding, holidays etc.) • More free-time → Use for self-realisation; Focus on individual well-being • More environmental orientation • Emphasis on small-family size, material well-being, leisure • Increase of one-person / single-parent households + couples without children • Closing gender gaps; more connected societies	
Mobility patterns	• Mobility-as-a-Service & Sharing platforms replace private ownership • Less car use by younger generations • Convenient and flexible service and mobility • High requirements for physical & virtual mobility	
Environmental awareness	• Increase; „sustainable consumption" culture • Negative impacts of (air) transport on people are not accepted	

Figure 7: Central scenario assumptions for the key field "Society"

Nevertheless, the annual population growth rates will continue to decline. While this was 2.1% per year in the period 1965-1970 and 1.1% per year in the period 2015-2020, the annual growth rate in the period 2014-2050 will be 0.8%. The global population growth until 2050 will be significantly different among world regions. Thus, the lion's share of this growth will be in

countries of sub-Saharan Africa (52%) and Central/Southeast Asia (25%)[15]. Due to the continuing increase in average life expectancy in combination with decreasing fertility rates, there are significant changes in the age composition of the world population, which is also described by the term "population ageing". The proportion of elderly people, especially in the current industrialised countries, will grow strongly by the middle of the century. On a global level, the number of people over 65 will more than double between 2019 and 2050[16,17].

Additionally, increasing global economic and demographic asymmetries will lead to a further increase in international migration. Europe, North America and Oceania will continue to be the main regions of destination and Africa, Asia, Latin America and the Caribbean countries will continue to be the main regions of origin of these migration flows. International migration can play an important role for future economic and social global challenges as a balancing factor for the labor markets in the regions of origin and destination as well as a means of increasing the living standards of family members of migrants[18,19,20].

Another megatrend in the coming decades will be the increasing urbanisation. Thus, in 2050, nearly 70% of the world's total population will live in urban areas; with a current rate of 55%. The lion's share of this urban population growth (90%) will be in Asia and Africa[21].

The development of the global middle-class society will also have a significant influence on future air traffic development through an increase of the proportion of the global population with sufficient available income for air travel. By the year 2050, this proportion will continue to grow strongly in the world population, eventually reaching 66%. Of particular importance for the development of air traffic is the growth of the middle class in Asia. Accordingly, aviation demand in the future will come especially from this region. By 2050, nearly 80% of global middle-class consumption will come from Asia with China and India making up the lion's share with a total of 55%[22,23].

In addition to purely demographic and socio-economic factors, general changes in future social values and behavior of global society will have some influence on aviation development in the future. Over the next few decades, there will be a continued increase in the importance of more active and healthier lifestyles in global society. At the same time, the urge for individualisation and more flexibility in global society will continue to grow. Also, more leisure time in society will

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[15] Cf. United Nations [UN] (2019).
[16] Cf. United Nations [UN] (2019).
[17] Cf. United Nations [UN] (2017).
[18] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).
[19] Cf. O`Neil. et. al. (2017).
[20] Cf. United Nations [UN] (2017).
[21] Cf. United Nations [UN] (2018).
[22] Cf. Futures Centre (2016).
[23] Cf. Futures Platform (2017).

be realised, e.g. by technological advances in automation, artificial intelligence or robotics. Leisure activities increasingly serve the purpose of self-realisation. In addition, the future society will continue to focus on individual wellbeing[24,25].

Other social trends that will shape the future society are the increased focus on smaller family sizes, a further increase in single-person households, the elimination of the "gender gap" and greater social networking with the help of digital technologies[26]. Also, the mobility behavior of the global society will change significantly in the coming decades. Mobility-as-a-Service (MaaS) approaches and sharing platforms will more and more replace privately owned cars. In addition, the need for flexible and comfortable mobility in society will continue to grow in importance[27,28].

The importance of environmental awareness in the global society will continue to grow until 2050. This will lead to an increased consumer culture in which any negative impact of traffic on society will not be accepted[13].

Technology

Technological advances in different areas will continue to have a significant impact on future aviation development. Especially concrete innovations and optimisations in the field of aviation technology have a direct impact on the cost-effectiveness, sustainability and performance of aircraft types. Vehicle-specific air traffic scenarios with different aviation technological assumptions, make it necessary to differentiate also in some key fields and factors from the technological "external" framework developments to ensure consistency and plausibility of the aviation scenarios.

According to the basic scenario characteristics of the DEPA 2050 project in the progressive scenario there will be greater progress in certain technology fields than in the conservative-evolutionary scenario. This includes in particular technologies that are necessary for the further development of specific aviation technologies until they are ready for the market. Thus, there is significantly greater progress in the field of advanced energy storage technologies in the progressive scenario which will enable hybrid-electric and all-electric aircraft concepts, particularly through more powerful battery technologies. With a high increase in the battery-pack specific energy by the year 2050, the prerequisites would be made possible for the extensive use of electric propulsion in aviation[29,30]. Major technological advances in areas such as Additive

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[24] Cf. Institute for Global Environmental Strategies [IGES] (2019).
[25] Cf. Mobility 4EU (2016).
[26] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).
[27] Cf. Institute for Global Environmental Strategies [IGES] (2019).
[28] Cf. European Commission (2018).
[29] Cf. Schäfer et al. (2019).
[30] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).

Manufacturing, robotics or smart production allow significant innovations and increases efficiency in aircraft maintenance in the progressive scenario.
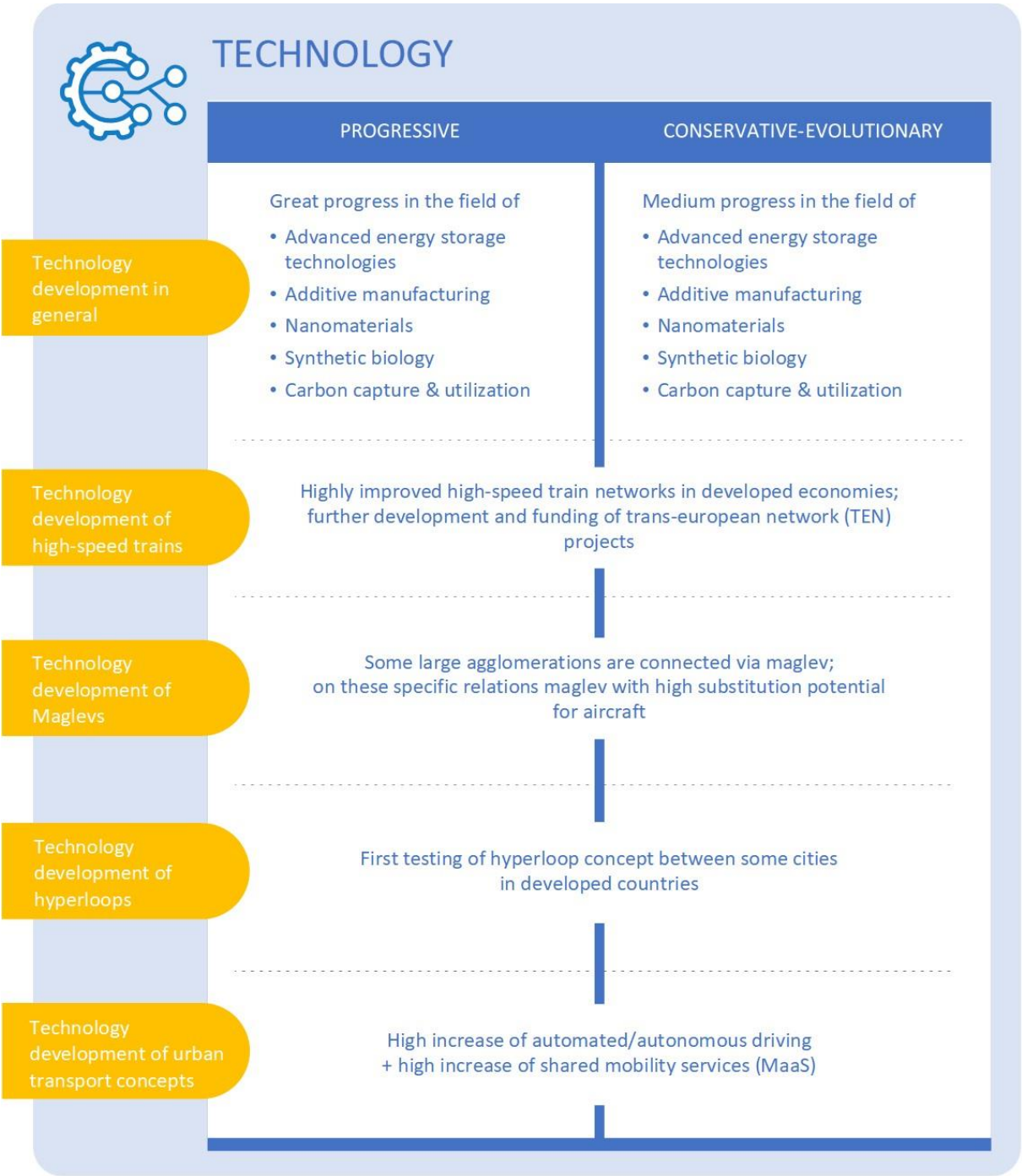

Figure 8: Central scenario assumptions for the key field "Technology"

In addition, the further development of nanomaterials enables great advances in aircraft construction. Examples include the integration of lightweight materials or nano-coatings of engine parts. The basic requirements for a larger proportion of SAF are the significantly greater

technological advances in the progressive scenario in areas such as synthetic biology and carbon capture & utilization (CCU), which can be used for the production of biokerosene and synthetic kerosene[31,16]. Research into new manufacturing processes for SAF (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. Efforts to enable the use of 100% SAF have been started by ASTM in February 2021.

Further technological factor developments are assumed to be largely the same for both scenarios. A wide variety of medical advances, such as in the field of neurotechnologies, support the already described increasing aging of the population. In the telecommunications and information technology sector, the widespread use of social media and various communication channels will lead to an increasing network of global friendships and business contacts.

At the same time, there will be significant advances in virtual reality over the next few decades. The diverse possibilities of telecommunications will represent an alternative for various business flights. However, these technologies will never be a complete substitute for face-to-face meetings made possible by air travel[32,33].

Further developments in traffic technology will lead to an expansion and optimisation of land-based modes of transport over the next few decades. Thus, there will be a continuous expansion of high-speed train connections (HGV) by 2050. Worldwide, new rail lines for HGV are currently being built over a total length of 10,000 kilometers; another 40,000 km are already being planned or are currently being discussed[34]. In addition to conventional high-speed trains, ultra-high-speed (UHS) rail will also gain in importance over the next few decades. On the one hand, this includes Maglevs, which will be built between various agglomeration areas in industrialised countries over the next few decades and which represent a great potential for substitution for flights on these routes. For example, the commissioning of a Maglev connection in Japan between Tokyo and Osaka is planned for 2027[20]. In addition, there will be the first test tracks for Hyperloops by 2050, which represent the second form of UHS. The first feasibility studies for the establishment of Hyperloop concepts between certain large cities, such as San Francisco - Los Angeles or Paris - Amsterdam, are currently being carried out[20].

In the future, mobility in urban areas will primarily be characterised by the increased use of sharing mobility services. Sharing offers such as bike sharing, car sharing or e-scooters will increasingly be combinable and bookable with other mobility services such as local public transport using MaaS approaches. These multimodal mobility services, which are tailored to the needs of the customer and can be booked through a central MaaS platform, will increasingly replace the private ownership of motor vehicles. In addition, automated and autonomous driving in road traffic will continue to gain in importance in the future, which will improve road safety and reduce traffic jams in the long term, especially in urban road traffic[35].

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[31] Cf. European Commission (2018).
[32] Cf. European Commission (2018).
[33] Cf. IATA (2011): Vision 2050.
[34] Cf. International Transport Forum [ITF] (2019).
[35] Cf. International Transport Forum [ITF] (2019).

Economy

Future air transport demand is strongly linked to global economic development. A look at the development of the world gross domestic product (GDP) shows that from 2030 to 2050 there will be an increase from 169 trillion dollars to 449 trillion dollars. Over the same period, there will be a stagnation or rather minimal decline of the annual global GDP growth rates from 3.03% in 2030 to 2.83% in 2050.

The increasing economic relevance of emerging economies in the global economy over the next few decades is leading to a significant shift of the world economic center of gravity from North America and Europe towards Asia. Within the much larger growth rates of the BRICS countries compared to OECD countries, China and India in particular are playing a major role. Thus, the economic power of these two countries in 2050 will be already greater than the total GDP of the USA, Western Europe and Japan. The increasing importance of these regions over the next few decades as markets for companies from various sectors goes along with the rapid growth of a new middle-class society with high consumption demand.[36],[37],[38]

Despite the described global economic developments, regional disparities will only be reduced to a limited extent in the coming decades. On the one hand there will be a modest reduction in regional disparities of disposable income in the coming decades. In 2050, however, there will still be large gaps in living standards between and within regions of the world[39],[40].

The world trade will grow slightly stronger than the global gross domestic product over the next few decades. The largest growth rates in trade of goods will occur in Asia and South/Central America. Overall, the average annual growth rate of 4% in emerging markets by 2050 will be significantly higher than in the current industrialised countries with 2.3%[41].

In addition to a further growing importance of the "platform economy", which comprises the trading and offering of services using digital platforms (e.g. Amazon, Airbnb or Uber), the "gig economy" will also become more important in the future. This includes the short-term awarding of small contracts to self-employed, freelancers or minor employed persons. Additionally, the importance of the "circular economy", which minimizes the use of resources and waste of energy by reusing them, will become increasingly important[42],[43].

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[36] Cf. Organisation for Economic Co-operation and Development [OECD] (2018).
[37] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).
[38] Cf. The Economist Intelligence Unit [EIU] (2015).
[39] Cf. Organisation for Economic Co-operation and Development [OECD] (2012).
[40] Cf. O`Neil, B. et. al. (2017).
[41] Cf. International Transport Forum [ITF] (2019).
[42] Cf. European Commission (2018).
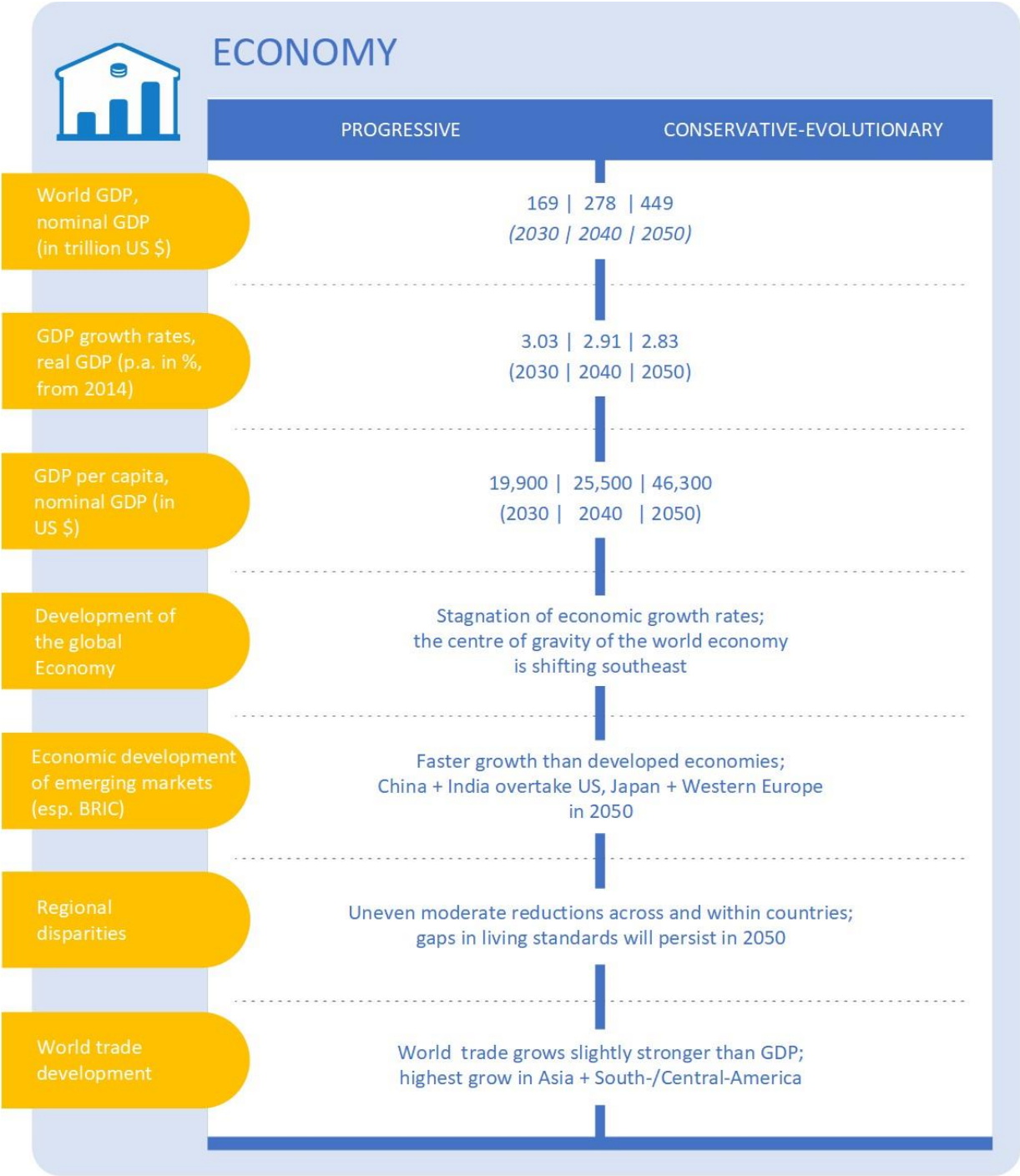[43] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).

ECONOMY

	PROGRESSIVE	CONSERVATIVE-EVOLUTIONARY
World GDP, nominal GDP (in trillion US $)	169 | 278 | 449 (2030 | 2040 | 2050)	
GDP growth rates, real GDP (p.a. in %, from 2014)	3.03 | 2.91 | 2.83 (2030 | 2040 | 2050)	
GDP per capita, nominal GDP (in US $)	19,900 | 25,500 | 46,300 (2030 | 2040 | 2050)	
Development of the global Economy	Stagnation of economic growth rates; the centre of gravity of the world economy is shifting southeast	
Economic development of emerging markets (esp. BRIC)	Faster growth than developed economies; China + India overtake US, Japan + Western Europe in 2050	
Regional disparities	Uneven moderate reductions across and within countries; gaps in living standards will persist in 2050	
World trade development	World trade grows slightly stronger than GDP; highest grow in Asia + South-/Central-America	

Figure 9: Central scenario assumptions for the key field "Economy"

Energy / Environment

The development of the global environmental system will continue to be negatively impacted by climate change and greenhouse gas emissions in the coming decades. However, especially with the help of energy technology developments, it is possible to successively reduce global

emissions. Moreover, as different advances in energy technologies are a fundamental requirement for the two air traffic scenarios (progressive and conservative-evolutionary) regarded in this study it is important to differentiate assumptions also in this framework development key field.

ENERGY

	PROGRESSIVE	CONSERVATIVE-EVOLUTIONARY
Energy demand (in EJ, in 2050)	Primary energy: 633 EJ Final energy: 423 EJ	Primary energy: 796 EJ Final energy: 575 EJ
Share of low-carbon Energy (in %, in 2050)	Primary energy: 57 % Final energy: 46 %	Primary energy: 30 % Final energy: 25 %
Energy price (crude oil import price in 2015 USD/bbl)	85 | 78 | 72 (2030 | 2040 | 2050)	111 | 124 | 137 (2030 | 2040 | 2050)
Fuel costs	Low fuel costs for alternative + conventional fuels	High fuel costs for alternative fuels + conventional fuels

Figure 10: Central scenario assumptions for the key field "Energy"

With the objective to develop plausible assumptions and concrete values for this key field, the energy technology scenarios of the International Energy Agency (IEA) were used. Energy technological assumptions for the conservative-evolutionary scenario are based on the so-called "Reference Technology Scenario" of the IEA, which describes average energy technology advances up to the year 2050. For the progressive scenario, however, a connection to the "2DS Scenario" of the IEA is made, which assumes significantly greater energy technology advances in the coming decades[44].

Thus, in the progressive scenario significantly greater reductions of emissions will be achieved with the help of energy technology innovations than in the conservative-evolutionary scenario. This is made possible especially by significantly greater energy efficiency increases, which in turn means that less energy is needed overall. For example, in 2050 the primary energy demand in the progressive scenario is 633 EJ and in the conservative-evolutionary scenario 796 EJ.

Demand for final energy, which includes the main end user sectors transport, housing, industry and agriculture is 423 EJ in the progressive scenario in 2050 and 575 EJ in the conservative-evolutionary scenario. In addition to higher increases in efficiency, the share of renewable energy in the progressive scenario is significantly higher than in the conservative-evolutionary scenario.

According to this, in the year 2050 this amounts to 57% for primary energies in the progressive scenario and only 30% in the conservative-evolutionary scenario. For final energy the share of renewable energies in the progressive scenario amounts to 46% in 2050 and only 25% in the conservative-evolutionary scenario[45].

Policies

Over the next few decades, countries such as China, India, Brazil and other BRICS countries and emerging economies will play a bigger role in world politics. Thus, similar to the already described economic developments, an increasingly multipolar world will occur until 2050.

In addition to a further market-oriented orientation with economic growth, climate policy goals will become more important in future world politics due to the increasing awareness of the effects of climate change. For example, there will be ambitious political goals to use natural resources more effectively and in a more sustainable manner. For example, the European Green Deal has the objective to reduce transport emissions by 90 % compared to 1990 levels.[46,47]

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[44] Cf. IEA (2017).
[45] Cf. IEA (2017).
[46] Cf. Organisation for Economic Co-operation and Development [OECD] (2016).
[47] Cf. European Commission (2020a).
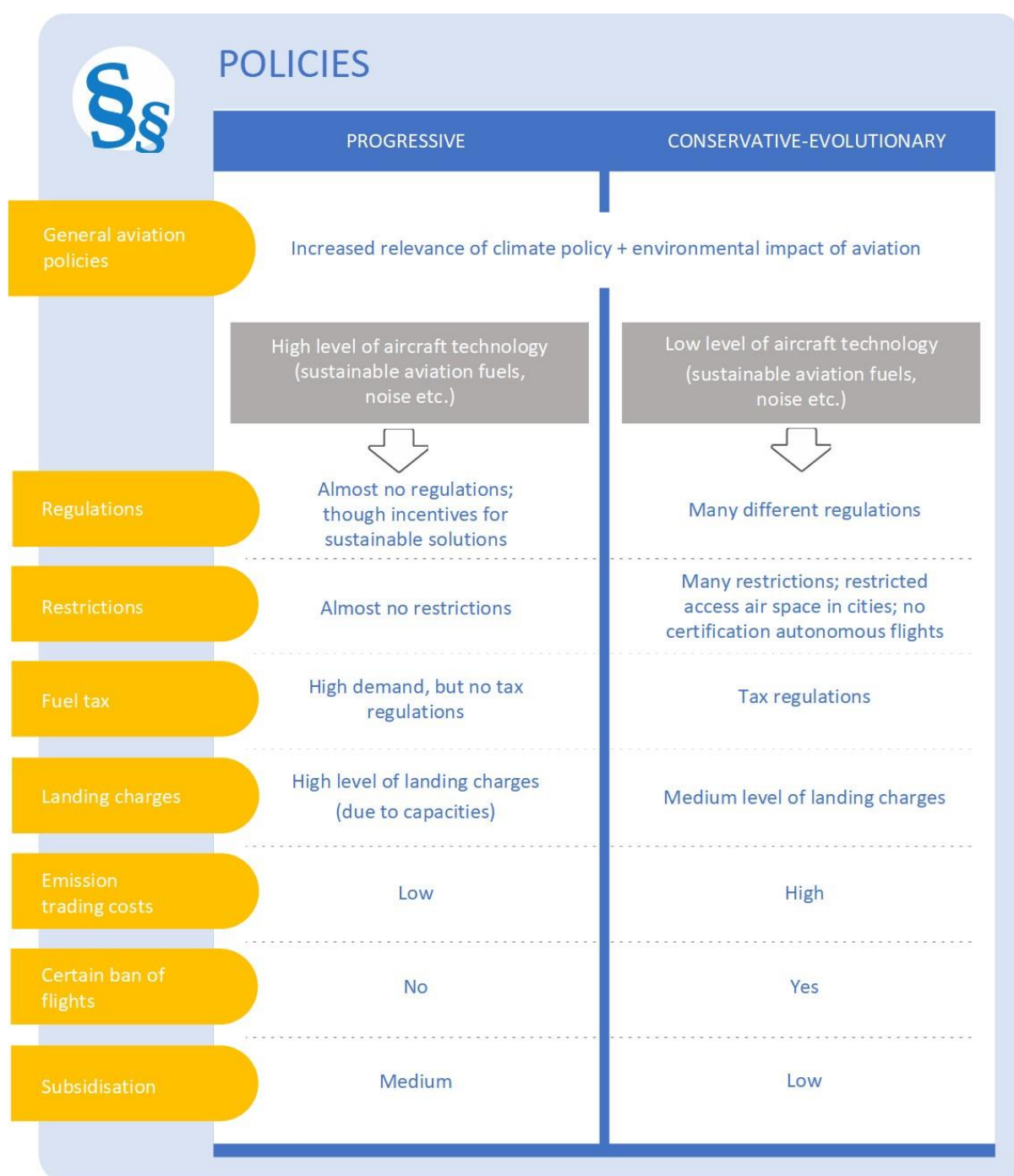
Figure 11: Central scenario assumptions for the key field "Policies"

However, the degree of target achievement of these political ambitions is significantly higher in the progressive scenario due to greater technological advances than in the conservative-evolutionary scenario.

In the next few decades, climate policy objectives and environmental impacts from aviation will also become more important for the aviation policy framework. However, due to the greater

advances in aviation technology in the progressive scenario (see section 3.1.5. for detailed assumptions) the degree of target achievement in this world is significantly higher than in the conservative-evolutionary scenario. Thus, more technological advances in areas such as sustainable aviation fuels or aircraft noise reduction in the progressive scenario lead to fewer restrictions and regulations than in the conservative-evolutionary scenario. As a consequence, the need for regulatory intervention decreases with the increase in aviation technology success.

In contrast, the landing fees are higher in the progressive scenario than in the conservative-evolutionary scenario due to the larger amount of flight movements. The emission trading costs are lower in the progressive scenario as the already high proportion of "green" or "clean" technologies is greater than in the conservative-evolutionary scenario. The same applies to the ban on domestic flights or night bans. Due to generally more environmentally-friendly and quieter vehicles, there are almost no domestic flight bans or night flight bans in the progressive scenario, though in the conservative-evolutionary scenario bans are still existent.

3.1.5. Vehicle-specific Scenarios

After the external framework developments - on which the respective scenarios are based - were described in the previous section, the progressive and the conservative-evolutionary scenario for the different vehicle types are explained in this section.

Mainliner
In the progressive scenario for mainliner aircraft, the share of SAF will increase from 10 to 20% in 2030 to 70 to 90% in 2050. It is assumed that there is a CO_2 reduction potential of around 80% over the life cycle for the non-fossil fuel shares. In the conservative-evolutionary scenario a share of 30-50% SAF will be achieved in 2050.[48]

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[48] See also section 4.7 for more detailed values/assumptions.

MAINLINER

- Medium fuel efficiency improvements

- Retrofit of aircraft

- Medium importance of sustainable aviation fuels (SAF)

- Few MRO (maintenance, repair & overhaul) improvements
- Lower importance of robotics and sensor technology

- Some advances in noise reduction; several measures

- Only some aircraft weight reduction advances

CONSERVATIVE-EVOLUTIONARY

- Sustainable aviation fuels (SAF): 5-10 %

- Entry-into-service (EIS): Riblets for long range (lr) and for medium range (mr)

- Entry-into-service (EIS): Sectorless air traffic management (ATM)

- Entry-into-service (EIS): Hybrid-laminar flow control for long range (lr)

- Sustainable aviation fuels (SAF): 30-50 %
- Entry-into-service (EIS): CLAIRE 3

2030	2035	2040	2045	2050

- SAF: 10-20 %
- EIS: Natural laminar flow (mr)
- EIS: Sectorless ATM

- Entry-into-service (EIS): Hybrid-laminar flow control (lr)
- Entry-into-service (EIS): A380 neo

- Entry-into-service (EIS): hybrid-electrical aircrafts (mr)
- Entry-into-service (EIS): CLAIRE 3

- EIS: hydrogen powered aircraft (lr)
- EIS: distributed propulsion (lr)
- EIS: Blended Wing Body
- EIS: „Double Bubble"

- SAF: 70-90 %
- EIS hybrid-electrical aircraft (lr)

PROGRESSIVE

- High fuel efficiency improvements

- New aircraft types + retrofits

- High importance of sustainable aviation fuels (SAF), hydrogen, electrical propulsion

- High importance of robotics & sensor technology
- Self-diagnosing aircrafts
- Prescriptive maintenance
- Significant improvement of aircraft utilization (new MRO Technology)
- Digitalisation, artificial Intelligence, cloud, block chain technology

- Significant advances in noise reduction; several measures

- Aircraft weight reduction, consideration of new materials in aircraft design process
- Extensive use of thermoplastics

Figure 12: Aviation technology assumptions for mainliner aircraft

While in the conservative-evolutionary scenario neither fully electric nor hybrid-electric aircraft concepts become operational, in the progressive scenario the EIS of hybrid-electric mainliners on short and medium-haul routes in 2040 and even on long-haul routes in 2050 are possible. In addition, in the progressive scenario, hydrogen-powered aircraft could be available from 2045 onwards. In the conservative evolutionary scenario, this technology does not play a role for mainliners.
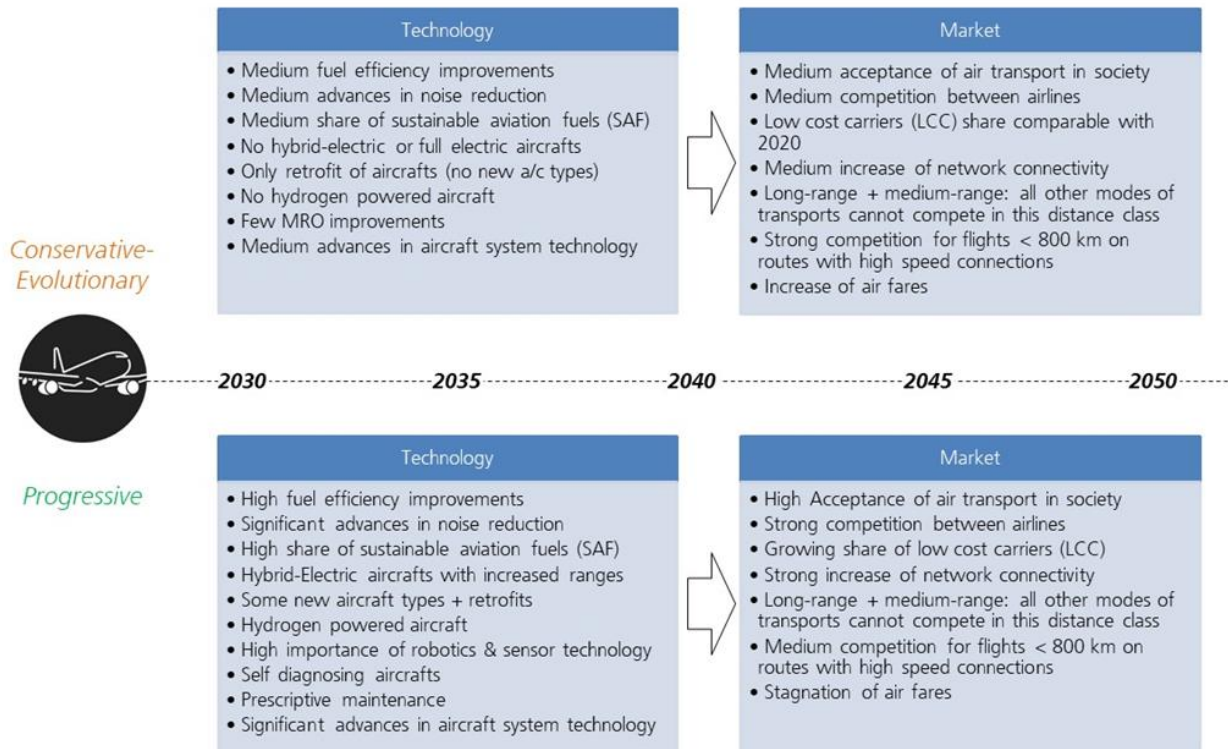
Figure 13: Aviation technological and aviation market related assumptions for the mainliner scenarios

The effects of the generally significantly larger share of "green" propulsion technologies in the progressive scenario are on the one hand that the acceptance in society for aviation increases significantly. Also, the costs for emissions trading are significantly reduced. On the other hand, the development costs for such technologies are significantly higher than in the conservative-evolutionary scenario, in which the proportion of these alternative propulsion technologies is significantly lower.

Due to the large aircraft size and on average longer flight distances of these vehicle types, the relevance of SAF for mainliners overall (in both scenarios) is significantly greater than for electrified vehicle concepts. A look at the increases in fuel efficiency shows that these are significantly greater in the progressive scenario than in the conservative-evolutionary scenario and, accordingly, the operational costs can also be significantly reduced. In addition, aircraft noise

reduction measures are significantly more successful in the progressive scenario, which in turn has a positive influence on the social acceptance of air traffic.

As can be seen on figure 12 and figure 13, the combination of consistent elements (e.g. 10 years earlier EIS of sectorless ATM and a resulting stronger increase of network connectivity in the progressive scenario) ensure the compatibility of the respective assumptions in both scenarios.

Next to significant weight reductions in aircraft construction, new aircraft types are also introduced in the progressive scenario. From the year 2045 onwards, blended wing body aircraft or "double bubble" aircraft concepts could enter the market. In the conservative-evolutionary scenario, only retrofits or modifications of existing aircraft types are implemented. In the field of maintenance, in the progressive scenario, the increasing use of robotics and sensor technologies, self-diagnosing aircraft and predictive maintenance will lead to a significant increase in aircraft utilization. As can be seen in figure 13, in the progressive scenario, the EIS of technological components from the aircraft system technology area is significantly earlier than in the conservative evolutionary scenario. In addition, sectorless air traffic management will be introduced ten years earlier in the progressive scenario than in the conservative-evolutionary scenario.

Supersonics

The possible future market developments of supersonic aircraft are primarily determined by further aviation technological developments and optimizations, which have a direct influence on the potential areas of application of this type of vehicle and therefore also influence market demand (see also detailed supersonic technology assessment and outlook in section 4.8.1.).

The scenarios outlined in the following represent the basic assumptions for the modelling of the supersonic scenarios in section 3.3.3

The main differences between the two supersonic scenarios and the respective central assumptions can be seen in Table 6.

Assuming significantly greater technological advances in the progressive scenario, in this scenario it is possible to significantly reduce the sonic boom with the help of low boom technology. As a result, with a market launch in 2025, flights over sea and over land will be possible at supersonic speeds. In the conservative-evolutionary scenario, flight phases at supersonic speed will only be permitted over the sea, since no significant progress has been made in reducing the sonic boom, which results in restrictions on supersonic flights over land. In addition, in the conservative-evolutionary scenario, a worldwide coastal buffer of 50 km must be considered, in which supersonics are not allowed to fly at supersonic speeds. The effects of these restrictions are that, in the progressive scenario, significantly more routes with significant time advantages compared to subsonic flights can be realised.

Table 6: Overview of central assumptions for the supersonic scenarios

Factor / Assumption	Progressive Scenario	Conservative-Evolutionary Scenario
Supersonic over-land Flight Restrictions	No (more feasible routes)	Yes (fewer feasible routes)
NOx Emission Level	Lower Emissions	Higher Emissions
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 SST time savings for feasibility	1 hr.	1 hr.
Minimum realtive SST time savings for feasibility	15%	15%

One consequence of the significantly greater demand for supersonic flights in the progressive scenario are stricter emission standards. Coupled with the generally greater technological advances in the progressive scenario, this will result in lower emissions from supersonic aircraft. In the conservative-evolutionary scenario, however, the emissions will be significantly higher. On the one hand, because of the generally higher emissions from engines due to lower technological advances. On the other hand, due to the mission-related additional acceleration phases, since in the conservative-evolutionary scenario more frequently switching between subsonic and supersonic phases have to be done and no, as in the progressive scenario, continuously supersonic speeds can be flown.

The demand for supersonic flights is therefore significantly greater in the progressive scenario than in the conservative-evolutionary scenario. On the one hand, this result is caused by the significantly higher number of airport connections with significant time savings compared to subsonic air traffic. On the other hand, another driver is the greater acceptance of supersonic flights, which among other things results from the lower emissions compared to the conservative-evolutionary scenario. As can be seen on table 8, the proportion of premium passengers who would switch from subsonic connections to corresponding supersonic connections is 30% in the progressive scenario and 20% in the conservative-evolutionary scenario. The proportion of additionally generated passengers on routes due to new supersonic connections is significantly higher in the progressive scenario with 15% than in the conservative-evolutionary scenario with 10%.

SUPERSONIC

CONSERVATIVE-EVOLUTIONARY

- Medium fuel efficiency improvements
- No reduction of sonic boom effect
- Medium importance of sustainable aviation fuels (SAF)
- Niche market
- Low profitability
- Routes only over sea and minimum 50 km coastline distance

- Some advances in noise reduction; several measures
- Medium speed improvements

2030	2035	2040	2045	2050

Above (Conservative-Evolutionary):
- Sustainable aviation fuels (SAF): 5-10 % (2030)
- Entry-into-service (EIS): Sectorless ATM (2040)
- Entry-into-service (EIS): Hybrid laminar flow control (2045)
- Sustainable aviation fuels (SAF): 30-50 % (2050)

Below (Progressive):
- Sustainable aviation fuels (SAF): 10-20 % / Entry-into-service (EIS): Sectorless ATM (2030)
- Entry-into-service (EIS): Hybrid laminar flow control (2035)
- Entry-into-service (EIS): Distributed Propulsion (2045)
- Sustainable aviation fuels (SAF): 70-90 % (2050)

PROGRESSIVE

- High fuel efficiency improvements
- Reduction of sonic boom effect
- High importance of sustainable aviation fuels (SAF)
- Successive supply expansion
- Successful reduction of sonic boom effect enables supersonic cruise speed over land & over sea

- Significant advances in noise reduction; several measures
- Significant speed improvements

Figure 14: Aviation technology assumptions for supersonic aircraft

The minimum number of two roundtrips per week required to operate a supersonic route economically is identical in both scenarios. Due to the lower proportions in the conservative-evolutionary scenario regarding switching and induced demand compared to the progressive scenario, automatically more routes are classified as "not economical" and accordingly are not considered in the supersonic network. In addition, the minimum time savings (1 hour absolute, 15% relative) that a supersonic aircraft has to achieve compared to a subsonic aircraft on a route is not differentiated between the scenarios. Due to the lower technological developments in the conservative-evolutionary scenario and the resulting ban on supersonic overland flights, fewer routes or rather a smaller network are realised compared to the progressive scenario, despite of the same minimum time savings criterium.

In addition to the scenario-specific developments of commercial supersonics that have been explained in the previous sections, supersonic business jets will also play a role in the progressive scenario and the conservative-evolutionary scenario. While these will enter the market in the progressive scenario in 2027, the entry-into-service in the conservative-evolutionary scenario will be in 2030. The introduction of a low boom supersonic business jet significantly increases vehicle demand in the progressive scenario, whereas in the conservative-evolutionary no reduction of the sonic boom effect could be realised.

Urban Air Mobility

The future market development of urban air mobility (UAM) will be influenced not only by the further development of suitable vehicle concepts and technologies, but also, above all, by legal regulations, social acceptance and the development of an adequate infrastructure. Thus, all these factors are crucial for the development of successful and suitable UAM business models. (see also detailed UAM technology assessment and outlook in section 4.8.3.).

The scenarios outlined in the following represent the basic assumptions for the modelling of the UAM scenarios in Section 3.3.4

Table 7 shows the main differences and central assumptions for both UAM scenarios. Accordingly, the proportion of the population that can afford UAM transports is greater in the progressive scenario than in the conservative-evolutionary scenario.

The infrastructural equipment for UAM with regard to the number and capacity of landing sites is also greater in the progressive scenario than in the conservative-evolutionary scenario. Together with the significantly lower operational restrictions and the aforementioned vehicle-specific more technologically innovative parameters in the progressive scenario, this leads to a significantly higher UAM demand than in the conservative-evolutionary scenario.

In the conservative-evolutionary scenario, UAM vehicles have - due to the generally lower technological progress in this scenario - only short ranges, low payloads and low cruise speeds.

Table 7: Central assumptions for the UAM scenarios

Factor / assumption	Progressive scenario	Conservative-evolutionary scenario
Total mobility demand (number of daily trips per person)	3,2	
Potential UAM demand	same	
Share of UAM for which people are willing / able to pay	high	low
Share of UAM handled depending on availability of TOLA	high	low
Share of UAM which can be handled based on TOLA capacity	high	low
Share of UAM handled depending on operational restrictions	high	low
Range of UAM vehicle	high	low
Seat capacity of UAM vehicle	high	low
Utilization of UAM vehicle	high	low
Cost/Price for UAM trips	low	high
Final UAM demand	high	low

The low progress in the field of battery technologies and autonomous flight technologies means that UAM traffic will still be dependent on pilots in the future and the technological performance indicators of the vehicles are significantly lower compared to the UAM vehicles in the progressive scenario. Also in 2050 only two passenger seats on average will be offered in UAM vehicles. At the same time, UAM trips are very expensive in the conservative-evolutionary scenario and are therefore primarily reserved for wealthy customers and/or business travelers. The public acceptance and political support for UAM is low in this scenario. In addition, the infrastructural equipment for UAM vehicles - vertiports with suitable charging infrastructure - is significantly less than in the progressive scenario. In the conservative-evolutionary scenario, UAM therefore remains exclusively a niche market for premium passengers.
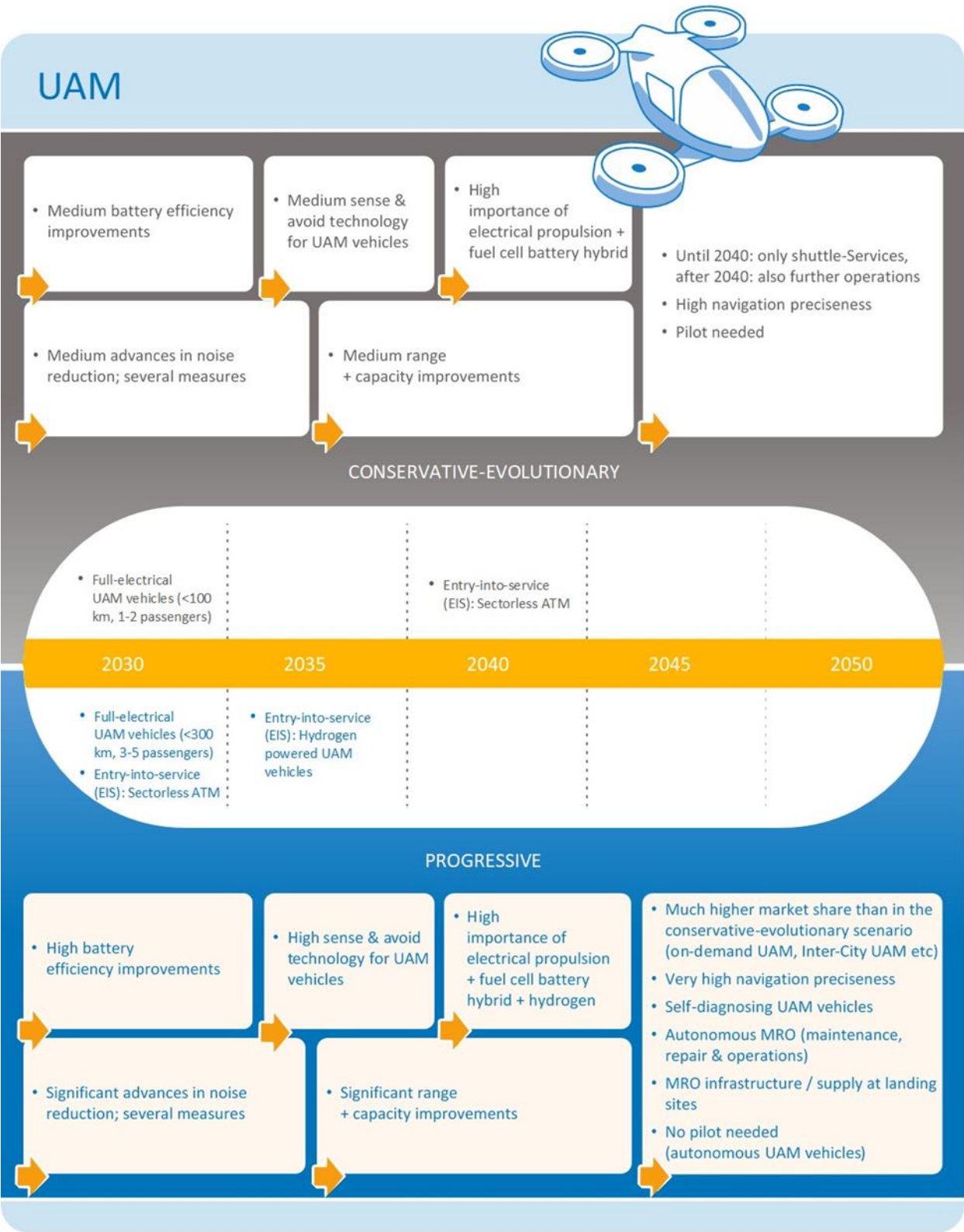
Figure 15: Aviation technology assumptions for UAM vehicles

In the progressive scenario, however, UAM is an integrated part of the urban transport system. Due to the enormous technological advances in this scenario, it is possible to significantly increase the range, speed and payload of UAM vehicles. Major advances in battery technology and autonomous flight technologies are also leading to a correspondingly larger market expansion of urban air mobility. In addition to airport shuttles and intra-city transport, UAM vehicles are also increasingly being used for inter-city transport. There is a high level of acceptance among the population, especially due to the significantly lower noise emissions from these new vehicles compared to the conservative-evolutionary scenario.[49] The costs for UAM transport are lower and roughly comparable to conventional taxi prices. Especially, due to the significantly greater availabilities of landing sites and corresponding UAM infrastructure in large cities, significantly more UAM traffic can be realised. Compared to the conservative-evolutionary scenario, urban air mobility is not only available in megacities of highly developed countries, but also in smaller cities worldwide.

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[49] Cf. also section 5.3.3.

Regional aircraft, business jet, small air transport, rotorcraft

REGIONAL AIRCRAFT

CONSERVATIVE-EVOLUTIONARY

- Medium fuel efficiency improvements

- Retrofit of aircrafts

- Medium importance of sustainable aviation fuels (SAF)

- Few MRO (maintenance, repair & overhaul) improvements
- Lower importance of robotics and sensor technology

- Some advances in noise reduction; several measures

- Only some aircraft weight reduction advances

- Sustainable aviation fuels (SAF): 5-10 %

- Entry-into-service (EIS): Riblets

- Entry-into-service (EIS): Sectorless ATM

- Sustainable aviation fuels (SAF): 30-50 %
- Entry-into-service (EIS): CLAIRE 3

2030	2035	2040	2045	2050

- SAF: 10-20 %
- EIS: Natural laminar flow
- EIS: Sectorless ATM

- Entry-into-service (EIS): Hybrid-electrical aircrafts
- Entry-into-service (EIS): CLAIRE 3

- Sustainable aviation fuels (SAF): 70-90 %

PROGRESSIVE

- High fuel efficiency improvements

- New aircraft types + retrofits

- High importance of sustainable aviation fuels (SAF), hydrogen, electrical propulsion

- High importance of robotics & sensor Technology
- Self-diagnosing aircrafts
- Prescriptive maintenance
- Significant improvement of aircraft utilization (new MRO technology)
- Digitalisation, artificial intelligence, cloud, block chain technology

- Significant advances in noise reduction; several measures

- Aircraft weight reduction, Consideration of new materials in Aircraft Design Process
- Extensive use of Thermoplastics

Figure 16: Aviation technology assumptions for regional aircraft

BUSINESS JET

CONSERVATIVE-EVOLUTIONARY

- Medium fuel efficiency improvements
- Retrofit of aircrafts
- Medium importance of sustainable aviation fuels (SAF)
- Few MRO (maintenance, repair & overhaul) improvements
- Lower importance of robotics and sensor technology
- Some advances in noise reduction; several measures
- Only some aircraft weight reduction advances

Timeline:

- 2030: Sustainable aviation fuels (SAF): 5-10 %
- 2035: Entry-into-service (EIS): Riblets
- 2040: Entry-into-service (EIS): Sectorless ATM; SBAS (Satellite based Augmention System) instead of ILS (Instrument landing system)
- 2050: Sustainable aviation fuels (SAF): 30-50 %; Entry-into-service (EIS): CLAIRE 3

Timeline (Progressive, below):

- 2030: SAF: 10-20 %; EIS Natural laminar flow; EIS Sectorless ATM; SBAS instead of ILS
- 2040: Entry-into-service (EIS): CLAIRE 3
- 2050: Sustainable aviation fuels (SAF): 70-90 %

PROGRESSIVE

- High fuel efficiency improvements
- New aircraft types + retrofits
- High importance of sustainable aviation fuels (SAF)
- High importance of robotics & sensor Technology
- Self-diagnosing aircrafts
- Prescriptive maintenance
- Significant improvement of aircraft utilization (new MRO technology)
- Digitalisation, artificial intelligence, cloud, block chain technology
- Significant advances in noise reduction; several measures
- Aircraft weight reduction, consideration of new materials in Aircraft Design Process
- Extensive use of thermoplastics

Figure 17: Aviation technology assumptions for business jet

Figure 18: Aviation technology assumptions for small air transport

ROTORCRAFT

CONSERVATIVE-EVOLUTIONARY

- Medium fuel efficiency improvements

- Retrofit of rotorcrafts

- Medium importance of sustainable aviation fuels (SAF) + electrical propulsion

- Few MRO (maintenance, repair & overhaul) improvements
- Lower importance of robotics and sensor technology

- Some advances in noise reduction; several measures

- Medium speed improvements

- Sustainable aviation fuels (SAF): : 5-10 %

- Entry-into-service (EIS): Sectorless ATM
- Entry-into-service (EIS): Hybrid-electric rotorcrafts

- Sustainable aviation fuels (SAF): 30-50 %

2030	2035	2040	2045	2050

- Sustainable aviation fuels (SAF): 10-20 %
- Entry-into-service (EIS): Sectorless ATM

- Entry-into-service (EIS): Hybrid-electric rotorcrafts

- Sustainable aviation fuels (SAF): 70-90 %

PROGRESSIVE

- High fuel efficiency improvements

- New rotorcraft types+ retrofits

- High importance of sustainable aviation fuels (SAF) + electrical propulsion

- High importance of robotics & sensor Technology
- Self-diagnosing aircrafts
- Prescriptive maintenance
- Significant improvement of aircraft utilization (new MRO technology)
- Digitalisation, artificial intelligence, cloud, block chain technology

- Significant advances in noise reduction; several measures

- Significant speed improvements

Figure 19: Aviation technology assumptions for rotorcraft

3.2. COVID-19 impact on aviation and DEPA 2050 scenarios

The objective of this section is to identify first effects of the global COVID-19 pandemic on global air traffic in 2020 and to outline the resulting influences on the defined DEPA 2050 air traffic scenarios.

The aviation industry is considered as one of the most affected industries by the current global COVID-19 pandemic. Although the global air traffic has repeatedly recovered from previous crises (oil crisis, Gulf War, 9/11, SARS, financial crisis) and continued its positive growth trend. However, the current corona crisis represents the greatest challenge for the aviation industry with an unprecedented collapse in global air transport demand. Especially the rapid global spread of the coronavirus had serious effects on the aviation industry and differs from previous crises, which either only affected certain regions or did not involve far-reaching travel bans or health risks. The COVID-19 pandemic is therefore already being described by some experts as the "perfect storm" for the aviation industry. The duration of this crisis and the long-term effects on aviation are connected with great uncertainty and must therefore also be addressed in the course of DEPA 2050.

Demand

As mentioned at the beginning, the demand for air transport services has fallen drastically worldwide due to the corona crisis. Especially the various political country-specific measures for reducing the spread of the coronavirus (travel restrictions, lockdowns, border closings, quarantine measures etc.) led to the collapse of the international air traffic volume. Additionally, the demand side of air traffic in both central user groups - business and private - will be negatively impacted by the consequences of the corona crisis in the medium- and long-term. Especially the population's generally lower disposable income in connection with changed demand behavior will lead to this development.

On the one hand, the demand segment of business travel in aviation has fallen sharply. Especially business trips in the MICE sector (meetings, incentives, conferences, exhibitions) will be reduced significantly over a longer period of time. Accordingly, the travel budget of companies - as a result of the negative effects of the corona crisis on the global economy - is drastically reduced and primarily only used for "necessary" business trips (maintaining relationships with business partners and customers). In addition, the digital transformation of companies (teleworking, video conferencing, virtual mobility, etc.), which was already increased before the pandemic, is being driven forward, which could replace certain international business trips in the long-term. Especially for company-internal meetings where a relationship and trust already exist, such digital solutions could represent serious alternatives to air traffic in the future. Even a small reduction in business travel of 5-10% could lead to problems for airlines in the long term, as these user groups tend to generate very high revenues.[50,51]

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[50] Cf. Suau-Sanchez et al. (2020).

Private and vacation travel represent the second central demand segment in air traffic. This segment is also strongly affected in the course of the current corona crisis. As a result of unemployment and short-time working in many sections of the population and industries, there is less disposable income and therefore a smaller travel budget in the population, which automatically results in a reduced global demand for private and holiday travel. Depending on the duration of the global economic recovery, this will result in a tendency towards lower demand for private and holiday travel. Compared to business travel, health concerns related to COVID-19 also play a greater role in private and leisure travel. This could lead to a change in travel behavior in the medium-term, when, for example, "staycations" (vacations in the home region) will play a greater role than more distant destinations. [52,53]

Movements

The result of the effects of the corona crisis on air traffic demand explained in the previous sections is a dramatic decrease in global flight movements. At the beginning of the crisis, airlines tried to maintain their regular flight plans. However, the numerous restrictions described (lockdowns, border closings etc.) finally forced the airlines to shut down their flight supply. The unequal political reactions and restrictions of the countries and regions around the world as well as the lack of corresponding bilateral agreements led to a drastically reduction particularly of international/intercontinental air traffic. By looking at figure 20, the dramatic collapse in global air traffic volume - and in particular international flight movements – can be seen.

Analysing the decline in sales as a result of the decrease of passenger traffic, the dramatic situation for long-haul traffic becomes apparent. Thus, in 2020 a decline in sales from passenger traffic of 388-400 billion dollars in total is expected. The loss margin in domestic air traffic of 131-136 billion dollars is well below than in the international air traffic of 257-264 billion dollars. The effects from the corona crisis on the segment of long-haul flights in air traffic will probability last as longest. Thus, the unequal lifting of travel restrictions in the different countries and regions of the world will lead to an uneven resumption of international travel markets (business & private) (ICAO 2020). The uncertainty about a final recovery of air transport is also very high as outlined in more detail in the section about the demand forecast of the DEPA 2050 study (cf. section 3.3).

Fleet

The negative effects of the corona crisis already described also have devastating consequences for the various players in the aircraft industry (airlines, airports, aircraft manufacturers, suppliers, Maintenance, Repair and Overhaul (MRO) etc.). In response to the strong decrease in demand for air transport services, airlines have already grounded a large part of their fleets and primarily only

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[51] Cf. Roland Berger (2020b).
[52] Cf. Suau-Sanchez et al. (2020).
[53] Cf. Roland Berger (2020b).

operate with newer aircraft. At the same time, new aircraft orders by the airlines are canceled or postponed to a later date. This leads to heavy losses in sales for aircraft manufacturers and corresponding redundancies. In addition to the airlines and aircraft manufacturers, in particular also MRO-related services are affected by the corona crisis, as the demand for MRO is reduced accordingly due to the fleet grounding. Which of these grounded aircraft will finally be retired and therefore no longer required for MRO services cannot be foreseen in the short-term. The question of which types of aircraft will be used when the demand for air transport services increases again cannot yet be answered either. Thus, in total the coronavirus crisis might also be a catalyst for fleet renewal making the progressive scenario a little bit more probable than the conservative-evolutionary one while it could also lead to a reactivation of parked aircraft and a longer usage of parts of the existing fleet after air transport's full recovery due to increasing cost pressure on the airlines caused by the current situation. A clear tendency is not visible yet.
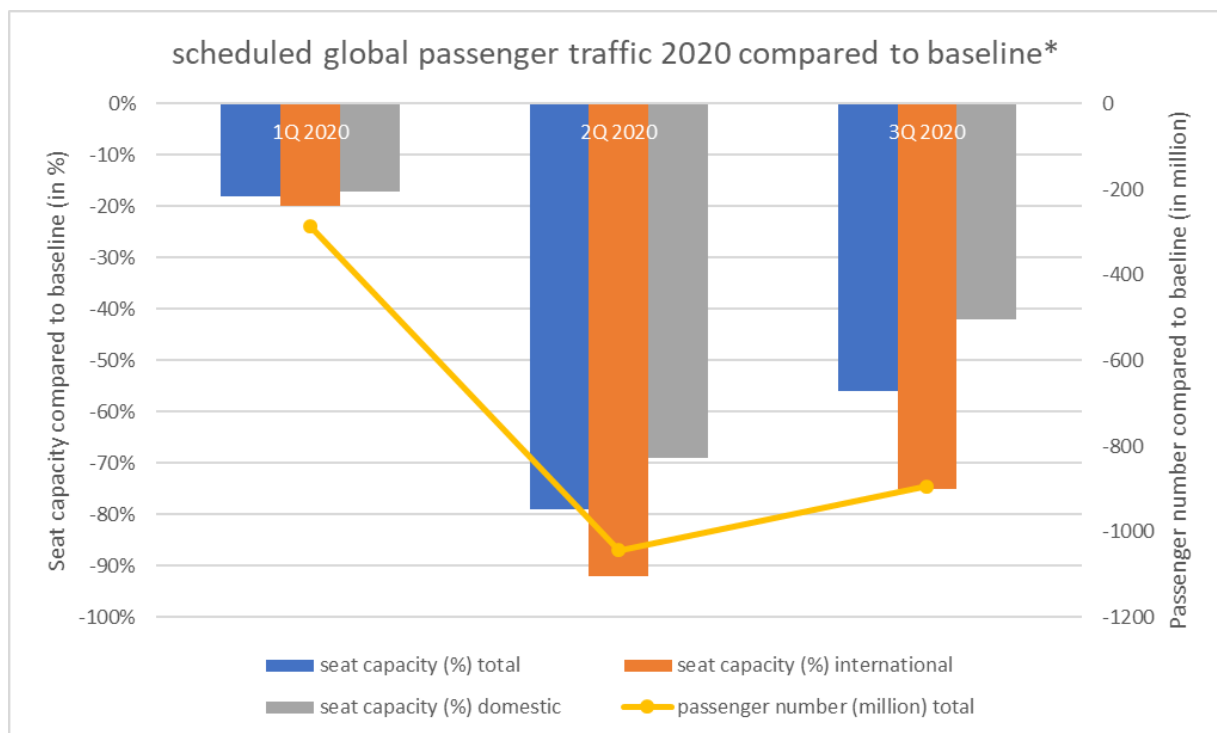
Figure 20: Impact of coronavirus on global scheduled passenger traffic; Baseline: Business as usual, originally-planned[54]

Thus, in the long term, due to the unclear further development and effects of the corona crisis, no estimations can yet be made on the likely development of aircraft orders or the development of new aircraft types. The extreme example of the Boeing 737 MAX shows how much new aircraft orders have decreased in the course of the corona crisis. Accordingly, in the period January-July of this year, 313 orders for this aircraft type were canceled and 192 orders for this

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[54] Own figure based on statistics of ICAO (2020a).

aircraft type were postponed to later dates. New orders for the A320neo from Airbus were canceled 29 times during the same period and were postponed to a later date in 143 cases. Initial forecasts assume a decline in new aircraft deliveries of 25-50% over the next 10 years.[55,56]

Potential trends

The further development of global air traffic in times of the corona crisis and in times after the corona crisis can only be forecasted with great uncertainty. The future development of global flight movements - depending on the further effects of the COVID-19 pandemic - can take a wide variety of forms.
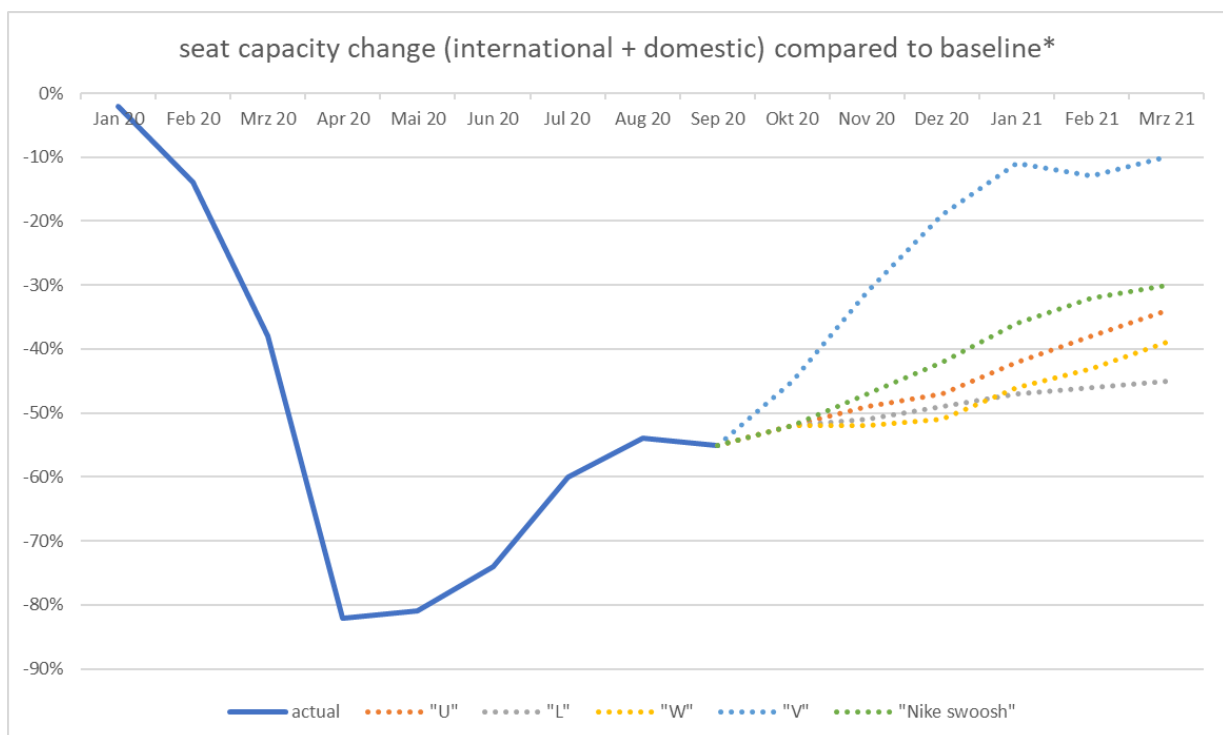
Figure 21: Possible developments of future global air transport; Baseline: Business as usual, originally-planned[57]

Figure 21 shows the various possible further developments of global air traffic based on the latest ICAO assessments. Depending on the scenario assumptions (which are not explained in detail here; only the range of possible developments should be shown) "U", "L", "W", "V" or even "Nike swoosh" profiles could describe the future air traffic developments. While a "V" development (short collapse, rapid recovery; as in most previous crises) is already assessed as

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[55] Cf. ICAO (2020a).
[56] Cf. Roland Berger (2020a).
[57] Own figure based on statistics of ICAO (2020a).

unrealistic, a possible "L" trend in future air traffic development represents the worst case, as it describes a constant trend to significantly lower supply levels than in pre-corona times.

Depending on which profile the future global air traffic development finally approximates, it can take years until the air traffic volume reaches values from 2019 again. Some forecasts assume that comparable volumes will only be achieved again in 2024 or even 2029 if the COVID-19 vaccine would not be effective.[58],[59]

The general effects of COVID-19 on the individual scenario categories of DEPA 2050 can be seen in the following figure.
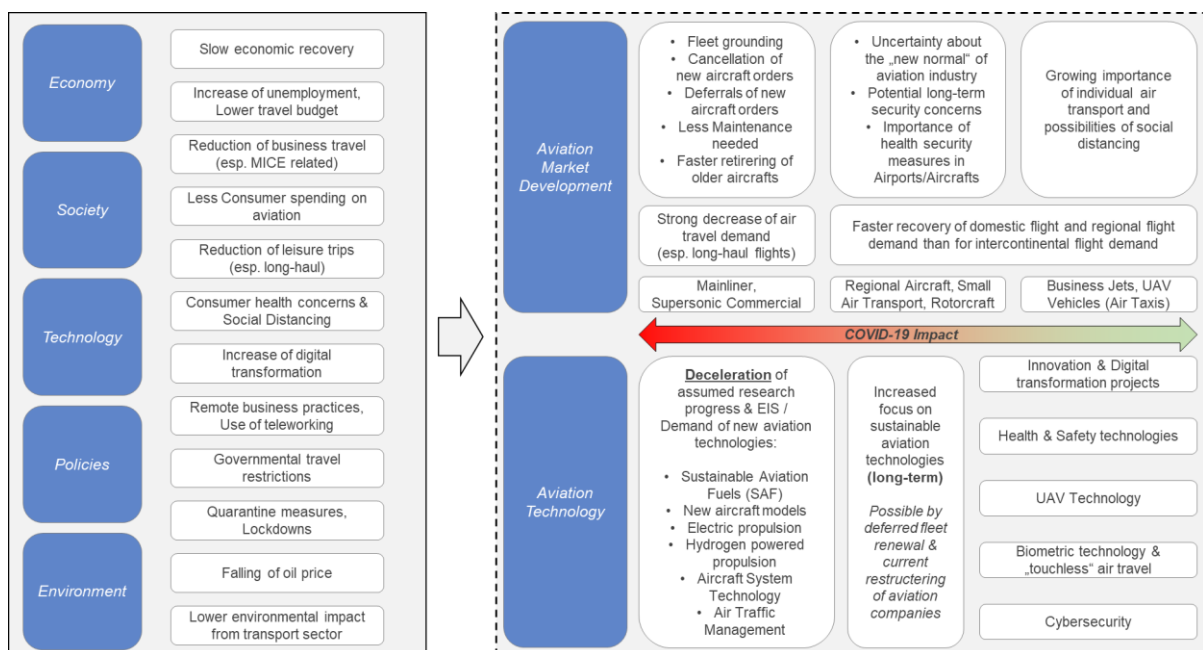
Figure 22: Central impacts from the COVID-19 pandemic on the DEPA 2050 scenario categories

Thus, the changes in the external framework developments ("Society", "Technology", "Economy", "Environment", "Policies") caused by the global pandemic have a direct impact on the aviation-specific scenario categories concentrated on aviation market development and aviation technology.

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[58] Cf. EUROCONTROL (2020a).
[59] Cf. ICAO (2020a).

3.3. Demand Forecast

3.3.1. Traffic Forecast Methodology for established Vehicle Concepts

This section covers the methodology of the passenger forecast 2014-2050. The methodology described in detail is applicable for the mainliner, regional and small air transport (SAT) passenger demand and flights, while for the business jet and rotorcraft forecast a different methodology is employed, which is based on a time series approach. The following figure summarises the model approach for the mainliner, regional and SAT:

- First, the unconstrained passenger demand and flight volume is forecasted by airport pair.
- Second, the passenger and flight volume are compared with current and expected airport capacity. The forecasted passenger and flight volume as well as the constraint situation at airports influence average future aircraft size, which is forecasted for each airport pair.
- Finally, expected passenger and flight volume is balanced with airport capacity and aircraft size development to yield the constrained passenger and flight volume.
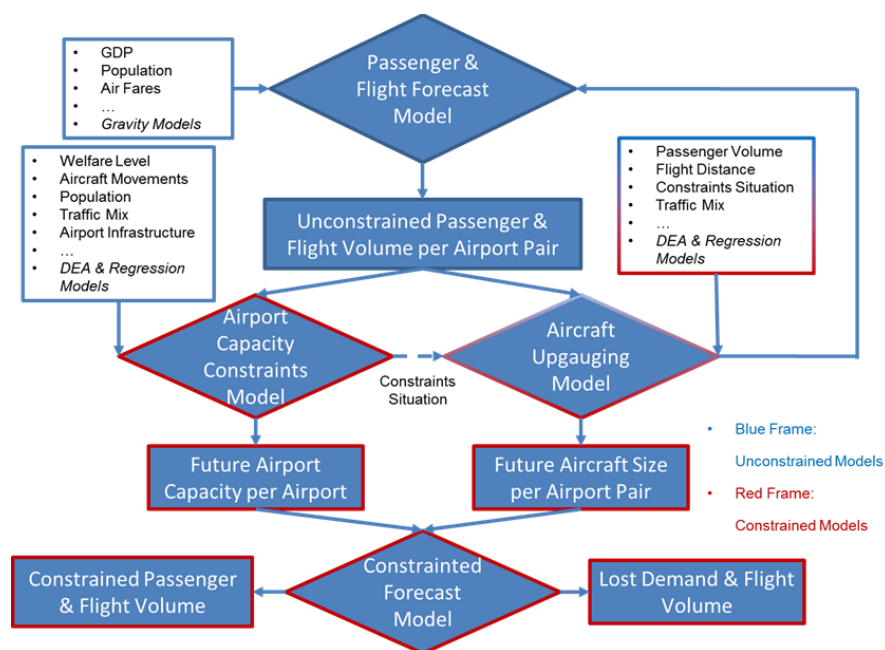
Figure 23: Overview of the mainliner, regional and SAT forecast models

The relationships between passenger demand, aircraft size and airport capacity are particularly important in a world where future airport capacity is limited, especially at the major hubs. The following figure displays this relationship between passenger demand (annual passenger volume), airport capacity (annual flight volume) and average aircraft size (passengers per aircraft) on a general level: In order to accommodate the forecast passenger demand, airport capacity in terms of flight movements is required, in combination with a pre-determined average aircraft size

(which is modelled endogenously). Both average aircraft size and airport capacity limit the maximum number of passengers that can be handled.

Aircraft size and airport capacity can substitute each other to some degree: If airport size is insufficient to serve a given passenger demand, increasing aircraft size can compensate for a lack of airport capacity to serve that demand. A lack in aircraft size can be substituted by more airport capacity, so that more flights, but with fewer average passengers per flight can be handled.

Typically, airport capacity is the bottleneck, as expansion of airport capacity, in particular the runway system, takes a long time or is even impossible e.g. because of limited available ground space or the opposition of the neighbouring population, especially in highly developed countries. A popular example for this is London Heathrow.
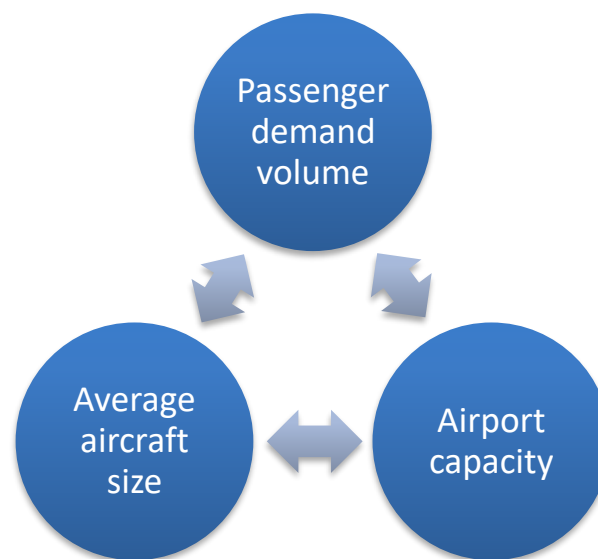
Figure 24: Relationship between passenger demand, airport capacity and aircraft size

The DLR model accounts for these interrelations between passenger demand, airport capacity and aircraft size by adjusting all three elements in a constrained forecast. This means for the future that there will be insufficient airport capacity (at least at a large number of major airports globally), an increase in average aircraft size and, ultimately, to some degree unserved passenger demand. In contrast, an unconstrained forecast always assumes the best case regarding the future development of airport capacities, which are not considered to become a bottleneck. However, this is not realistic as can be seen with the example of London Heathrow. Moreover, unconstrained forecasts underestimate the long-term increase in average aircraft size as a measure to compensate for the shortfall in airport capacity. The following description of the models is based upon the publication "Airport Capacity Constraints and Strategies for Mitigation – A Global Perspective". (2020).[60]

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[60] Cf. Gelhausen et al. (2020).

The origin-destination (OD) passenger demand model (cf. figure 25) is based on the fundamental theory of the gravity law. Whilst variables like distance, population and gross domestic product (GDP) are rather common in gravity models, we expected further insights by including an airfare variable. For better discrimination between different types of origin and destination, for example, tourist destinations, we have included variables such as tourism receipts and expenditures and population density. Furthermore, we have employed a Poisson pseudo maximum likelihood (PPML) estimator to produce better and more reliable forecast results. As result, a series of relevant demand elasticities have been derived from the model, e.g. if GDP per capita increases in the origin country by 1%, then OD passenger demand rises by 0.45% and if GDP per capacity rises in the destination region by 1%, the OD demand grows by 0.27%.
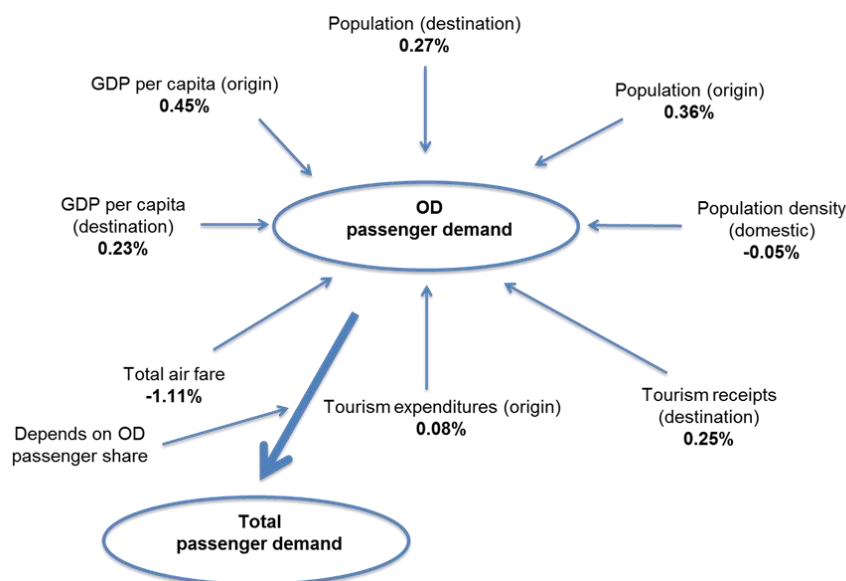
Figure 25: The OD Demand Model

For assessing the effects of limited airport capacity on global air traffic, the DLR model uses a problem-specific approach suited for application at the global level. However, it cannot be a substitute for a detailed capacity analysis in airport-specific studies. A data envelopment analysis (DEA) has been applied and a regression analysis was conducted based upon the DEA results. DEA is a non-parametric empirical method of operations research to estimate production frontiers employing linear programming techniques. This approach enables to compute current and future annual service volumes of airports worldwide. The model allows forecasting 5% peak hour volume and average hourly volume in a situation of the highest possible capacity utilisation.

The DLR model focuses on a method that produces robust results with input information which is generally available, i.e. the runway system, as this typically limits overall airport capacity in the long term. For our generic airport capacity model, we aimed for an as-high-as-possible degree of accuracy on average on global level, but we do not pretend it is as accurate as detailed airport capacity analyses for specific airports.

The approach for estimating future airport capacity is based on data envelopment analysis (DEA) and regression analysis. DEA is a standard tool for efficiency analyses and benchmarking of so-called decision-making units (DMUs). DEA allows us to compare DMUs which differ in their input and output structure. Examples of such DMUs comprise hospitals, energy production or cost-/profit-centres of large organisations and in our case airports. The model analyses airport capacity utilisation with the leading question in mind, "Which airport achieves what output given a particular input structure?" Figure 26 provides an overview of the airport capacity model:

- The first step is the aforementioned DEA analysis to estimate current airport capacity (figure 26)
- In a second step, the average number of aircraft movements per runway and operating hours at the highest possible level of capacity utilisation for each airport is calculated.
- The last step is to perform a regression analysis based on the DEA results.
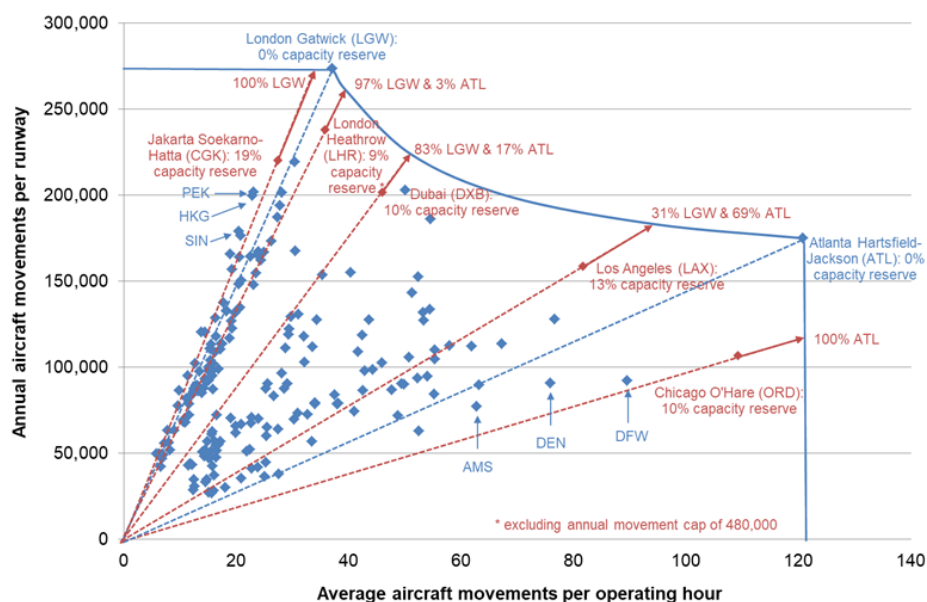
Figure 26: Estimation of the Generic Airport Capacity Model

With the model of forecasting realisation probabilities of airport capacity enlargements and limits, we have introduced an approach which incorporates limited airport capacity in air transport forecasts that varies over time. The starting point of the model is that if there is a current or future capacity gap at an airport, we need to analyse whether adding new runways is possible in time, with regard to the demand development, and, if realisation is not possible within an appropriate time, how long this process may be delayed or if capacity expansion is possible at all. This analysis is conducted for each airport and each new runway at an airport. The model is based on the idea that there is a particular degree of opposition to airport expansion from the population surrounding the airport. This depends on factors like noise annoyance, welfare level, economic opportunities, participation level and intermodal substitution. The degree of opposition may range from almost no opposition to such an intense opposition that airport expansion is

virtually impossible. As a result, the estimated model enables us to estimate the probability of realisation of a new runway which can be transformed into an expected value of delay. The approach used is a probabilistic one based on Markov chains[61] and discrete choice theory.[62]

The aircraft size model is an efficient and robust approach to forecast the development of the key forecast variable passengers per flight ("aircraft size") by airport pair to extend the forecast of airport capacities to available passenger volume capacities. As in the case of airport capacities, the approach is highly problem-specific and cannot be a substitute for a detailed flight route analysis in terms of aircraft fleet characteristics and their future development. The method is very similar to the modelling of airport capacities. The basic analysis is a DEA, which is further refined by regression analyses to generalise the results, so that they can be used for forecasting and projection, respectively.

In a first step, a DEA is performed for all airport pairs to obtain current values of passenger capacity potential and its utilisation for each airport pair. In the next step, these values are updated on the basis of the passenger demand forecast by means of the passenger capacity potential utilisation model and the passenger capacity potential model. Finally, we can calculate the future number of passengers per flight, which translates into the average aircraft size, when subsequently a seat load factor is applied. Here, we take a weighted average of the projected number of passengers per flight and the most recent DEA results, typically the base year of the forecast. The weights are calculated on the basis of the passenger volume for the base and the forecast year for each route. Thereby, we try to smooth large fluctuations on particular routes where we find large increases or decreases of passenger volumes.

3.3.2. Traffic Forecast Results for established Vehicle Concepts

In this section, we present the flight and passenger volume forecast results for mainliner and regional aircraft as well as business jets, rotorcraft and SAT. Starting point for the forecasts is the year 2014. From today's perspective, however, it may be questioned to what extent the coronavirus disease 2019 (COVID-19) crises would impact the long-term development of the market. Figure 27 illustrates the long-term development of global air transport in the light of major crises, which happened to occur around every ten years. After these previous crises, the sector used to return back to its original growth path within few months or years, sometimes even at an increased pace.

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[61] Cf. Markov (2006).
[62] Cf. McFadden (1974).
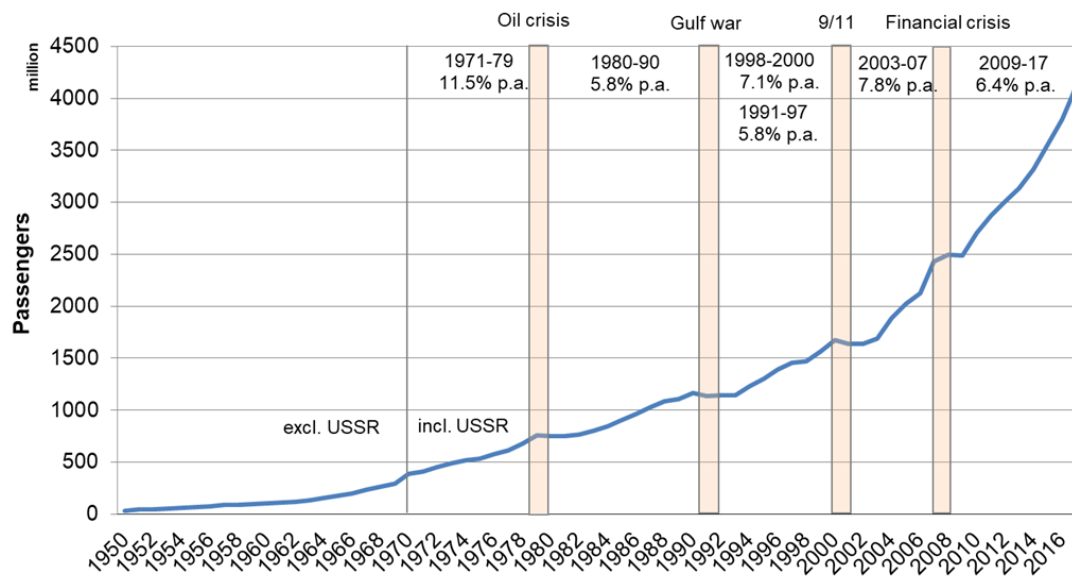
Figure 27: Development of Global Air Traffic since 1950[63]

The current short-term break down of the air transport sector, caused by COVID-19, is unprecedented in its extent. Nevertheless, there is no evidence why the sector should not recover after a few years. Moreover, in future, global growth is likely to be more and more shaped by emerging countries especially in Asia and the Middle East, and less by Europe and North America.[64] The main reason for this development is, on the one hand, rising income levels in these countries (GDP per capita) and, on the other hand, increasing capacity constraints especially in Europe, which inhibit further development. Thus, it is possible that air traffic returns to its original growth path within a few years and long-term forecasts for 2050 are not too seriously affected. However, there are some voices that say that there could be a permanent setback in air traffic development because of the COVID-19 pandemic, at least in the short-term. Most of these voices like IATA, several (but not all) EUROCONTROL scenarios, aircraft manufacturers and airlines say that there will be a permanent setback of a few years, which is around five years, so that air traffic levels of 2019 will be reached again around 2024. However, there is also a pessimistic scenario of EUROCONTROL in which ten years will be needed for full recovery in case that there is no vaccine. But this seems to be of rather low probability given recent developments regarding the vaccine. So, we think that the future development will be between a "no long-term effect" scenario and a "five years setback" scenario. Consecutively, the results presented are based on the "no long-term effect" scenario. If we take the "five years setback" scenario, passenger and flight volume would be 13% and 7%, respectively, lower in 2050. This is significant, but probably not as much as one would assume given the sharp decline of air traffic volume during 2020. Nevertheless, there is still more research needed, e.g. regarding the future GDP development, air travel behavior and fleet retirement in the light of COVID-19, to truly assess the impact of the pandemic on future air traffic development.

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[63] Gelhausen et al. (2020).
[64] Cf. Ibid.
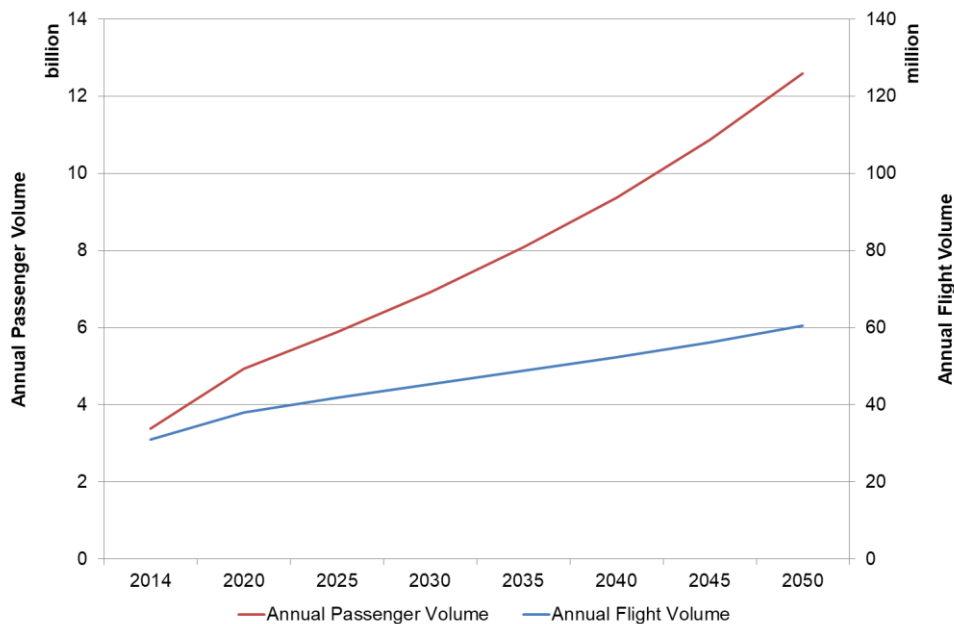
Figure 28: Forecast results of mainliner and regionals' passenger demand and flights

Figure 28 displays the passenger and flight forecast results from 2014 to 2050. Passenger volumes are expected to rise from 3.4 billion in 2014 to 12.6 billion in 2050, which equals a compound annual growth rate (CAGR) of 3.7%. The annual flight volume rises from 31 million in 2014 to almost 61 million in 2050, i.e. by around 30 million, which equals a CAGR of 2.0%. As passenger volume increase significantly faster than flight movements, the average number of passengers per flight is expected to increase substantially. The trend to larger aircraft has already existed in the past, but is expected to accelerate in the future because of capacity constraints, and here especially at the largest hubs which handle an over proportional large amount of the global flight volume. Already in 2016, about 50% of the global flight volume has been handled by just 120 airports.[65] However, less utilised airports will also be affected by the trend to employ larger aircraft, as a study from 2015 shows[66]: the capacity problem at large hub airports and its mitigation measures, especially the operation of larger aircraft, extends also to smaller and less utilised airports. Increasing aircraft size and new airport infrastructure each contribute about a half to handling additional demand. It is increasingly hard to realise new runways at major hub airports, especially in Europe, but there are still many new runways expected to be realised in the future, especially at smaller airports or airports in the Asian region. There will be a significant number of heavily constrained airports in the future, but global growth rates of passenger volume are only little affected. However, the impact of limited capacity is huge for affected airports, one of the most affected being London Heathrow.

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[65] See e.g. Gelhausen et al (2020).
[66] Cf. Berster et al. (2015).
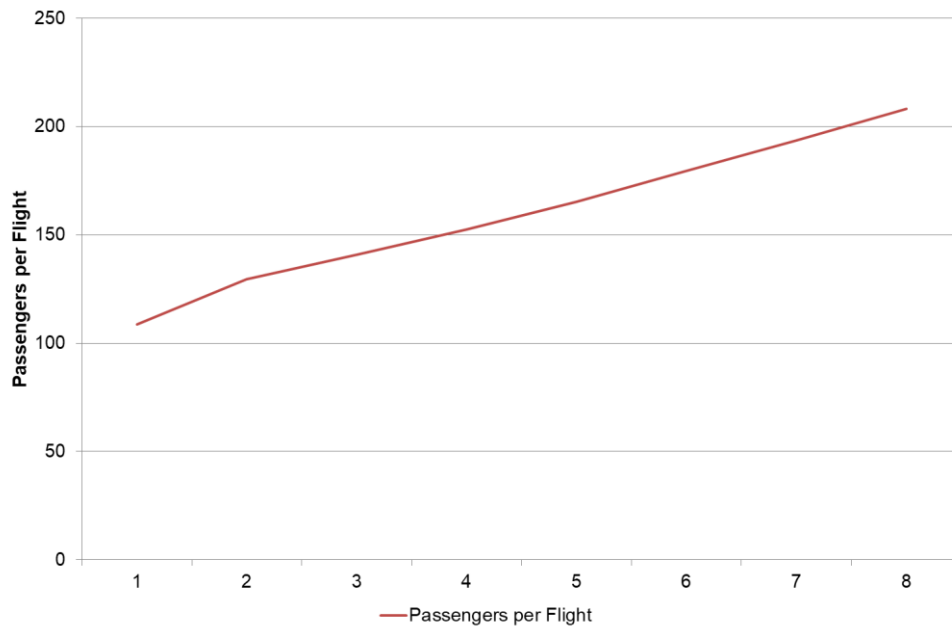
Figure 29: Development of the number of passengers per flight between 2014 and 2050

The figure above displays the development of the number of passengers per flight from 2014 to 2050. The number of passengers per flight increases from 109 in 2014 to 208 in 2015, which equals a CAGR of 1.8%, almost equalling the CAGR of the flight volume. As a result, the number of passengers per flight almost doubles until 2050.
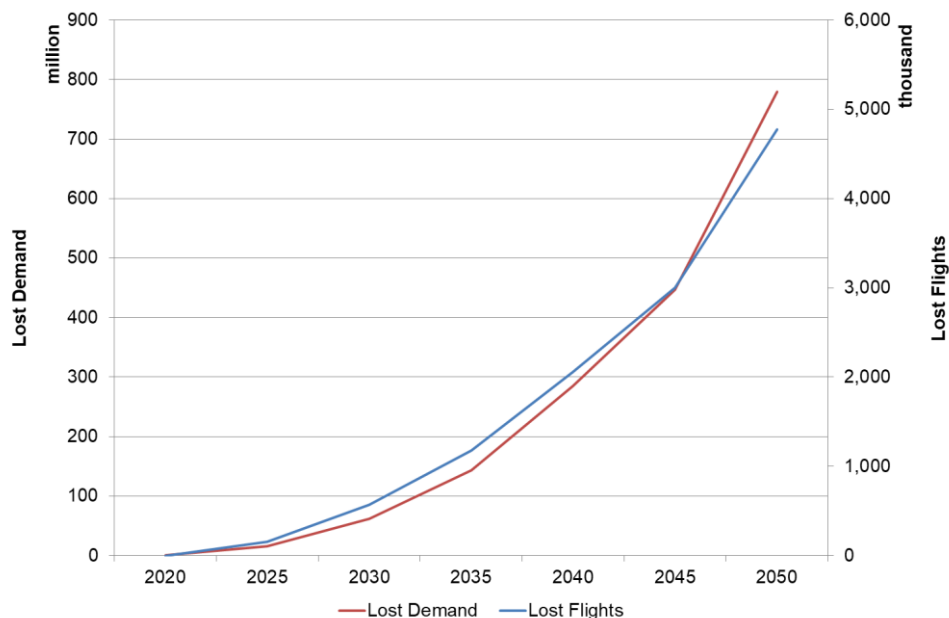
Figure 30: Lost demand and lost flights until 2050

Figure 30 displays the development of lost demand and flights between 2020 and 2050 as a result of insufficient airport capacities. These values continually increase from very low values in

2020 to 800 million lost passengers and five million lost flights in 2050. Furthermore, the rate at which these values grow increases continually. Eventually, 6% of the passenger and 8% of the flight volume cannot be served in 2050 due to airport capacity limitations.
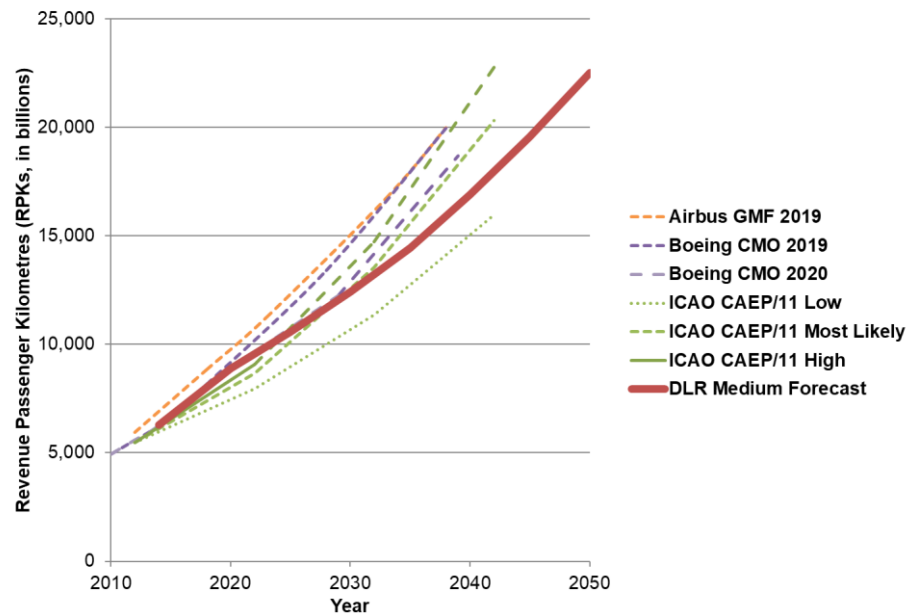
Figure 31: Comparison of DLR Forecast to other forecasts in terms of revenue passenger kilometres (RPK)

Figure 31 compares the DLR Medium Forecast, in terms of revenue passenger kilometers (RPK), with forecasts from ICAO CAEP/11, Airbus and Boeing, all of which have different time horizons (Airbus GMF 2038, Boeing CMO 2038 and ICAO CAEP/11: 2042; DLR: 2050).[67] The DLR scenarios end up between the ICAO CAEP/11 Most Likely and Low forecasts. The ICAO CAEP/11 High is significantly higher and close to the Airbus and Boeing forecasts We can conclude that the forecast results are very plausible; especially because all these forecasts with the exception of the DLR forecast do not include future limits in airport capacities, which is supposed to be of major relevance for the higher forecasts, i.e. Airbus, Boeing and ICAO CAEP/11 High.

Consecutively, we present the forecast results for the segments rotorcraft, business jets and SAT. SAT is a 19-seat commuter with new technology with an entry into service in 2030. However, scheduled 19-seat commuters are considered before 2030 already in the mainliners and regionals segment, and additionally in the SAT/UAM segment from 2030 on. Passenger volumes are usually not considered to be a meaningful indicator for the development of the rotorcraft and business jets segments, and hence not tracked. Hence, we focus on flight volume for these aircraft types.

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[67] Cf. Airbus (2019), Boeing (2019), ICAO (2015b).
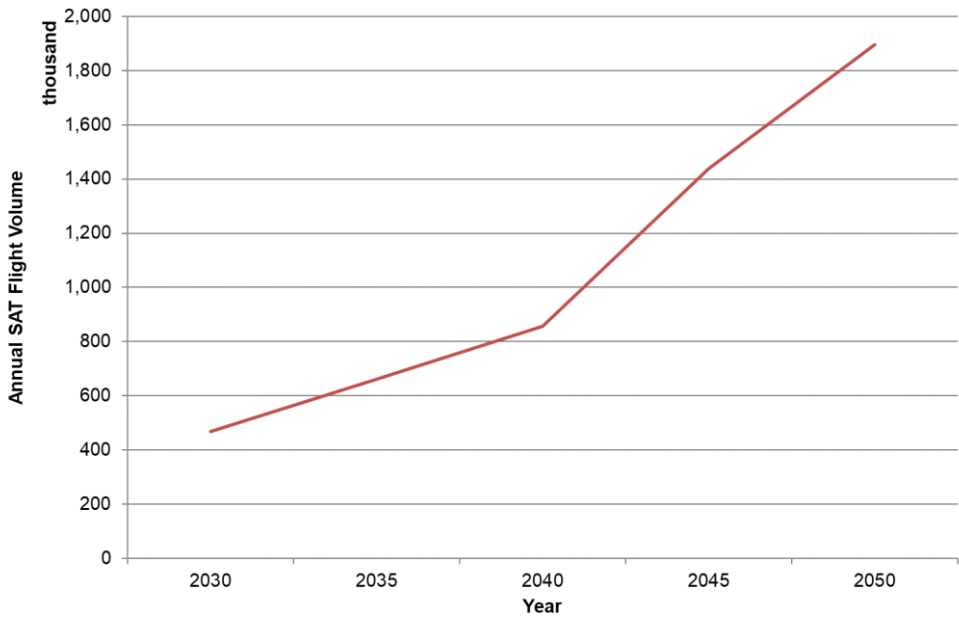
Figure 32: Results of the SAT flight forecast for the time period 2030 to 2050

Figure 32 illustrates the results of the SAT flight volume forecast until 2050. Flight volume rises from about 500 thousand in 2030 to over 1.9 million in 2050, which equals a CAGR of 7.2%. As SAT with a larger flight range becomes available over time, flight volume increases more and more, as more demand can be served. Flight range increases in several steps from 1,110 km in 2030 up to 1,350 km in 2050. Given the rather low level of flight range compared to other aircraft, an increase of more than 200 km makes a big difference in terms of demand potential that can be served. Thus, the flight volume growth of SAT is composed of two parts: the general demand growth which transforms into flight volume growth and the range growth, which makes more demand accessible for SAT services.
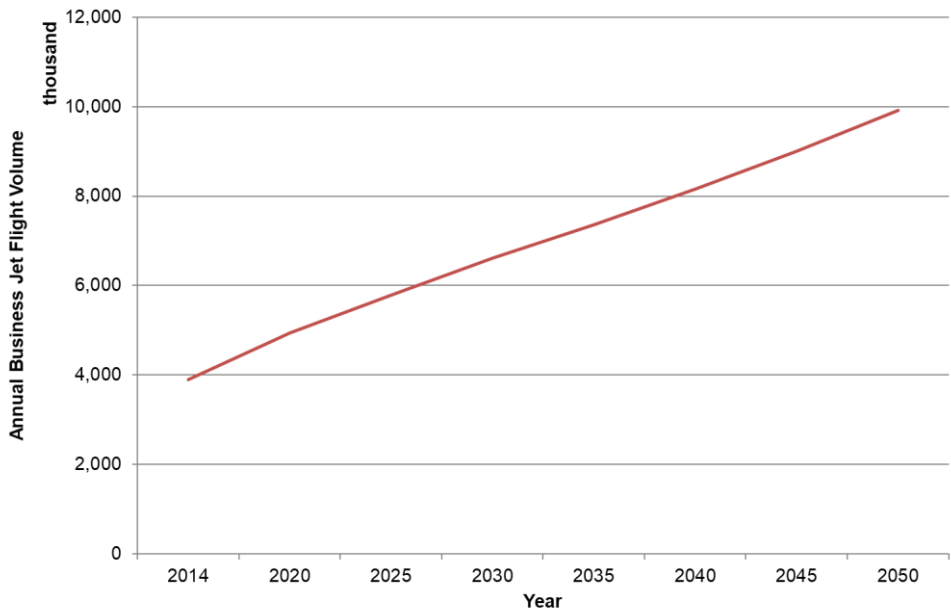
Figure 33: Results of the business jet flight forecast for the time period 2014 to 2050

Figure 33 displays the results for the business jet flight forecast for the period between 2014 and 2050. Flights are forecasted to rise from 4 million in 2014 to almost 10 million, which equals a CAGR of 2.6%.
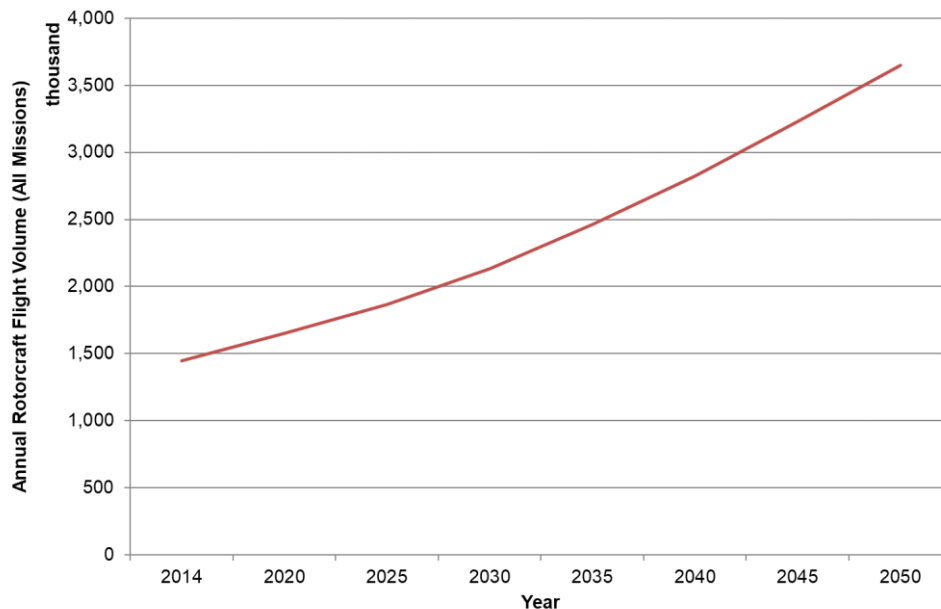
Figure 34: Results of the rotorcraft flight forecast (all missions) for the time period 2014 to 2050

Figure 34 depicts the number of annual rotorcraft movements (missions) forecast for the time period 2014 to 2050. We expect the number of flights to increase from almost 1.5 million in 2014 to over 3.5 million, which equals a CAGR of 2.6%.

3.3.3. Traffic Forecast Results and Methodology for Supersonic Aircraft

The scenario-specific assumptions and storylines for the supersonic scenarios have already been explained in section 3.1.5. These represent the central parameters for quantifying a progressive and a conservative-evolutionary demand scenario for supersonics.

At this point it should be mentioned that, depending on the methodology used, other (especially higher) results can be achieved in supersonic modeling. Especially the selected subsonic passenger data base has a significant impact on the supersonic transport (SST) results, as the general demand potential for supersonic flights is determined on the basis of this data. In the course of DEPA 2050, origin-destination passengers (instead of leg passengers, which would result in much higher values) were used as subsonic data basis. The switching percentage and the induced demand percentage assumptions can also be applied either to the total number of subsonic

passengers or only to premium passengers. The latter was used for the DEPA 2050 supersonic scenarios.

The basic vehicle-specific parameters and properties of the commercial supersonic aircraft are identical for both scenarios as input for the modelling and the further quantification. Accordingly, in the progressive as well as in the conservative-evolutionary scenario, a commercial supersonic aircraft will enter the aviation market in 2025, with the performance indicators shown in Figure 35. This is based on the performance data of the supersonic concept from Boom Technology, whose EIS is forecasted for the year 2025.

Performance Indicator	Progressive Scenario	Conservative-Evolutionary Scenario
Number of Passengers	55	
Supersonic Cruise Mach No.	2.2	
Subsonic Cruise Mach No.	0.95	
Maximum Range	8,300 km	
Maximum Take-Off Weight	120 Tonnes	
Maximum Fuel Weight	60 Tonnes	
Take-Off Field Length	3 km	

Figure 35: Performance indicators of the commercial supersonic vehicle regarded in DEPA 2050

According to this, in both scenarios up to 55 passengers can be transported in the supersonic aircraft at a cruising speed of Mach 2.2 over a maximum range of 8,300 km.

While flying at supersonic speed over land is permitted in the progressive scenario, in the conservative evolutionary scenario there is a ban on supersonic flights over land and at a distance until 50 km along coasts. In addition, the percentage of switching passengers and induced passengers (30%, 15%) is higher than in the conservative-evolutionary scenario (20%, 10%).

Figure 36 shows the total number of supersonic routes for both scenarios in the period 2025-2050. It can be seen that the number of routes in the progressive scenario increases significantly from 244 in 2025 to 838 in 2050. In the conservative-evolutionary scenario, the number of routes in 2025 is significantly lower with 82 due to the supersonic overland flight restrictions and the lower switching and induced demand percentage. Even in 2050, the number of routes is with 358 significantly lower than in the progressive scenario.
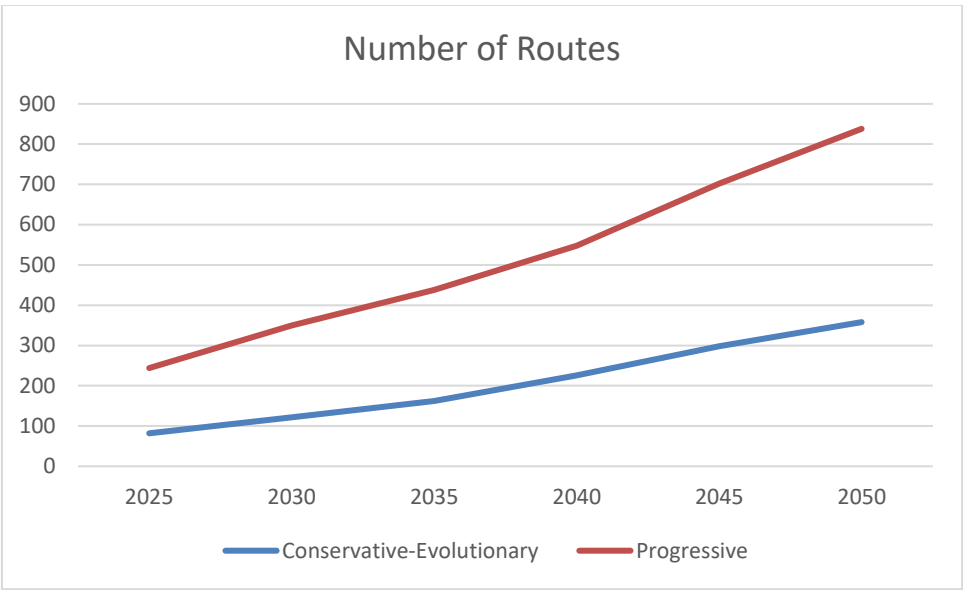
Number of Routes

Figure 36: Number of supersonic routes in both DEPA 2050 scenarios

A similar development can be seen with regard to the number of annual supersonic flights in the aforementioned period of time. It can be seen that in the progressive scenario the number of supersonic flights increases continuously from 53,182 in 2025 to 220,815 in 2050. In the conservative evolutionary scenario, the total number and the increase are significantly lower with 17,191 flights in 2025 and 84,797 flights in 2050.

The development shown with regard to the number of routes and flights in both scenarios results in a different fleet size. As shown in figure 38, the size of the required supersonic aircraft fleet in the conservative-evolutionary scenario grows from 49 in 2025 to 221 in 2050. In the progressive scenario, however, the number is significantly larger with 152 in 2025 and 538 in 2050.

Number of Flights (per year)
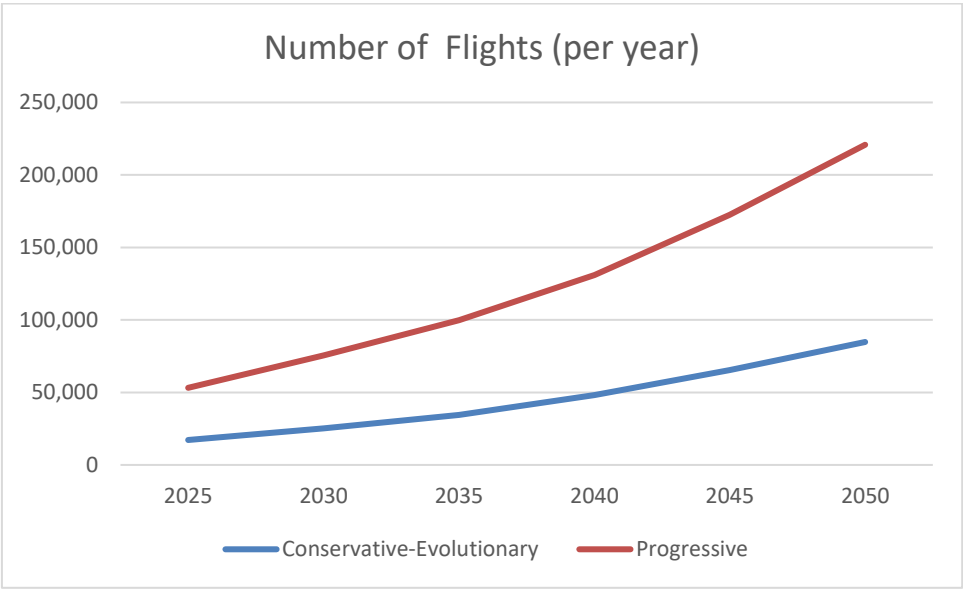
Figure 37: Number of supersonic flights in both DEPA 2050 scenarios
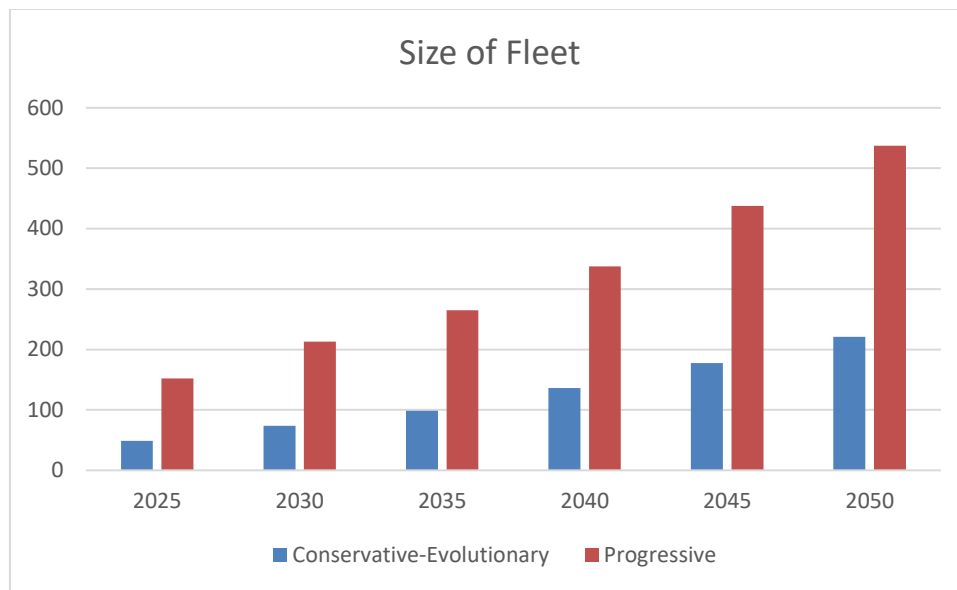
Figure 38: Size of supersonic fleet in both DEPA 2050 scenarios

Methodological steps regarding supersonic modelling

The following methodological steps were undertaken to derive the figures as given above:

- Estimation of OD demand passenger data from DLR subsonic forecast for the years 2025, 2030, 2035, 2040, 2045, 2050
- Filtering out of all OD routes between 2,778 km (minimum distance for significant SST time advantages) and 15,001 km (two times maximum range of SST vehicle, 8,334 km, minus 10% buffer)
- Identification of the number of premium passengers on these routes by using the premium ratios (premium passengers/total passengers)
- Calculation of routings for the conservative-evolutionary scenario (no supersonic overland and in 50 km distance to coast allowed) and the progressive scenario (supersonic overland allowed)
- Determination of SST routes, SST flights and SST fleet for both scenarios by using different assumptions regarding minimum time savings and minimum roundtrips per week

3.3.4. Traffic Forecast Results and Methodology for Urban Air Mobility

The scenario-specific assumptions for the UAM scenarios have already been explained in section 3.1.5. These represent the central parameters for quantifying a progressive and a conservative-evolutionary scenario for UAM.

At this point it should be mentioned that the quantification of the UAM scenarios is not based on any capacity restrictions regarding ATM and only the intra-city and the airport shuttle business cases are considered in the UAM modelling. Inter-city traffic is not part of this quantification.

After market launch of UAM vehicles in 2025, demand continuously grows. The strongest growth is noted between 2030 and 2040 where most of the cities implement UAM services. Afterwards, demand will increase less strongly as only a few more cities introduce UAM.

The progressive scenario has a potential demand of around 0.32 million trips per day in 2030 and 3.51 million trips per day in 2050. Because of great acceptance by users and society, UAM vehicles are widely used in the future. Furthermore, infrastructure will be expanded on a large scale which leads to a high density of takeoff and landing areas (TOLAs) and increasing capacity.

In the conservative-evolutionary scenario a demand of around 0.03 million trips per day in 2030 and 1.08 million trips per day in 2050 is forecasted. Low political support hinders the launch of UAM vehicles services in cities with low affinity towards UAM. In conjunction with high service prices, UAM is only attractive for a few wealthy users.

A strong demand leads to about 0.27 million movements per day in 2030 and 2.04 million UAM movements per day in 2050 within the progressive scenario. Starting with 2 seats per UAM vehicle in 2025, the number of available seats rises by 30% to 2.64 seats per UAM vehicle on average in 2050. Technological progress and a growing demand lead to UAM vehicles with higher performance.
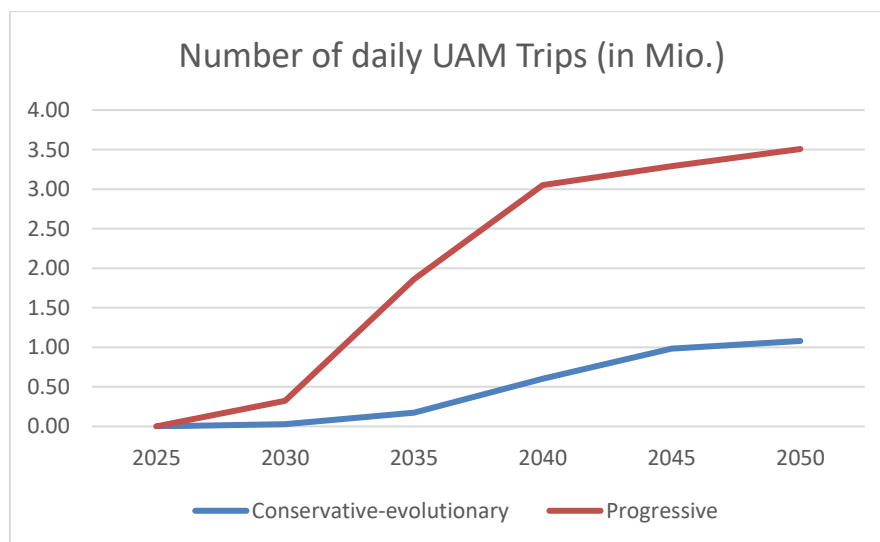
Figure 39: Number of daily UAM trips in both DEPA 2050 scenarios[68]

In the conservative-evolutionary scenario cities with low affinity towards UAM are reserved to launch UAM services. Therefore, just 0.03 million movements per day in 2030 and around 1.25

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[68] Trip = one passenger trip

million movements per day in 2050 serve the market in this scenario. The average UAM vehicle size remains constant over the entire period with 2 seats per vehicle.
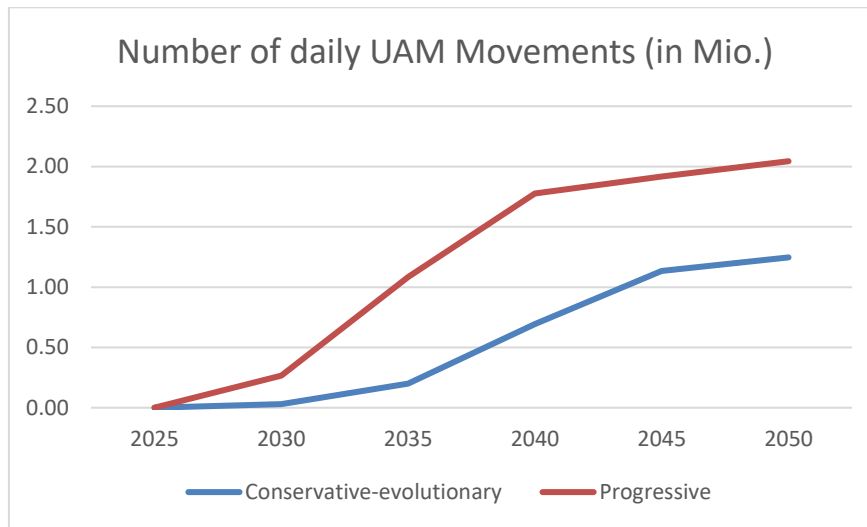
Figure 40: Number of daily UAM movements in both DEPA 2050 scenarios[69]

The progressive scenario depicts a potential fleet size of around 170,000 UAM vehicles in 2050. Despite growing demand, numbers of UAM vehicles decline between 2040 and 2050 as a main result mainly of increased daily utilisation and of higher seat capacity per vehicle. Between 2025 and 2050 utilisation is assumed to rise by around 50%.

In the conservative-evolutionary scenario UAM vehicles undergo no considerable technological progress and the utilisation of the vehicles increased only minimal between 2025-2050. As a result, the fleet size increases from around 3,700 in 2030 to around 138,000 UAM vehicles in operation in 2050.
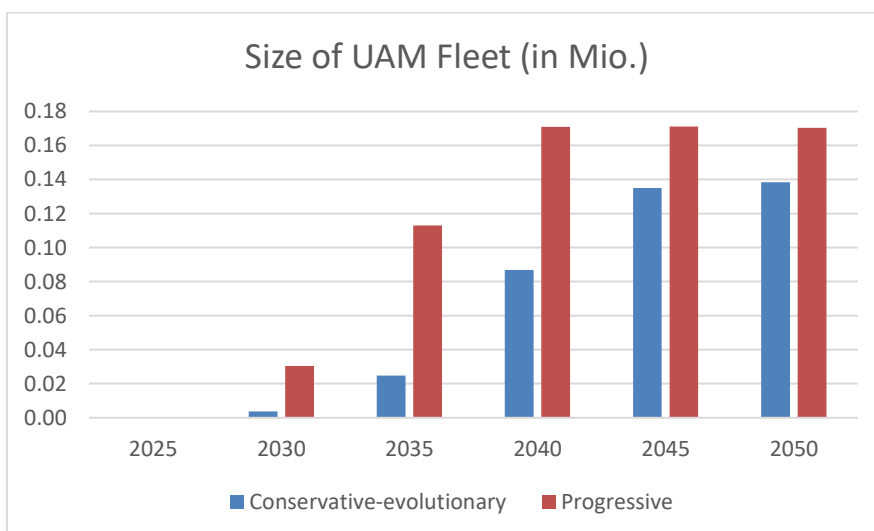
Figure 41: Size of UAM vehicle fleet for both DEPA 2050 scenarios

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[69] Movement = one UAM vehicle trip

Methodological steps regarding UAM modelling

The following methodological steps were undertaken to derive the figures as given above:

- Identification of cities with more than 2 million inhabitants
- Determination of total mobility demand by using an average value for the number of trips per person
- Determination of potential UAM demand by using an average share of UAM demand at total mobility demand
- Creation of reduction factor ranges (min. & max., always between 0 and 1) for four constraint categories and for both scenarios separately (progressive: generally less reduction, conservative-evolutionary: generally more reduction)
  - Minimum and maximum share of UAM for which people are willing/able to pay (willingness to pay constraint)
  - Minimum and maximum share of UAM handled depending on availability of TOLA (infrastructure constraint)
  - Minimum and maximum share of UAM which can be handled based on TOLA capacity (capacity constraint)
  - Minimum and maximum share of UAM handled depending on operational restrictions (restriction constraint)
- Determination of reduction factor (e.g. 0.8 = 80 % of the UAM demand remains) for every city and every constraint category based on several indicators (e.g. GDP per capita, population, traffic index values are especially important for the willingness to pay constraint)
- City-specific value lies within the range depending on the city-specific UAM affinity. The lower boundary is associated to cities with low affinity, and the upper boundary to cities with high affinity
- Finally, the potential UAM demand for every city was reduced by the four constraint categories for the progressive scenario and for the conservative-evolutionary scenario which result in final UAM demand

3.4. Fleet Forecast

3.4.1. Fleet Forecast Methodology

This section outlines the methodology and results of the fleet mix forecast in the DEPA 2050 study for the major market segments of mainliner and regional aircraft as those are important elements of the impact analysis of the DEPA 2050 study and the further impact assessments. The fleet mix forecast for the advanced vehicle/transportation concepts of UAM and supersonic aircraft is described and presented in section 3.3.

To predict the future fleet mix for mainliner and regional aircraft the fleet forecast model of DLR's Institute of Air Transport and Airport Research was used. The components of the model consider the following assumptions and inputs:

- Flight schedules including flights by airport pair and aircraft types supplemented by further fleet information for the DEPA 2050 reference year 2014
- Results from the passenger traffic forecast (number of passengers and flights per airport pair in 5-year-steps up until 2050)
- A S-Curve-shaped increase in seat load factor up to a saturation level of 88% in 2050, uniformly applied over all airport pairs globally.
- Aircraft retirement curves based on input data by ICAO-CAEP and assumptions on aircraft utilisation based on data by Flightradar24.
- List of available aircraft for replacement (including information on the production window = time span between entry-into-service and out of production date for each aircraft type/seat category)

The data for the flight schedules stem from the Official Airlines Guide (OAG) and Innovata. Both data sources deliver homogenous and high-resolution data on the level of airport city pairs to guarantee a compliance with the passenger traffic forecast. Although this schedules' data does not cover business aviation and charter flights as non-scheduled operations the share of these two market segments is relatively low[70] and therefore negligible. This holds for the resulting impact on air traffic as well as for the impact on emissions as business aircraft is relatively small compared to aircraft used for scheduled and commercial flights resulting in a significantly lower number of emissions. Finally, there is only a relatively small difference between scheduled and actually operated flights. While flight data collected by automatic dependent surveillance broadcast (ADS-B) has the advantage to count only actually operated flights it has still larger gaps than schedules data. For this reason, the reliability of schedules data especially for extended analyses in the environmental domain is preferable to ADS-B data and was used for the impact assessments in this study.

Concerning the fleet data for the reference year 2014 Cirium's "Fleet Analyzer" has been used which delivers important reference data for ICAO CAEP, for example. The data allows to search and sort aircraft by different technical categories (e.g. dates of first flight, delivery, change of owner/operator, retirement). Corresponding to the study focus only aircraft for scheduled passenger services were extracted from the database by suitable selection criteria. Business jets and UAM vehicles were not regarded within this scope to be compliant with the schedules data that impedes the forecast of flights in those segments as they are typically unscheduled and therefore not available in the regular statistics. However, as pointed out before, the share of current business and air taxi aircrafts' emissions in the overall aviation emissions is negligible.

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[70] For instance, for the year 2009 only 5.9% of all IFR flights in the EUROCONTROL area have been charter flights. Business aviation flights oscillated around 5.9% in the same year (cf. EUROCONTROL (2010)).

Thus, for the further impact analysis within the DEPA 2050 project the consideration of these market segments mainly focused on the elaboration of scenario storylines and separate flights forecasts. For UAM (air taxis) this was done with another methodological approach to address new demand, innovative drivers and operating conditions separately. As there is the tendency that especially UAM vehicles will in this context be empowered by electrical energy in the future the exclusion of UAM vehicles from the fleet forecast is therefore even more maintainable.

Taking these conditions into account, the aircraft fleet composition for the year 2014 as base for the further emissions analysis is as follows.

Table 8: 2014 reference year aircraft fleet by seat class in comparison to ICAO CAEP/11 (2015)

Seat Class Number	Seat Class	Number of Aircraft DLR 2014	Number of Aircraft ICAO 2015
1	1-19 Seats	1,885	n.a.
2	20-50 Seats	2,424	2,041
3	51-70 Seats	1,111	1,060
4	71-85 Seats	1,240	1,454
5*	86-100 Seats	148	705
6*	101-125 Seats	1,359	1,334
7	126-150 Seats	3,346	3,965
8	151-175 Seats	3,496	4,595
9	176-210 Seats	5,273	4,526
10	211-300 Seats	2,144	2,689
11	301-400 Seats	1,435	1,131
12	401-500 Seats	156	200
13	501-600 Seats	0	131
	Total	24,017	23,831
	Total >19 Seats	22,132	23,831

* For the seat categories 5 and 6 only one concept aircraft was considered per DEPA 2050 scenario (cf. section 4.3.2). However, to compare the aircraft data set of DLR with ICAO CAEP both seat categories are listed here separately.

The comparison to other forecasts for aircraft with more than 19 seats (e.g. as outlined above in reference to the ICAO CAEP 11/Forecast) shows no major deviations. While ICAO reports 23,831 aircraft >19 seats in usage for scheduled passenger flights for the year 2014 the DLR analysis has identified 24,017 aircraft. Deviations in specific seat classes are caused by the fact that Cirium's Fleet Analyzer does not contain seat data on individual aircraft for historical dates and so the DLR analysis was oriented at average seats per aircraft type, while ICAO probably applied a different methodology. Based on this overall value for 2014 the aircraft replacement for the forecasted years up to 2050 is conducted by usage of ICAO CAEP's aircraft retirement model. The model allows to differentiate between turboprop aircraft as well as between regional, widebody and

narrowbody jets. The probability of retirement for each of those categories with an increasing aircraft age is given in coefficients that result in four different retirement curves. Those are summarised in the following figure and were applied to retire and subsequently replace existing aircraft by the DEPA 2050 aircraft types as described in section 4.2 and 4.3.
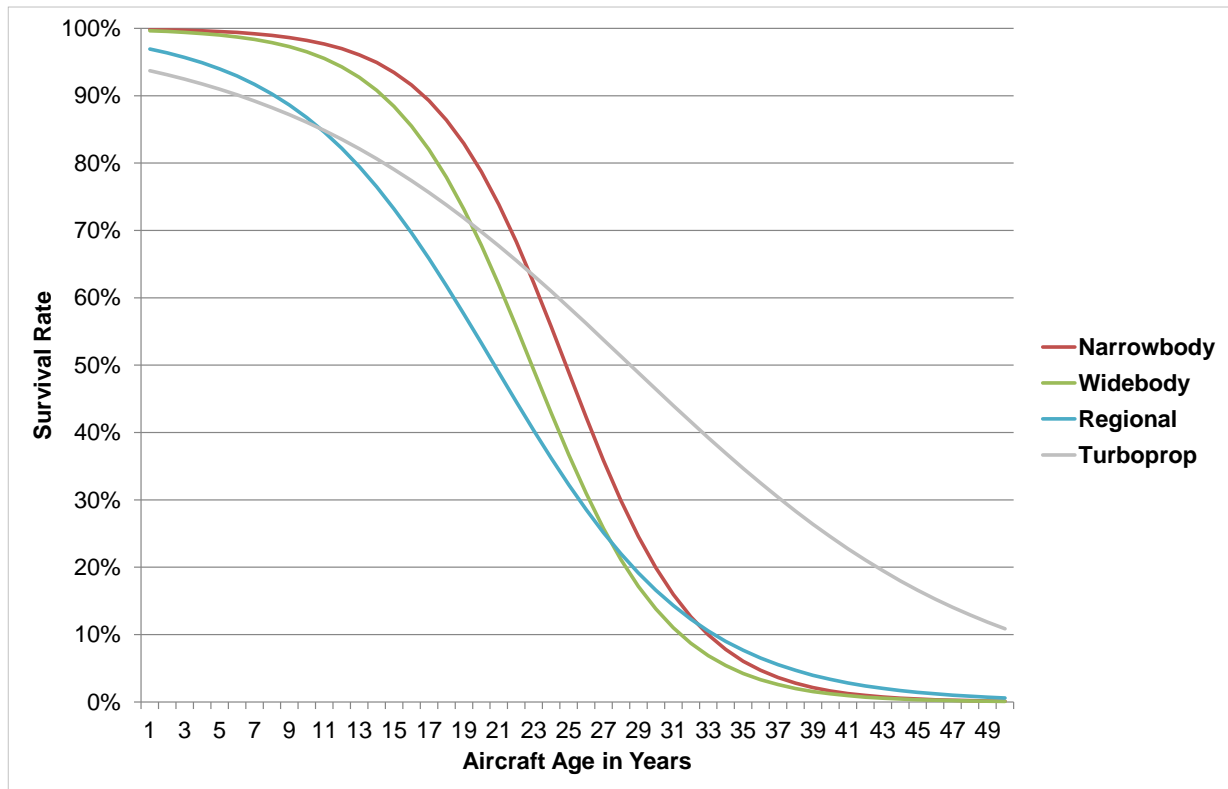
Source: Based on VOLPE

Figure 42: Aircraft retirement curves (survival probabilities depending on aircraft age)

While the ICAO retirement curves in combination with the aircraft data from Cirium's "Fleet Analyzer" allow to estimate the probability of retirement for each aircraft over the long-term the aircraft utilisation model is a further processing step to match fleet and forecast modelling. It was calibrated with ADS-B data from Flightradar24 for the year 2019 and has an important bridge function between the forecast and fleet modelling by quantifying the number of aircraft which are needed to operate the future flight schedule based on the passenger flight and demand forecast. Considering the total annual aircraft utilisation deriving from the annual distance flown in relation to the average flight length the model provides the opportunity to match the forecasted flights with the fleet by identifying the specific aircraft type that is needed on a specific route in relation to the estimated demand. In combination with the information on the individual aircraft age originating from Cirium's "Fleet Analyzer" and the retirement curves from ICAO the model allows then to identify aircraft replacement needs over time and provides information on needed aircraft in the future in terms of passenger capacity and aircraft utilisation requirements.

Based on this architecture and model output any future aircraft configuration can be inserted adequately into to the future aircraft fleet mix as far as the entry-into-service is given as well as further technical characteristics (i.e. aircraft capacity, range, size, etc.). Based on the DEPA 2050 scenarios and the technology roadmaps for the considered aircraft as outlined in detail in section 4.2 and 4.3, 12 aircraft configurations (one for each ICAO seat category with merged seat categories in the case of category 5 and 6) were used per scenario to replace aircraft from the global aircraft fleet starting from the year 2035 onwards. Those aircraft configurations are given in the following tables.

Table 9: Overview DEPA 2050 aircraft and in-production window (conservative-evolutionary scenario)

ICAO seat category	Ø number of seats	Aircraft type used in DEPA 2050 (conservative-evolutionary scenario)	Entry into service in forecast model	Out of production
1-19	19	Do228NG	2015	2034
1-19	19	Do228NG-Successor Conservative Scenario	2035	2050
20-50	35	ATR42-500	2015	2034
20-50	35	ATR42-500-Successor Conservative Scenario	2035	2050
51-70	60.5	ATR72-600	2015	2034
51-70	60.5	ATR72-600-Successor Conservative Scenario	2035	2050
71-85	78	Dash8-Q400	2015	2034
71-85	78	Dash8-Q400-Successor Conservative Scenario	2035	2050
86-125	105.5	Embraer E190	2015	2017
86-125	105.5	Embraer E190-E2	2018	2034
86-125	105.5	Embraer E190-"E3" Conservative Scenario	2035	2050
126-150	138	Airbus A319	2015	2015
126-150	138	Airbus A220-300	2016	2034
126-150	138	Airbus A220-300neo Conservative Scenario	2035	2050
151-175	163	Airbus A320	2015	2015
151-175	163	Airbus A320neo	2016	2034
151-175	163	Airbus A320neo-Successor Conservative Scenario	2035	2050
176-210	193	Airbus A321	2015	2016
176-210	193	Airbus A321neo	2017	2034
176-210	193	Airbus A321neo-Successor Conservative Scenario	2035	2050
211-300	255.5	Boeing 787-8	2015	2034
211-300	255.5	Boeing 787-8 - Successor Conservative Scenario	2035	2050
301-400	350.5	Airbus A350-900	2015	2034
301-400	350.5	Airbus A350-900neo Conservative Scenario	2035	2050
401-500	450.5	Boeing 747-8I	2015	2021
401-500	450.5	Boeing 777-9	2022	2034
401-500	450.5	Boeing 777-9 - Successor Conservative Scenario	2035	2050
501-600	550.5	Airbus A380-800	2015	2021
501-600	550.5	Airbus A380-800neo Conservative Scenario	2035	2050

Table 10: Overview DEPA 2050 aircraft and in-production window (progressive scenario)

ICAO seat category	Ø number of seats	Aircraft type used in DEPA 2050 (progressive scenario)	Entry into service in forecast model	Out of production
1-19	19	Do228NG	2015	2034
1-19	19	Do228NG-Successor Progressive Scenario	2035	2050
20-50	35	ATR42-500	2015	2034
20-50	35	ATR42-500-Successor Progressive Scenario	2035	2050
51-70	60.5	ATR72-600	2015	2034
51-70	60.5	ATR72-600-Successor Progressive Scenario	2035	2050
71-85	78	Dash8-Q400	2015	2034
71-85	78	Dash8-Q400-Successor Progressive Scenario	2035	2050
86-125	105.5	Embraer E190	2015	2017
86-125	105.5	Embraer E190-E2	2018	2034
86-125	105.5	Embraer E190-E3 Progressive Scenario	2035	2050
126-150	138	Airbus A319	2015	2015
126-150	138	Airbus A220-300	2016	2034
126-150	138	Airbus A220-300neo Progressive Scenario	2035	2050
151-175	163	Airbus A320	2015	2015
151-175	163	Airbus A320neo	2016	2034
151-175	163	Airbus A320neo-Successor Progressive Scenario	2035	2050
176-210	193	Airbus A321	2015	2016
176-210	193	Airbus A321neo	2017	2034
176-210	193	Airbus A321neo-Successor Progressive Scenario	2035	2050
211-300	255.5	Boeing 787-8	2015	2034
211-300	255.5	Boeing 787-8 - Successor Progressive Scenario	2035	2050
301-400	350.5	Airbus A350-900	2015	2034
301-400	350.5	Airbus A350-900neo Progressive Scenario	2035	2050
401-500	450.5	Boeing 747-8I	2015	2021
401-500	450.5	Boeing 777-9	2022	2034
401-500	450.5	Boeing 777-9 - Successor Progressive Scenario	2035	2050
501-600	550.5	Airbus A380-800	2015	2021
501-600	550.5	Airbus A380-800neo Progressive Scenario	2035	2050

The lists of available aircraft for the two DEPA 2050 scenarios were amended in a second step by a scenario that assumes no change in aircraft technology as a hypothetical reference case. The corresponding aircraft types are given in the following table.

Table 11: Overview aircraft types and in-production window ("doing-nothing" scenario)

ICAO seat category	Ø number of seats	Aircraft types ("doing nothing" scenario)	Entry into service in forecast model	Out of production
1-19	19	Do228NG	2015	2050
20-50	35	ATR42-500	2015	2050
51-70	60.5	ATR72-600	2015	2050
71-85	78	Dash8-Q400	2015	2050
86-125	105.5	Embraer E190	2015	2017
86-125	105.5	Embraer E190-E2	2018	2050
126-150	138	Airbus A319	2015	2015
126-150	138	Airbus A220-300	2016	2050
151-175	163	Airbus A320	2015	2015
151-175	163	Airbus A320neo	2016	2050
176-210	193	Airbus A321	2015	2016
176-210	193	Airbus A321neo	2017	2050
211-300	255.5	Boeing 787-8	2015	2050
301-400	350.5	Airbus A350-900	2015	2050
401-500	450.5	Boeing 747-8I	2015	2021
401-500	450.5	Boeing 777-9	2022	2050
501-600	550.5	Airbus A380-800	2015	2021

The basic idea in adding this "doing-nothing" scenario was to show the benefits of the progressive and the conservative-evolutionary development pathways in comparison to a situation of no technological progress. Although this situation is not that likely despite the current level of stagnancy in the aircraft manufacturers' market driven by the Covid-19 pandemic it is useful to demonstrate a kind of "worst case" to illustrate corresponding effects. For this reason, additional reference aircraft were compiled and added on a third list as given above to prepare the collection of data for this additional scenario. This approach offered finally also the possibility to discuss the consequences of the DEPA 2050 scenarios in a wider context with regard to the development of emissions and climate impact (cf. section 5.2 and 6.1).

Finally, the fleet modelling forecast provides interesting results itself. In combination with traffic data from the demand forecast the future fleet can be analysed from different perspectives in this way. Compliant with the storylines of the DEPA 2050 scenarios and the earliest assumed entry-into-service of the DEPA 2050 aircraft configurations in 2035 the future fleet will develop as illustrated in the following section.

3.4.2. Fleet Forecast Results

The following figures provides an overview on the future fleet mix of the DEPA 2050 study.
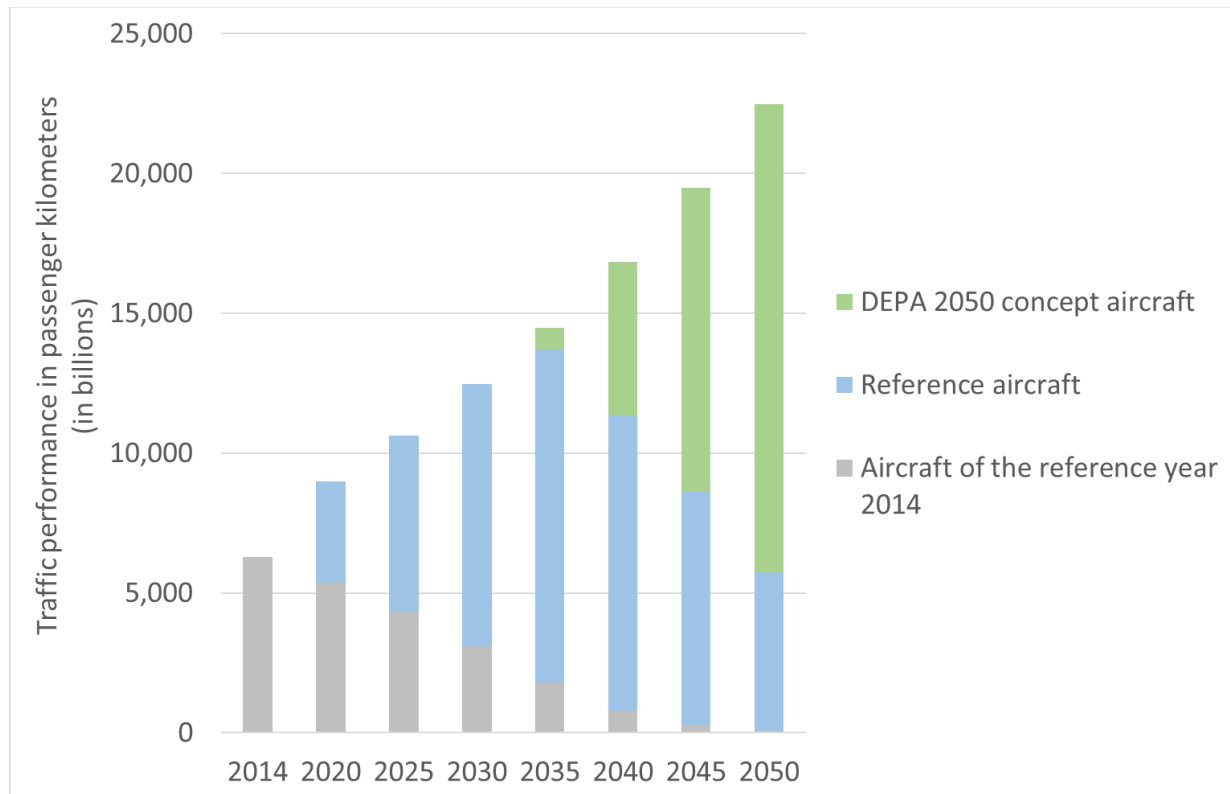
Figure 43: Future fleet mix in the DEPA 2050 scenarios

In the year 2045, approximately half of the total passenger kilometers (PKM) will be provided by DEPA 2050 aircraft configurations. Already in the year 2050 this share will increase to a level of 74% while only 26% of total PKM will be offered by aircraft with technologies from the reference year 2014 or older. In this respect, the calculations support the significance of the impact assessments on emissions and mobility/vehicle productivity as described in section 5.1 and 5.2. If the share of the DEPA 2050 aircraft would have been lower (e.g. if a lower time horizon for the DEPA 2050 scenario study would have been chosen) the impact of future aircraft technologies would also be lower and less robust with regard to the conclusions. The findings demonstrate in this respect how important the entry-into-service is in order to exploit technology potentials as complete and as early as possible. From an industry's and political point of view it should therefore be of interest to speed up the development processes and market introduction of aircraft technologies. This allows to generate earlier benefits in terms of emissions' reduction and with regard to the overall traffic performance. Of course, cost-benefit analyses have also to be considered in corresponding discussions to define concrete priorities.

Another tendency that is obvious by the review of the fleet modelling results is the trend towards bigger aircraft. This trend is a result of rising air traffic demand in combination with increasing airport capacity constraints in the future. As airlines in such a situation would generally tend to use bigger aircraft to satisfy increasing demand the fleet model addresses this topic by replacing smaller aircraft partially with bigger aircraft on specific routes over a given time frame. The identification of these routes and the corresponding demand increases stem from the passenger demand forecast as described in the preceding section. Structured according to the ICAO seat category scheme the outcome of the fleet model in relation to the forecasted number of flights per seat category is shown in the following figure.
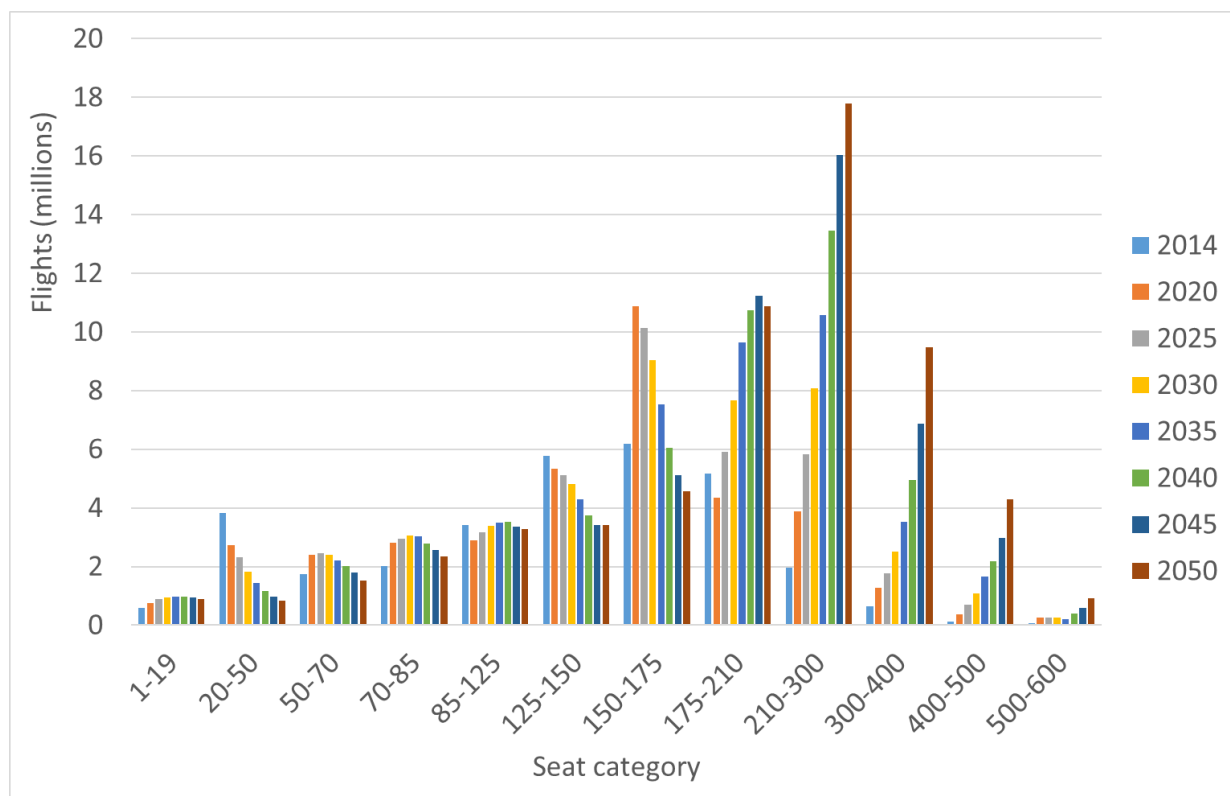
Figure 44: Distribution of flights by seat class

Especially the importance of the aircraft seat category of 125-175 seats will shrink up to the year 2050 while the neighboring seat classes on the upper level starting with the category of 175 seats will gain a higher market share. For the aircraft seat categories along the boundaries of the classification scheme (i.e. 1-19 and 500-600 seats) a stagnation is expected. Nevertheless, also with regard to shorter routes and despite of the end of production of the A 380 the fleet model indicates a certain demand for a "A 380 neo" as it was considered for this study.

With regard to the concrete numbers of aircraft in each seat category the following figure presents another snapshot of the situation in the year 2050.
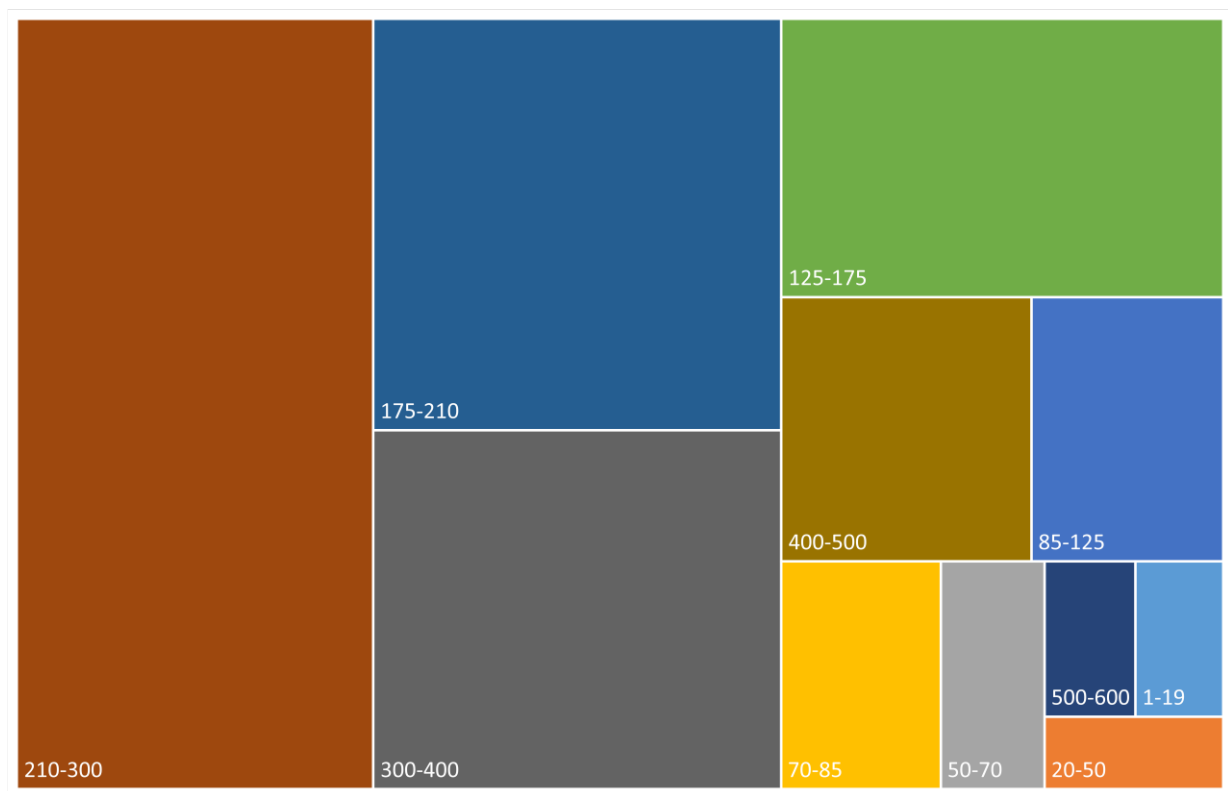
Figure 45: Share of total flights in the different seat classes for the year 2050

The left part of the graph shows the dominance of aircraft stemming from the seat categories from 175-210, 210-300 and 300-400 seats.

Although the impact of the Covid-19 pandemic and weak air traffic demand within the next years might lead to a stronger usage of smaller aircraft for a certain period of time the long-term trend based on a full recovery of passenger demand supports the general use of bigger aircraft with regard to the year 2050.If the development of the different seat categories over the long-term is put in relation to the traffic performance in terms of available seat kilometers the picture looks a little bit as illustrated by the following graph.
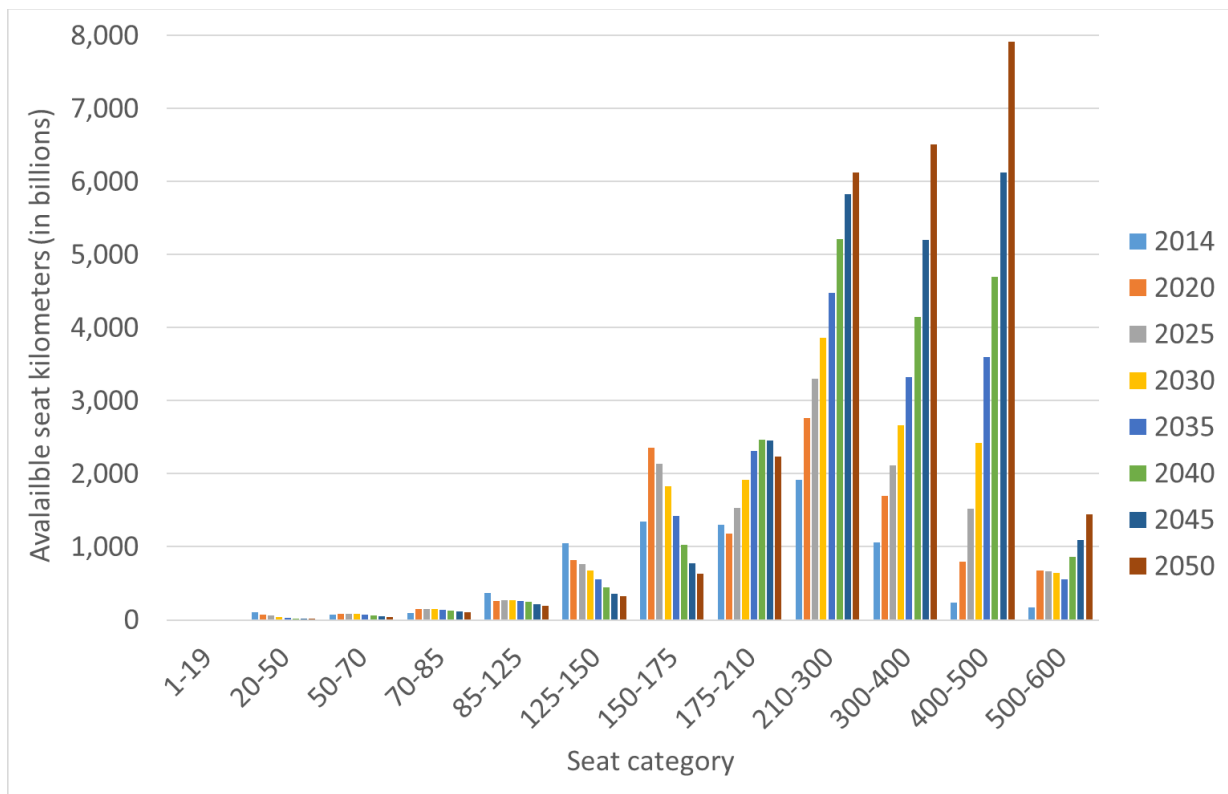
Figure 46: Share of total flights in the different seat classes for the year 2050

If the trips length is considered in the analysis the shift towards bigger aircraft becomes even more obvious as in terms of available seat kilometers smaller aircraft play no major role in the global aviation system and this trend is clearly visible for the future. Of course, this is only one side of the coin.

Smaller aircraft are no essential driver of aviation's total emissions and they have an important function in the global aviation system by handling feeder traffic and providing access to remote regions. This is why a segment-specific analysis of vehicles and a differentiated impact analysis as done in this study is important in order to regard chances and limitations for the future air transport development from a holistic point of view.
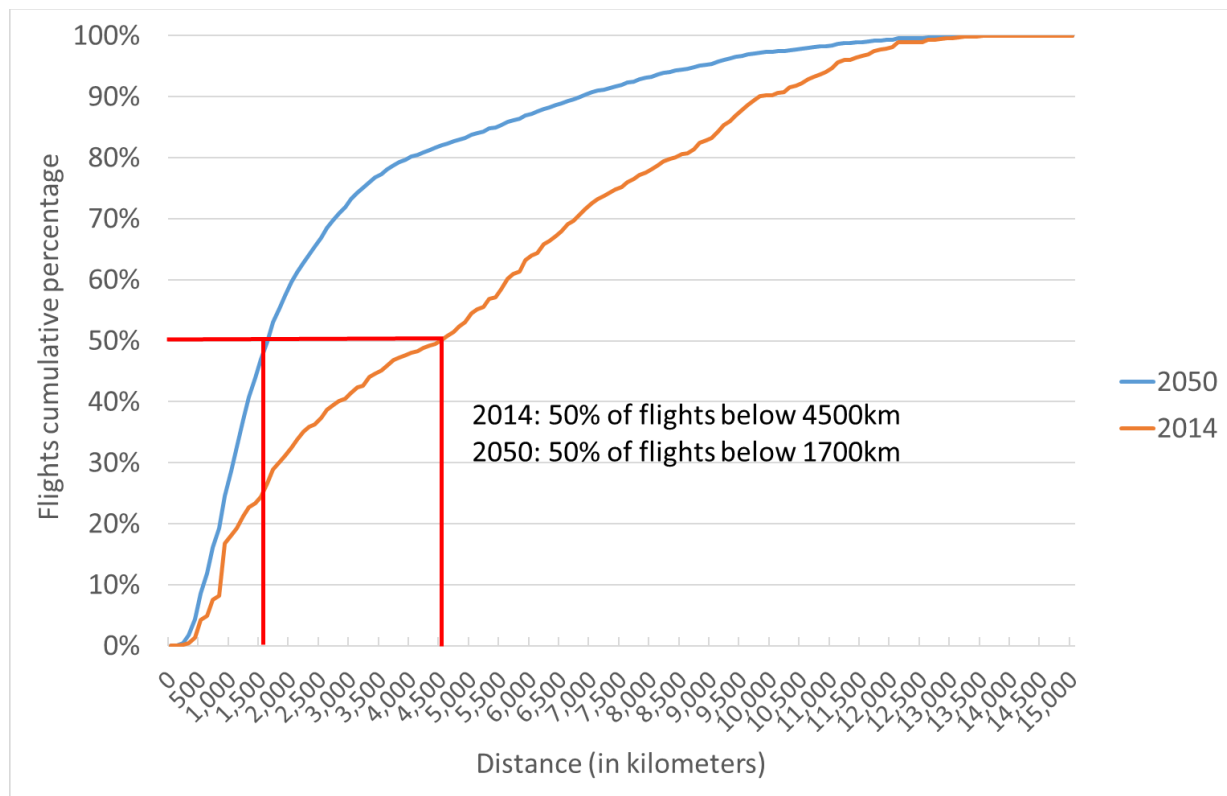
Figure 47: Distribution of flights according to flight distance for aircraft >300 seats (2014 vs. 2050)

Interestingly, there comes also the trend to use bigger aircraft on shorter routes along with the general trend of an increasing number of bigger aircraft in the global fleet. This is illustrated in the figure above. While in 2014 50% of flights with aircraft of more than 300 seats have a distance of less than 4,500 kilometers it is assumed that the average flight distance performed by this aircraft group will substantially shrink further. Thus, in 2050 about 50% of flights operated with aircraft with more than 300 seats are expected to have a distance of less than 1,700 kilometers. Again, the main driver behind this development is the forecasted air traffic growth in combination with rising airport capacity constraints. This development also creates chances. For instance, if growth is achieved through larger aircraft this could turn into a positive impact on the overall fuel consumption and aviation emissions' development. In addition, there is the opportunity to design and optimise bigger aircraft specifically for shorter distances to reduce emissions further from the technological point of view and not only from the traffic side by changes in the flight frequency. This could be addressed in the future by a separate investigation of a "people mover" aircraft concept specifically designed for short distances.

Finally, it has to be pointed out that the analysis has shown a significant structural change in the future fleet. Driven by the forecasted high aviation growth and limited airport capacities over the long-term, a clear increase in average aircraft size, especially driven by aircraft with more than 300 seats, is likely. The outcome of the corresponding impact analysis is discussed in section 5 and 6 in more detail.

3.5. Expected Development and Efficiency Gains in Airport and Terminal Management

Travel will have changed significantly in 2050. Airports will be characterized by faster and more automated processes, ground-based vehicles with revolutionary eco-friendly propulsion, ecologically sustainable facility management and expansion of the non-aviation sector. Clear goals were formulated to make air traffic more intermodal, digitalised, automated and more environmentally sustainable. However, one of the most important aspects is to declare the time needed to get from the traveller's front door to the seat on the plane and onwards to the destination's door (door-to-door) as a non-stop process. The current pandemic situation all over the world has driven many ideas and innovations in travel and especially at airports, as new technologies will make future airport processes more touchless and seamless.[71] The following sections describe what changes are to be expected and what effects they will have.

Intermodal airport connection

The way travellers get to the airport will change towards a higher proportion of car-sharing offers, ground-based taxi traffic will be partially replaced by UAM with air taxis and local public transport will become largely electric. Appropriate ground infrastructure will be available for all types of aviation and other modes of transport such as bus, rail and UAM. This includes major hubs as well as secondary airports, vertiports and heliports, bus stations and metro stations alike, all seamlessly integrated into a multimodal transport system. The intermodal networking at the airport will increase to an optimum, so every mode of transport can play to its strengths. Several mobility points will connect the individual modes of transport with each other, so for at least three modes of transport there will be a kind of stopover at these mobility points. For example, a mobility point at the airport connects a vertiport for air taxi, bus and train platform for local public transport and sufficient parking spaces for private cars.[72] These mobility points will also be used for carsharing exchanges and other modes with a "free floating" principle for carsharing, where, similar to e-scooters, vehicles can be parked anywhere within an area of validity.

For passengers with reduced mobility (PRM) all vehicles and aircrafts will be barrier-free and may be used by everyone without exception. Even for air taxis a kind of stair lift for PRMs will provide access with little or no help from ground-staff needed. This ensures maximum comfort and service.

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[71] Cf. Chapman (2020).
[72] Cf. Hannon (2019).

Figure 48: Intermodal networking/ mobility points[73]

Integration of intermodal transport is made possible by connecting several transport chains, providing a non-stop process even on the way to the airport, since those mobility points allow a direct connection with other modes of transport. Passengers will have full information and choice available at any time, spanning the whole travel chain from door-to-door. However, this will only be achieved by a high degree of digitalisation and automation.

Digitalisation and Automation

The greatest impact on airport process development, their seamlessness, efficiency and resulting time savings will stem from automation and digitalisation. The longstanding trend towards automation and the quest for efficiency in airport processes will ultimately ensure that exchange of information between all stakeholders in the travel chain is optimally improved. This is achieved by future communication devices and cloud-based technology, which can provide travellers with all the information they need in real time, such as departure times, the closing of gates before departure, but also revolutionary information such as the perfect time to leave home and the optimal choice of the right means of transport and the most effective route to the airport. With cloud technologies airport operators will be empowered to act more flexible and to scale operations up or down based on demand. At peak times, such as public holidays, festivals, or national sporting events, additional passenger handling services can be rolled out quickly and without the need for any fixed infrastructure, as systems connect via internet technologies. Information about travellers is stored in digital passports using face recognition. Such information includes name, age, weight of luggage and the passenger's state of health (e.g. body temperature to rule out fever). This is possible thanks to thermal imaging cameras in biometric

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[73] Volocopter (2018).

facial recognition systems. Investment in biometric technologies will increase as airports strive to raise throughput while streamlining passenger travel to create a seamless experience at every touch point.[74] Recognition of the weight of the luggage is made possible by "smart luggage" systems, e.g. with an integrated scale in the luggage.[75] Every system in this process, whether it is an application, face recognition system or "smart luggage" is connected via future near field communication technologies. Data exchange takes place in seconds and it is capable of locating end devices at a certain distance from each other. Furthermore, increasing demand for punctuality, reliability and convenience will lead to high degrees of automation of processes. The COVID-19 pandemic also will have had a major impact on automation of processes at airports, as there will no longer be any points of contact. The simple scanning of faces will be sufficient to facilitate travel processes at airports. Streams of people pass through the airport and there will be no more queues at security area or at other checkpoints. Every process is accelerated to a maximum, every imaginable step, which sometimes caused long waiting times, will be happening without anyone noticing. The way from the traveller's front door to the seat in the plane is one single process, which merges almost seamlessly and onward to the destination door. Less congestion at these touchpoints will make the airport of the future more enjoyable, giving passengers more time to explore retail and entertainment opportunities throughout the terminal.[76] Total travel time will be reduced to a minimum. Important information from all areas of the airport is brought together on a data cloud platform. Responsible airport staff will be equipped with a uniform overview of all relevant operational status, plan and forecast information backed with KPIs for quick analysis. For example, if long queues build up in the terminal, an airport operating system will provide alerting and a forecast of how many people will be arriving at a given time.[77] Intelligent networked devices can also be of great benefit on airport aprons. Augmented reality functions will provide employees e.g. with information on cargo load, servicing or other status of the aircraft. For example, if oil pressure in a forklift truck is low, a notification is given and maintenance work can be carried out at a favourable time before any major damage occurs.[78] By interconnecting intelligent systems at the airport, a much faster response to disturbances will be achieved.

The fleet of airport vehicles will also be automated in order to achieve maximum efficiency in this area as well. One example of the automation of airport vehicles is autonomous winter road clearance service. Fully automated trucks will keep the runway, apron or even access roads to the airport free from snow and ice. By using one manned vehicle driving ahead with a small group of unmanned vehicles following, efficiency is achieved while providing that the single manned vehicle can react appropriately to irregularities thus ensuring a high level of safety.[79]

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[74] Ariff (2020).
[75] Cf. IATA (2019).
[76] Cf. Landgrebe (2020).
[77] Cf. Arato (2018).
[78] Cf. Ibid.
[79] Cf. Innofrator (2020).

To enable processes to run as smoothly as possible and to provide supplemental information services, so-called chat bots will be used for interaction with customers.[80] Such use of artificial intelligence, also in areas of customer interaction, will improve economic efficiency of airports. Push-back procedures will be shortened by equipping the aircraft with a self-diagnosis capability, thus reducing maintenance by ground-staff. As a result, less human personnel at the airport will be needed, thus increasing economic efficiency. In addition, push-back operations may be reduced by partly moving terminal piers and loading facilities underground. This has the advantage of a clean apron area, enabling straight-line taxiing.[81] There will be many different needs that airport operators will have to meet. Therefore, it is important to make all processes as efficient and sustainable as possible. As a result, all intra-European connections can be handled as door-to-door services within 4 hours.[82]

Airport Security

Automation and digitalisation – as described above – will also have a huge impact on airport security. One important aspect will therefore be cyber security due to increased IT dependency and resulting vulnerabilities. This requires highest levels of demands on technology development and the resulting individual technologies in the fields of program security, operating safety and disaster recovery to provide quick and unimpeded recovery of systems after possible cyber-attacks on intelligent software of artificial intelligence.[83] Air transport data networks, including navigation, air-to-ground communications and all key on-board processing elements, are completely secure, hardened and resistant to cyber-attacks, enabling the operation of all aircraft types.[84]

Security and customs / immigration processes for passenger and baggage screening will not only be more efficient, but also largely invisible to the passenger. Biometric systems and interlinked cloud platforms will ensure that every passenger in every part of an airport will be immediately recognized and assessed according to the actual threat level. These processes will mostly be completed well before the passenger's journey by profiling and categorizing of passengers and luggage according to the degree of potential risk. Like the rest of the travel experience, all security processes such as body scanning or baggage screening will be completely touchless and seamless. Since virtually all processes will be highly automated and to a large part autonomously, it is essential that these processes run undisturbed and safe. Similar to other areas, security will also involve staff redundancies that will be replaced by artificial intelligence, but this will create new opportunities and labour profiles. The use of artificial intelligence instead of conventional airport personnel in security areas requires constant monitoring of the autonomous systems for potential misinterpretation of error messages. A wrong assessment of possible dangers can cause immense detriments for airport operators, airlines, authorities and passengers. Autonomous

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[80] Cf. Arato (2018).
[81] Cf. European Commission (2015).
[82] Cf. European Commission (2011).
[83] Cf. Kapersky (2020).
[84] Cf. European Commission (2011).

systems and artificial intelligence, however, depend on successful interaction between man and machine. Connectivity throughout the system should be a top priority in a high-tech, autonomous airport. Human personnel will get a new role in the cooperation between man and machine. Supported by autonomous operating security monitoring systems, personnel will act as process managers to ensure optimum security results at airports.[85]

Environment

The desired automation and the use of new means of transport will require new infrastructures, not only in the city itself, e.g. for urban air taxis, but also at airports. Dealing with future propulsion technologies such as hydrogen, solar energy or purely electric drives requires generally structural changes at airports, e.g. in form of hydrogen tanks or new ground operation facilities, and will also have an impact on the deployment of trained personnel for the optimal handling of these propulsion technologies (cf. section 4.1.1). By using sustainable fuels, it will be possible to significantly reduce emissions of pollutants, up to the ultimate goal of emission-free travel. The use of hybrid-electric and electric propulsion also significantly reduces noise and emission footprint of airports, which means that future airports will make a major contribution to climate neutrality.[86] The use of hybrid-electric aircraft and other alternative propulsion systems as well as application of latest engine technologies will lead to a significant reduction in aircraft noise, thus also contributing significantly to social acceptance.[87] New landing procedures make it possible to balance airport utilization better with associated noise and pollution, thus improving environmental sustainability of airports. Overflying densely populated areas can be avoided flexibly so that only as little as possible airport residents are affected by aviation noise (see section 5.3). The so-called Efficient Flight Profile Concept (EFP) (cf. section 4.4) supports continuous descent (Continuous Descent Operations), thus enabling fuel-efficient and low-emission landings.[88] In future, the EFP will give pilots and aircraft clearance for a landing approach with a lead time of up to half an hour.[89] This concept was developed in 2020 during the Covid-19 pandemic, when almost all aircraft were grounded.

Future travel tickets may have an integrative validity for all possible modes of transport, according to the Mobility as a Service (MaaS) concept.[90] A single application may then provide on demand access to mobility with a single payment channel instead of multiple ticketing, payment and liability regimes. Based on this principle and with decision support by KPIs and an appropriate real time information service, travellers may then opt for a most suitable travel solution according to their actual requirements and preferences. Preferences like environmental friendliness, speed, efficiency etc. could help to improve the environmental sustainability of individual travel. Then the system will calculate a route including most appropriate means of transport that will take the

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[85] Cf. Trumpf (2019).
[86] Cf. BDL (2019).
[87] Cf. Van Audenhove (2018).
[88] Cf. Lufthansa (2020),
[89] Cf. Ibid.
[90] Cf. MaaS Alliance (2017).

traveller to the destination as environmentally eco-friendly as possible. This will also provide dynamic optimization and on the go change of priorities in real time while permanently adapting to eventualities or disturbances such as possible traffic jams or other delays.

Future sustainability efforts will also reduce climate impact at airport level. Numerous measures can and will help to reduce CO_2 emissions and to achieve the ambitious climate goals. Starting with the use of renewable energies, optimization of heating and ventilation technology, an energy supply from a nearby combined heat and power plant, energy efficient IT infrastructure. Furthermore, energy-efficient lighting will dynamically adapt to weather and ambient light conditions as well as actual flow of passengers in the terminal and throughout the airport. Illumination of areas will then be demand-actuated according to actual passenger loads. Another area where CO_2 emissions can be significantly reduced is the integration of the airport into a multimodal overall transport network with optimal connections as described above as well as through e.g. "Rail&Fly"-like offers.[91] Through a perfect embedding in a multimodal transport network, non-essential journeys will be reduced, regardless of the means of transport. Such reduction of non-essential travel will also contribute to reduce environmental pollution from airport traffic and aviation as a whole.

Expansion of the non-aviation sector

To ensure economic viability of airports it will be increasingly important to identify new sources of revenues.[92] Increasing purchasing power of society and changing consumer behaviour will lead to a trend where airports increasingly resemble shopping malls, especially in non-aviation areas of airports.[93] In addition, passengers will be offered as much comfort as possible outside the aircraft, for example special areas for families, massage salons, a number of green areas, free city tours for connecting flights with long waiting times and modern infrastructure.[94] Accordingly, future airports will no longer be used exclusively for travel, but will serve as a comfortable place to stay with a wide range of leisure activities for convenience and comfort of travellers and visitors. All these leisure activities and shopping opportunities are connected through secured data networks for maximum user-oriented travel and leisure experience.

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[91] Cf. Klimaschutz-Portal (2018).
[92] Cf. Arato (2018).
[93] Cf. IATA (2011).
[94] Cf. Arato (2018).

4. Technological Developments/Technology Roadmaps

4.1. Technological Developments "Passenger Aircraft"

4.1.1. Propulsion

4.1.1.1.   Conventional Propulsion Systems

One major focus of the work with regard to the technological development in the field of "passenger aircraft" was on consistent modeling of the aircraft propulsion systems for the aircraft configuration roadmaps developed within the project. As discussed in more detail in chapter 3.4, the fleet considered within the project consists of twelve seat classes for which propulsion system models were provided as a reference and in the evolutionary and progressive technology development scenarios, depending on the needs of the overarching analysis process.

For the aircraft configuration under consideration with a passenger capacity of more than 125 seats, models of existing engines were first provided for the reference configurations. Assumptions were then made about the evolutionary technological development potential of the respective engines within the period under consideration, which were fed back into the models as a cumulative technology improvement in a final step. The resulting engines are referred to as the "NEO option" in the following.

All engine models generated are based on classical engine performance, in which the individual engine components are represented by their thermodynamic behaviour and the overall system can be modelled by their synthesis, taking into account the physical conservation equations. In addition, simplified designs of the engine annulus were made in order to take account of any limitations in terms of aerodynamics, structure or installation space.

The reference engines were modelled on the basis of publicly available information, such as documents from certification authorities, manufacturers' data sheets and other scientific literature sources. It was possible to use preliminary work from other projects and plans to a large extent. The modelling of the NEO options was preceded by the identification of possible evolutionary technology modules and the associated assessment of their potential for improvement. Optimisation of engine components including component interaction, an increase in process temperatures, a reduction in cooling air requirements through new materials and designs (e.g. CMC) and an increase in propulsion efficiency through UHBR technologies were considered. From the individually identified technology potentials, a customized cumulative technology improvement factor was condensed for the respective propulsion system.

In order to take future developments in combustion chamber technology in the 2050 timeframe into account two promising technologies were considered. For the usage of liquid fuels, the potential of the Flameless Oxidation (FLOX©) technology was estimated based on a broad experimental and simulation experience of the authors. To evaluate the potential of liquid hydrogen as a primary fuel the Lean Direct Injection (LDI) combustion was considered on the basis

of literature. For both technologies an expected time for reaching TRL 9 was predicted as well as the NO_x emissions compared to the combustor of a CFM56-7B24 engine.

The FLOX© technology is a combustion technology which originates from industrial furnaces. It was transferred to combustion chambers of stationary gas turbines by DLR. In this field it demonstrated its high potential of emission reduction and fuel flexibility for a wide range of power classes, applications and fuels.[95] The technology uses partly premixed high-momentum jets which penetrate into the combustion chamber and generate a strong inner recirculation zone. This leads to homogeneous temperature profiles suppressing peak temperatures and therefore keeping the NO_x emissions at very low levels. Furthermore, the technology shows a wide stable operating range and a high fuel flexibility which makes it suitable for Jet A-1 as well as sustainable aviation fuels (SAF). In the past this technology was not in the focus of aircraft gas turbine engine manufacturers. But recently, new projects are exploring this technology for the aviation sector. For aviation application the authors therefore classify the technology at TRL 3 in 2020 expecting a TRL 9 in 2040. Due to single burner measurements[96] the NO_x reduction potential of this technology utilising liquid fuels is predicted to approximately 60% emission at TRL 9 compared to a combustion chamber of a CFM56-7B24 engine. For gaseous fuels such as hydrogen or LNG the authors predict a reduction potential of 80% in NO_x compared to a CFM56-7B24 engine utilizing Jet A-1.

For using liquid hydrogen multi injector LDI combustors are considered as a promising technology[97] beside FLOX-based combustors. In hydrogen utilising LDI combustors the fuel is injected directly into the combustion chamber and mixes quickly with large fractions of air.[98] In order to achieve this, most of the combustor dome area is occupied by a field of injectors which are orientated axially in comparison to the liner. A very fast mixing is crucial to a safe operation and low NO_x emissions due to the high reaction rates of hydrogen as well as the very short ignition delay times. Peak flame temperatures at medium to high power can be reduced if fuel and air are mixed well before the reaction is completed. The mixing is done by opposing small holes injecting the hydrogen into the air flow at cross-flow arrangement.[99] The technology is considered by the authors to be at TRL 3 in 2020 reaching TRL 9 at 2040-2045. The NO_x reduction potential of LDI combustion chamber utilising hydrogen is predicted to be at approximately 70-80% compared to a CFM56-7B24 engine utilising Jet A-1.

For future gas turbine engines, the steam-injecting and recovering aero engine (WET)[100] is considered to be a very promising concepts for reducing fuel block burn. In this concept a high degree of heat recovery is combined with means of NO_x reduction. This is done by the use of high amounts of steam which is injected into the compressed air in front of the combustion chamber. The steam helps to decrease the NO_x emissions by the means of a reduced combustion

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[95] Cf. Severin et al. (2017), Gounder et al. (2016a), Zanger et al. (2015), Zornek et al. (2015).
[96] Cf. Gounder (2016b), Zizin et al. (2015).
[97] Cf. Rondinelli et al. (2017).
[98] Cf. Khandelwal et al. (2013).
[99] Cf. Marek et al. (2005).
[100] Cf. Schmitz et al. (2020a).

temperature as well as changes in the chemical reaction process. The exhaust gas flow contains a much higher fraction of water vapour compared to conventional gas turbine engines. This steam is extracted from the exhaust gases by the help of a condenser and a droplet separator in the exhaust gas duct. The extracted liquid water is used in the condenser as cooling fluid. Here, the liquid water is generated into steam which is fed back into the cycle in front of the combustion chamber. An industrial and academic consortium evaluates this concept recently in a lab-scale demonstration project.[101] If the most challenging technical questions could be solved, e.g. combustion at very high water contents and achieving high water recovery factors, the concept promises a reduction in fuel burn by approximately 15%[102] compared to geared turbo fan engines of the newest generation.

4.1.1.2.   Alternative Propulsion

To achieve Flightpath 2050 goals despite continuous growth of air traffic in the last years, a dramatical reduction of CO_2 and NO_x in propulsion systems is needed. To achieve such a high level of emissions reduction, using electric propelled aircrafts instead of common gas turbine powered aircrafts can be a solution. To investigate the possibility of using electric aircrafts in the future, alternative fuel cell-based propulsion system concepts have been analysed.

Available data of the fuel cell and battery system components regarding their masses, volumes and power consumptions has been gathered based on already developed systems which have been tested both in the lab and in real flight operations e.g. in the aircraft Hy4. This data has been analysed and scaling factors for the system components (e.g. cooling system, air supply system, hydrogen storage systems) have been determined. Based on this generic data it was possible to set up powertrain systems for certain aircrafts and aircraft missions.

Specific gravimetric power and energy densities of the fully electric powertrain system is lower in comparison with common combustion engine-based powertrain systems. Therefore, main focus of the feasibility study conducted in the DEPA 2050 project was the maintaining of weight constraints for the chosen aircrafts and aircraft missions. First, preliminary calculations showed that due to very low gravimetric energy density of the batteries, batteries cannot be the only energy source of a commercial passenger aircraft. For example, if we would like to fly a DO-228 mission with 500 km range with 180kt cruise speed with SOA battery system the powertrain system mass would exceed the MTOW of the DO-228 significantly. Even assuming that the battery systems will become significantly lighter (400-500 Wh/kg on system level) in the future, the powertrain system for such a mission would still be too high to be integrated in a DO-228 class aircraft. For larger aircraft categories the battery mass is becoming increasingly problematic. Also using a fuel cell system as the only power source leads to a very high powertrain mass for the flight missions where take-off and climb have high power demands (2-3 times higher than required for cruise). Therefore, combining the high-power density of the battery with the high

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[101] Cf. Schmitz et al. (2020b).
[102] Cf. Schmitz et al. (2020a).

energy density of the fuel cell has been chosen as the preferred solution for further investigations. This means that the battery system provides additional power for the short high-power peaks during take-off and climb while the fuel cell system is sized for providing enough energy for cruise.

In the first step, feasibility of electric operation of the commonly used aircraft classes has been investigated based on aircraft technical specifications. In this step, only the main characteristics (MTOW, installed power) of the aircraft have been analysed to determine if it is possible to integrate a fully electric powertrain system which provides the needed maximum power and energy and maintains the weight constraints of the aircraft. This implies, that the electric powertrain will just "replace" the commonly used powertrain. Possibilities of power and energy reductions due to lower cruise speed, better aerodynamics in the future and lower structure mass due to advanced materials in the future have not been considered for these calculations.

The calculations showed that aircraft categories up to 70 passengers can be driven by a fuel cell-battery hybrid powertrain system even in a conservative scenario. Larger aircrafts which can carry more than 100 passengers should not be powered with a battery/fuel cell powertrain with the current technology outlook in the progressive scenario.

In the second step, detailed flight mission data (power demand over time, range, payload) of small aircrafts has been analysed which also showed that aircrafts with up to 70 passengers' capacity (e.g. ATR 72) can be operated with a fully electric powertrain system without significant drawbacks according to payload and range but other economic and ecologic advantages.

The following figure[103] shows that up to 43% of the CO_2 emissions are caused by the flights with a distance below 2,000 km. Such regional flights in this range can be operated by small fuel cell hybrid powered aircrafts with up to 70 passengers' capacity. As the smaller capacity of the aircraft also means a higher amount of flights to transport the same number of passengers, a change of the airport infrastructure will be needed. But the potential to reduce 43% of the CO_2 emissions to zero can be the driving force for such a change.

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[103] Cf. Graver, B. et al (2019).
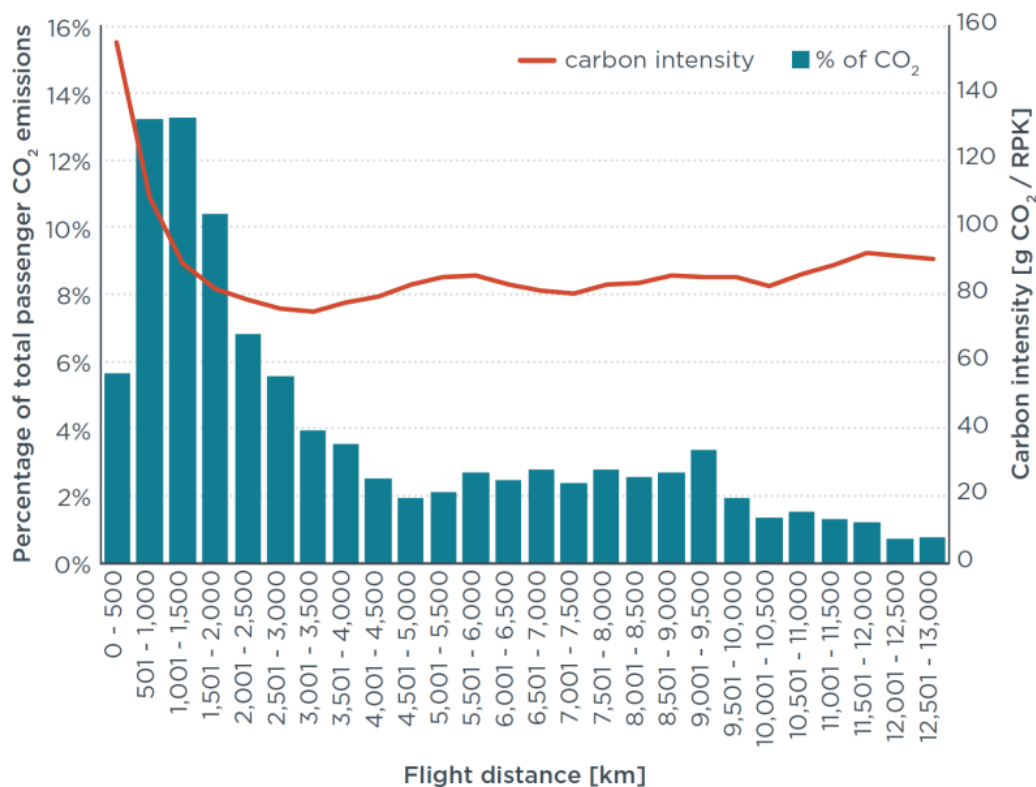
Figure 49: Flights under 2000 km are accountable for 43% of CO_2 emissions[104]

4.1.2. Aircraft Technology

In preparation to DLR-internal workshops and during the project, technology bricks were collected in order to feed the aircraft design. In addition, a comprehensive literature review was performed. The major sources of information are listed in the following.

- **ICAO CAEP** publishes in a regular cycle (every 3 years) an "Environmental Report" based on the work of its team members.[105] A variety of environmental challenges are addressed in these reports, like „Aircraft Noise", „Local Air Quality", „Climate Change and Mitigation: Technology and Operations". The publicly available information includes a collection of technologies considered.
- The **Clean Sky 2 Programme** is a public-private partnership between the European Commission and the European aeronautics industry that coordinates and funds research in environmentally friendly aircraft. Starting with aircraft configurations (i.e. regional aircraft, short/medium/long-range aircraft, business jets) technologies are identified and investigated in detail in order push the technology readiness level of these technologies.[106] Additionally, some revolutionary concepts are investigated (e.g. Blended Wing, Box Wing).

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[104] Cf. Ibid.
[105] Cf.: https://www.icao.int/environmental-protection/Pages/environment-publications.aspx.
[106] Cf.: https://cleansky.eu/an-overview-of-all-our-work-in-innovative-technologies.

- A revised version of the technology roadmap published by the **BDLI**[107] (German Aerospace Industries Association) incorporates in addition to aerospace technologies that aim at the mitigation of GHG emissions during flight a variety of measures that address the whole lifecycle of an aircraft. This includes e.g. the reduction of development times and costs as well as lifecycle emissions. With respect to a more sustainable aerospace industry this publication can be seen as the most comprehensive.

- **IATA**[108] publishes on a regular basis a technology roadmap to assess the potential to reduce the climate impact of aviation. Besides aircraft technologies, areas regarding "Operations", "Infrastructure" and "Market-based Measures" are addressed. The derivation of quantitative values, e.g. for aircraft efficiency, is based on experts´ opinion. The results are fed into simulations that model global fleet development and traffic forecasts to derive emissions of the air transportation system on a global scale.

In the DEPA 2050 project the focus for technology screening was on the identification of aircraft-specific technologies in order to reduce fuel consumption during the different phases of a flight (block-fuel). The selection of technologies should be assessed against the background that competing products, e.g. operational approaches coming from ATM-related measures, might have a similar potential to reduce emissions. A parallel and competing development of technologies must be avoided, if there is no convincing justification, e.g. redundancy of system for safety reasons.

Classically, improvements in aerodynamics, structure and propulsion are used to derive efficiency gains (in terms of block-fuel savings). The impact of technologies might then be evaluated in a very efficient way. An example of such an approach is given in Figure 50 for a typical SMR aircraft (e.g. A320neo).
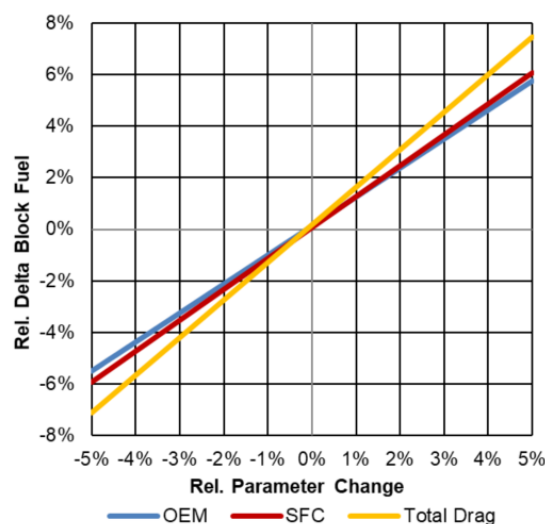
Figure 50: Impact of the parameter variation of operating empty mass (OEM), specific fuel consumption (SFC) and total drag on block fuel for a short/medium-range aircraft

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[107] To be published.
[108] Cf. IATA (2013).

This approach, using precalculated response curves or response surfaces, can help to efficiently prepare technology roadmaps. For more revolutionary concepts this approach reaches its limits. Taken the example of a BLI-configuration, there is a strong link between "propulsion" and "aerodynamics". Modifications of one discipline or another impact the performance of the whole aircraft. In a similar way the introduction of hybrid-electric aircraft configurations work, but the variety of options how these aircraft are operated adds to the complexity (see also chapter 4.3.1).

Furthermore, other phases of a "flight" need to be considered, i.e. Taxi, Turnaround, and Maintenance. For the taxi-phases, where a significant portion of block-fuel is spent, it is stated[109]: *"Airport surface congestion at major airports in the United States is responsible for increased taxi-out times, fuel burn and emissions […] Similar trends have been noted in Europe, where it is estimated that aircraft spend 10-30% of their flight time taxiing, and that a short/medium range A320 expends as much as 5-10% of its fuel on the ground [..]".*

In Figure 51 the product lifecycle definition according to Bombardier is shown. In addition to the „product-use", which was described in more detail in the previous section and is the focus of the DEPA 2050 project, technologies must also meet requirements stemming from the other phases of the product lifecycle. This includes ecological and economical aspects. Taken these considerations as a basis, it must be stated that the derivation of technology bricks very likely leads to a suboptimal solution. Since most of the lifecycle phases are not addressed for the assessment.
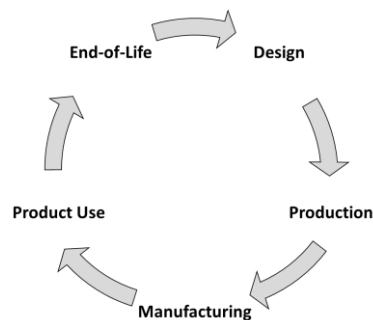
Figure 51: Product Life Cycle for an Aircraft [110]

In the following sections an overview will be given in order to give an impression about the variety of possible technical solutions for the design of aircraft. The focus of DEPA 2050 (and most – if not all – of the published technology roadmaps) is on passenger aircraft, simply for the reason that most of the GHG emissions can be attributed to this class of vehicles. Other possible emission sources:

- Passenger Aircraft (including Supersonic, Business Aircraft, General Aviation)
- Freighters (excluding passengers)
- Helicopters

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[109] Simaiakis (2014).
[110] Bombardier (2021).

- Drones/Air-Taxis
- Military Aircraft
- Other (e.g. aerostats)

In DEPA 2050 the focus of technology screening, technology roadmapping and the corresponding emission calculations and climate impact assessments is on passenger aircraft. A rough subdivision of aircraft classes, in line with other publications (e.g. Clean Sky 2), is:

- Regional Aircraft
- Short/Medium Range Aircraft
- Long-Range Aircraft

As described in chapter 3.4.1 these classes are subdivided in different seating classes.
Most of today´s aircraft are based on typical "tube & wing" configurations. Especially in research, there is big diversity of alternative concepts and configurations (some examples are given in Figure 52):

- Tube & Wing (e.g. high-/low-wing, forward-swept wing, v-tail, elliptic/ dubble-bubble fuselage, boundary-layer ingestion, upper-blown flaps)
- Blended Wing Body
- Box Wing
- etc
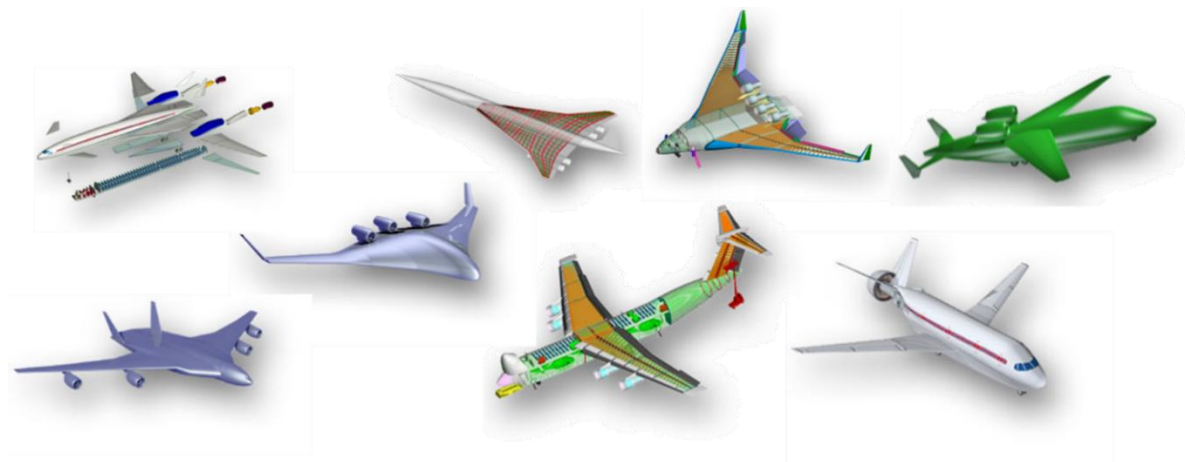
Figure 52: Examples of different aircraft configurations[111]

Furthermore, these configurations can be designed for different propulsion system architectures, e.g. (see also chapter 4.1.1):
- Jet Engines
- Turboprob
- Piston Engines

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[111] Taken from: https://www.dlr.de/as/en/Desktopdefault.aspx/tabid-188/379_read-640/, accessed: 11.01.2021.

- Electric Flight (Battery, Fuel Cell (e.g. polymer electrolyte membrane (PEM), solid oxide fuel cell (SOFC), solid acid fuel cells (SAFC))
- Hybrid-electric (series-hybrid, parallel-hybrid, series/ parallel partial hybrid, turboelectric, partial turboelectric)

Furthermore, the type of used fuel can have far-reaching consequences on the design of aircraft (see also chapter 4.4). Next to nowadays most frequently used "fossile kerosene" there are, among others (see also chapter 4.7):

- „Drop-In Fuels", e.g. synthetic kerosene
- „Non-Drop-In Fuels", e.g. hydrogen, etc.

Consequently, there is a huge variety of combinations and variations for the design of aircraft. In this respect, the factor „time" has an important role. In DEPA 2050 this factor is accounted for by the definition of a "technology readiness level" (TRL) for single technologies or even aircraft configurations in combination with the definition of an "entry-into service" of an aircraft. The TRL (see Figure 53) allows for an estimation of the possibility, whether a technology might be applied for a future aircraft programme. In DEPA 2050 it is assumed that a technology must have reached TRL6 five years in advance to the EIS of an aircraft (more explicitly: TRL6 must be reached in 2030). It is difficult to quantify the periods for other TRL and it must be stated that the financial investments might speed up the timescales. A rough estimate for TRL timeframes is shown in for engine and airframe technologies.

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

Figure 53: Definition of the Technology Readiness Level according to NASA[112]

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[112] Taken from: https://www.nasa.gov/509838main_TRL.png, accessed 12.01.2021.

TRL Maturation Timeline
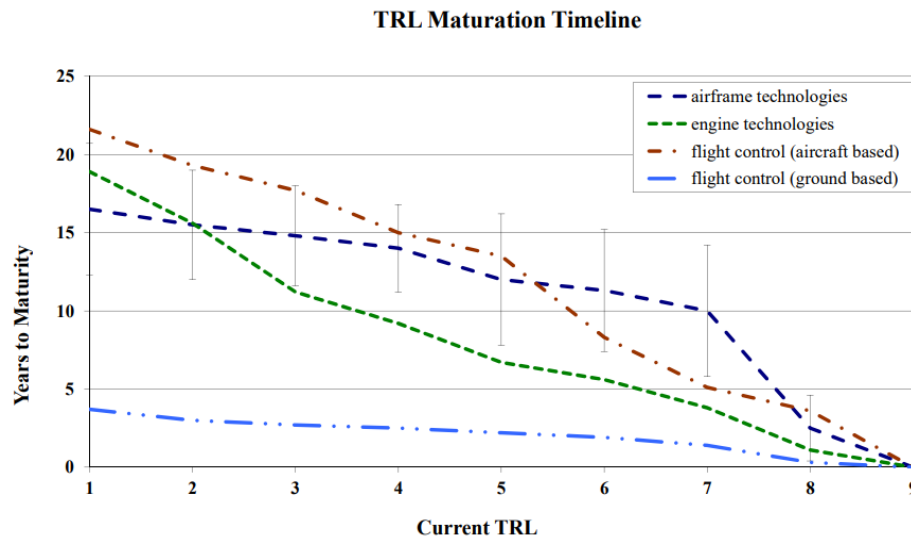
Figure 54: Time to TRL9 for different aircraft technologies based on literature review[113]

It is noted that, focusing solely on the TRL neglects a variety of other aspects that are important in order to successfully introduce an innovation (sometimes denoted as the "Valley of Death"). Other perspectives to assess the probability for an EIS are e.g. [114]:

- Manufacturing Readiness Level (MRL)
- Integration Readiness Level (IRL)
- System Readiness Level (SRL)
- Regulatory Readiness Level (RRL)
- Commercial Readiness Level (CRL)[115]

The proposed definitions for different readiness levels illustrates the complexity of the "EIS-problem" and might explain why some of the more advanced aircraft concepts are not taken over by the market.

This shows, that – just in the field of aircraft design – the design space is huge, and as a consequence a variety of possible "development pathways in aviation" are possible.

4.2. Aircraft Configuration Roadmaps

As described in chapter 3.4 the fleet considered in DEPA 2050 consists of twelve different seat classes. For each of these seat classes a reference model a conservative-evolutionary and progressive technology scenario is defined. In a first step the configuration and the propulsion architecture are defined (see Figure 55). Generally, there are no big changes expected with

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[113] Nolte et al. (2012).
[114] Cf. Boeing (2017).
[115] Cf. Australian Government/Australian Renewable Energy Agency (2014).

respect to the configuration of the future aircraft, i.e. the configurations are based on the reference aircraft (tube & wing). For aircraft with seating capacities below 125 seats (i.e. seat categories 1-5) novel propulsion architectures are assumed for both scenarios. For higher seat categories the technologies are less ambitious. In the conservative-evolutionary scenario efficiency gains are solely based on improved engine performance (denoted as "NEO-Version"), in the progressive scenario technologies to improve aerodynamics and structure are added (denoted as "NEO-Version + Technologies").

Figure 55: Roadmap for aircraft configurations for different seat classes and scenarios (conservative (-evolutionary), progressive) and EIS 2035

In the following the assumptions for each aircraft within the different seat categories is described in more detail. Additionally, the main results are presented. These are limited to fuel consumption and emissions (CO_2, NO_x) on selected trajectories and for defined load factors. The corresponding datafiles will be used for the calculation of the emission inventories and the climate impact modelling, correspondingly.

It is noted that, due to the extensive modelling efforts, some of the aircraft are based on simplified assumptions. Namely this applies to seat categories 1-5 and 11 (due to a lack of a proper reference model). This approach is justified by the expected impact of these aircraft on overall emissions, as shown in Figure 56, where seat categories 1-5 comprise for less than 10% of total fuel consumption. Of course, if the aviation market changes significantly to shorter flights

and smaller aircraft these simplifications impact the overall results and need to be improved. More details about the overall approach, as well as most of the performance data (payload-range-diagrams, emissions, etc.) are given in the documentation of the DEPA 2050 project.[116]
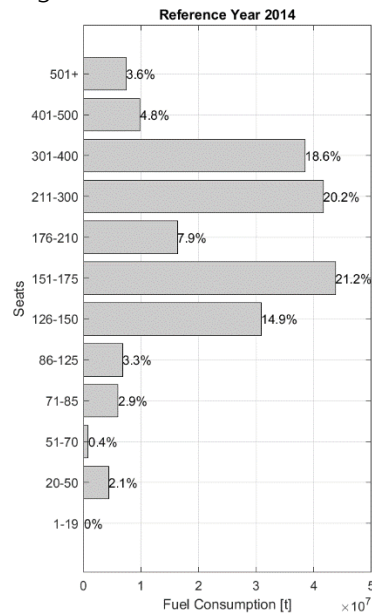
Figure 56: Global fuel consumption of passenger aircraft on the basis of the reference year 2014

4.3. Passenger Aircraft within DEPA 2050

4.3.1. Seat Category 1-4

Seat Categories 1-4 comprise of small air transport and regional jets. The flight distances of these aircraft are usually in a range where battery-electric flight becomes an option. Especially for aircraft with up to 19 seats there are numerous research projects that investigate potential propulsion architectures. As an example, the application of an innovative propulsion architecture within the CoCoRe (Cooperation for Commuter Research) project is shown in Figure 57.
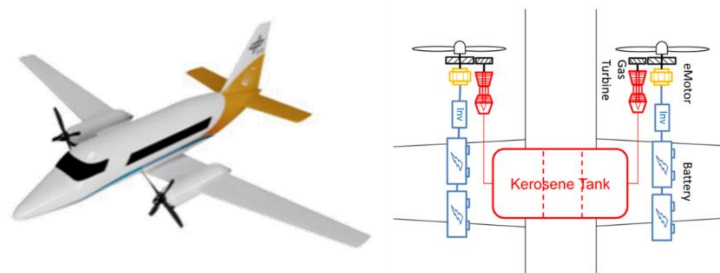
Figure 57: Aircraft design study using batteries and a range extender developed within the CoCoRe project[117]

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[116] Cf. Dzikus et al. (2020).
[117] Atanasaov (2020).

Within the DLR-project SynergIE (Untersuchung von verteilten hybrid-elektrischen Antrieben an Kurzstreckenflugzeugen) the potential of hybrid-electric propulsion architectures for regional aircraft with up to 100 passengers is investigated. This includes detailed research of distributed propulsion systems as shown in Figure 58. In addition to the emission reduction stemming from the innovative propulsion architectures, distributed propulsion potentially enables:

- More efficient aerodynamics
- Improved wing loads
- (and thereby) reduced wing weight
- reduced aircraft noise
- new approaches in flight mechanics (e.g. yawing)
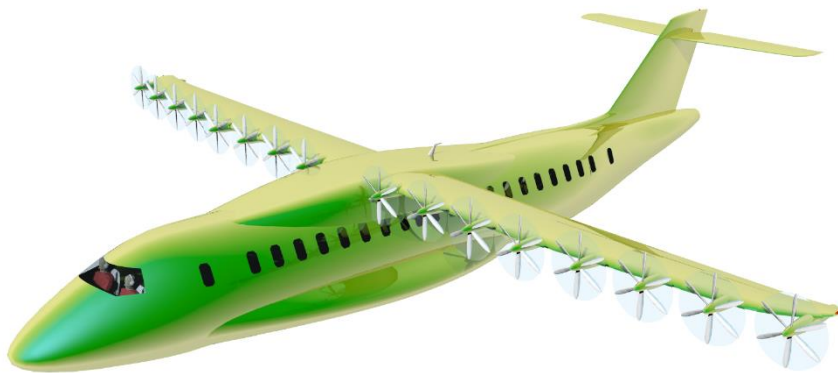
Figure 58: Concept of a regional aircraft with hybrid-electric propulsion and distributed engines[118]

Aviation industry is also doing research for improved regional aircraft. New developments within that seat category are investigated in e.g. the European Clean Sky program[119]. One of the main themes in the Clean Sky initiative is the development and assessment of future regional aircraft "with a seating capacity ranging from 20 to 130 seats, on short to medium-haul routes". Consequently, the technologies identified in Clan Sky could be transferred up to seating category 6 for this study. According to the initiatives website there are several technical solutions that can be applied to regional aircraft:

- Low weight structural solutions
- Low external noise applied to critical items
- Advanced aerodynamics
- Load Alleviation
- All electric solutions

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[118] SynergIE Project: "Investigation of distributed hybrid-electric propulsions on short-range aircrafts", URL: https://www.dlr.de/as/desktopdefault.aspx/tabid-15870/25719_read-66107/.
[119] N.N.: „Clean Sky 2 – Joint Undertaking", URL: https://www.cleansky.eu/.

This implies that there are no radical solutions planned for the propulsion system for this kind of aircraft (e.g. electric propulsion, hybrid-electric propulsion). Nevertheless, regional aircraft will serve as a testbed for the electrification of airliners[120].

Since energy densities that for aircraft with an EIS in 2035 are assumed to be insufficient in order to allow for enough flexibility with respect to the flight distance (especially if diversions are considered[121]), the use of a range extender is foreseen in both scenarios in the DEPA 2050 project and for all aircraft. System architectures for hybrid-electric propulsion systems are described in more detail in chapter 4.1.1. For trajectory modelling the impact on emissions is estimated on existing reference data.

There are two different operational concepts considered for battery-electric flight with a range extender, depicted in Figure 59. In DEPA 2050 the focus is on the second concept, i.e. using the range extender during cruise for ranges that exceed the full-electric flight range.
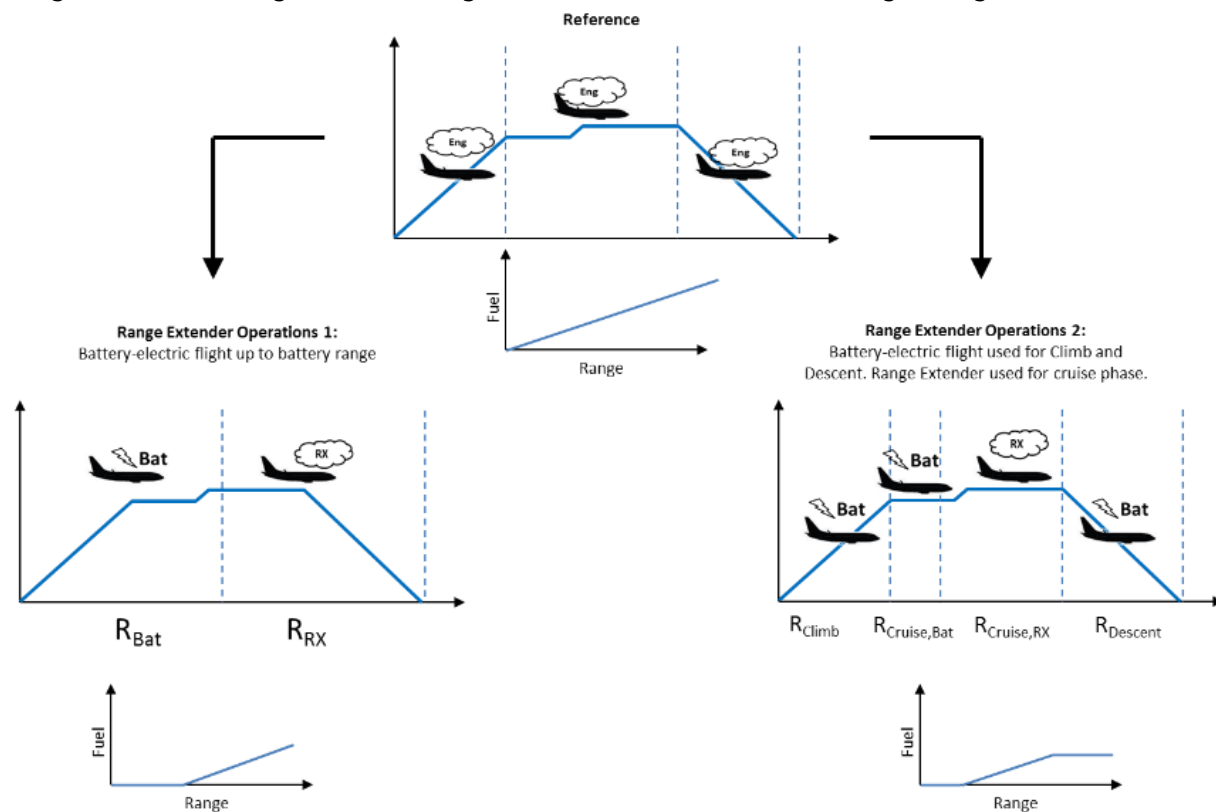
Figure 59: Operational concepts for hybrid-electric aircraft in DEPA 2050

The general approach to derive the trajectory data is shown in Figure 60. The energy density of the batteries is set to 300kW/kg, whereas in the conservative-evolutionary scenario the range extender is fueled with kerosene. The progressive scenario assumes that the range extender is runs "emission-free", e.g. by using a fuel cell.

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[120] Cf. Wolfe (2020).
[121] Cf. Hepperle (2012).

The flow chart content:

Define basic input data (incl. energy density, seat load factor, MTOW, OEW, pasenger weight number of seats)

$f_{MTOW} = OEW_{ref} / MTOW_{ref}$

$MTOW_{Successor} = (m_{maxPayload} + m_{Battery})/(1 - f_{MTOW})$

$f_{fuel} = MTOW_{Successor} / MTOW_{ref}$

Read perfomance data of the reference aircraft (i.e. trajectory, fuel flow, emissions)

Calculate battery-electric range based on „Martin Hepperle" equation

$R_{Bat} > R$ → CO2 and NOx-Emissions = 0

Caluclate Ranges for Climb and Descent $R_{Climb}, R_{Descent}$

Calculate Battery-Range in Cruise $R_{Cruise,Bat} = R_{Bat} - (R_{Climb} + R_{Descent})$

Calculate Range-Extender flight distance on Cruise Level $R_{Cruise,RX} = R - (R_{Bat} + R_{Climb} + R_{Descent})$

Determine Fuel Comsumption for $R_{Cruise,RX}$ based on Reference Aircraft:

1) interpolate refrenece trajectory at $R_1 = R_{Bat} + R_{Climb}$ and $R_2 = R_{Bat} + R_{Climb} + R_{Cruise,RX}$
2) read fuel consumption and emissions for this range intervall
3) Correct with f_{fuel}

Write Output File

Figure 60: Flow chart to illustrate the derivation of flight trajectories and emissions for hybrid-electric aircraft

Again, for a more detailed representation of specific aircraft performances and trajectory data, attention is invited to the consolidated notes of the project´s deliverables.

4.3.2. Seat Category 5-12

The seat categories 5-12 comprise of short/medium/long-range aircraft. For seat category 5, which is represented by Embraer´s E190 aircraft, the configuration roadmap provided that the successor aircraft are equipped with a hybrid propulsion system. An exemplary aircraft design study for such a concept will be introduced later in this chapter. Embraer´s successor, so called E-

Jet2, are based on "traditional" improvements in the fields of aerodynamics, propulsion, and structure [122] [123] [124]:

- aerodynamic improvements are achieved by increasing the wing aspect ratio through a new winglet design
- engine efficiency is increased by geared turbofan engines
- the wing, made of conventional aluminium, is optimized for maximum weight reduction
- a 4th generation flight-by-wire system to reduce aircraft system weight

Apart from improvements to reduce fuel consumption and emissions, improvements in maintenance ("onboard maintenance system") are introduced.

The largest part of global emissions of aviation stems from the aircraft which can be assigned to aircraft of the A320/B737-family, the "top-selling aircraft on the market"[125]. Consequently, a lot of research and aircraft design studies are related to seat categories 6-8, which are represented by the A220-300, the A320neo and the A321neo, respectively. Improvements in the short-/medium-range (SMR) market in fuel efficiency will have a big impact on air transport system level.

Electrification plays an increasing important role in aviation, and this also applies for this category of aircraft. A rough division of technical solutions and some examples for applications are shown in the following figure. Especially the "More Electric Aircraft" (MEA) strategy resulted in significant fuel savings for airlines.
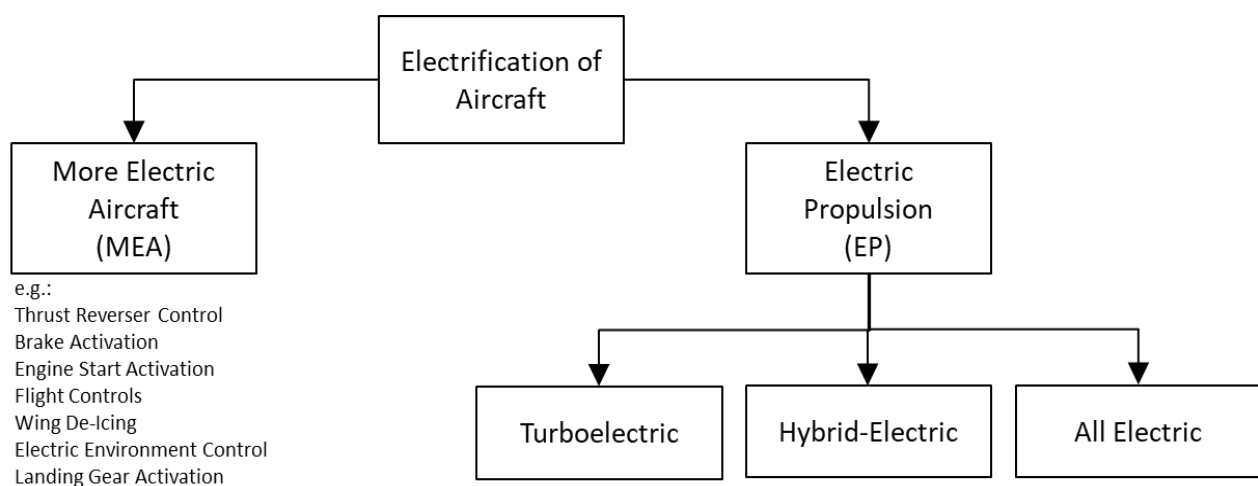
Figure 61: Division of possible solutions for the electrification of aircraft

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[122] Cf. Flightglobal (2013).
[123] Cf. Embraer (2021).
[124] Cf. Flugrevue (2016).
[125] Business Insider (2019).

Electrical systems have significant advantages in terms of efficiency, weight and maintainability compared to pneumatic, hydraulic or mechanical systems. The fly-by-wire system is only one example for this purpose. The following figure shows for various aircraft types how electrification increasingly replaced conventional aircraft systems.

	Boeing 737	A380	Boeing 787	A350	F-35 JSF
Environmental Control System	P	P	E	P	P
Flight Control System	H	E H	H	E H	E
Landing Gear	H	H	H	H	H
Wheels & Brakes	H	H	E	E	H
Ice Protection	P	P	E	P	E
Thrust Reverser	H	E	H	E	F

E Electric   H Hydraulic   P Pneumatic   F Fuel
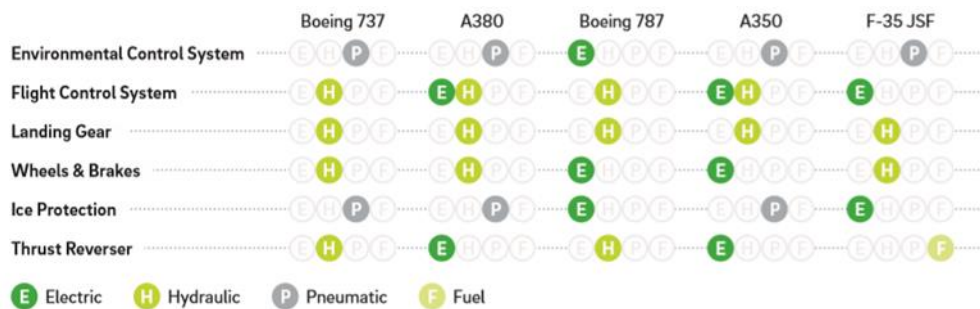
Figure 62: Penetration of electrical systems by aircraft type[126]

Electric propulsion for SMR aircraft seems to be less popular for aircraft manufacturers than for research institutes. E.g., a concept introduced by the NASA is a single-aisle turboelectric commercial transport aircraft with boundary layer ingestion (STARC-ABL). "The turboelectric architecture consists of two underwing turbofans with generators extracting power from the fan shaft and sending it to a rear fuselage, axisymmetric, boundary layer ingesting fan". Thereby fuel consumption can be reduced by 7-12% compared to a reference aircraft. A similar approach is investigated by the DLR.
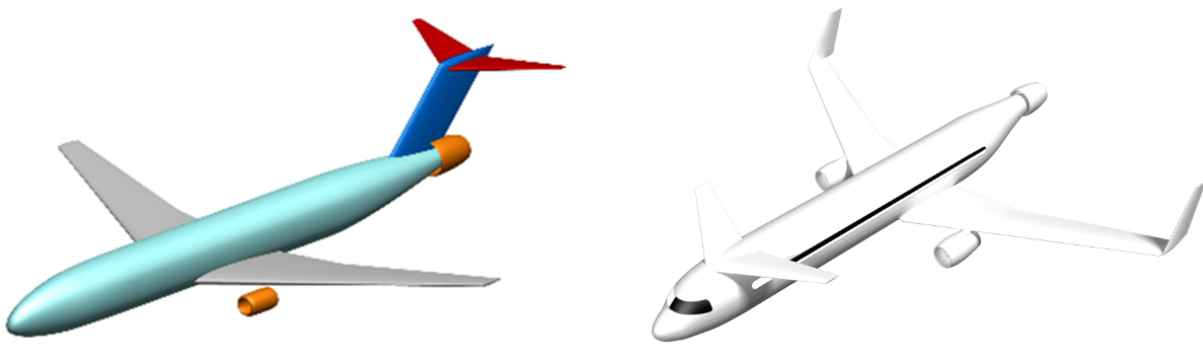
Figure 63: BLI-configurations and electric propulsion from NASA[127] and DLR[128]

Another concept developed by NASA is the "ESAero ECO-150", a fully turboelectric system with 2 turbogenerators and 16 motor-driven fans embedded in the wing[129]. A graphical representation of the concept is shown in the following.

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[126] Roland Berger (2017).
[127.] Welstead et al. (2016).
[128] Iwanizki et al. (2019).
[129] Madavan (2016).

Figure 64: The ESAero ECO-150 turboelectric concept by NASA[130]

Another concept introduced by the DLR is based on the use of a hybrid-electric propulsion system with a high-temperature fuel-cell system providing electricity to the main engines[131]. The concepts are denoted as "HOD165lite", "HOD165advanced", and "HOD165full" depending on the type of integration and technology assumptions made. The fuel cell runs on kerosene, i.e. hydrogen is obtained from conventional fuel through a reformer. The electricity produced supports the propulsive power of the main engines during off-design conditions (i.e. cruise conditions). This approach allows for engines that are optimized for e.g. cruise conditions and therefore lead to fuel savings of around 9%. In the following figure the basic design of the system is shown.
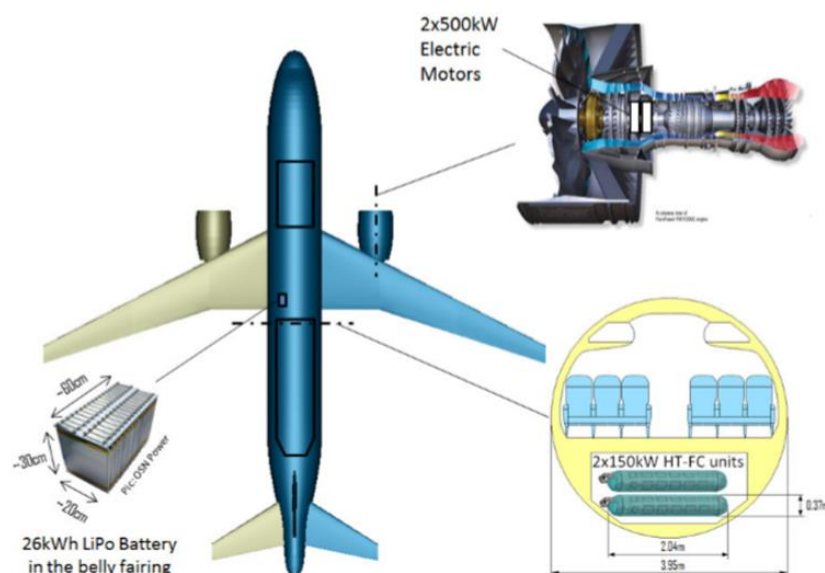
Figure 65: HOD165lite propulsion components integration into the aircraft

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[130] Ibid., p. 12.
[131] Cf. Atanasov et al. (2020).

In order to address the more "radical" solutions, the project NACOR (New Aircraft Concepts Research) is mentioned at this place. In this project a number of different unconventional configurations for the SMR class was investigated, among them:

Figure 66: Examples for unconventional aircraft configurations of the NACOR project (upper figure: strut-braced wing, middle figure: tail-less aircraft, bottom figure: Blended Wing Body) [132]

Seat Category 9 with a capacity range of 176-210 seats. In DEPA 2050 it is represented by the Airbus A321NEO. Seat Category 10 with a seating capacity range of 211-300 seats includes numerous aircraft types, including aircraft from the B757/B767-family. In DEPA 2050 it is represented by the Boeing B787. The step from seating category 9 to 10 represents the step from a single-aisle aircraft to twin-aisle aircraft as well as from medium- to long-haul aircraft. The introduction of a so called "Middle-of-the-Market" approach, aims at filling this gap (with focus on Low Cost Carriers) for the following reasons[133]:

- shorter ranges with increasing demand and scarce airport capacities
- on longer ranges to compete against traditional airlines by offering direct flights instead of using a hub-and-spoke network

How the leading manufacturers Boeing and Airbus addressed this demand in a "new" aircraft type is described in various articles. The basic outcome is, that Boeing addressed the demand through the introduction of a new aircraft (so called "B797" or "NMA (New Midsize

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[132] Iwanizki et al. (2020).
[133] Airliners.de (2019).

Aircraft)")[134]. There are two versions under consideration, the NMA-6X (with a seating capacity of 225 passengers and a range of 5000nm) and the NMA-7X (with a seating capacity of 265 passengers and a range of 4500nm). Compared to the B787-8/-9, range and capacity differ considerably. Airbus offers modified options of their existing aircraft as "Middle of the Market" options. On the lower end, the A321Neo can cover the market niche, whereas a A330Neo is a possible option to modify a long-range aircraft. Finally, the decision was made to introduce a long-range version of the A321neo, namely the A321XLR. In the meantime, Boeing abandoned its plans for the NMA.

DLR´s research on a "Middle-of-the market"-aircraft was brought together in the project ATLAS (Advanced Technology Long-Range Aircraft Concepts). There are several technologies investigated in this project for an aircraft able to carry 257 passengers and a design range of 4600nm:

- Hybrid Laminar Flow Control
- Ultra-High Bypass Ratio Engines
- CO_2 managed cabin
- High Aspect Ratio CFRP wing
- Maneuver load alleviation

A graphical representation of the ATLAS configuration is shown in the following figure.
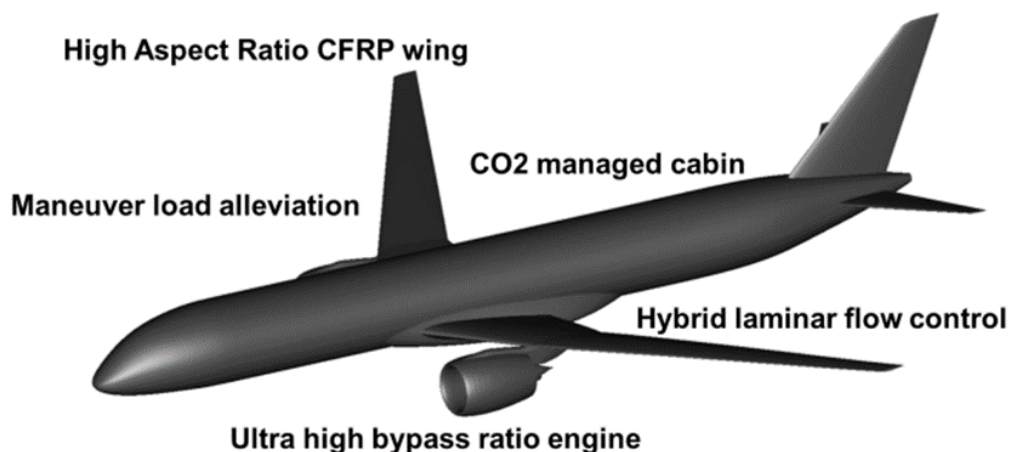
Figure 67: Aircraft Design of the ATLAS project (Advanced Technology Long-Range Aircraft Concepts)

Electric propulsion plays no role for long-haul aircraft and high seating capacities (seating class 10-12). These are represented by the A350, B777-9 and A380 in DEPA 2050. As shown in figure 61, the extended use of electrical systems is one of the measures to increase aircraft efficiency. Additionally, the use of lightweight materials plays an important role when it comes to ling-range

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[134] Cf. International Flight Network (2019).

aircraft. As an example, the pie chart in shows the material breakdown of the A350-900 XWB[135], where more than the half of the structure is based on composites.
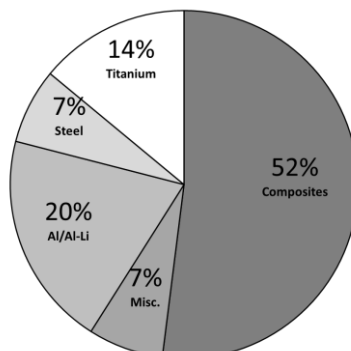
Figure 68: A350-900 XWB material breakdown[136]

In DEPA 2050 the improvements within the seating classes 5-12 are less progressive than some of the beforementioned design studies. The main reason is the short timeframe until the EIS of these aircraft which is set to the year 2035. The efficiency gains of the propulsion system are described in more detail in chapter 4.1.1. Improvements regarding e.g. the aerodynamics are based on the technologies selected in a project-internal workshop. It is assumed that the technologies can be applied to all aircraft of the higher seat categories. This approach is discussed at the end of the report.

An illustration of the technologies that were selected in the workshop is given the following figure. Most of these technologies are mentioned in this chapter and there are various arguments that these technologies are technologically mature enough to be considered for aircraft with an EIS in 2035.
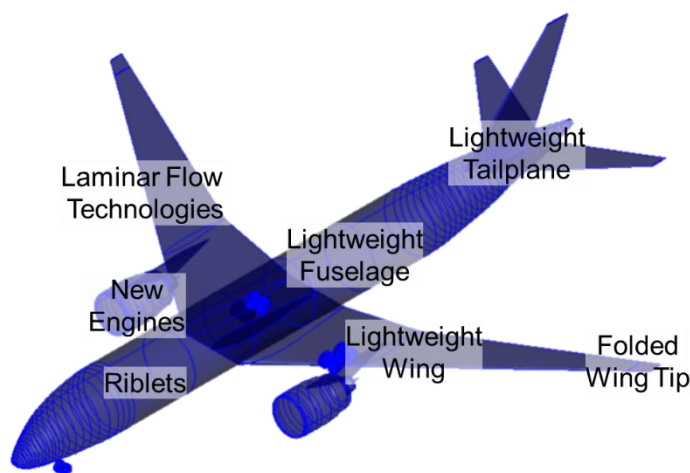
Figure 69: Technologies considered in DEPA 2050 for aircraft in seat categories 5-12

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[135] Cf. Criou (2007).
[136] Cf. Ibid.

The technology factors are listed in table 12. As mentioned before, the factors are based on experience gained in previous projects.

Table 12: Technology factors for the progressive (all) and conservative-evolutionary (only propulsion system) aircraft[137]

Aircraft			Design Parameters for Successor Aircraft (percentage compared to Reference Aircraft)										
			Propulsion System			Structure						Aerodynamics	
Type	Seat Cat	Seats	ENG$_{Offtakes}$	ENG$_{BPR}$	ENG$_{Mass}$	LG$_{Mass}$	Fuselage$_{Mass}$	Wing$_{Mass}$	TP$_{Mass}$	Cabin$_{Mass}$	Systems$_{Mass}$	Aspect Ratio	Drag
Do228	1	19	simplified approach for hybrid-electric aircraft										
ATR42-500	2	42	simplified approach for hybrid-electric aircraft										
ATR72-600	3	70	simplified approach for hybrid-electric aircraft										
Dash8-Q400	4	82	simplified approach for hybrid-electric aircraft										
E190	5	114	simplified approach with 15% improvement (conservative-evolutionary) and 30% improvement (progressive)										
A220-300	6	140	-4,25%	16	18%	const.	-5%	-5%	-3%	const.	const.	12	-5%
A320neo	7	165	-4,25%	16	18%	const.	-5%	-15%	-3%	const.	const.	12	-5%
A321neo	8	185	-4,25%	16	18%	const.	-5%	-15%	-3%	const.	const.	12	-5%
B787-9	9	290	-4,25%	16	18%	const.	-5%	-5%	-3%	const.	const.	12	-5%
A350-900	10	315	-4,25%	16	18%	const.	-5%	-5%	-3%	const.	const.	12	-5%
B777-9	11	450	simplified approach with 15% improvement (conservative-evolutionary) and 30% improvement (progressive)										
A380-800	12	555	-4,25%	16	18%	const.	-5%	-5%	-3%	const.	const.	12	-5%

In the following figure an example for an aircraft design of the conservative-evolutionary scenario is shown. In this scenario the technological improvements are based on efficiency gains of the propulsion system. The increase of the BPR leads to some (minor) changes of the aircraft design, namely a longer landing gear. Apart from this, there are hardly modifications necessary.
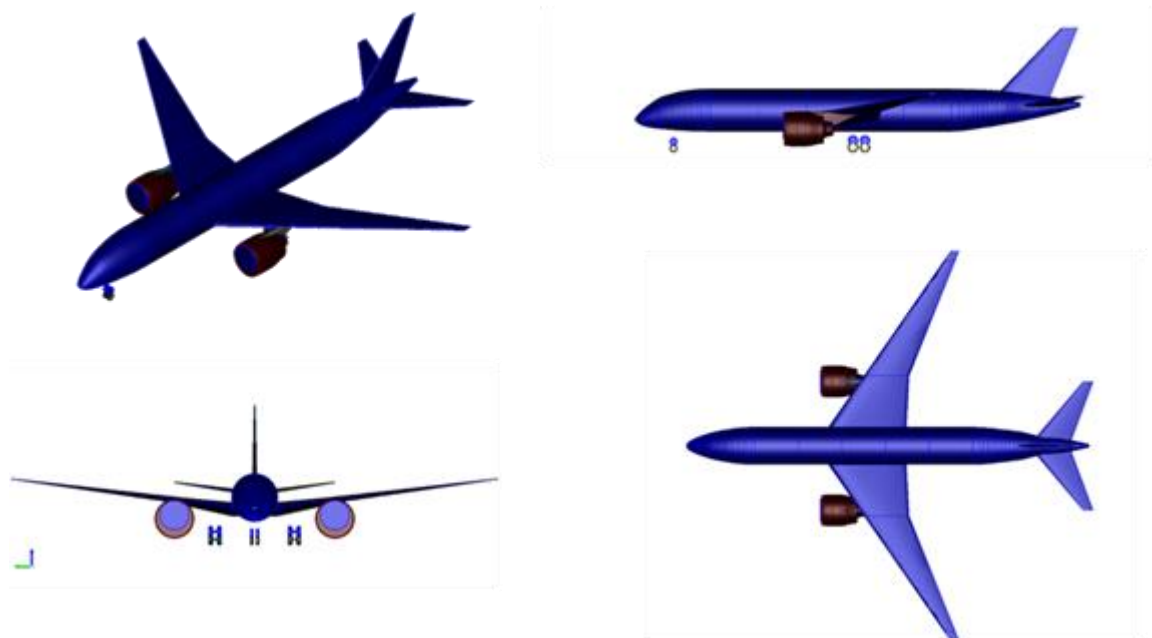
Figure 70: Exemplary representation (TIGLviewer-software) of aircraft design changes on the basis of the conservative-evolutionary scenario (red) compared to the reference aircraft (blue).

[137] Aircraft synthesis by openAD-software.

In contrast to the conservative-evolutionary scenario, technology assumptions for the progressive scenario require the design of a "new" aircraft. Some of the modifications directly stem from the technology factors defined by the experts, e.g. the higher aspect ratio leads to a higher span, some of the modifications result from the modifications itself, e.g. adaption of the tailplane area or extended landing gears. An example of the impact of technology assumptions on aircraft design in the progressive scenario is shown in the following figure.
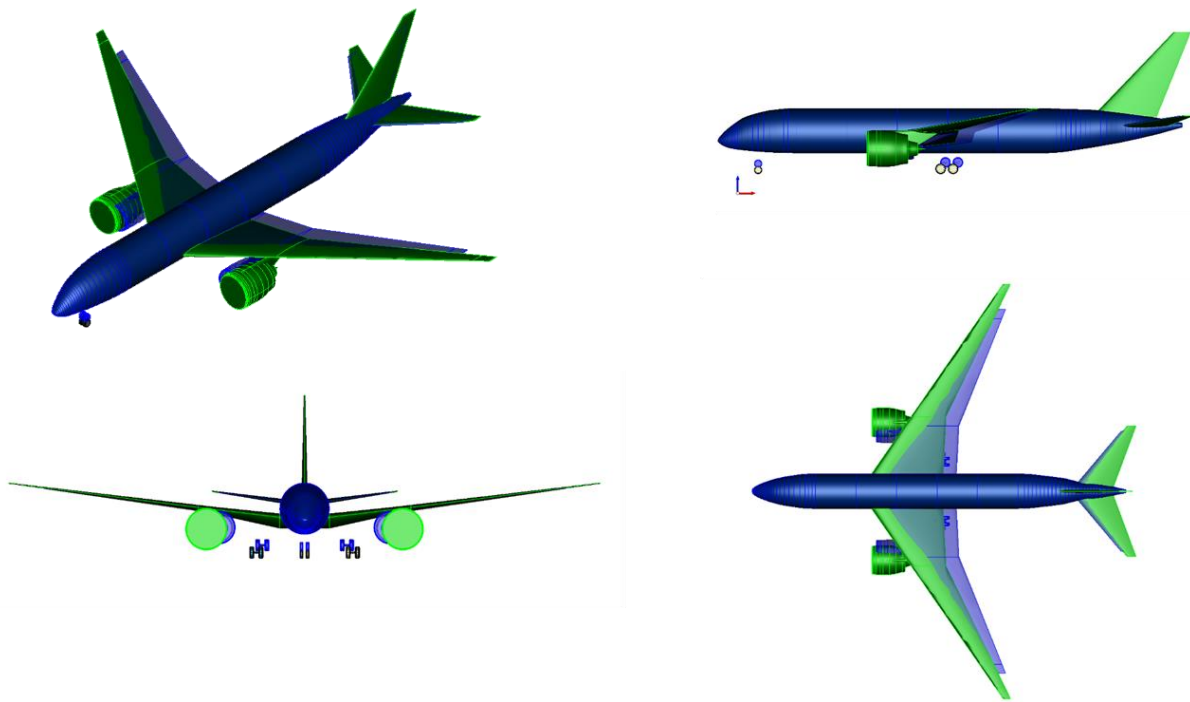
Figure 71: Exemplary representation (TIGLviewer-software) of aircraft design changes on the basis of the progressive scenario (green) compared to the reference aircraft (blue).

4.4. Hydrogen Aircraft

For the reduction of GHG in aviation a system-wide use of alternative fuels or sustainable aviation fuels is required. In DEPA 2050 the large-scale introduction of synthetic fuels aims at fulfilling this requirement. Another option, nowadays again in the scientific and industrial focus, are hydrogen powered aircraft.

The use of hydrogen as an aviation fuel has a significant impact (not only) on the design of an aircraft. The specific energy of hydrogen, or more specific liquid hydrogen (LH_2), requires a complete redesign of the aircraft's fuel system, since the volume needed for LH_2 is four times bigger than for kerosene. For this reason, most of the aircraft designs integrate the fuel tanks inside of the fuselage, as some of the examples in figure in this section show.

There are several aspects (advantages as well as disadvantages) that need to be considered for the design of hydrogen powered aircraft.
Positive aspects (among others):

- Fuel weight decreases due to the higher energy density [MJ/kg] of LH_2
- there might be weight benefits for a hydrogen-based APU, since power generators can be dispensed
- wing area is not determined by fuel capacity and could therefore be optimized

Negative aspects (among others):

- Tank volume increases due to a lower volumetric energy [MJ/dm³], approximately by a factor of 4
- The ratio of "surface-to-volume" for fuel tanks is minimized through spherical tanks and therefore the evaporation rate ("boil-off") is minimized. Consequently, the integration of LH_2 tanks in the wing is not possible. This can lead to a higher structural weight of the wing in order to compensate for aerodynamic/aeroelastic loads
- Depending on the requirements of the "boil-off"-rate, the tank weight can increase significantly
- Changes in mass distribution can lead to negative effects with respect to "weight-and-balance", which can lead to e.g. a higher tailpane surface, increased trim drag, etc.
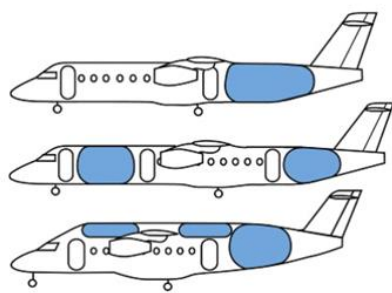
Figure 72: Concept studies for the integration of hydrogen tanks in the fuselage of an existing regional aircraft, namely the ATR72 (left figure)[138], and the use of outer tanks on a DO228 (right figure)[139]

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[138] Rondinelli (2017).
[139] Faaß (2001).
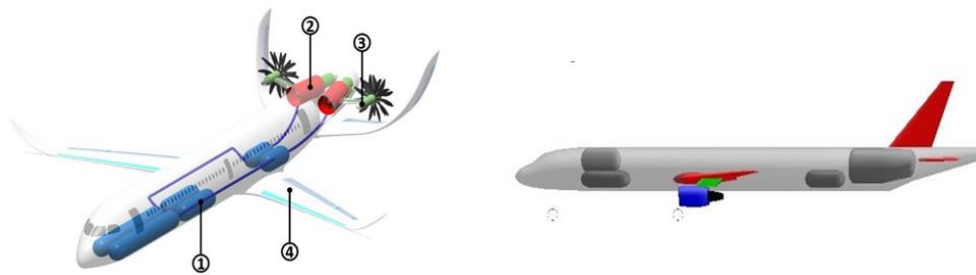
Figure 73: Concept study for a hydrogen-powered mid-range aircraft as a possible successor for an A320 (left figure)[140] and a possible successor for the A321 with a seating capacity of 180 passengers (right figure)[141]
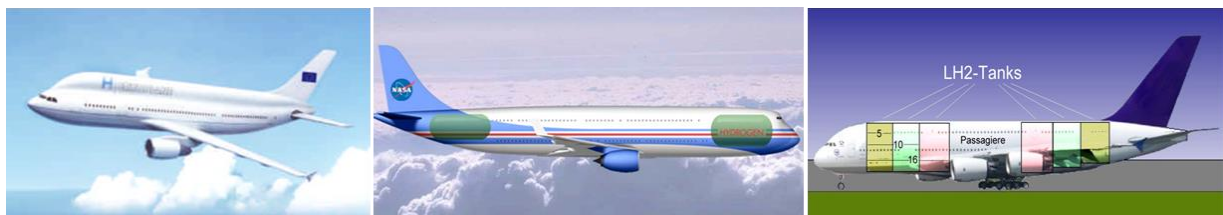
Figure 74: Concept studies for hydrogen-powered aircraft on the basis of an A310 for 240 passengers (left figure), for 300 passengers (middle figure)[142], and 211 passengers in a 3-class-layout (right figure)[143]

The positive and negative aspects of hydrogen on aircraft design do not allow for an estimation on overall aircraft performance. As an example, the literature states[144]:

" … due to the excessive tank volume required for LH_2, energy consumption would increase with 9-14% depending on the aircraft type. This in contrast with earlier studies where energy utilization for hydrogen is lower than for kerosene and is most likely related to the minimal change approach."

In the same source it is mentioned that:

"The smaller wing and bigger fuselage of the hydrogen-fueled aircraft lead to a reduction in aerodynamic efficiency. This is however compensated by the lower block fuel weight leading to a reduction in energy utilization for the flight of around 11%."

In summary, the design of hydrogen powered aircraft needs a revision of the classical design approaches and requires intensive research. Especially, tracking of other research fields, e.g. latest developments in fuel cell or battery research, is mandatory in order to leverage the full potential of so called "zero-emission" aviation.

For the sake of completeness, it is noted that hydrogen is also an option for other aviation markets, namely super-/hypersonic flights and business aircraft. Some examples of studies regarding this field are given the following figure.

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[140] Dietl et al. (2018).
[141] Scholz et al. (2015).
[142] Smith (2005).
[143] Schulte (2007).
[144] Verstraete (2013).
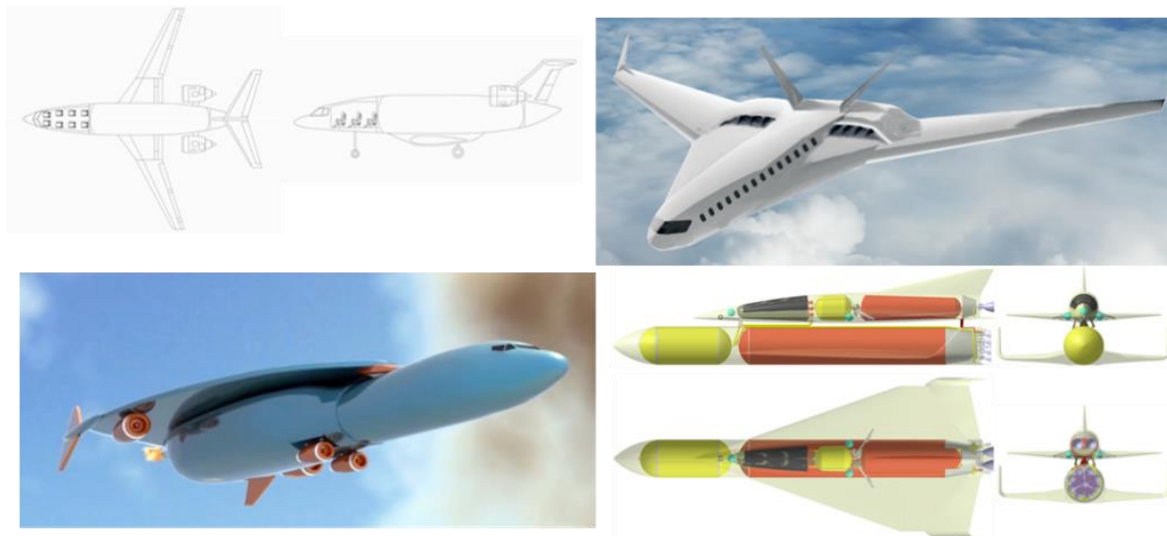
Figure 75: Concepts for hydrogen-powered business aircraft (upper figures)[145] [146] and supersonic concept studies[147] [148]

During the duration of the project DEPA 2050 a variety of research projects was initiated as well as announcements by industry[149]. Additionally, some consulting companies addressed hydrogen for aviation. While a study conducted under the lead of McKinsey[150] had a closer look at the aircraft designs and corresponding emission reduction (including aspects of climate impact), the consulting company Roland Berger identified 5 key challenges that need to be addressed in order to make a hydrogen-based aviation system possible[151]:

- A redesign of much of the aircraft, from the propulsion system to fuel storage.
- Advancements in light-weighting storage tanks and cryogenic cooling systems, in order to take advantage of hydrogen's high energy density.
- A significant ramp-up in "green" hydrogen and/or carbon capture and storage (CCS) to increase the share of emissions-free hydrogen production.
- Hydrogen infrastructure improvements in fuel delivery to airports and airport refueling.
- A reduction in the price of production methods for "green" hydrogen in order to compete with kerosene on a cost basis.

These challenges point out that, apart from the aircraft design itself, hydrogen requires adaption of the overall air transportation system (especially airports) as well as an extensive expansion of

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[145] Pochari (2019).
[146] Szondy (2019).
[147] Daily Post (2016).
[148] Sippel, M. (n.d.).
[149] Airbus (2021).
[150] Cf. Clean Sky Joint Undertakting/ Fuel Cells and Hydrogen Joint Undertaking (2021).
[151] Cf. Roland Berger (2020c).

regenerative energies. Several DLR projects address these challenges, e.g. the project EXACT (Exploration of Electric Aircraft Concepts and Technologies).

4.5. Technological Developments "ATM"

Future challenges to Air Traffic Management are a result of a steady increase in demand and execution of conventional air traffic (at least in pre-COVID times) as well as growing kinds and numbers of new entrants from parcel delivery drones via personal air vehicles to stratospheric transport vehicles. Important topics to consider here are the large number of vehicles, a wide spread in speeds and altitudes and different levels of equipment and automation.

Environmental requirements and economic aspects have to be considered and last not least the safety of air traffic as the fundamental goal of ATM has to be maintained and improved.

Aviation is a transnational cross-border transport mode and future developments are coordinated in international and intergovernmental bodies and initiatives as well as stakeholder groups. The following sections give a broad overview of important initiatives for air traffic management development and modernization focusing on the development within ICAO as the overall framework and in Europe as example for regional implementation. The intention is to introduce an aviation but non-ATM specialized reader to the strategic roadmaps of ATM development for the next decades especially in Europe. A section covering Urban Air Mobility development plans mainly in the U.S. is serving as an example for the consideration of new entrants in the field of aviation and air traffic management.

Special emphasis is then given to effects on the Horizontal Flight Efficiency of current and future Air Traffic Management due to its direct relation to CO_2 emissions which are in turn used as a major performance parameter to assess the future scenarios developed and modeled in DEPA 2050.

4.5.1. ATM Roadmaps on World Level and European Level

4.5.1.1. ICAO

The major body for the worldwide coordination of air traffic management development is ICAO, the International Civil Aviation organization. ICAO's Global Air Navigation Plan (GANP) is a triennial publication covering a fifteen-year lookout and guidance on the future development of air traffic management.

The 2019 GANP was under preparation at the time this report was written. Its actual status is accessible via ICAO's online portal.[152] On a strategic level the 2019 ICAO GANP is containing four evolutionary steps in a conceptual roadmap:

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[152] Cf. ICAO (2021).

- Step 1: Flight operations in a digital-rich environment
- Step 2: Time-based operations enabled by an information revolution
- Step 3: Trajectory-based operations enabled by full connectivity through the internet of aviation
- Step 4: Total performance management system focus on business/mission needs

The 2016 and 2019 GANPs are based on the concept of Basic Building Blocks (BBB) consisting of a framework under the headlines Meteorological Information, Aeronautical Information, Search and Rescue, Air Traffic Management and Aerodrome Operation. The BBBs are continuously improved over time by **Aviation System Block Upgrades (ASBU).** A Block Upgrade is performed through the introduction of certain **Modules** in one of the four **Performance Improvement Areas** (*Airport operations, Globally interoperable systems and data, Optimum capacity and Flexible flights and efficient flight paths*). Dependent Modules across consecutive Blocks are connected through the timeline by coherent transition **Threads**. In total GANP 2019 defines within Blocks *0/1/2/3* 22 Threads each containing 1 to 26 elements.[153]

ASBUs are combined and coordinated in trees to achieve strategic improvements i.e. to develop Trajectory Based Operations (TBO).
The ICAO GANP 2016[154] contained 10 Technological Roadmaps for the domains Communication, Navigation, Performance-Based Navigation, Surveillance, Information Management and Avionics. The ICAO GANP 2019 currently is containing 4 Technology Roadmaps for the ASBUs ASUR, COMI, COMS, NAVS.[155]

4.5.1.2. Europe

Following the "Flightpath 2050, Europe's Vision for Aviation" from 2011[156] the European Commission worked out "An Aviation Strategy for Europe" in 2015 in order to tackle the limits to growth in the air and on the ground by reducing capacity constraints and improving efficiency and connectivity. The "European aviation in 2040, Challenges of Growth" study of EUROCONTROL from 2018[157] underlined the needs resulting from the air traffic system constraints.

In 2019 and 2020 during the project duration of DEPA 2050 a number of indicatory documents have been published and updated further detailing the proposed development of European Air Traffic Management. They are mainly based on the vision of a Digital European Sky outlined in

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[153] Cf. ICAO (2016b).
[154] Cf. ICAO (2016a), p. 37.
[155] Cf. ICAO (2021).
[156] Cf. ACARE (2011).
[157] Cf. EUROCONTROL (2018).

the "ATM Master Plan - Digitalising Europe's Aviation Infrastructure" Edition 2020.[158] The Master Plan names the steady increase of conventional traffic in relation to the limited capacities both on ground and in the air, growing environmental concerns and emergence of new entrants in the airspace as reasons to act. The SESAR vision towards a digital European sky is outlined as follows:[159]

> "*THE DIGITAL EUROPEAN SKY*
>
> *By 2040, increasing numbers of aerial vehicles* [(1)] *(conventional aircraft and unmanned aircraft, such as drones) will be taking to Europe's skies, operating seamlessly and safely in all environments and classes of airspace. Trajectory based free-route operations will enable airspace users (civil and military) to better plan and execute their business and mission trajectories* [(2)] *within an optimised airspace configuration that meets safety, security and environmental performance targets and stakeholder needs. The system infrastructure will progressively evolve with the adoption of advanced digital technologies, allowing civil and military ANSPs and the Network Manager to provide their services in a cost-efficient and effective way irrespective of national borders, supported by secure information services. Airports and other operational sites (e.g. landing sites for rotorcraft and drones) will be fully integrated at the network level, which will facilitate and optimise airspace user operations in all weather conditions. ATM will progressively evolve into a data ecosystem supported by a service-oriented architecture enabling the virtual defragmentation of European skies. Innovative technologies and operational concepts will support a reduction in fuel and emissions while also mitigating noise impact, in support of the EU's policy of transforming aviation into a climate-neutral industry. Performance based operations will be fully implemented across Europe, allowing service providers to collaborate and operate as if they were one organisation with both airspace and service provision optimised according to traffic patterns. Mobility as a service will take intermodality to the next level, connecting many modes of transport, for people and goods, in seamless door-to-door services.*
>
> *(1) Traditional aircraft will be complemented by new entrants such as very low-level drones, military medium-altitude long-endurance unmanned aircraft systems, automated air taxis, super-high-altitude (FL600+) operating aircraft, next generation supersonic aircraft and electrically propelled aircraft.*
> *(2) Meaning that aircraft and drones can fly their preferred trajectories.*"

A major step towards realising the vision is seen in a **decoupling of service provision from local infrastructure** and **increasing levels of collaboration and automation support** (see "A proposal for the future architecture of the European airspace (2019)").[160]

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[158] Cf. SESAR Joint Undertaking (2020a).
[159] Ibid., p. 17.
[160] Cf. SESAR Joint Undertaking (2019).

The transformation of the Air Traffic Management System is divided in four partly overlapping phases A to D:

Phase A addresses known critical network performance deficiencies while phase B provides an efficient services and infrastructure delivery. Phase C will enable the defragmentation of European skies through virtualisation and phase D will realise the Digital European Sky. Currently (i.e. 2020) roughly two thirds of phase A are completed and phase D will be fully available in 2040 at the earliest.[161]

The corresponding levels of automation leading to the realization of the Digital Sky Vision are as follows:

- **Level 0 (Low Automation)** supports the human operator in information related tasks.

- **Level 1 (Decision Support)** supports the human operator in addition to level 0 in action selection for some tasks/functions.

- **Level 2 (Task Execution Support)** adds action implementation for some tasks/functions.

- **Level 3 (Conditional Automation)** extends the action implementation to most tasks/functions and enables automation to initiate actions for some tasks.

- **Level 4 (High Automation)** enables automation to initiate action for *most* tasks/functions.

- **Level 5 (Full Automation)** Automation performs all tasks/functions in all conditions. There is no human operator.

Automation levels are mapped differently on the master plan phases A, B, C, D for air traffic control and for U-space services. For **air traffic control** Phase A covers automation level 0, Phases B and C cover level 1 and 2 and Phase D is covering automation levels 2 to 5. A full automation level 5 is not in scope for the air traffic control part of the Digital Sky vision. The **U-space services** part in contrast is omitting Phase A and is starting straightaway with level 3 automation covered by Phases B and C. In Phase D levels 4 and 5 of automation are targeted.

Full operational capabilities for Phase A is scheduled to be achieved in 2025, for Phase B in 2030, for Phase C in 2035 and for Phase D in 2040 or 2050 depending on the timeliness of technical developments and necessary regulatory changes.

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[161] Cf. SESAR Joint Undertaking (2020a), p. 29 et seq.

Table 13: Relation between ATM improvements in important subdomains and corresponding automation levels[162]

Automation Level	1: Decision Support	2: Task Execution Support	3: Conditional Automation		
Airborne Automation					
Cockpit Evolution	Augmented Approaches	4D trajectory	Self Separation		
	Wake vortex detection and avoidance	Video based navigation system	ACAS-X		
U-Space	Atomic gyros inertial navigation	Tracking	Emergency Recovery	Dynamic Geofencing	Detect and avoid
Ground Automation					
Evolution of the Ground System	Wake separation	4D Trajectory	Complex digital clearances	Speech recognition	
	Traffic complexity resolution	Assistance for surface movement	Role of the human	Safety nets	
	Runway status and surface guidance	Advanced Separation Management	Intelligent queue management		
U-Space	Traffic information	Flight planning	Dynamic capacity management	Automatic deconfliction (multiprovider)	
Virtualization					
Virtual & augmented reality	Approach and landing aids for the cockpit	Visual aids for tower control			
Virtual Centers	Rationalization	Contingency	Dynamic cross border	Delegation of Services	
Remote Tower	Single airport	Multi-source surveillance data fusion	Multiple and large airports		
Connectivity					
Cockpit Evolution	Multilink management	Broadband satellite comm. (ESA-Iris)	Broadband airport comm. (Aeromacs)	Cellular link for GA/RC	
U-Space	Command and control	Tracking and telemetry	Vehicle to vehicle	Vehicle to infrastructure	
Data Sharing					
	Collaborative airport and network	Digital aeronautical information (AIM-MET)	Flight object sharing (IOP)	Cloud-based drone information management	
System-wide information management	Yellow profile for web services	Blue profile for flight services	Purple profile for air/ground advisory information sharing		

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[162] Cf. Ibid., p. 80.

The following steps in Automation Levels 4 and 5 are covered by a series of keywords:[163] urban air mobility, single pilot operations, autonomous cargos, autonomous large passenger aircraft, digital cockpit assistant, digital ground assistant, emulating U-space, AI powered ATC environment, defragmented European sky, all weather operations, pan European service provision capability, pan European mobility of staff, fully dynamic airspace, resilient operations, hyper connectivity for high automation, next generation links, Internet of Things for aviation, CNS as a service, future data services and applications, interconnected network, passenger centric ATM, open data, multimodality and advanced analytics for decision making.

The time schedules to deploy the essential operational changes up to 2035 are further detailed in stakeholder specific roadmaps. The European developments within the ATM Master Plan are well connected to ICAO's planned Aviation System Block Upgrades.

Important performance ambitions in the DEPA 2050 context foreseen to be reached in 2035 compared to baseline values from 2012 are as follows:[164]

- *Network throughput* raises from 9.7 to 15.7 million IFR flights per year (+60%).

- *IFR movements at most congested airports* from 4 to 4.2-4.4 million (+5% to +10%).

- *Reduction of departure delay* from 9.5 min per flight to 6.5-8.5 min per flight (-10% to -30%).

- *Gate-to-gate fuel burn* reduced by 250-500 kg per flight (-5% to -10%) equaling a *reduction in CO$_2$ emissions* by 800-1600 kg per flight (-5% to -10%).

- *Reduction of the additional gate-to-gate flight time* from 8.2 min to 3.7-4.1 min per flight (-50% to -55%).

The feasibility of these ambitions and the necessary steps were studied in "*A proposal for the future architecture of the European airspace*".[165] The study conducted simulations for two scenarios 2035, one was the AS-IS European en-route scenario and the other was the full implementation of the transition strategy within in the network. The main results were expressed in number of accommodated flights vs. average en-route delay per flights:

- AS-IS   2035   16 Mill flights   8.5 min/flight en-route delay
- Full implementation   2035   16 Mill flights   0.5 min/flight en-route delay
- Actual traffic   2017   11 Mill flights   0.8 min/flight en-route delay

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[163] Cf. Ibid., p. 80.
[164] Ibid., p. 37.
[165] Cf. SESAR Joint Undertaking (2019).

One decisive assumption for the results of the simulation was a theoretical maximum sector flight processing capacity of *45* flights per hour for the AS-IS scenario assuming the current performance and a sector capacity of *107* flights per hour for the full implementation scenario in 2035. An intermediate scenario was considered with a sector capacity of *68* flights per hour leading to an en-route delay of **2.8 min/flight** in 2035.

In terms of flight efficiency the simulations showed a reduction of **18 NM** average route length for a full implementation of Free Route Airspace for 2035 against the current situation. Additionally, the report lists an estimated reduction of Nautical Miles flown between 4 and 10 NM in 2030 and between 7 and 13 NM in 2035[166] based on simulation results.

Airport capacity issues which are foreseen to constraint the possible number of flight movements up to 2040[167] were neither addressed in the study nor included in the simulations.

Some important risks which are mentioned in the EATM Master Plan are:

- SESAR developments are not sufficient to deliver the required airspace capacity
- Pre-SESAR requisites are delayed.
- Inability to develop solutions for drone integration.
- Unaddressed cybersecurity vulnerabilities.
- The pace of solution development is to slow to cope with demand.
- Human performance issues cannot be managed properly.
- Failure to coordinate with other regions.

Taken all together a lot of technological possibilities to improve air traffic management exist and are under research and development. Their success is depending of course on their technical feasibility but also heavily on political decisions to realize the digital single European sky. Up to today the outcome of the decision processes is hard to predict although the communicated intentions of the major players are pointing in the required direction.

4.5.2. Expected Efficiency Gains in ATM

The DEPA 2050 project plan states ATM related efficiency improvements of trajectories as core input developed by WP 3.3 for the following work packages. The efficiency improvements should be distinguished by time horizon (2030, 2040 and 2050 in relation to baseline 2014), by scenario (conservative-evolutionary and progressive), by trajectory segment (ground or en-route) and geographical region (continent).

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[166] Cf. Ibid., p. 67.
[167] Cf. EUROCONTROL (2018).

In 2009 ICAO's *Manual on Global Performance of the Air Navigation System* has defined 11 Key Performance Areas within the ATM system and Efficiency is one of them.[168] It identifies two focus areas "Temporal Efficiency" (i.e. delay) and "Flight Efficiency" (trajectory oriented). The examples given for common metrics in the KPA Efficiency are concentrating on the delay aspect (e.g. average departure delay of delayed flights or per cent of flights with on-time arrival).[169]

The *2016-2030 Global Air Navigation Plan*[170] of ICAO describes a performance-based approach for the further development of the Air Navigation System. Thus, ICAO promotes a focused set of Key Performance Indicators (KPIs) divided into Core KPIs and Additional KPIs. For the KPA Efficiency the following KPIs were proposed

- KPI02 Taxi-Out Additional Time (Core),
- KPI13 Taxi-In Additional Time (Core)
- KPI04 Filed Flight Plan en-Route Extension (Additional)
- KPI05 Actual en-Route Extension (Additional)
- KPI08 Additional time in terminal airspace
- KPI16 Additional fuel burn

A phased development approach was foreseen with the agreement on a simple set of KPIs until 2019 based on existing best practices. The linkage between ASBU Modules and KPIs was planned to be illustrated up to 2022 together with the update of the performance related Manuals (Doc 9883[171] and Doc 9161). For 2022 and beyond standardisation of performance data and enhanced data exchanges were scheduled. A more detailed description of the Efficiency KPIs used is given in the "Description of the potential performance indicators presented in the GANP 2016" which was published by ICAO in 2015[172]:

Table 14: ICAO Efficiency KPI descriptions[173]

Taxi-out	**KPI02**	Taxi-out additional time	Actual taxi-out time compared to an unimpeded taxi-out time [avg. per airport or per cluster of airports]
Taxi-in	**KPI13**	**Taxi-in additional time**	**Actual taxi-in time compared to unimpeded taxi-in time [avg. per airport or per cluster of airports]**
En-route	**KPI04**	**Filed flight plan en-route extension**	**Flight planned en-route distance compared to a reference ideal trajectory distance [avg. per traffic flow or airspace volume]**
	KPI05	**Actual en-route extension**	**Actual en-route distance flown compared to a reference ideal distance [avg. per traffic flow or airspace volume]**

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[168] Cf. ICAO (2009).
[169] Cf. Ibid.
[170] Cf. ICAO (2016).
[171] Cf. ICAO (2009).
[172] Cf. ICAO (2015a).
[173] Cf. Ibid.

Descent & terminal area arrival	KPI08	Additional time in terminal airspace	Actual terminal airspace transit time compared to an unimpeded time [avg. per airport or per cluster of airports]
Per flight phase or gate to-gate	KPI16	Additional fuel burn	Additional flight time/distance converted to estimated additional fuel burn attributable to ATM [avg. per flight, airport or per airspace volume]

The **current issue of the Global Air Navigation Plan** is documented mainly in a web portal.[174] The Performance Framework KPIs and the Performance Objective Catalogue are adding three additional KPIs within the KPA Efficiency:

Climb	KPI17	Level-off during climb	Distance and time flown in level flight before Top of Climb
Cruise	KPI18	Level capping during cruise	Flight Level difference between maximum Flight Levels on a measured airport pair and maximum Flight Levels on similar unconstrained airport pairs.
Descent	KPI19	Level-off during descent	Distance and time flown in level flight after Top of Descent.

4.5.3. ATM Efficiency Measurements and Forecasts

4.5.3.1. Pre-2000 studies

ATM Efficiency has been defined and measured at least from the early 90s of the last century on. The IPCC report from 1999[175] is taken here as an initial point in estimating ATM efficiency and possible improvements to it. The IPCC report estimates that improvements in air traffic management and other operational procedures could **reduce aviation fuel burn by between 8 and 18 %**, the large majority of **6 to 12 %** was anticipated to be gained by implementation in the next twenty years (i.e. 1999-2019) through improvement in holdings, inefficient routings and sub-optimal flight profiles. Other operational measures like increasing load factors, eliminating non-essential weight, optimising aircraft speed, limiting auxiliary power use and reducing taxiing were estimated to potentially reduce fuel burned in the range 2 to 6 %.

The IPCC report refers to earlier studies in that area and their results performed by EUROCONTROL, FAA and ICAO from 1992 to 1998.[176]

It is assumed here that ATM Efficiency is calculated by the following formula:

> ***ATM Efficiency = fuel burn for great circle trajectory***
> ***/ (fuel burn for great circle trajectory + excess fuel burn)***

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[174] Cf. ICAO (2021).
[175] Cf. IPCC (1999).
[176] Cf. EUROCONTROL (1992, 1997); FAA (1998); ICAO (1998).

In 2008 the CANSO report "ATM Global Environment Efficiency Goals for 2050"[177] consolidated regional ATM efficiency studies from Australia, Europe and the USA and concluded that the then current (i.e. 2005) global ATM system efficiency was between 92% and 94%. According to the report a 100% efficiency is not achievable due to interdependencies such as Safety, Capacity, Weather, Noise, Airline Practices, Military and Institutional reasons

A breakdown of ATM system total inefficiencies between *air* (5.5%-7.9%) and **ground** (0,9%-1.4%) was performed for Europe, USA and Australia in the year 2007. These numbers covered horizontal en-route inefficiencies, vertical climbing and descending inefficiencies and terminal area inefficiencies including holdings. In addition, the ATM system efficiency baseline 2005 was estimated for four different geographical areas covering the world completely with a value range from 89% to 99%.[178]

In 2014 an Independent Expert Operational Goals Group (IEOGG) of ICAO published a report[179] which estimated potential environmental goals in terms of fuel usage and atmospheric emissions for target years 2020, 2030 and 2040 in relation to the 2010 level. Goals are considered as achievable environmental benefits if potential operational improvements are implemented.

The term "operation" was further refined to ATM Operations, Airport Operations and Aircraft operations (not technology associated). As one major input the report took some 30+ studies from between 2000 and 2012 into account as well as the SESAR, NextGen and ICAO ASBU programs. The study then differentiated between a static (i.e. unchanged) ATM system and an ATM system with anticipated operational improvements. For the static ATM system it was concluded, that efficiency would decrease starting from 87.5% in 2010 to 85.5% in 2020, 83.5% in 2030 and 81.5% in 2040 due to the forecasted growth in demand and the resulting congestion.

Then operational fuel usage and emission goals efficiency improvements for an enhanced ATM system were estimated:

2020:   3.25%   2030:   6.75%   2040:   9.00 %

As these values were considered to be more on the optimistic side, only lower limits of a confidence range were provided:

2020:   2.25%   2030:   4.5%   2040:   5.75 %

The Performance Review Report of the Performance Review Commission[180] is reporting the performance of the European Air Traffic Management on a yearly basis. One topic of the report is

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[177] Cf. CANSO (2008).
[178] Cf. Ibid., p. 7.
[179] Performance Review Commission (2019).
[180] Cf. Ibid.

the analysis of ATM Efficiency in Europe. For the analysis flights are split in different phases and the performance indicators are aggregated for each phase.

There is a taxi-out phase from off-block to take-off followed by a climb phase up to the crossing of a 40 NM circle around the origin airport, the en-route phase ending with the entry into the 40 NM circle around the destination airport, which is followed by the approach phase up to the landing and the taxi-in phase finished by the on-block process step of the flight. Inefficiencies during these phases are divided into taxi-in and taxi-out inefficiencies, horizontal flight inefficiencies en-route and during approach and vertical inefficiencies during climb, cruise and descent. The report estimates a theoretical maximum benefit pool which can be influenced by Air Navigation Services in percent of total aviation CO_2 emissions for unimpeded gate-to-gate operation. The estimate is totaling some 6% of unimpeded gate emissions which could possibly be activated by ATM improvements. Horizontal efficiency benefits are estimated. The contribution of horizontal flight inefficiencies during cruise is > 2%, horizontal flight inefficiencies during arrival add between 1 and 2 % and vertical flight inefficiencies during cruise and during descent as well as taxi-out inefficiencies add between 0.5 and 1 % each.

The report also notes that these benefits will not be achievable due to unavoidable interdependencies with separation minima, adverse weather or avoidance of 'Danger Areas'.

The Comparison of Air Traffic Management-related Operational Performance: U.S./Europe[181] from 2019 delivered performance indicators for both regions mainly compiled for the traffic to and from the top 34 airports each. The report concludes with the estimation of a theoretical maximum benefit pool in terms of travel time and fuel burn for an example flight of an Airbus A320 flying 450 NM en-route in both airspaces. It is clearly outlined in the report, that the numbers are subject to improvement e.g. by including vertical inefficiencies, airline intent or aircraft performance. Measured in delay minutes, the total theoretical benefit pools for such a flight was estimated to be 10 to 13 min per flight total with main contributions from taxi-out (~40 - 50%) and horizontal flight efficiency en-route and in the terminal area (~33 - 44%). Translated into fuel consumption the benefit pool was computed as ~260 - 290 kg per flight with horizontal flight efficiency contributing 65 – 77 % to these numbers.[182]

In 2019 ICAO published the **Global Horizontal Flight Efficiency Analysis[183]**. It was initiated due to the availability of true global traffic movement data from new sources of surveillance like ADS-B. The Horizontal Flight Efficiencies 2017 by region were estimated from 96 to 98 % for European, African and American ICAO Regions, while Middle East and Asia Pacific ICAO regions were found between 93 and 94 % mainly attributed to political instability or inaccessible airspace due to political circumstances.[184] The results of the study were considered as **ICAO's first step in assessing global flight efficiency.** It was noted that the estimated efficiencies may be distorted and influenced by routing restrictions through convective weather, neighboring airport flows or

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181 Cf. EUROCONROL/FAA (2019).
182 Cf. Ibid., p. 81.
183 Cf. Brain et al. (2019).
184 Cf. Ibid., p. 142.

flow management measures as well as wind-optimal routes flown in relation to great circle distances.

One of the closing remarks of the study is cited here as a state-of-the-art statement for global ATM efficiency analysis in 2019:[185]

> *"ICAO would like to emphasize that this study should be viewed as the first of a multi-step process on the path to identifying global flight efficiency. Further steps would also need to address such factors as: vertical flight efficiency, the relationship between HFE and VFE, efficiency in terminal airspaces and on airport surfaces around the world, as well as trying to fill those data gaps that were identified in this analysis."*

4.5.3.2. DEPA 2050 ATM Efficiency Assumptions

In DEPA 2050 ATM efficiency is used as percentage value which expresses the minimum possible fuel consumption in relation to the actual fuel consumption of a flight, e.g. a 5000 kg minimum possible fuel consumption and an actual consumption of 5500 kg lead to an efficiency value of 5000kg/5500kg = 90.9%. As minimum possible and actual fuel consumption values are not available in a sufficient quantity for actual and especially for future scenarios some approximations are made. The current state of the DEPA 2050 ATM efficiency modelling is including exclusively inefficiencies concerning the horizontal flight path of an aircraft, other areas like taxiing or vertical inefficiencies are foreseen for future modelling.

The HFE (horizontal flight efficiency is used here as an approximation for the fuel efficiency of the airborne part of a flight in terms of air traffic management. It describes the length of an actual flight trajectory from runway threshold to runway threshold in relation to the great circle distance.

Within DEPA 2050 two models were developed to incorporate HFE in the worldwide CO_2 emission modelling:

- *DEPA 2050 HFE Model 1* is taking account of the route structures designed into the ATM system to structure traffic flows en-route as well as in the vicinity of airports
- *DEPA 2050 HFE Model 2* is allowing for the fact that considerable additional flight times in the approach area of highly loaded airports are used to deconflict arrival traffic during tactical ATC

DEPA 2050 HFE Model 1

For the development of *DEPA 2050 HFE Model 1* the results of the DLR project "World-wide Air Traffic Management WW-ATM" were used. WW-ATM developed a flight plan and trajectory

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[185] Ibid., p. 144.

dataset for one day of scheduled air traffic of the whole world.[186] Based on that data set some indicators for horizontal flight efficiency were defined and computed. The computations were performed within the DEPA 2050 project in order to have an own data set at hand to analyze specific details of route efficiency and to come to own conclusions. The WW-ATM dataset contains 105,435 flights as source/destination pairs with aircraft types and scheduled arrival and departure block times assigned for each flight. Using these input data two different routing scenarios were computed in the WW-ATM project. The first routing scenario (*route-based scenario*) took a navigation data base as input and computed planned flight plan routings along defined departure procedures from the source airport via en-route waypoints to the arrival procedures of the destination airport. The second routing scenario (*direct scenario*) tried to minimize the horizontal length of a route as far as possible. It constructed rudimentary departure and arrival procedures using only two departure and two arrival waypoints in the vicinity of the airports as shown in the following figure.

As the original schedule source did not contain any runway information for the source or destination airport a runway allocation algorithm was developed and used within the WW-ATM project.[187]
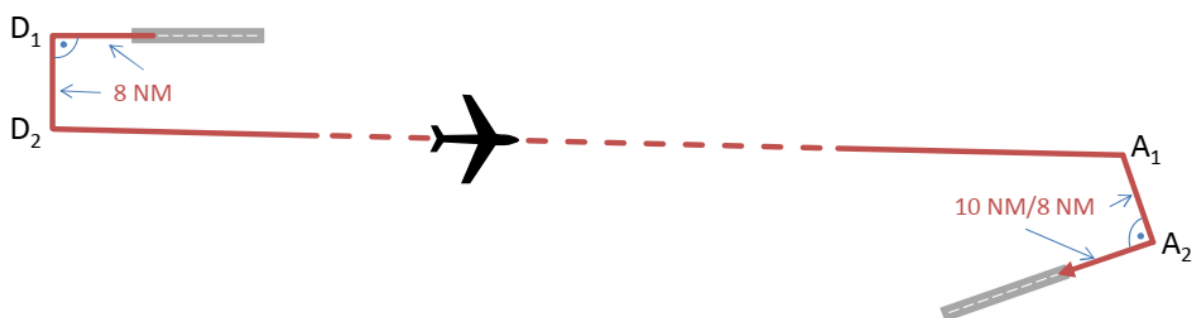
Figure 76: Runway based routing construction for WW-ATM direct scenario[188]

The average route lengths of all flights for route-based/direct/beeline scenarios were 893/818/798 NM. In terms of horizontal flight efficiency, the WW-ATM scenario achieved overall averages of 88.1 % for the route-based scenario and 97.5% for the direct scenario. The HFE for the route-based scenario is considerably lower than en-route HFE observed in other studies. One reason could be the inclusion of the complete airborne trajectories from take-off to touch-down within the WW-ATM scenarios in comparison to the en-route part of trajectories used only in other studies.

In order to investigate this aspect further the trajectories of the route-based WW-ATM scenario two datasets from EUROCONTROL's Demand Data Repository (DDR) were added.[189] The datasets covered one day of flights over Europe each.

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[186] Cf. Kuenz (2018).
[187] Cf. Kuenz (2019).
[188] Kuenz (2018), Figure 5.
[189] Cf. EUROCONTROL (2021).

Spot-checks of WW-ATM route-based trajectories showed that the approach routes especially in the terminal area tend to be on the upper limits of possible flight paths lengths.

On the other hand, spot-checks of the DDR2 data used suggested a lack of trajectory points in the terminal area for approach trajectory which reduces the respective trajectory length.

A deeper investigation will be required in both data set groups to consolidate the results.

Based on these results the following values for a biased piecewise linear model are proposed for DEPA 2050 modelling (WW-ATM direct scenario values are included for comparison and may be used for estimating a theoretical upper border):

Table 15: DEPA 2050 model parameters for ATM attributed horizontal flight efficiency in scenario 2050

Scenario 2050	Bias (NM)	HFE Gradient 100-1000 NM	HFE Gradient > 1000 NM
Baseline	40	3.5%	2.0%
Conservative	35	3.0%	1.5%
Progressive	30	2.5%	1.0%
WW-ATM direct	20	0.0%	0.0%

Interim values for time horizons between 2020 and 2050 for Conservative and Progressive Scenarios may be interpolated in a linear fashion starting from the baseline scenario in 2020 (e.g. HFE Gradient > 1000 NM for Progressive Scenario in 2035 = 2.0% − 1.0% ((2050-2035)/(2050-2020) = 1.5%).
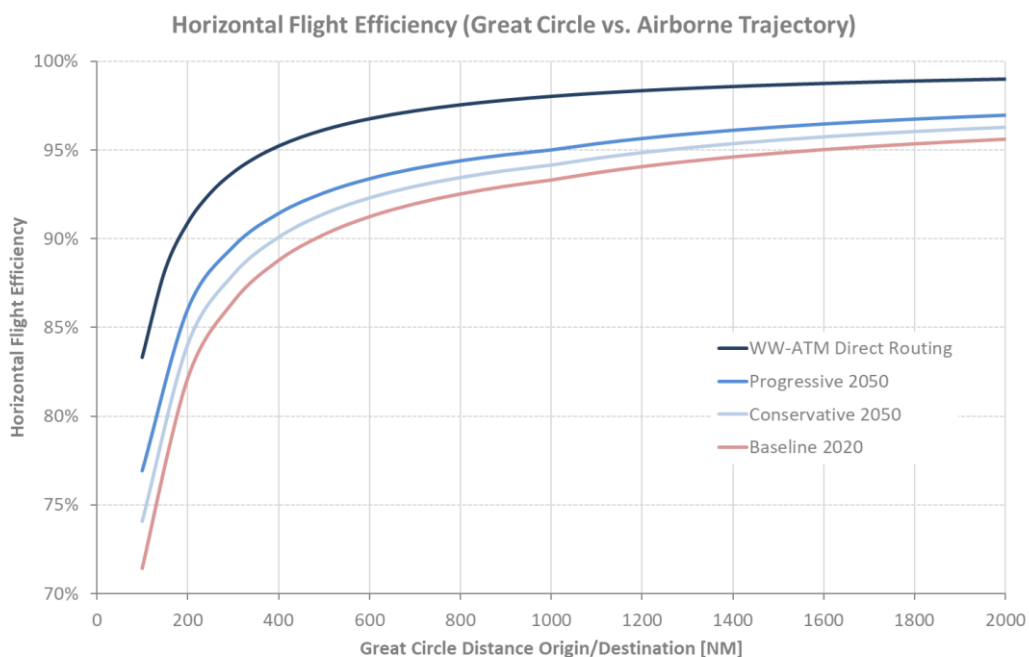
Figure 77: DEPA 2050 Model 1 Horizontal Flight Efficiencies

Wind effects may result in considerable horizontal flight path extensions in order to maximize the fuel efficiency of real-life flights. ICAO stated in "Operational Opportunities to Reduce Fuel Burn and Emissions"[190] that great circle routes usually provide the best fuel savings for routes up to 1000 NM, for longer routes wind effects determine fuel optimal routings. These effects are not addressed here but may be a considerable effect on HFE computations of the order of some percent for long haul flights.

DEPA 2050 HFE Model 2

A second model was developed to incorporate considerable additional flight times in the approach area of highly loaded airports due to traffic jams during tactical ATC.
For this purpose, two data sources were combined. One source is a statistics collected by the Performance Review Unit of EUROCONTROL which summarises the average additional flight times for arrivals in the vicinity of European airports of one year.[191] The other source is a model of DLR which estimates the utilization factor of airport runway capacities worldwide for system relevant airports up to 2050.[192] Data from both sources were combined under the assumption that higher utilization factors cause higher additional flight times. As a result, additional flight times in the airport vicinity may be computed for each flight:

Table 16: Extract of results from DEPA 2050 HFE Model 2 for example airports

ICAO Code	Capacity Utilization							Average ASMA Additional Flight Times [min/arrival] Model 2016**3						
	2020	2025	2030	2035	2040	2045	2050	2020	2025	2030	2035	2040	2045	2050
EGLL	97%	100%	100%	100%	100%	100%	100%	5,7	6,1	6,1	6,1	6,1	6,1	6,1
LTBA	80%	90%	99%	89%	81%	91%	100%	3,6	4,6	5,9	4,6	3,7	4,7	6,1
EIDW	79%	85%	91%	97%	100%	100%	100%	3,4	4,1	4,8	5,6	6,1	6,1	6,1
EDDM	75%	80%	86%	93%	99%	100%	100%	3,1	3,6	4,3	5,0	6,0	6,1	6,1
EDDF	65%	70%	76%	82%	88%	95%	100%	2,3	2,7	3,2	3,7	4,4	5,4	6,1

The Horizontal Flight Efficiency models developed in DEPA 2050 are capturing a major part of flight inefficiency in ATM. Vertical inefficiencies and airside inefficiencies performed on ground will have to be included in later stages of development in order to get a more complete picture. The expected ATM HFE improvements within the Conservative and Progressive Scenarios of DEPA 2050 are a first approximation and subject to refined updates in the future as more information becomes available from ongoing research programs.

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[190] Cf. ICAO (2016c).
[191] Cf. EUROCONTROL (2020b).
[192] Cf. Gelhausen et al. (2020).

4.6. Technological Developments "Aviation MRO"

This section provides at first a general overview of various technology trends in the context of aircraft maintenance and their qualitative potential. Subsequently, current and future implications of sustainable propulsion concepts for aircraft maintenance are addressed.

In the wake of generally increasing demands and requirements in global air traffic, the efficient maintenance, repair and overhaul of aircraft is emerging as a strategic success factor. Even in times of crisis, when large parts of the fleets are on ground, appropriate MRO measures become highly relevant in terms of profitability, reliability, availability and safety of the aircraft fleet.

Generally, maintenance costs belong to the variable direct operating cost (DOC) of an airline, representing a share of about 10-20% of the DOC of a completed flight.[193] Accordingly, failure rates and aircraft on ground times are to be minimised in order to realise a high utilisation level. Furthermore, the consideration of high safety requirements is an essential factor for maintenance operations.[194] To meet these different requirements, various technological developments in aviation maintenance can be crucial and should therefore be analysed continuously.

4.6.1. Technological Trends in Aviation MRO

In the following, a general insight into the future of aviation maintenance is given on the basis of four technological trends:

- Prescriptive Maintenance
- Mobile Robots and Drones
- Virtual and Augmented Maintenance
- Additive Manufacturing

The developments imply far-reaching impacts on operational aircraft maintenance with promising optimisation potentials.

Prescriptive Maintenance

The progressing digitalisation and the increasing number of sensors in aircraft lead to high amounts of available data. In order to process, evaluate and utilise them appropriately, Big Data analyses and algorithms will be needed.[195] In maintenance context, simulation and prognosis models become crucial for efficient repair, overhaul or service activities since they help to minimise aircraft system downtimes and avoid (expensive) unscheduled maintenance events. Beyond the prediction of events, it is essential to also be able to determine how and under what resource utilisation certain maintenance processes should be carried out.

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[193] Cf. Mensen (2013).
[194] Cf. Ibid.
[195] Cf. BDLI (2020a).

As stated in the definition of Ansari et al. (2017), Prescriptive Maintenance aims to provide recommendations for optimising upcoming maintenance events while involving expert knowledge, machine learning, prognostics and semantic reasoning. As a result, maintenance decision-making will be automated and appropriate measures proposed. With regard to Knowledge-Based Maintenance (KBM) strategies, prescriptive approaches represent the highest complexity and maturity level since they also include descriptive, diagnostic and predictive elements (cf. the following figure).[196]

Aircraft Engine Degradation and Tire Pressure Indicating System (TPIS) are two examples of on-going research conducted by DLR to develop novel prescriptive maintenance models and related strategies. Furthermore, knowledge-based Artificial Intelligence (AI) methods are being investigated and used to determine correlations between data and better plan pending maintenance events on flight operations level.

Since these approaches are digitally based, the concept of Digital Twins (virtual image of real products and its properties) plays a central role for Prescriptive Maintenance. Accordingly, digital platforms such as Aviatar from Lufthansa Technik or Skywise from Airbus provide various opportunities to make the operation and maintenance more efficient, economic, viable and sustainable.
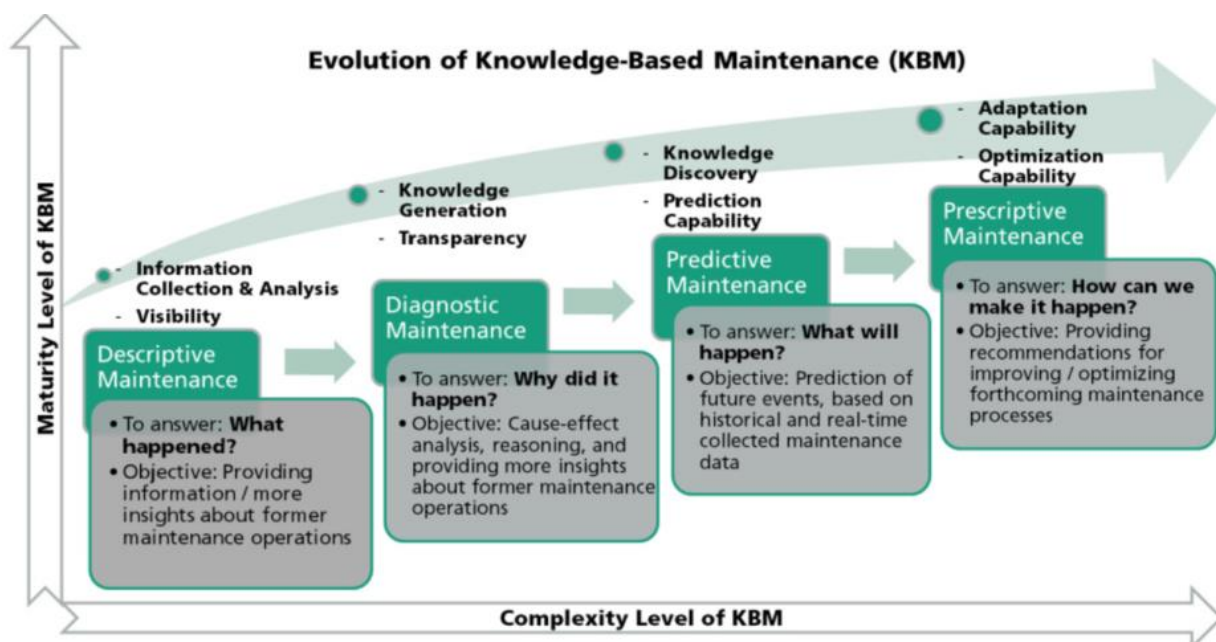
Figure 78: Knowledge-Based Maintenance strategies[197]

Mobile Robots and Drones

Regular inspection tasks often represent the initial part of a maintenance process and are therefore of high relevance regarding the detection of first fault signs. However, various aircraft

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[196] Cf. Ansari et al. (2017).
[197] Ansari et al. (2017).

components such as the wing fuel tanks or fuselage surface contours are heavily to access involving confined spaces and health risks for the mechanics. Consequently, the field of mobile robotics and drones will be a continuously growing technological area for aircraft maintenance.

According to a recent review by Kaur Dhoot et al. (2020), robotic automation has the potential of significantly improving the consistency and efficiency of inspection tasks by detecting, analysing and thereafter repairing damages. The complex environments would require the consideration and appropriate development of parameters like navigation, communication, locomotion and design.[198]

Referring to the example of fuel tank inspections, the DLR has started researching on a minimally invasive eel-like exploration robot (figure 79) aiming to relieve and support the fuel tank mechanics.

Concerning external damage inspections, several research projects and companies recently addressed the development of respective inspection drones (figure 80), seeking to considerably reduce aircraft on ground times for (large) aircraft fleets.[199]

With a variety of potential applications for mobile robots and drones in aircraft maintenance context, several technological interfaces will be feasible. For instance, the collected data can be transferred to a Digital Twin, where it can be utilised to derive condition monitoring measures and prescriptive analysis.

Figure 79: Digital Fuel Tank Maintenance (FuTaMa) robot 'Eeloscope'[200]

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[198] Cf. Kaur Dhoot et al. (2020).
[199] Cf. RWTH Aachen University (2020a); European Union (2019); RAPID (2017).
[200] DLR (2021).

Figure 80: Automatic, multicopter-based indoor inspection of large surfaces[201]

Virtual and Augmented Maintenance

The concepts of Virtual and Augmented Maintenance are technologically based on the utilisation of Virtual Reality (VR) and Augmented Reality (AR) for maintenance activities. In accordance with Dörner et al. (2013), VR generally describes the usage of three-dimensional visualisation with interaction devices such as head-mounted displays to multimodally explore 3D-content in real-time. In contrast, AR refers to the extension of the reality in real-time with precisely matching parts from the virtual environment.[202]

From an aircraft maintenance perspective, such systems and devices will enable new forms of collaboration between multiple mechanics and technicians, which would be essential during a pandemic. For instance, remote assistance can be realised, so that technical experts at other locations can flexibly examine defects and accordingly advise the on-site team in real-time.[203] Moreover, visual data captured by drones or robots in hardly accessible areas could be inspected ergonomically by mechanics. Future applications could also enable gestural and haptic anomaly classification and thus, extend the digital continuity of aircraft and component condition monitoring.

A recent study conducted by Utzig et al. (2019) demonstrated a damage assessment scenario on a real component while experiencing the respective Digital Twin through AR and VR (figure 81).

While such a concept seeks to increase maintenance quality and reduce costs and downtimes, (Virtual and) Augmented Reality can also be utilised for aircraft maintenance training to improve

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[201] RWTH Aachen University (2020a).
[202] Cf. Dörner et al. (2013).
[203] Cf. Utzig et al. (2019).

qualification and learning.[204] Furthermore, this trend will be enhanced through the introduction of 5G technology as bandwidths and data transmissions will be more robust and safer.[205]

Figure 81: Demonstration of damage assessment through AR and VR[206]

Additive Manufacturing

As a key factor in aviation context, Additive Manufacturing (AM) or 3D-Printing will enable a faster, lighter and cheaper production of different aircraft parts.[207] This development leads to various repair techniques and promising potentials in terms of aircraft maintenance.

According to Gebhardt (2017), Additive Manufacturing processes automatically create components and their desired geometry by joining solid elements preferably in layers together.

As an exemplary Additive Manufacturing process, laser cladding proves to be a relevant method for the fabrication and repair of mechanical parts with extensive wear, since compared to conventional welding, it involves advantages like a lower heat input.[208] In addition, laser cladding can be utilised to add material when a unique, high value part has been over-machined by mistake.[209] Similarly, maintenance companies use methods like laser metal deposition to repair aircraft engine parts such as compressors and blades aiming to both reduce costs and extend lifetimes.[210] Moreover, the potential of process time reduction is given by Rapid Tooling, which implies the additive, fast production of injection moulds, mandrels, cutting dies and other tools in small quantities.[211] As for (unusual) spare parts, Wits et al. (2016) concluded that the 3D print and

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[204] Cf. De Crescenzio et al. (2010).
[205] Cf. Lufthansa Technik (2020).
[206] DLR (2019).
[207] Cf. BDLI (2020a).
[208] Cf. Molina et al. (2020).
[209] Cf. Wits et al. (2016).
[210] Cf. Guo & Leu (2013).
[211] Cf. Singamneni et al. (2019).

subsequent replacement could be much faster and more resource-efficient than conventionally manufacturing or ordering the required part.

Current research is addressing relevant questions such as how new dynamic repair process chains can be developed using additive methods (figure 82).[212] Another ongoing project is aiming to integrate RFID chips into the additive production process of aircraft components to identify original parts and prevent reverse engineering.[213]

With regard to the increasing complexity on aircraft system and air traffic level, for instance through alternative propulsion concepts, a more flexible and responsive maintenance will be required. In this sense, Additive Manufacturing can play an essential role in future aircraft maintenance.

Figure 82: New repair processes using Additive Manufacturing[214]

4.6.2. Implications of Sustainable Propulsion Concepts for Future Aviation MRO

Besides the technological disruptions in aircraft maintenance context, future aviation will obviously also entail changes at **component level**. Since current engines often involve the most significant[215] maintenance costs of an aircraft, their efficient maintenance is crucial for operators and MRO-providers. In the light of current research and development on innovative and sustainable propulsion concepts in aviation, questions arise concerning the associated implications for future maintenance. Thus, potential technological changes of the propulsion systems as well as resulting challenges for maintenance must be identified and analysed, in order that new measures can be derived appropriately.

Primarily, **sustainable aviation fuels** that are chemically similar to conventional kerosene in terms of properties are of special interest in aviation context. So-called drop-in fuels describe

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[212] Project 'MRO 2.0 - Maintenance, Repair & Overhaul'; cf. BAM (2020).
[213] Project 'PrintAndTrack'; cf. RWTH Aachen University (2020b).
[214] BAM (2020).
[215] Cf. Ackert (2011).

approved blends of synthetic and conventional fuels, which can already be utilised across all aircraft types and infrastructures without changes and restrictions.[216] Such drop-in fuels can be bio-derived kerosene from for instance waste biomass, vegetable or algae oil, or power-to-liquid kerosene, which is based on renewable electricity and CO_2.[217] In contrast to drop-in fuels, where currently only up to 50% blending with conventional kerosene is approved, the use of near-drop-in fuels would enable much higher blending rates, while eventually making slight changes of aircraft, infrastructure or operations (and maintenance) necessary.[218] Structural changes, e.g. to the turbines or the tank, can therefore require new maintenance approaches. However, the DLR found out that the utilisation of synthetic fuels considerably reduces soot and particle emissions,[219] which in turn can improve the wear behaviour of the engine. Similarly, aireg (2020) states that near-drop-in fuels should be further developed and promoted since they could reduce the pollutant emissions and therefore also the maintenance costs.

As synthetic fuels contain less impurities compared to fossil fuels,[220] it can be expected that the fuel tank system, including pipes, valves and filters, is less prone to corrosion and sludge formation. However, there is a general research need regarding the corrosive effects of sustainable fuels and the appropriate protection. Correspondingly, the usage of additives like corrosion inhibitors as well as microbial growth and other contaminations should be further investigated in the long term.

Over the course of the project 'burnFAIR' from 2010 to 2013, Lufthansa carried out an operative long-term testing on an engine with bio-derived kerosene mixture, monitoring the behaviour of the engine condition continuously.[221] Detailed inspections of the engines and all fuel-carrying parts revealed that neither differences in behaviour nor negative impacts on components were found. On the contrary, an improvement with regard to the material wear of the fuel pumps could be detected. Concerning the storage of the biokerosene mixture, no abnormalities such as microbiological contamination beyond the normal level were observed.[222] Hence, the project results indicate that the usage of a drop-in fuel like blended bio-derived kerosene would not be associated with changed maintenance measures.

Since 2018, the DLR has been researching the development and application of sustainable fuels in the interdisciplinary project 'Future Fuels', where among others, near-drop-in fuels represent a research objective.[223] In order to derive further implications of synthetic fuels for aircraft maintenance, holistic approaches and cross-system considerations need to be conducted.

In terms of **electrical propulsion**, according to Roland Berger (2017) there are three broad aircraft architectures being focused on in current aviation research and development. The first

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[216] Cf. DLR (2020a).
[217] Cf. Zech et al. (2016).
[218] Cf. DLR (2020a).
[219] Cf. DLR (2020a).
[220] Cf. Zech et al. (2016).
[221] Cf. Zschocke (2014).
[222] Cf. Zschocke (2014).
[223] Cf. DLR (2018).

architecture is hybrid-electric, which can either consist of a traditional turbo-fan with an electric motor in a parallel hybrid configuration, or include a turbo-shaft and generators combined with a battery and electric motor-driven fans as a series configuration. The second configuration is based on turbo-electric, which includes a turbo-shaft and a generator to feed multiple distributed electric motor-driven fans. In contrast, the all-electrical architecture drives the fans by electric motors with energy drawn solely from a battery.[224]

The described electrical propulsion concepts will introduce new electrical components to the aircraft, which will imply new challenges for future maintenance operations. Compared to current, conventional propulsion systems, electrical components contain fewer moving and wearing parts, which is why it can be assumed that in the future – considering new structural concepts – the costs for maintenance and repair of electrical aircraft components will probably be lower.[225] A study on electrified propulsion concepts for automobiles have concluded that electrified drivetrain architectures require, compared to conventional ones, about 25% less maintenance costs due to their significantly reduced system complexity.[226] For instance, an all-electrical configuration would eliminate all maintenance and inspection work regarding oil, cooling water or fuel tank since the gas turbine and fuel system would be completely removed. Furthermore, there would be less brake wears due to power recuperation.[227] Another study on maintenance cost estimation by Ploetner et al. (2013) concluded that the maintenance costs of an all-electric-powered aircraft are assumed to be 34% lower compared to a conventional turbofan architecture. However, the distribution of the overall maintenance costs on the different electrical components needs to be further analysed in order to identify particular parts as major cost drivers.

Although electric motors may require less maintenance than gas turbines, Naru & German (2018) state that electric motors will not be completely maintenance-free. Replacement of motors due to damage to bearings or coils cannot be ruled out and must be considered in appropriate maintenance concepts such as condition monitoring. Moreover, factors like vibration, abrasion, contamination or voltage surges can lead to winding damages. Other potential maintenance issues can result from thermal damages of insulating parts or problems regarding magnet security.[228]

With regard to the use of **batteries** as energy storage, various maintenance challenges will arise. A recent study on degradation mechanisms of large format lithium ion batteries, which are the currently favourited cells of choice for electric aircraft, has shown that a loss of active lithium, fatigue of the cathode, microcracks, comprised structural changes within the surface and higher resistances can occur in high operating temperatures over time.[229] Hence, the resulting loss of cell capacity would pose the need of condition monitoring and further maintenance concepts for

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[224] Cf. Roland Berger (2017).
[225] Cf. DLR (2020a).
[226] Cf. Propfe et al. (2012).
[227] Cf. Propfe et al. (2012).
[228] Cf. Naru & German (2018).
[229] Cf. Lang (2018).

batteries in order to predict future conditions and derive corresponding measures. Particularly, preventing issues such as a thermal runaway, which describes a short circuit and combustion of the battery cells, is of high importance for future maintenance to ensure aircraft safety.[230] Furthermore, new inspection and repair protocols as well as the requirement for adequate training will be needed for high-power batteries. Their installation or removal could damage connectors and involves the risk of a battery being dropped.[231]

According to DLR (2020a), propulsion systems based on **hybrid-electric** concepts generally lead to a higher total weight due to the additional mass of cables, power electronics and buffer batteries, which has to be compensated for instance by extreme lightweight construction. Respective parameters such as the type of material or design have various implications on the particular maintenance and must therefore be examined on the overall system level. In addition, the maintenance of the cooling system, which will also get heavier and larger, needs to be further investigated.[232]

The electrical energy to power electric motors and fans can also be delivered through **fuel cells** by directly converting chemical energy.[233] Using for instance hydrogen as an energy carrier will output pure water as a reaction product, which could be utilised for the water and waste system of the aircraft, thereby reducing water storage and corresponding weight.[234] As the resulting fuel cell propulsion system requires numerous energy storage systems, load-levellers and multiple auxiliary devices, various challenges are to be expected from a maintenance perspective.[235] Regarding the fuel cell itself, a proton-exchange membrane fuel cell, which can operate at low temperatures and contains a simple structure, is currently most suitable in aviation context.[236] Nevertheless, Knowles et al. (2010) stress out that high maintenance costs and short lifecycles are main issues concerning fuel cells, which need to be addressed. Accordingly, possible shortcomings might include dehydration, fuel/gas starvation, physical defects of membrane, catalyst poisoning and hydrogen leaks. Moreover, repairing a fuel cell should be performed by personnel with specific skills and potential faults ought to be analysed through condition monitoring tools to prevent costly malfunctions and increase reliability.[237] With regard to similar attributes with electric aircraft such as power electronics and cabling, fuel cell aircraft would realise synergies like compatibility with growing electric automobile and aerospace sectors while unlocking scale effects,[238] which could also enable maintenance benefits.

An accurate estimation of the maintenance costs of electric propulsion concepts will be possible in future through the development of new models and calculation methods which consider the novel system architectures and components. At the beginning of 2020, the DLR has started an

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[230] Cf. NASA (2019).
[231] Cf. Naru & German (2018).
[232] Cf. DLR (2020a).
[233] Cf. Guzzella & Sciarretta (2013).
[234] Cf. Bruce et al. (2020).
[235] Cf. Guzzella & Sciarretta (2013).
[236] Cf. Knowles et al. (2010), McKinsey & Company (2020).
[237] Cf. Knowles et al. (2010).
[238] Cf. Roland Berger (2020c), McKinsey & Company (2020).

internal project that includes all disciplines necessary for system wide Exploration of Electric Aircraft Concepts and Technologies (EXACT).[239] As part of this, the DLR Institute of Maintenance, Repair and Overhaul works among others on models that estimate the operating and maintenance costs of sustainable drive systems over the entire product life cycle.

Another current project called MAHEPA (Modular Approach to Hybrid Electric Propulsion Architecture) develops and tests two new hybrid-electric powertrains aiming to bridge the gap between the research and product stage.[240] The resulting flight test data can be used to gain new insights for future maintenance operations and corresponding needs.

In contrast to the electrical fuel cell propulsion system, **hydrogen** being combusted as a fuel can replace kerosene in modified jet engines.[241] As main development needs regarding the gas turbine lie in the combustion chamber,[242] questions arise concerning respective degradation changes. Due to the higher heat transfer, new cooling systems have to be developed.[243] Beyond that, the maintenance efforts of gas turbines for hydrogen can be expected as equivalent as for conventional kerosene. Nevertheless, hydrogen is classified as a non-drop-in fuel since its implementation requires radical changes in aircraft design or infrastructure.[244]

Stored in liquid form, hydrogen requires about half as much volume of a tank than as pressurised gas, which makes the tank significantly lighter.[245] However, a liquid hydrogen tank is still considerably larger than a corresponding kerosene tank, which poses the question of a suitable position of the storage system while considering to handle maintenance, safety and modularity aspects.[246] For instance, a practically uncomplicated and safe access to the tanks must be given in order to perform regular inspection tasks. An integration of the tank into the fuselage might extend the airframe of the aircraft,[247] eventually resulting in higher maintenance efforts. As a corresponding study conducted by Airbus with various tank layouts has shown, the optimal layout depends on the aircraft category and size.[248] Thus, implementing different designs may complicate the adoption of comprehensive maintenance standards across aircraft types. Regarding the tank structure, the specific properties of hydrogen such as density, ignition range, vaporisation or compatibility have to be considered. Therefore, the (lightweight) material selection and insulation of the tank are essential questions that need to be addressed, especially under the circumstances of cryogenic temperatures, embrittlement on metallic materials and weakened carbon steels.[249] Similarly, a specific fuel distribution system with pipes, valves, sensors and

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[239] Cf. DLR (2020b).
[240] Cf. MAHEPA (2017).
[241] Cf. Roland Berger (2020c).
[242] Cf. BDLI (2020a).
[243] Cf. BDLI (2020a).
[244] Cf. BDLI (2020a).
[245] Cf. McKinsey & Company (2020).
[246] Cf. McKinsey & Company (2020).
[247] Cf. McKinsey & Company (2020).
[248] Cf. Airbus Deutschland GmbH (2003).
[249] Cf. Airbus Deutschland GmbH (2003).

compressors being able to handle cryogenic temperatures has to be further developed and tested, while ensuring leakage detection, fire prevention and fire extinguishing.[250] Particularly in the first years after launching a liquid hydrogen aircraft, the maintenance costs may rise since the fuel systems and tanks require more checks, while in contrast decreasing maintenance costs may occur in the long term.[251]

The on-going project HEAVEN (High power density FC System for Aerial Passenger Vehicle fuelled by liquid Hydrogen) aims to design, develop and integrate a powertrain with high power fuel cell and cryogenic liquid hydrogen into a small aircraft for testing in flight operation.[252] Hence, the results can help to better estimate maintenance efforts over the entire lifetime of liquid hydrogen aircraft and components.

Due to its similarity to conventional fuels, synthetic kerosene as an alternative energy carrier apparently has no direct implications for the overall aircraft configuration.[253] On the contrary, the integration of new electrical or hydrogen components leads to a high relevance of an efficient maintenance on **overall aircraft level** and thus needs to be considered at an early stage. For instance, the positioning of various parts such as batteries, fuel cells or hydrogen tanks must be evaluated across systems, enabling accessibility for technicians during ground maintenance. One key factor towards a higher maintainability can be a modular design of electrical or hydrogen-specific components, enabling efficient inspection and replacement tasks of certain parts without substituting the unit as a whole.

In terms of an **air traffic level**, airports and maintenance companies will have to adjust their processes and infrastructure such as fast-charging stations, additional battery inventories and battery exchange systems in order to meet the changed maintenance, repair and overhaul requirements.[254] In addition, a comprehensive hydrogen refuelling infrastructure with appropriate equipment will need to be established. Current hydrogen refuelling (for vehicles) consumes a lot of energy and mainly relies on mechanical compressor technologies associated with high maintenance costs.[255] Alternatively, electrochemical compression could be utilised to obtain high pressures without moving parts, possibly making the process more efficient and less maintenance-intensive.[256] Generally, the operational integration of such novel processes dealing with alternative technologies like fuel cells or hydrogen will crucially require appropriate safety regulations, task/handling guidelines and maintenance manuals. Furthermore, ground maintenance processes need to be timely analysed and coordinated in order to minimise aircraft on ground and turnaround times. Correspondingly, potential changes in airspeed (e.g. slower) and respective influence on fleet and rotation planning should be identified and evaluated with regard to maintenance process and interval planning.

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[250] Cf. McKinsey & Company (2020), Airbus (2003).
[251] Cf. McKinsey & Company (2020).
[252] Cf. Hydrogen Europe (2020).
[253] Cf. DLR (2020a).
[254] Cf. Roland Berger (2017).
[255] Cf. Kee et al. (2019), Bruce et al. (2020).
[256] Cf. Ibid.

With respect to the above mentioned, multi-layered technological changes of the propulsion system and the related implications on overall aircraft and air traffic level, maintenance personnel will face a transformation of **qualification** requirements. New techniques and skills will be necessary with a view to monitoring batteries, replacing fuel cells or insulating hydrogen tanks. Likewise, shop floors will need to adjust their training processes and equipment accordingly. For instance, the German government proposes the professional and scientific education and training of maintenance staff in the field of hydrogen technologies for the purpose of an efficient and safe handling.[257]

For operators, manufacturers and passengers, the safety, availability and longevity of future aircraft will remain crucial and require novel, suitable approaches from a maintenance perspective.

At the same time, sustainable, human and economic factors must be considered over the entire product life cycle in order to realise and integrate highly technological maintenance solutions on component, overall aircraft and air traffic level.

As this contribution generally reviewed potential implications of sustainable propulsion concepts for future aircraft maintenance, further research needs lie in the derivation of appropriate maintenance measures and strategies. Concurrently, the various technological fields, both on maintenance and propulsion side, require profound investigations with the intention of matching both dimensions. Furthermore, quantitative studies concerning the estimation of maintenance costs for alternative propulsion technologies and their influence on the overall programme planning of maintenance tasks need to be conducted. In addition, further research should also address the ecological assessment of maintenance measures with a view to a resource-efficient and sustainable aviation MRO.

4.7. Technological Developments "Synthetic Fuels/Alternative Fuels"

4.7.1. Current Status of SAF – Approval and Technology

The first synthetic jet fuel blend, the Sasol semi-synthetic jet fuel, was approved already in 1998 in the DefStan 91-91. Back then, approval was a tedious task and fuel production was limited to the approved production facilities at Sasol. It took over 10 years of hard work until ASTM international provided a systematic framework for the approval of new synthetic jet fuel production pathways: ASTM D4054[258]and a specification for synthetic aviation fuels, i.e. ASTM D7566[259]. A successful approval process in ASTM D4054 now leads to an Annex in the ASTM

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[257] Cf. BMWi (2020).
[258] Cf. DO2 Committee, Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives.
[259] Cf. D02 Committee, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.

D7566 specification for the specific production pathway. This is a paradigm shift towards the production site specific approval in DefStan 91-91, because now everyone can produce synthetic jet fuels, if the specifications in the respective Annex in ASTM D7566 for the production technology and the resulting product are met. The first Annex in ASTM D7566 was released 2009 for Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), the same production pathway that Sasol was using. As a result of the systematization of the approval by D4054, the speed increased and already 2011 an Annex for Hydroprocessed Esters and Fatty Acids – SPK (HEFA-SPK) was released, followed by an Annex for Synthesized Iso-Paraffins (SPI) in 2014. New production pathways were added continuously and currently seven pathways are listed as Annexes in ASTM D7566: FT-SPK, HEFA-SPK, SIP (Farnesane), FT-SPK/A, AtJ, CHJ, HC-HEFA. Many more production pathways are currently in the approval process and others are in the pipeline, aiming either to be implemented as a new Annex in ASTM D7566 or on expanding the allowed feedstocks for already approved pathways.

An important breakthrough was the development of the "drop-in" fuels concept (ASTM D7566). If a synthetic jet fuel blending component is produced via one of the approved production pathways and meets the specifications in the respective Annex, it has to be blended with a certain amount of conventional crude-oil based jet fuel and the final blend has to meet the specifications defined in ASTM D7566. If this is the case, the resulting blend automatically meets the requirements of crude-oil based jet fuel of ASTM D1655 and more important, it shall be treated as an ASTM D1655 fuel. All relevant properties of the drop-in fuels lie in the same (or even narrower) specification range as the properties of conventional fuels. This avoids extremely costly recertification of aircrafts to fly on (shares of) synthetic fuels, new infrastructures or other costly adaptions since the blend is a drop-in fuel.

This drop-in concept is extremely powerful, because it enables the reduction of the climate impact of the whole existing and future fleet without any recertification needs. Since the synthetic blending components usually have very low or no contents of aromatics, they have a significantly lower sooting propensity[260] and hence also decrease the non-CO_2 impact[261,262]. Currently, the maximum SAF blending ratio is limited to 50 %vol for most of the approved pathways (only SIP and HC-HEFA are currently limited to 10 %vol). Potential increases are reviewed regularly, for example, the maximum blending ratio of ATJ-SPK was already increased from 30 %vol to 50 %vol. In the case of HC-HEFA the low limit is set due to the fact that this was an approval using the new fast-track method in ASTM D4054 which significantly reduces the time needed for approval, but limits the maximum blend amount to 10%vol by definition.

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[260] The correlation between aromatic content and black carbon matter emissions is only a rough estimate and correlations with hydrogen content are better. There are still some open questions on soot formations, but the measurements are clear that SAF (especially designed SAF for low soot emissions) significantly reduce soot emissions (See ECLIF, JETSCREEN and others).
[261] Bock et al. (2019).
[262] Burkhardt et al. (2018).

100% SPK was always a topic in research, to fully exploit the potential of SAF for reduction of CO_2 and non-climate impact, for example in research projects, like QSTP and JETSCREEN[263] (https://www.jetscreen-h2020.eu). It is also a topic in current (FUTURE FUELS, TP3) and future research projects like VOLCAN, NewJET[264] and others. One reason for aiming at 100% SPK is that the reduction of radiative forcing is non-linearly[265] depending on the number of initial ice crystals and lower soot emissions reduces ice crystal forming (see chapter 5.2.3). Hence it is more effective to use SAF in high concentration for flights with contrail forming conditions than distribute the available SAF over all aircrafts and flights evenly.

In 2018 Boeing and FedEx showed with the eco-demonstrator, that current aircrafts are technically capable of flying with aromatics-free 100 % SAF, which today would be called a near-drop-in fuel. They used a Boeing 777F and made hundreds of flight hours with pure HEFA-SPK. Basically, all OEMs[266] are currently working towards 100 % SPK capability of their aircraft or systems. Boeing announced, that their aircraft will be able to fly 100% SAF in 2030.[267] Recently, ASTM started a task force dealing with 100% SAF specifications.

Currently, the produced quantities of SAF have an estimated share of below 1 % of all used jet fuel world-wide and are usually far away from the specification limits. The main reason is the extremely low cost of conventional jet fuel. However, many production sites are planned or under construction and will become operational in the next years. CAAFI estimates an increase of production capacity from 59 Million gallons per year in 2020 to over 1 Billion gallons in 2025, which is roughly a factor of 16 and indicates the current speed.

4.7.2. Current SAF Development

Several new production pathways are currently in the approval process. In summary, they are expanding the allowed feedstock, either through new Annexes or through an extension of an existing Annex. One of the production pathways in approval process is the IH[2], which has very promising properties and might be the first fuel candidate for 100 % drop-in capability.

A new production pathway which will soon enter the approval process is hydrothermal liquefaction (HTL). HTL itself has a high feedstock flexibility including e.g. lignocellulosic material like forest residue or sewage sludge. Lignocellulosic material is extremely interesting due to its availability and sewage sludge is a good example to even use waste streams.

The already approved Fischer-Tropsch synthesis (FT-SPK) is of high flexibility, since the input to the FT is syngas, consisting only of H_2 and CO. This production of this syngas is part of several projects. Two production types are currently in the focus. One is Power-to-Liquid, where renewable power is used to provide the syngas from water and CO_2. The CO_2 is taken from direct

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[263] Rauch 2019.
[264] https://www.openaccessgovernment.org/sustainable-alternative-fuels/85154/
[265] Burkhardt et al. 2018.
[266] Cf. Rolls-Royce 2020.
[267] https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels.

point sources like industries or (more expensively) from direct air capture (DAC). The other type is thermochemical conversion in the Sun-to-Liquid (StL) facilities. Both, PtL and StL have a significantly lower need for water (orders of magnitude) and land (PtL almost factor 10) compared to bio-derived SAF.

Another option to reduce the non-CO_2 climate impact of jet fuels is the hydrotreatment of conventional jet fuel, which is assessed in the JETSCREEN project. The additional hydrotreatment increases the cost, but decreases the socio-economic cost due to lower non-CO_2 impact and better local air quality leading to better health. This hydrotreatment might become an option for short time reduction of climate impact until the production facilities for SAF can produce enough volume.

Besides these developments on the production side, research and actions are ongoing to steadily increase the maximum allowed blending ratio.

4.7.3. Potential Limitations and Opportunities

One challenge for truly sustainable SAF is the availability of suitable feedstock and/or the required energy. For biomass based SAF, RED II imposes strong restrictions on feedstock regarding sustainability to avoid conflicts with food production. In addition, SAF production pathways in approval aim at a broader feedstock flexibility, using also lignocellulosic feedstocks and/or waste streams. Staples et al. concluded that up to 97% of the projected need in 2050 for combustion-generated electricity and heat, and liquid transportation fuels could be satisfied by an optimal bioenergy deployment[268]. However, there is also a regional variation of availability of sustainable land for biofuel production. This availability is complementary to the regions, which are suitable for solar thermochemical jet fuel production[269] via the Sun-to-Liquid (StL) pathway. This indicates that a regional diverse jet fuel production will be the future. StL is still under development, but the fuel synthesis in the StL itself will be performed via the already approved FT-SPK path and hence can be used without new approval. Falter et al. have assessed the availability of suitable sustainable land for the production of jet fuel via thermochemical processes (StL) and stated, that the production potential is more than 50 times higher than the current global jet fuel demand.[270]

The areas which are suitable for StL are potentially also suitable for PtL. PtL also is under heavy development and uses the already approved FT-SPK pathway for jet fuel synthesis. The first flights with PtL are expected within the next years. The carbon source for PtL is either local CO_2 emissions from industry, which is limited and will decrease in future decarbonized industry, or direct air capture (DAC), which is not limited, but more expensive.

This indicates that most likely there will be no limitations in feedstock or land limit jet fuel quantity, if jet fuel is produced from a mix of production pathways in their respective suitable areas. However, since most synthetic jet fuels are of higher cost than conventional jet fuels, the

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[268] Staples et al. (2017).
[269] Falter et al. (2020).
[270] Ibid.

price and political measures like mandates, subsidies, CO_2 taxes, and others will play a major role for the success of SAF.

4.7.4. Assumptions for the DEPA 2050 Scenarios

Conservative-evolutionary scenario

In the conservative-evolutionary scenario, the assumptions are that a certain pressure from the society is present, which forces policy makers to some smaller actions. These include small but slightly increasing mandates for SAF and eventually for specific production pathways like PtL in Germany with the hope to become PtL technology leader. Also, a minor part of passengers voluntarily pays an increased ticket price for SAF. This can already be done at some airlines, e.g. the compensaid program at Lufthansa/Swiss[271], or the programs at BRA, SAS and Finnair. It is also assumed that existing tax rules like in California continue. This stimulates SAF industry to continue the construction of new production plants. Steadily decreasing renewable energy cost and increased availability reduces the price difference of SAF and conventional kerosene. It is assumed that in the next two decades, the maximum allowed blending ratio is extended to over 50 %vol.

Progressive scenario

In the progressive scenario it is assumed that the pressure from the society is extreme, which forces politics and companies to take significant actions towards climate neutral aviation. This includes high mandates, significant subsidies and measures to financially de-risk the investment in new production plants. Increasing number of climate-related disasters enforces public actions and also more passengers are paying a small surplus for SAF. A significant fraction of battery-electric vehicles and hydrogen powered vehicles reduce the need of alternative fuels for the traffic sector. This frees capacities for SAF production. Also, renewable energies are available at steadily lower cost and production pathways like StL are producing large quantities. It is also assumed that many different production pathways like HTL and others are utilizing the locally available feedstocks and energy sources efficiently.

It is further assumed that the jet fuel demand is decreasing slightly since hydrogen powered and electrical powered aircrafts are available for short range flights. Jet fuel demand is assumed to be lowered by a reduced number of business travels since digital meeting technologies are used more widely. Moreover, it is assumed that the increased number of climate-related disasters also reduce the passenger numbers and hence jet fuel demand.

It is assumed that in the next two decades, the maximum allowed blending ratio is extended to near 100 %vol for almost all relevant production pathways – at least for capable aircrafts. In 2050, only a negligible percentage of very old aircrafts will not be able to fly on 100 % SPK which then have to fly with new production pathways with 100 % drop-in capability like e.g. the IH2 or multiblends of different SAF with synthetic aromatics.

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[271] https://compensaid.com/.

It has to be noted, that some of the above assumptions for SAF are partially not in agreement with the overall DEPA 2050 assumptions, since progressive assumptions for SAF like high cost for conventional fuels would enable a high SAF share, but this assumption would also decrease the number of passengers and hence is an assumption in the conservative scenario.

Estimated SAF fraction

There are studies in literature which try to estimate the available SAF production in the next ten to fifteen years. The estimations differ significantly due to their extremely different settings.

Due to the high uncertainty in the political and economic boundary conditions and the related uncertainties for 2050, we decided to perform an expert review with several experts. Their estimates were collected and averaged, while outliers were neglected. The estimated SAF fractions for the conservative and progressive scenarios are given in the following table. Studies[272,273] estimate SAF shares of 47% to 90% in 2050. (Note that it would have been beneficial to perform a complete study for SAF production capability uptake with consistent settings to the DEPA 2050 settings (conservative and progressive scenarios) in order to get the values backed up by a more extensive survey or even own calculations.)

Table 17: Estimated SAF fractions for the conservative-evolutionary and the progressive scenario in DEPA 2050

	2030		2050	
	estimated range	selected	estimated range	selected
conservative	5-10%	10%	30-50%	40%
progressive	10-20%	15%	70-90%	80%

Note, that the quantitative values are highly uncertain. They not only depend on the production capacities, but also depend on the real fuel demand in future: the lower the fuel demand, the more likely is a higher SAF fraction and hence there is a coupling between the projected flight numbers and SAF fraction. Furthermore, the economic and political boundary conditions are crucial: if conventional jet fuel would not cost 40 to 50 Cent per liter, but a price comparable to gasoline or diesel, some SAF production pathways could already be cheaper and massive investment would be made in production facilities. Hence, production capabilities would drastically increase. Furthermore, COVID-19 pandemic showed the high uncertainty in all parameters.

Derived soot reduction

As described earlier, SAF tend to decrease soot emissions significantly. Aromatic content is the most sensitive parameter for soot reduction. However, also lower sulphur content reduces soot. SAF usually does not contain sulphur and aromatics.

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[272] Cf. ATAG (2020).
[273] Cf DESTINATION 2050 (2021).

In order to derive the soot reduction potential from the estimated SAF fractions for the DEPA 2050 scenarios, the DLR SimFuel platform is used. It contains the DLR jet fuel database with data for over 15000 conventional jet fuels and over 450 SAF as well as fuels from research projects and data of thousands of molecules. The data includes properties and compositions of the fuels with varying level of detail.

When correlations between composition and soot are desired, hydrogen content performs better than aromatics content. Hence, the DLR SimFuel platform contains correlation models for soot propensity depending on hydrogen content. They are derived from measurements in ECLIF and JETSCREEN. Note, that the hydrogen content not fully explains soot formation as the molecules structures as well as the physical properties affecting the fuel preparation also play a role and hence, the results do have an uncertainty. However, since the SAF fractions and the resulting soot reduction is significant, the uncertainty is not dominating the result.

Composition and properties of jet fuel have a wide variance over time and region and hence also the hydrogen content varies. As a reference for conventional jet fuel, the median hydrogen content is taken from the CRC world fuel survey data[274] in the DLR SimFuel platform. The hydrogen content for SAF also varies widely depending on the production pathway and the production facility, but all SAF in the DLR jet fuel database have higher hydrogen content than the highest hydrogen contest of the conventional fuels of the CRC world fuel survey. Forecasting the produced volumes of each SAF pathway and virtually blending it with the locally available conventional fuel and its properties to predict the final blend properties and soot reduction potential at a specific airport would be technically feasible with the SimFuel platform, but was far beyond the given timeframe of the current project. In this first approach, the median of the variation in hydrogen content of all SAF is taken for the conservative scenario. The assumption for the progressive scenario is that both SAF and the conventional fuels (through hydrotreatment) are optimized for low soot propensity. Hence, the maximum hydrogen value is used in the progressive scenario. The derived soot emission reductions (black carbon number) relative to the median jet fuel soot emission are given in the following table for the two scenarios. The reduction in black carbon mass is not proportional to the black carbon number emission reduction but usually results in even higher reductions especially for low SAF blending rates.

Table 18: Derived soot emission reductions (black carbon number)

	conservative	progressive
2030	-5 %	-10 %
2050	-20 %	-54 %

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[274] Hadaller et al. (2006).

Note, that the values are rounded and have a significant uncertainty range, since the uncertain, estimated SAF fuel fractions are used as input as well as other parameters are not known with high accuracy.

Further potential benefits from SAF

SAF do have other potential added values, which are not yet assessed in DEPA 2050. Due to the higher net heat of combustion of SAF compared to conventional jet fuels, specific fuel consumption is slightly decreased, leading to lower emissions. Due to the higher hydrogen content, the emissions of CO_2 are reduced while H_2O emission is increased. Higher net heat of combustion and less coking can reduce maintenance cost, especially if high SAF ratios or even 100 % SAF is used. These added values could be further increased through optimized SAF.

An even higher benefit would be achievable, if fuel and burner are co-optimized. Here, the higher thermal stability could lead to burner concepts with significantly lower emissions. Ideally, the fuel would be co-optimized not only with the burner, but together with the whole aircraft. The development of hybrid-electric aircrafts would be a good opportunity to investigate the full potential of SAF and co-optimization for the goal of climate-neutral aviation.

4.8. Technological Developments "Advanced Vehicle Concepts"

4.8.1. Technological Developments "Supersonic Aircraft"

After a supersonic passenger aircraft with the Concorde was already operated in the period 1976-2003, there has been a growing interest in supersonic aircraft, especially in recent years. This is primarily due to the advances in aircraft technology over the last few decades, which have enabled various manufacturers great potential for newly developed supersonic aircraft.

Table 19 provides an overview of current and future planned projects in the field of supersonics and thus also shows the range of selected performance indicators and expected entry-into-services. It can be seen that the first supersonic aircraft models can be expected to enter the market from the mid-2020s. In contrast to the Concorde (120 passengers), the passenger capacity of the new commercial supersonic aircraft is initially limited to a maximum of 55 people.

Table 19: Key data on current and planned future supersonic / hypersonic projects[275]

Manufacturer/Developer name	Aircraft/Project name	Performance Indicators			Entry-into-service
		Cruise Mach	Passengers	Range (km)	
Spike Aerospace	S-512	1,6	18	11.482	2023
Aerion	AS2	1,4	12	8.704	2025

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[275] Source: own research.

Manufacturer/Developer name	Aircraft/Project name	Performance Indicators			Entry-into-service
		Cruise Mach	Passengers	Range (km)	
Boom Technology	Overture	2,2	55	8.334	2027
Exosonic	-	1,8	70	9.000	2031
Tupolev	-	2,0	30	8.000	n.a.
TsAGI	SDS	1,8	8-10	9.260	n.a.
TsAGI	SPS	1,8	82	8.334	n.a.
Lockheed Martin	QSTA	1,8	40	9.630	n.a.
Jaxa	S4	1,6	36-50	6.482	2035
Virgin Galactic	-	3,0	9-19	n.a.	n.a.
Hermeus	-	5,0	20	n.a.	n.a.
Boeing	-	5,0	20-100	n.a.	2045
Airbus	ZEHST	4,0	100	n.a.	2050
Dassault	HISAC-A	1,6	18	7.400	n.a.
DLR	Spaceliner Class1	10	50	17.000	n.a.

For supersonic business jets, the maximum passenger capacity is 12 or 18 people (see Aerion and Spike Aerospace). A look at the speed of the individual planned supersonic aircraft shows that these are primarily designed for cruising speeds of Mach 1.4 to Mach 2.2. From the mid / late 2040s, novel hypersonic aircraft concepts with speeds of Mach 5 and more could also enter the market.

However, these projects are still in a very early conceptual phase, which means that statements about the market entry of such aircraft concepts have a correspondingly high level of uncertainty. However, the technological development ranges and expected entry-into-services of corresponding supersonic aircraft in the next 15-20 years can be shown using Table 19. Certain technological hurdles must be overcome for new supersonic aircraft to be commercially successful in the long term. Accordingly, various factors prevented the long-term success of the Concorde, which still exist today (or have even intensified) and have to be addressed accordingly by the manufacturers of supersonic aircraft. In addition to the problem of the supersonic boom, high operating costs, limited ranges and environmental aspects are among the primary restrictions for supersonic aircraft. Figure 83 shows the most important factors and restrictions which, among other things, should be reduced in the course of further aircraft technological developments and optimisations in order to enable a future market expansion of supersonic aircraft.
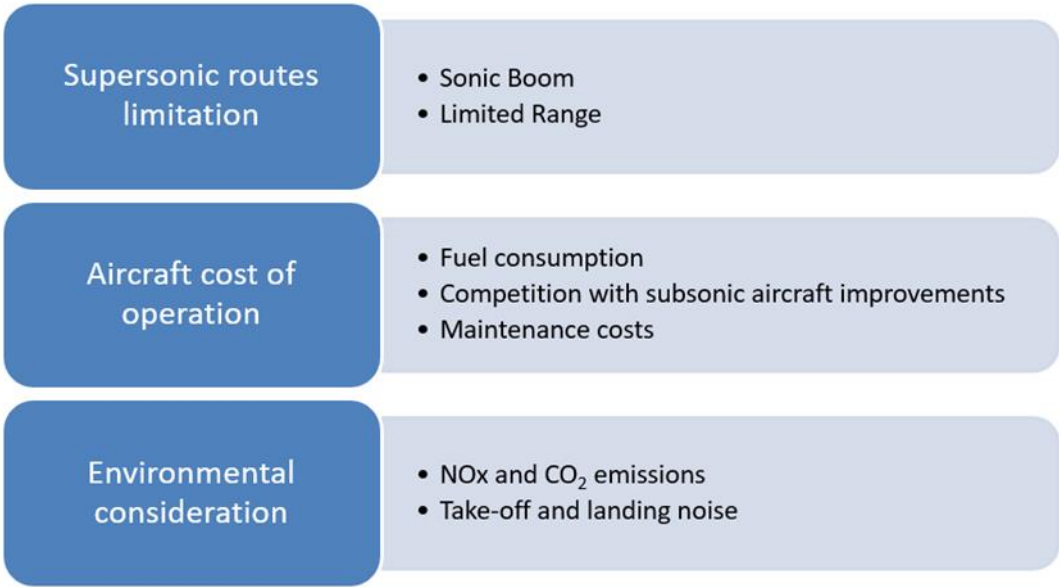
Figure 83: Technological limitations and challenges for the operation of supersonics

The supersonic boom represents a central limitation for supersonic aircraft. Already in the times of Concorde this led to considerable restrictions, since flights at supersonic speeds over land were prohibited due to the great noise.

Research on Quiet Supersonic Technology could also enable supersonic flights over land in the future. The aerodynamic design seems to be a suitable lever for reducing the sonic boom. Corresponding research projects are ongoing e.g. at the Japan Aerospace Exploration Agency (JAXA). For the new first-generation supersonic, however, the sonic boom will continue to lead to significant route limitations, as flights at supersonic speed will probably only be permitted over the sea and at a corresponding minimum distance from the coast.
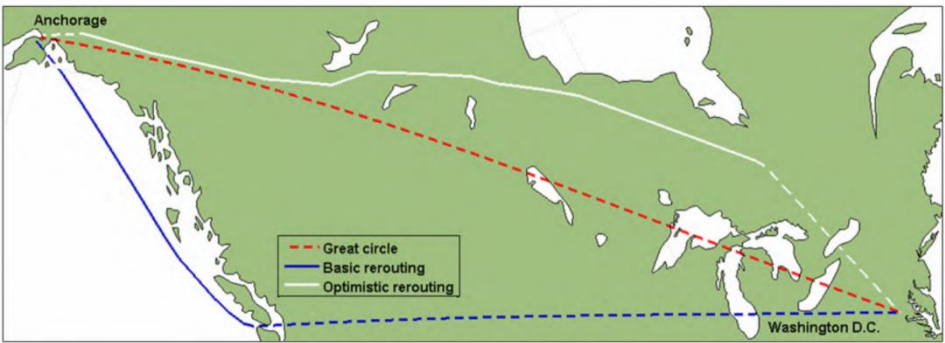
Figure 84: Rerouting of a supersonic flight in comparison to the great circle distance[276]

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[276] Cf. LIE (2014)
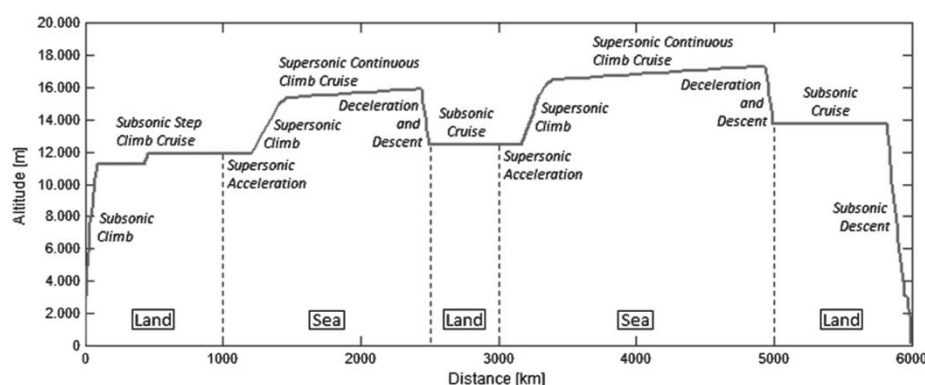
Figure 85: Generic supersonic-trajectory[277]

With regard to noise emissions close to the airport, in RUTH (2019) the following is mentioned: *"The exact LTO noise footprint of emerging commercial SSTs will vary by design and cannot be estimated precisely given that the designs are still in the early development stages. Still, some general observations can be made. Early design studies and recent aircraft-level modeling suggest that emerging commercial SSTs would need to adopt special measures, namely modified LTO procedures and engine derating strategies, to meet Section 4 noise limits. Those aircraft are unlikely to meet the current Section 14 noise standard for subsonics because doing so would require new, more expensive clean sheet engines rather than the derivative engines that are currently under consideration".[278]*

In addition to the noise problem, the lower range compared to subsonic aircraft will also limit routes. Though, the current supersonic concepts have a greater range than the Concorde. However, some routes that could be reached with subsonic aircraft are outside the maximum possible flight distance of supersonics.

Fuel consumption is closely related to the achievable flight distance. This represents a major challenge for supersonic aircraft. If it was about four times higher with the Concorde than with conventional aircraft, it is expected that it will be significantly lower with the current supersonic concepts. Here, too, aerodynamics and the reduction of the vehicle's air resistance play an important role. In the NEXST-1 project of JAXA, for example, a 13% reduction in air resistance compared to the Concorde was achieved.[279] In addition, lighter materials are used for the cell, which also reduces fuel consumption (according to the company Boom up to 30%).[280]

In the field of propulsion technology, the manufacturers are therefore also investigating new propulsion concepts. For example, Airbus presented a concept for the use of a rocket propulsion

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[277] Cf. LIE (2014)
[278] Cf. RUTH (2019)
[279] JAX (2005)
[280] GUA (2020)

system and two hydrogen-powered ramjet engines.[281] Even with the classic types of fuel, there is potential for reducing the environmental impact of supersonic aircraft, e.g. by adding synthetic fuels.

Despite these innovative approaches, the energy requirement will continue to be significantly greater than that of subsonic aircraft and thus lead to increased operating costs. Further technological optimizations of subsonic aircraft as well as the generally higher maintenance costs of supersonics are further factors that have to be considered in the operating costs of Supersonics (see [RUTH2019]): "*[…] emerging commercial SSTs could emit 5 to 7 times as much CO$_2$ per passenger as comparable subsonic aircraft on equivalent routes, while failing all applicable environmental standards for new subsonic jets. […] new SSTs are unlikely to achieve fuel burn parity compared with current subsonic business class*".[47]

Finally, environmental aspects represent a challenge for future supersonic aircraft. The reduction of aviation-related emissions will continue to gain in importance in the future. In addition, the stricter noise regulations at airports pose certain hurdles for supersonic aircraft.[282] Challenges that must be met for the successful introduction of supersonic aircraft.

The market entry of supersonic aircraft will inevitably also have an impact on conventional subsonic air traffic. In addition to newly induced supersonic connections, there will also be a certain degree of displacement of subsonic connections on certain routes by significantly faster supersonic alternatives. Aircraft types that are principally suitable for supersonic connections range (as can be seen in Table 19) from business jets to aircraft with a capacity of up to 100 people. In addition, only routes that have a certain minimum time advantage over subsonic aircraft are considered for supersonic connections. Also, only certain airports are suitable for supersonic aircraft that meet sufficient infrastructural conditions. Another factor is that - due to the sonic boom - certain minimum distances to the coast have to be considered for the routes of supersonics. Compared to conventional subsonic connections, the passengers on supersonic connections are initially exclusively very wealthy customers or business travelers. Current research by CAEP on the effects of the reintroduction of global supersonic traffic as well as the attempt by the US industry with various projects to bring supersonics to the market make the emergence of worldwide supersonic connections from the mid-2020s look very likely.

As mentioned above, in addition to research on supersonic aircraft, there are studies on hypersonic concepts. These concepts can reach airspeeds up to Mach 10, whereby e.g. for the route Europe-Australia 90 minutes would be needed. At DLR, research is being carried out on the so-called Spaceliner concept, which was designed for suborbital flights.[283] Due to the very low level of technological maturity, it is difficult to estimate the market entry of these concepts.

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[281] MAR (2015)
[282] ICAO (2018)
[283] Cf. Sippel, M. et al. (2016).

According to Sippel, M. et al. (2016), this can take place from 2040, depending on the concept. For these aircraft, due to the different cruising altitudes and drive concepts, there are different boundary conditions with regard to environmental compatibility and economy.

4.8.2. Technological Developments "Rotorcraft"

As mentioned in chapter 2.3 and chapter 3.1.4 fuel efficiency is one of the major factors driving innovations in the field of rotorcraft design. Additionally, an increase of flight speed is envisaged in order to reduce travel time and to increase flight distances. Similar requirements are set by the Cleans Sky Programme, where a reduction of *"CO2 emission by 25 to 40% per mission (for rotorcraft powered respectively by turboshaft or diesel engines)"* is claimed[284]. Also the impact of noise is one of the research objectives that is addressed by the Clean Sky Programme by reducing *"the noise perceived on ground by 10 EPNdB or halving the noise footprint area by 50%"*.

Since there is a significant overlap between rotorcraft research and research on vehicles on Urban Air Mobility vehicle concepts, only a brief overview on the approaches in the field of rotorcraft design are given in the following.

Generally, the approach taken by European research is based on tilt-rotor or tilt-wing concepts. By applying this approach the rotorcraft ca make use of the vertical take-off and landing capability and additionally make advantage of an increased flight speed through its capability to use the tilted rotors as engines comparable to a turboprop aircraft. An example of such a configuration is shown in Figure 86.

Figure 86: Concept of a rotorcraft with tilting rotors by Clean Sky[285]

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[284] Clean Sky Joint Undertaking (2021b).
[285] Ibid.

4.8.3. Technological Developments "Urban Air Mobility"

The rapidly growing proportion of the urban population in the world population as well as the overall growth of megacities are already causing overloading of ground-based urban traffic in some regions of the world. The further advances in aircraft technology and battery technology that are taking place at the same time have led to the rising importance of Urban Air Mobility (UAM) and air taxis in recent years. Accordingly, there are already a large number of UAM concepts from various manufacturers worldwide. In addition to the well over 100 vehicle concepts, the first prototypes have already been built, which have also completed their first test flights.

Vehicle and ground infrastructure

In the field of UAM vehicles, many designs and ideas have been presented in recent years, which can be roughly divided into the following categories:

- Folding Wing STOL
- Folding Wing VTOL
- Fixed Wing VTOL
- Multicopter
- Multicopter, Impeller
- Multicopter, Tilting Rotors
- Multicopter, Tilting Wing
- Gyrocopter

With regard to the energy sources, there are approaches with the following variants:

- conventional
- electric
- hybrid-electric
- alternative (e.g. hydrogen)

In the following figure some exemplary concepts are shown together with a qualitative description of the main performance characteristics as well as possible use cases.
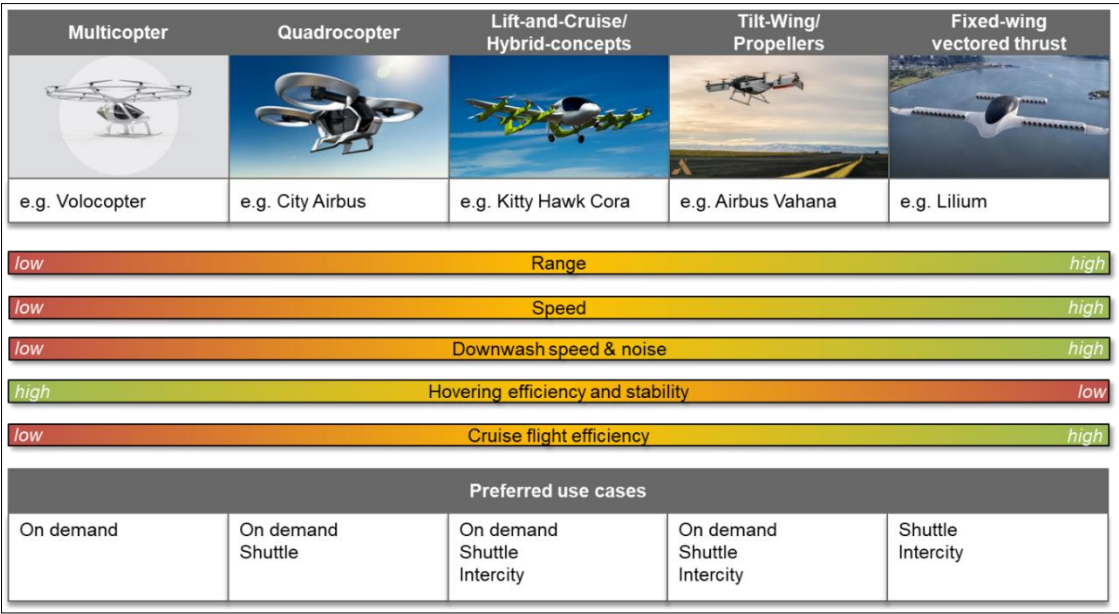
Figure 87: Examples for UAM vehicle concepts together with a qualitative description of some performance characteristics and possible use cases.

Basically, vehicle concepts with VTOL capabilities for urban air traffic, i.e. for operation in densely populated areas, are the favored concepts. For a vertical take-off, the entire energy will have to be provided for the take-off and climb phase by the rotors (i.e. no aerodynamic lift by wings), but the great advantage is the comparatively small space requirement for the ground infrastructure (often referred to as "vertiports"). This is shown in the following figure in which the space requirements of different STOL variants were compared.

Figure 88: Space requirements of different STOL variants[286]

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[286] Cf. NASA (2015).

The majority of the published concepts for possible take-off and landing sites are therefore based on VTOL-capable aircraft concepts (see e.g. a publication from NASA from 2015[287]) In the following several variants are shown how a vertiport with two take-off and landing sites could be designed based on the design guidelines for helicopter landing pads.
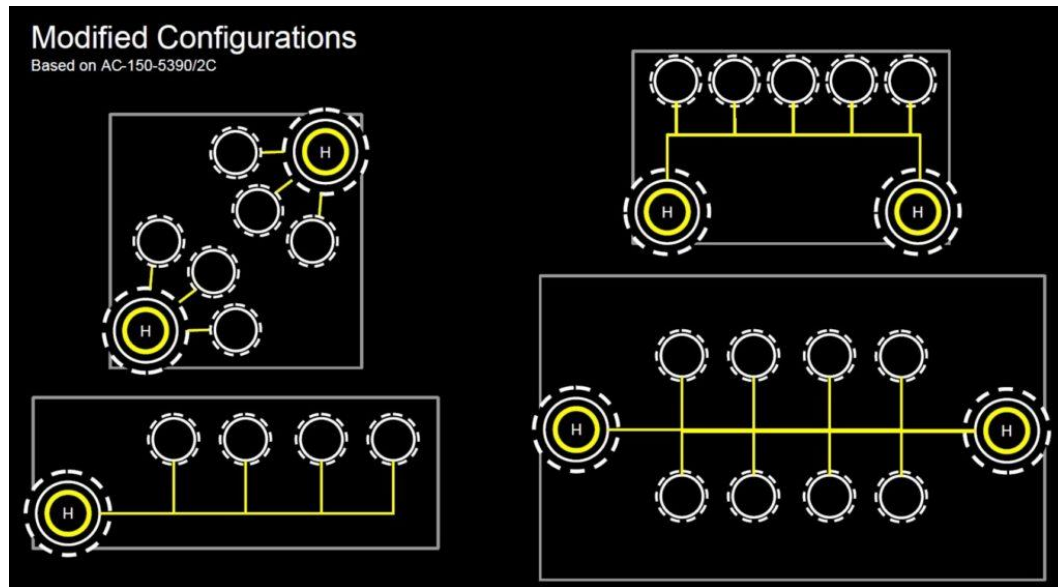
Figure 89: Possible configurations of vertiports[54]

A detailed discussion of the concepts cannot be carried out at this point, but from a purely qualitative point of view, the space requirements for the ground-based infrastructure should not be underestimated, especially for a higher traffic volume. The compromise that has to be drawn will, among other things, move between the boundary conditions "ticket price" and "travel time": If the distance between potential customers/passengers and the vertiports is too high, the travel times increases and the product may become unattractive. If the spatial distance to the customer is reduced, it can be expected that the demand will increase because the time advantage over other modes of transport is increasing. Due to the rising infrastructure costs, however, the ticket price may also increase and thus have a dampening effect on demand. Other aspects that need to be taken into account include environmental impacts, i.e. essentially the noise pollution of the population from the vehicles.

In addition to guaranteeing take-off and landing processes, specific charging infrastructures for the electrically operated UAM vehicles must also be available at the vertiports. In addition, devices for maintenance and parking areas for accommodating passengers must be taken into account. In addition, the new UAM vehicles need to be integrated into the existing urban transport network. Successful operational business models can only be developed through the existence of

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[287] Cf. Aviation Today (2020).

suitable and sufficient UAM infrastructures in connection with multimodal transport connections. [288,289,290]

As described in the introduction, hopes lie not only in shortening travel times but also in reducing emissions (local air quality). For this reason, conventional propulsion based on fossil fuels are not included in most vehicle concepts. The current demonstrators with the highest level of technological maturity are based almost exclusively on battery-powered drive systems (see Table 20).

Table 20: Performance indicators of selected UAM vehicle concepts[291]

Project	Type	Category	MTOW [kg]	Pax	Target EIS	Cruise altitude ([ft]	Cruise Speed [kt]	Payload ([kg]	Range [km]	Engine power [kW]
Uber Elevate	Electric	VTOL	N.A.	up to 4	2023	1,000 - 2,000	130	498.96	97	N.A.
Lilium	Electric	VTOL	639.6	5	2025	3300	160	200	300	320
Kitty Hawk Cora	Electric	VTOL	N.A.	2	2022	up to 3000	95	N.A.	100	N.A.
Airbus (A^3) Vahana	Electric	VTOL	725.7	1	2020	N.A.	95	113	100	360
Airbus City Airbus	Electric	VTOL	2199.2	4	2023	N.A.	59	N.A.	96	8*100
Airbus/Audi Pop up	Electric	VTOL	N.A.	2	N.A.	N.A.	N.A.	N.A.	130	N.A.
Boeing Aurora eVTOL	Electric	VTOL	798.3	2	2020	N.A.	48.6	N.A.	N.A.	N.A.
Ehang 184	Electric	VTOL	N.A.	1	N.A.	9843	54	100	16	106
Volocopter 2X	Electric	VTOL	450	2	2018	6562	27	160	27	N.A.

The problem of the "energy density" of batteries (and the energy density to be expected) has already been discussed in the field of passenger air traffic in connection with aircraft in the lower seat classes (seat categories 1-4) and can be seen on table shown above. The ranges of the vehicles are usually in the range of up to 100 km. The relevant sources do not reveal whether the calculation was carried out with full payload and corresponding reserves. However, here too the trend is moving in the same direction that energy sources with higher energy density are being investigated. E.g. the concept of the company Alakai Technologies, which is based on a hydrogen drive.[292]

By looking at the number of seats in the vehicles from Table 20, it also becomes clear that the subject of "autonomous flying" will be of great importance in a possible market. A topic which in classic aviation markets was initially expanded through research approaches in the area of "single pilot operations" and in the area of unmanned cargo aircraft".[293] In addition to the technical feasibility of these approaches, certification issues are an important point that must be addressed in the future in order to establish UAM as a further aviation market that differs significantly from an inner-city helicopter business model. The area of cyber security will increasingly play an important role in questions of security. Redundancy effects through the use of several rotors and

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[288] Cf. NASA (2019)
[289] Cf. Porsche Consulting (2018)
[290] Cf. Roland Berger (2018)
[291] Cf. ICAO (2020)
[292] Cf. SAE (2019).
[293] Cf. DLR (2017).

safety parachutes do not provide sufficient answers to safety-related questions, especially in densely populated areas.

ATM and Cybersecurity

In addition to the technical and economic challenges in relation to the vehicles and the ground infrastructure, new solutions for the air traffic management of an urban air transport system must also be found. This air traffic management can be based to a large extent on an Unmanned Aircraft Systems Traffic Management (UTM), but will nevertheless encounter a number of challenges in order to enable the propagated visions of an UAM market:

- The integration of the UAM traffic into the airspaces of the existing air traffic (airspace C) without overloading of the flight controllers can basically only take place with a very high degree of automation
- A UTM system must be able to react extremely flexibly, especially for "on-demand" operation with short-term requests
- A conflict-free route allocation and routing must take place under many boundary conditions and taking into account safety (no flying over large crowds of people, government buildings, etc.), private interests, nature reserves, etc.
- Contingency plans and corresponding capacities must be developed for a wide range of scenarios.

In the European research project CORUS (Concept of operations for European UTM systems) requirements of a future UTM system for urban air mobility and a possible future roadmap were analysed and discussed.[294]

Next to a suitable ATM/UTM system also several challenges and aspects from the field of cybersecurity have to be considered for a future UAM traffic system:

- Integrity of data
- Future communication infrastructure (FCI)
- Secure data links
- Higher update rate
- Clear corridor assignment
- Precise navigation & surveillance
- Trusted infrastructure
- Safety-critical data
- Cyberphysical Security („UAM vehicle as weapon", wrong video signal for pilots etc.)
- Physical Layer Security
- Spoofing, spamming, jamming, highjacking

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[294] See CORUS project for more information (https://www.sesarju.eu/projects/corus).

- Cryptographic system (e.g. „TESLA", Galileo) as protection from spoofing
- Training of AI models needed for ensuring UAM data processing

Roadmap and challenges

The UAM market includes a number of technological and operational innovations, all of which must have a high level of technological maturity in order to ultimately realize the forecasted flight movements and consequently business models. Apart from the economic viability, it is therefore important to develop the vehicles, the ground infrastructure and the air traffic management with their corresponding requirements. In addition, social acceptance and legal regulations play an important role for the future successful introduction of a comprehensive urban air mobility system.

The anticipated EIS for a selection of vehicles are given in table 20. Many of these concepts have already completed a successful flight test based on a demonstrator. Nevertheless - especially against the background of the high safety requirements in air traffic and the requirements of a possible UAM market in terms of payload, range and emissions - there will still be a need for further development here. Therefore, the EIS data given can be viewed as very ambitious. In some cases, the specified performance data of the vehicles are increasingly questioned (see e.g. [295]).

Currently, possible providers of UAM business models are orienting to the regulations for the design of heliports with regard to UAM ground infrastructure. Some conceptual layouts based on these regulations are shown as examples in figure 89. The manufacturers sometimes publish far more visionary concepts (so-called "vertiport hubs") which, in addition to the air-side design, also include the land-side infrastructure. It can be assumed that the challenge with these concepts will be less the technological maturity than the construction costs, approval procedures and ultimately the construction times. The use of existing heliports can be a temporary solution, but it will not be the solution to achieve the target traffic volumes (and thus the target economic viability).

Another key component for the successful introduction and long-term success of UAM is the creation of consistent regulations and certifications. There are currently no globally standardized legal frameworks for UAM vehicles, which are essential to ensure the safety of people and buildings. Regulating aspects of urban air mobility can include, for example, regulations for the approval of UAM vehicles, operator certifications, weight and flight height restrictions, pilot licenses or air traffic management. [296,297,298]

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[295] Cf. Aerokurier (2020).
[296] Cf. NASA (2019)
[297] Cf. Porsche Consulting (2018)
[298] Cf. Roland Berger (2018)

DLR is already active on this topic in the course of various research work - for example the project "City ATM" [2018-2020] or the study "Concept for Urban Airspace Integration" [2017].

Social acceptance is a factor that should not be underestimated for the long-term success of UAM vehicles and their respective areas of application. With regard to the estimation of operational noise, the first analyses with regard to the propulsion technology were also carried out in course of DEPA 2050. These show that propulsion concepts do exist to reduce operational noise (see section 5.3.3). Against this background, it is important to show the population that with the integration of new means of transport such as UAM vehicles into city traffic, everyone benefits in the medium term and that UAM transports are not only developed for wealthy customers.[299]

Areas of application and entry-into-service

Due to their construction, all vehicle categories outlined have various advantages and disadvantages with regard to potential areas of application. Due to their very high hovering efficiency and stability, multi-rotor vehicles are particularly suitable as air taxis within cities. The technical properties of the multi-rotor are most suitable for these intra-city UAM transports on relatively short route distances. In addition to intra-city transport, the Lift & Cruise vehicle category is also suitable for inter-city transport and as an airport shuttle. Above all, the higher speed and range of this type of vehicle compared to multirotors significantly expand the UAM areas of application. Tilt wing/rotor/duct vehicle concepts are particularly suitable for intercity and airport shuttle traffic due to their very high speed and range[300,301,302].

The market launch of the first commercial UAM traffic services is expected - depending on progress in the key areas described - in the period between 2025-2030. On a purely vehicle-technological level, certification and the corresponding market launch for multi-rotor vehicle types have progressed furthest, so that in the progressive DEPA 2050 scenario one can assume that these vehicles will start operating from 2025, while in the conservative-evolutionary scenario a market launch in 2030 seems more likely with a corresponding delay in market penetration. The other two vehicle categories (Lift & Cruise + Tilt-Wing/-Rotor/-Duct) will therefore most likely enter the market a little later due to their generally more complex design.

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[299] Some experts predict that air taxis will be a mass transportation mean in the future (cf. ADAC (2020). Besides the resulting added value for individual customers the complete population in an UAM region might also benefit in this respect by a better local air quality and traffic relocation accompanied by travel time savings in regions with a generally high traffic congestion.
[300] Cf. FEV (2019)
[301] Cf. NASA (2019)
[302] Cf. Roland Berger (2018)

5. Impact Analysis for the DEPA 2050 Scenarios

5.1.   Results on Mobility and Vehicle Productivity

The impact analysis with regard to mobility and vehicle productivity plays an important role in the DEPA 2050 assessment framework. Especially the benefits for the overall society by established aircraft concepts was in the centre of the analysis as there is a huge overlapping with the social dimension of sustainability. However, due to the huge diversity of the analysed vehicles and market segments in the scope of the study in combination with different levels of uncertainty (cf. table 2; section 2.3), a coherent and complete impact analysis was not possible. Especially for the advanced vehicle and transportation concepts such as supersonic aircraft and UAM concrete benefits are hardly predictable as those concepts are not introduced yet. Thus, the impact assessment on mobility and vehicle productivity concentrated on the following vehicle types[303] including partially also different geographic levels.

- Mainliner and regional aircraft (European and global scale)
- Small air transport (European scale)

The results for mainliner and regional aircraft as well as for small air transport are presented in separate sub-sections due to different methodological approaches. For both types of air traffic special emphasis was put on the European perspective to address the ACARE 4-hour-goal.

5.1.1. Mainliner/regional aircraft

European focus: ACARE 4-hour-goal

One major aspect of the DEPA 2050 assessment scheme concentrated on the ACARE 4-hour-goal. The major objective behind this goal is that 90% of travellers within Europe should be able to complete their journey door-to-door in a time span of four hours.[304] A concrete estimation of the degree of achievement of this goal is difficult to date although there were some studies conducted in this context. The main obstacle for an analysis is the availability of origin-destination demand data on small geographical scale for all European countries. The most prominent study is the "DATASET2050" project which found that only 10% of intra-European air passengers spend

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[303] Business jets were also excluded from the analysis. As they typically operate on demand by adapting routes and timings to the individual passengers' choice the level of service and the connectivity degree is already high. The impact on mobility and vehicle productivity might only change significantly through the change of the business jet design (e.g. through the introduction of supersonic cruise speeds). Accordingly, the potential outcome of this development is described in the section about supersonic aircraft in this section. As rotorcraft also play a subordinated role in commercial air traffic they are also not discussed here.
[304] Cf. ACARE (2011).

less than four hours by travelling from door-to-door, while six hours has been the average mean and 90% of travellers complete their journeys within 7.5 hours.[305]

To deliver further analyses on the achievement of this goal in regard of scheduled air traffic (i.e. mainliner and regional air traffic) two approaches were used in the scope of this study:

1. The first approach analysed the percentage of the accessible population within a four-hour time frame. For this purpose, Europe was regarded on the level of NUTS-3 regions covering 1,385 regions in total[306]. Furthermore, air travel was analysed in combination with car traffic as airport access and egress mode as well as car traffic solely in comparison to the "car-air-car" variant. Although this theoretical approach is not covering real air travel demand it provides a good overview of the general degree of connectivity throughout Europe and the role of air transport and road traffic.

2. For the second approach real (airport-to-airport) origin-destination air passenger demand data of Sabre Market Intelligence (MI)[307] was used to filter the number of air trips within Europe for the year 2018 to consider actual travel choices of passengers and the associated duration of their trips. As the concrete origin and the final destination addresses of the passengers are not known, very optimistic airport access/egress and process times were assumed to test if these allow a fulfillment of the ACARE 4-hour-goal under optimal conditions. In addition, it was assumed that all passengers choose a direct flight and therefore the shortest connection between their final origin and destination airports, wherever such a direct connection was available according to flight schedules. This reflects the notion of the Flightpath 2050 4-hour-goal that passengers <u>should be able</u> to complete their journey within four hours. Although this decision behavior does not necessarily reflect real journeys in some cases,[308] this assumption had to be made to identify the shortest travel distances from a theoretical point of view to analyse the percentage of theoretically completed air trips within four hours.

As pointed out above, the first approach to address the ACARE four-hour-goal considered 1,385 NUTS-3 regions and compared shortest travel times for travelling by "car only" and for the travel chain "car-air-car" by considering trips that started and ended in the population center of each region. For the choice of flight options in the travel chain "car-air-car" airports in the surrounding of at least 300 kilometers of each population center and their individual connections (with a minimum frequency of one flight per week) were regarded. Furthermore, for the airport

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[305] Cf. INNAXIS (2017).

[306] Concretely, these regions include the complete European Economic Area (EEA) plus Switzerland and United Kingdom.

[307] Cf. SABRE (2014).

[308] For example, passengers partly choose flights with one or two stops for several reasons (ticket price, frequency, airline loyalty). However, the share of direct travellers throughout Europe is already today relatively high with 93% (cf. Grimme/Maertens (2019)).

processing times 45 minutes in total (30 minutes for departure processes and 15 minutes for arrival processes) were assumed. All considered air travel segments could consist of two stops at maximum.

Based on these assumptions, the temporal dependencies of reached inhabitants from each NUTS-3 region to each other NUTS-3 region could be analysed. The results are given in the following figure.
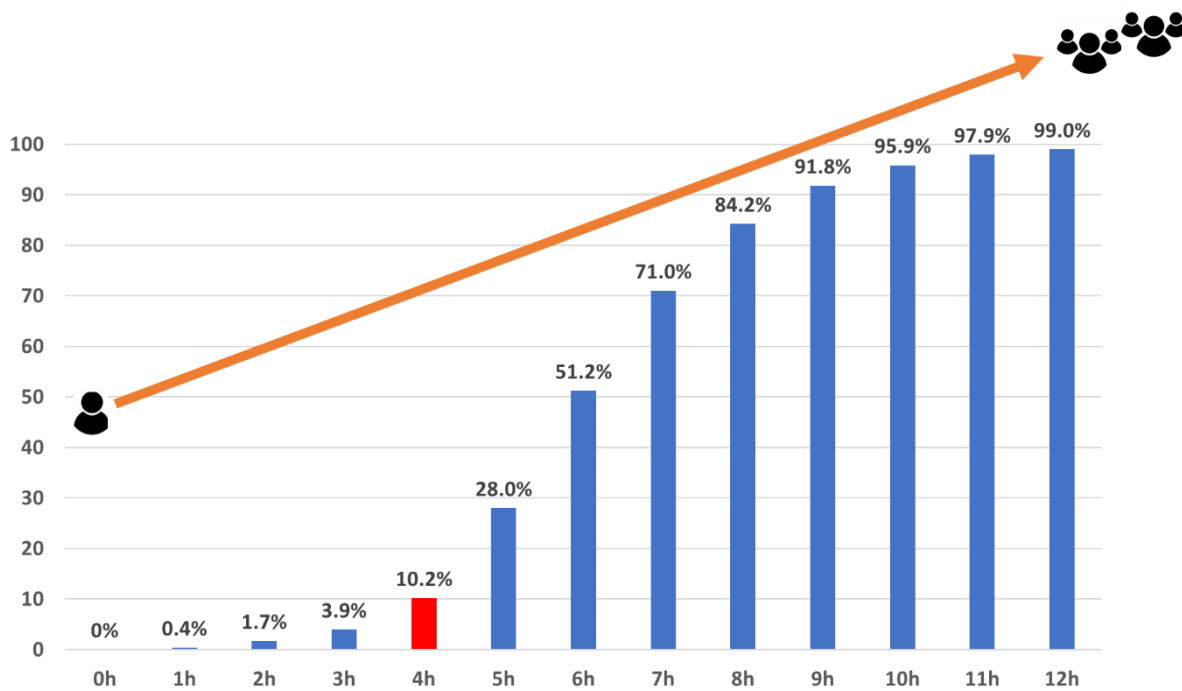
Figure 90: Average reached persons [in %] in EEA from NUTS-3 regions by time

In reference to the direct comparison of "car only" travel and "car-air-car" travel for the ACARE time slot of four hours the "car-air-car" variant has been faster with regard to 25% of all analysed connections. However, the share of the overall population in the EEA region that can at least be reached in a four-hours' time frame is relatively low with 10%. If 50% of the population in the EEA region should be reached, for instance, already six hours have to be spent for travelling and for 90% nine hours have to be invested.

With a higher granularity the following figure shows the geographical distribution of the percentage of the accessible population that can be reached in a four hours' time frame (either by the "car only" or by the "car-air-car" variant from each of the NUTS-3-regions.
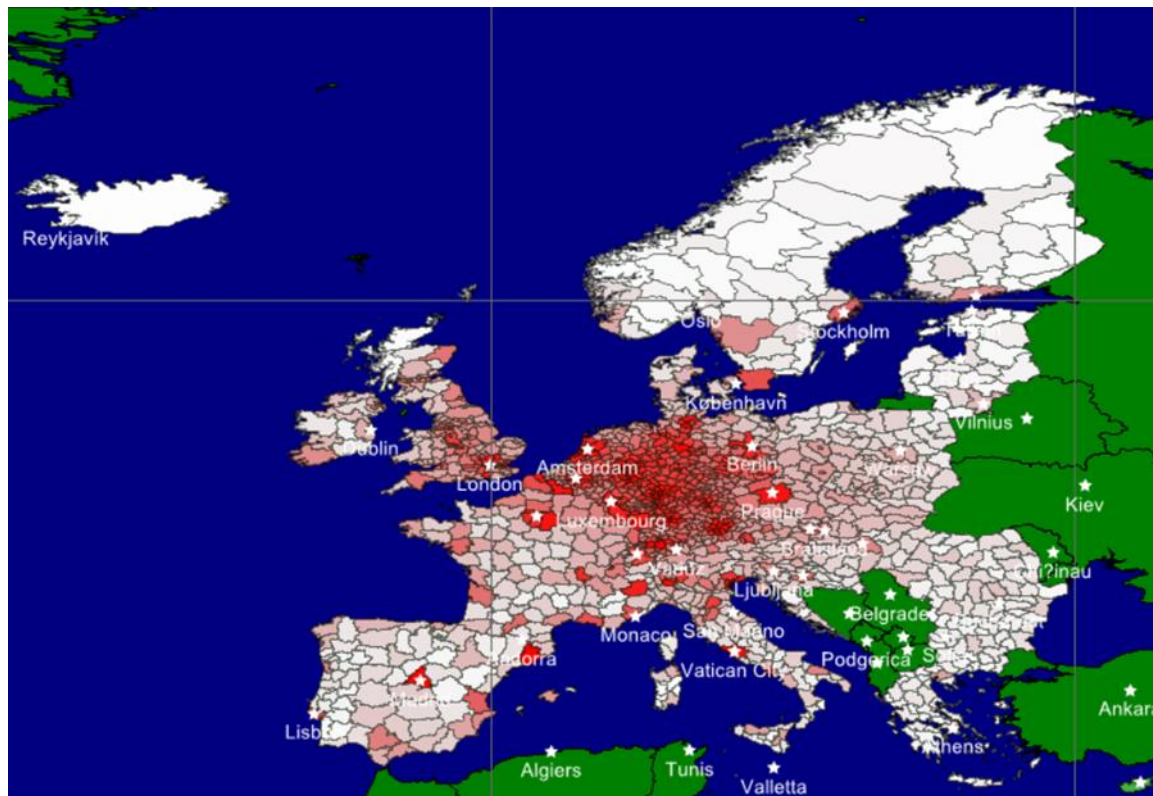
Figure 91: Population reached from each NUTS-3 region within 4 hours using fastest connection possibility

The deep red colour shows the highest degrees for the accessible population in the EEA region given the constraint of the four-hour travelling time frame. It is evident that the best connectivity and access to relatively higher population volumes is given for the bigger cities and metropolitan areas (mainly concentrated in the center of Europe). Nevertheless, if the whole map is regarded, the disadvantageous situation for many areas can be shown, from which a relatively high share of the population in the EEA region is not accessible within four hours. This indicates a low level of connectivity especially for remote/peripheral regions. As a consequence, there might be potential especially for small air transport to close some of those connectivity gaps by operating at low demand routes to improve travel times and connections. On base of the findings presented in the context of mainliner and regional air traffic this is also discussed and analysed in the sub-section on small air transport.

As described above, the second approach analysed the real demand passenger data to identify typical travel distances of passengers throughout Europe and to check the time span they need for their individual journeys considering uniform airport access/egress and processing times. The outcome of this investigation is illustrated in the following figure.
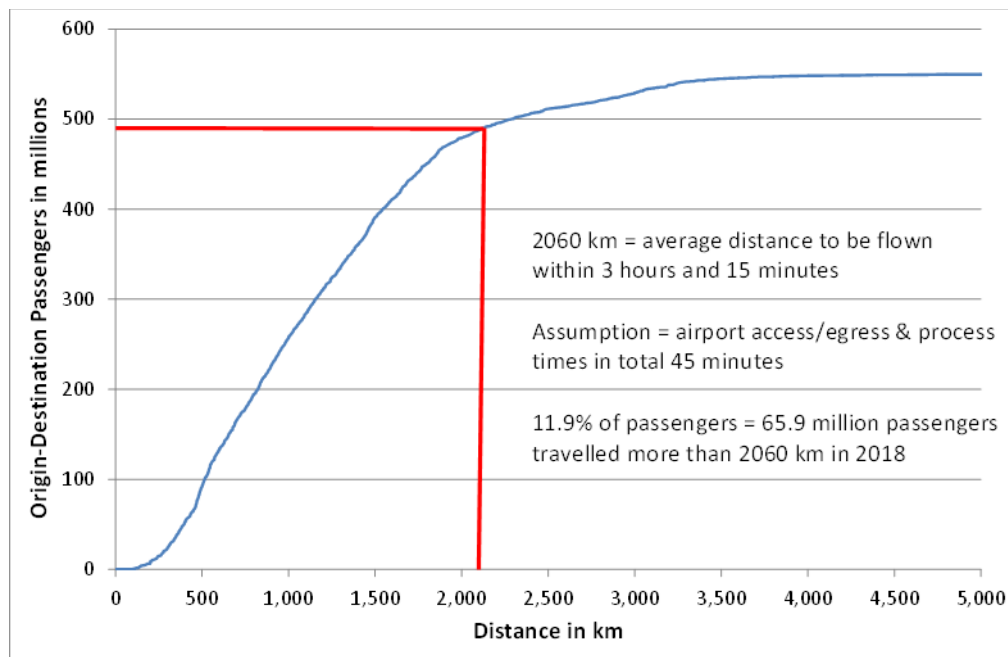
Figure 92: Cumulative distribution of origin and destination air passengers in relation to flight distance in the year 2018

The cumulative distribution of passengers in relation to different flight distances and needed travel times shows with regard to the year 2018 that the distance limit for air trips to be flown within 3 hours and 15 minutes was approximately at 2,060 kilometers. If this distance is exceeded, and under the extremely optimistic assumption of a total of 45 minutes for airport access/egress and process times, which is already far away from reality, the 4-hour-goal cannot be kept anymore. Thus, on base of existing connections and average subsonic flight speed 2,060 kilometers is the maximum flight distance for travelling to meet the ACARE four-hour time constraint. According to this impact assessment framework, passengers that fly a longer distance within Europe fail to meet this goal, even if direct services are available. Interpreting the figure above in this context it becomes visible that only 88.1% of all European passengers in the year 2018 had been able to realise their journey in a four-hour time frame by flying 2,060 kilometers or less.[309] Meanwhile, 11.9% or 65.9 million passengers in total were not able to complete their journey from origin to destination airport in a four-hour time frame. As especially the airport access/egress and processing times as bottleneck will unlikely improve in the future it is also not realistic that the ACARE 4-hour-goal might be reached over the long-term if the results of air trips to be theoretically completed within four hours are regarded.

As consequence from the conducted analysis on European level with regard to mainliner and regional aircraft it can be concluded that an achievement of the ACARE 4-hour-goal seems not to be realistic even over the long-term. The airport network is already very dense, passengers choose to a large extent direct routes to speed up their travel times and for airport process times it is

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[309] In reality this share is even a little bit lower considering that approximately 7% of all passenger are not choosing a direct connection to reach their final destination airport and longer airport access/egress times can be found in reality (cf. Grimme/Maertens (2019)).

unlikely that they still can be reduced in the future. The findings that are presented in the next sub-section on mainliner/regional aircraft and connectivity on global scale indicate a similar tendency and support the findings on the European level. Thus, a limited potential to improve travel times and connections could only be realised through new operations of small air transport on low demand routes as it is outlined in the corresponding sub-section of the SAT section.

Global focus

Innovative air transport and vehicle concepts should not only be geared toward ecological improvements but above all should be tailored to the needs of the users. Under this premise, the following section provides an impact analysis with focus on the investigation of connectivity and mobility changes in relation to mainliner air traffic on global scale, which is responsible for a significant share of total scheduled traffic. In general, connectivity and mobility benefits can be expressed in terms of travel time savings (also based on changes in operational concepts) and improved accessibility (global connectivity). To put this analysis in its economic context, mainliner air traffic originating from the 200 largest cities by GDP per capita was analysed at the global level.

Methodology

The connectivity between the 200 largest cities by GDP per capita was evaluated as well as the connectivity to all possible destinations worldwide. The assessment examined the extent to which the number of connections worldwide has changed in recent years, to which extent the connectivity of the world regions has changed, and what insights can be derived from this analysis for the future.

Limitation of the study is that the actual existing passenger demand is not examined. Only the number of connections that exist based on the applied parameters are highlighted and analysed. Also, the frequency of a connection is not considered. However, as the connections cover cities with high economic prosperity and mainly long-term connections, it can be assumed that passenger demand is relatively high for the connections in the investigated data set.

The data for GDP per capita values at city level was derived from The Brookings Institution and from the European Commission - Global Human Settlement database. Source of the flight schedule for the third week of June in 2000 and 2019 is Sabre Market Intelligence.

The study approach was as follows:

- Selection of cities: Selection of 200 largest cities by GDP per capita worldwide
- Selection of airports: Localisation of airports within 150 km great circle distance from center of the decisive cities

- Fastest connection: Identification of the fastest connection including car travel time between airport and city centers and fastest non-stop, one-stop and two-stop air connection from the connected airports
  - Access time: Car travel time from the city center, constant access time of 01:00 hour at the airport
  - Minimum connection time of 00:45 hours, maximum connection time of 04:00 hours between two flights
  - Egress time: Constant egress time of 00:45 hours at the airport, car travel time to the city center
- Analysis of:
  - Number of cities and airports at world region level
  - Non-stop, one-stop, and two-stop connections originating from airports located within 150 km great circle distance from the specified cities which offer scheduled service on mainliner air traffic to all possible destinations worldwide
  - Connectivity between the 200 largest cities by GDP per capita of mainliner air traffic between 2000 and 2019

In the following, the description of the "200 largest cities by GDP per capita" is abbreviated to "Top 200 Cities".

Connectivity development on global level

The flight connections originating from the "Top 200 cities" worldwide were analysed for the years 2000 and 2019. Within these years, the GDP per capita of the cities considered changed. 184 cities remained in the analysis with 16 new cities joining the "Top 200 cities" and replacing others due to the increase in economic output per capita. The newly added cities are mainly located in China and mostly replace cities in Europe especially in the UK. Airports were considered to be those that offer scheduled air connections and are located no more than 150 km from the respective city center. Thus, some of the analysed cities are within the catchment area of the same airports. From a global perspective, the cities with the highest GDP per capita are primarily located in three regions of the world. These are North America (USA, Canada), Europe and, at a distance, North-East Asia (China, Japan, Taiwan and South Korea). The following table shows the number of cities and the number of airports located in the vicinity of the designated cities.

Table 21: Number of cities and airports of the "Top 200 Cities"

World Region	Number of Cities[1]		Number of Airports[2]	
	2000	2019	2000	2019
North America	88	88	290	254
Europe	72	65	223	193
East Asia	23	35	70	97
Pacific and	8	7	24	22

World Region	Number of Cities[1]		Number of Airports[2]	
	2000	2019	2000	2019
South East Asia				
Middle East	6	4	22	11
South America	2	0	4	0
Central America and Caribbean	1	0	2	0
South West Asia	0	1	0	2

[1] Number of the "Top 200 Cities"

[2] Number of airports localised within 150 km great circle distance from the center of the designated city.

The number of flight connections is shown in the next table. The world regions South America, Central America and Caribbean and South West Asia are not listed separately in this table, as they are not of significant relevance when considering the "Top 200 Cities". A connection between two cities can be made either via a non-stop, one-stop or via a two-stop connection. The shortest one in terms of travel time is decisive. A connection between the origin city and final destination is included in the analysis at maximum twice, once for the outgoing connection and once for the return connection. Whereby the number of stops on the outgoing connection does not necessarily have to be the same as on the return connection. Both directions could be connected via different airports. Thus, it can be assumed that a non-stop connection takes the least time, whereas a two-stop connection takes the longest time to travel between an origin and a destination city.

Table 22: Development of air connections originating from the "Top 200 Cities"

Origin World Region	Non-Stop[1]		One-Stop[1]		Two-Stops[1]	
	2000	2019	2000	2019	2000	2019
North America	5,636	7,191	69,248	80,057	197,506	248,996
	+28%		+16%		+26%	
Europe	5,928	10,719	54,754	68,064	142,360	201,881
	+81%		+24%		+42%	
East Asia	1,025	3,191	8,403	22,826	25,580	93,724
	+211%		+172%		+266%	
Pacific and South East Asia	505	642	3,591	5,570	10,144	19,056
	+27%		+55%		+88%	
Middle East	501	645	3,877	5,320	8,128	10,921
	+29%		+37%		+34%	

[1] Based on the "Top 200 Cities"

Furthermore, the preceding table shows how the number of corresponding connections has changed between the years 2000 and 2019. Growth can be seen in all of the listed world regions. The growing mobility behaviour can be assigned to several reasons. For example, demand increases with growing incomes but also the expansion of infrastructure and new business models in air transport, such as the rapid growth of low-cost carriers have contributed to this.

Although the number of airports in North America and Europe is declining, an overall increase in the number of connections can be observed, especially for non-stop connections. In Europe, the growth in non-stop connections stands out. This is partly due to the expansion of low-cost carrier services, which serve cities via point-to-point connections and tend to avoid large hub airports.

The East Asian market is characterised by high growth figures. Compared to all other world regions, the number of cities among the "Top 200 Cities" is increasing, as is the number of airports (see table 21). This growth is also evident in the number of flights, which is increasing at a much faster rate than in other regions of the world. This growth is largely due to the development in China. While the number of connected airports in the rest of East Asia has remained the same, the number of airports in China has almost doubled from 131 to 249 between 2000 and 2019.

The development of connections starting from the "Top 200 Cities" is shown in the table below. In North America, the flights within this region have mainly developed in favour of direct flights. While two-stop connections are declining, direct connections are increasing by almost the same amount. The moderate growth figures for connections within North America compared to other regions of the world suggest that the market is well served and direct connections have more growth potential in the future. Connections that have their destination beyond North America are growing more strongly. Here, it can be noted that direct connections have grown the most, too.

On the European market, growth has also developed in favour of direct connections. Between the years 2000 and 2019, non-stop connections have increased by 86% and have thus made a significant contribution to improving connectivity in terms of accessibility and travel time savings within Europe although this had no significant impact on the ACARE 4-hour-goal as outlined above. Connections with destinations outside Europe are growing at a similar rate, and here as well the market has developed in favour of direct connections.

Of all the world regions, the strongest growth can be seen in East Asia and especially in China. The reasons for the significant growth rates are described above. Connections to destinations outside China have grown particularly strongly, with non-, one- and two-stop connections increasing by ten times. Originating in Pacific and South East Asia, connections beyond this region grew more strongly than connections within Pacific and South East Asia. In the Middle East, the number of connections within the region has declined. With the increasing importance of hub airports such as in Dubai, Doha and Abu Dhabi, growth is shifting to connections with destinations outside the Middle East.

Table 23: Development of air connections within and beyond the world regions

Origin World Region	Stops	Development of connections <u>within</u> the world region[1]	Development of connections <u>beyond</u> the world region[1]
		2000 – 2019	2000 – 2019
North America	Non-Stop	18%	97%
	One-Stop	3%	44%
	Two-Stop	-22%	53%
Europe	Non-Stop	84%	74%
	One-Stop	20%	30%
	Two-Stop	19%	51%
East Asia (China, Japan, Korea, Taiwan)	Non-Stop	210%	214%
	One-Stop	161%	176%
	Two-Stop	196%	270%
(China alone)	*Non-Stop*	*(632%)*	*(440%)*
	One-Stop	*(936%)*	*(418%)*
	Two-Stop	*(752%)*	*(681%)*
Pacific and South East Asia	Non-Stop	15%	70%
	One-Stop	26%	83%
	Two-Stop	54%	96%
Middle East	Non-Stop	-36%	65%
	One-Stop	-14%	42%
	Two-Stop	23%	35%

[1] Based on the "Top 200 Cities"

Connectivity among the "Top 200 Cities"

From 2000 to 2019, connectivity among the "Top 200 Cities" improved as expected. Inter-city connectivity increased by about 20% from an average of 62 to 74 direct connections. The cities with the highest number of direct connections are London (136) followed by Chicago (133) in 2000 and New York (150) followed by London (141) in 2019.

In general, cities in North America and Europe connect a higher number of cities among the "Top 200 Cities" via a direct flight than other world regions such as East Asia. This is due to the fact that, on the one hand, the number of North American and European cities among the "Top-200 cities" is more frequent (see table 22), and thus can be directly connected by small aircraft with appropriate range, whereas the geographical location of cities in East Asia makes it necessary in many cases to link to other regions of the world via a one-stop connection.

Furthermore, demand between city pairs is of great importance. Only routes that are economically profitable and for which there is sufficient demand are served. For this reason, long-haul flights on which large aircraft operate tend to be connected to hubs, which in most cases are located in economically strong metropolises with a large population or in capitals. From there, smaller cities are connected with smaller aircraft. Among the "Top 200 Cities", there are some cities that are not located in the vicinity of such a hub and are therefore more frequently connected via a transfer. For example, Hamburg, which is not located within a radius of 150 km from a hub airport, and Hong Kong are connected via Helsinki.

Technological progress and new aircraft with a long range improve the connectivity of very distant cities. For example, in 2000, the connection between Hong Kong and New York was only possible via a one-stop, whereas today these two cities are connected by a direct flight. Direct flights with very long distances and travel times are offered by aircraft such as the Airbus A350-900 or the Boeing 787-9 and connect cities where in the past at least one transfer was necessary. The trend to offer long distances with small aircraft is also reflected in the improvement of the range of existing aircraft. Modified existing models such as the new long-range versions of the A321 Neo, the LR (long range) and XLR (extra-long range), connect distant cities on long-haul routes between which demand is at a lower level but sufficient to be handled efficiently by smaller aircraft.

Overall, it can be seen that connectivity between the "Top 200 Cities" has improved significantly between the years 2000 and 2019. The figure below depicts the connectivity that results from direct connections. A general shift toward higher levels of connectivity can be identified. While in 2000, 13 cities were connected to 60%-70% of the total 200 cities via a direct flight, the number has increased to 15 in 2019. Furthermore, 11 cities reach 70%-80% of the total 200 cities in 2019. However, the most non-stop connections for this consideration are still within and between North America and Europe. This is due to the density of cities and short distances within these world regions. Moderate long-haul distances connect Europe and North America with each other. The direct connection between London and New York is one of the most frequently flown ones in the world. However, there has been a particular increase in cities in East Asia, which have been able to significantly increase the level of non-stop connectivity.

Often, more than one city that is listed in the "Top 200 Cities" dataset fall within the catchment area of several airports, as it can happen that an entire region is affected by a high GDP per capita, which then includes several large cities. Thus, these cities can benefit from being located near many or particularly large airports. These include, for example, New York and Philadelphia, Nuremberg and Munich or, above all, the region in the South of China, which comprises the cities of Guangzhou, Hong Kong, Macao and Shenzhen and a total population of over 50 million.
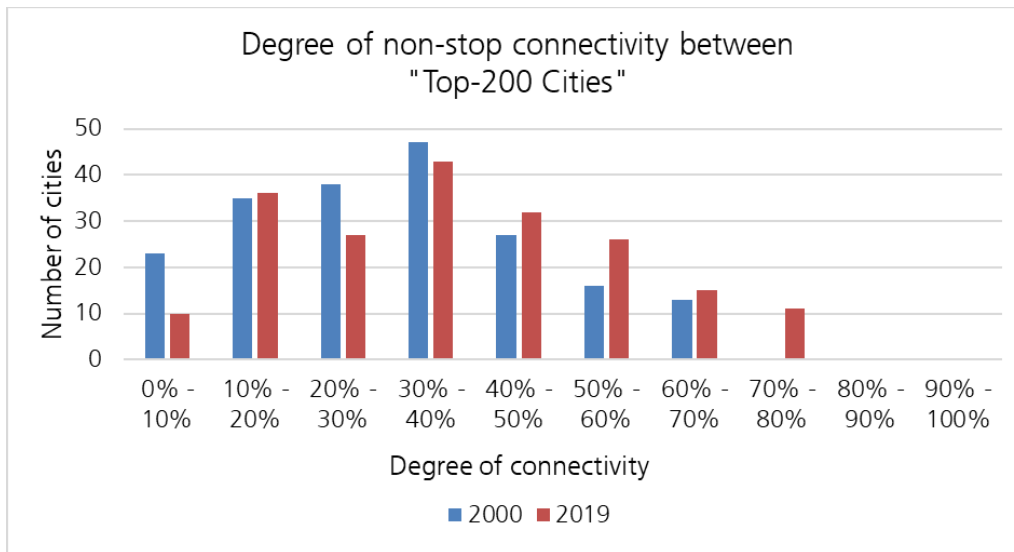
Figure 93: Degree of non-stop connectivity between the "Top 200 Cities"

As expected, one-stop connectivity also increased between 2000 and 2019, as shown in the next figure. Although the development is not quite as clear as for non-stop connections, the trend towards a high degree of connectivity can also be seen. Among the cities where one-stop connectivity has increased most significantly are cities located in remote countries such as Australia. Due to the development of hub airports especially in the Middle East the connectivity of cities in remote regions increases. The example of Adelaide in Australia illustrates how the connectivity of a remote region has developed between the years 2000 and 2019. Whereas in 2000 Adelaide was only connected to 8 cities in Europe via Kuala Lumpur and Singapore, the connection to Europe via hubs in the Middle East like Doha or Dubai connected Adelaide with 41 cities in Europe in 2019.

Using a two-stop connection, all airports could be connected to each other in 2000 as well as in 2019, which means that in this case the level of connectivity is 100% for all the decisive cities.
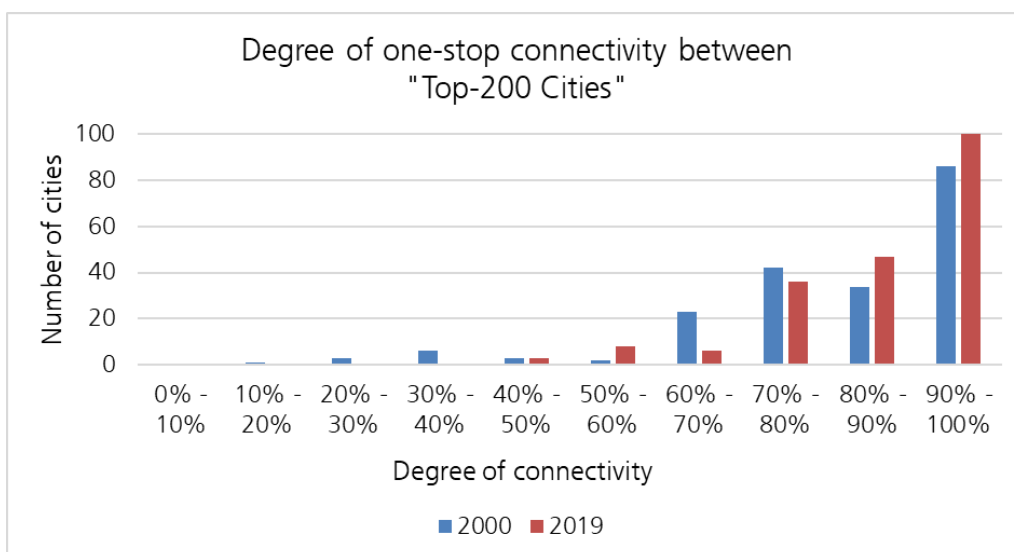
Figure 94: Degree of one-stop connectivity between the "Top 200 Cities"

Directness of connections

The detour factor refers to connections that are not served by a direct flight. It is calculated from the actual distance traveled by one-stop and two-stop connections and the equivalent direct great circle distance between the origin and destination. It shows that on one-stop as well as on two-stop connections, geographically remote cities such as Honolulu, United States or Auckland, New Zeeland have the lowest average value of about 1.1 (10%) on their connections. Cities on the East and West Coasts of North America also have a low factor, as well as a few cities in Eastern Asia. The detour factors for flights originating in Europe with a destination outside this region is moderate compared to indirect flights within Europe. This is due to the fact that the air transport network within Europe is already very dense with a high share of direct connections. When cities are not directly connected, a longer detour via a hub airport is often necessary.
Furthermore, the density of airports is high. Cities can often only be connected economically by a direct flight if the distance is sufficient and the demand in air transportation is high enough. Thus, in many cases, even smaller regional aircraft, which are more economical to operate over short distances with fewer passengers, would be suitable. This holds especially for a dense air transport market such as Europe and also to connect decentralised locations with each other. It should be considered that on routes that are currently not directly connected by air, an intermodal approach may be suitable to complement a direct flight with a ground-based mode of transportation and to take advantage of the airport as a multimodal transportation hub.

Conclusion

Technological advances have increased the range of aircraft, making it possible to directly connect cities that a few years ago could only be reached by an indirect connection with at least one stop. This has also led to an increase in the number of direct connections at major hubs around the world. If there is sufficient demand between distant cities, long-haul aircraft can also be used to connect these cities by direct flights. Strong growth can be seen in East Asia and especially in China. The development has shown that, according to GDP per capita, cities in this region of the world are gaining in importance, which is also clearly reflected in air connections. Thus, connectivity within East Asia is expected to increase as well as connectivity between East Asia and all other world regions, especially with Europe.
The air traffic network within Europe and North America has grown on short- and medium-haul routes due to operating concepts such as the low-cost carriers, especially with regard to direct connections, which has led to a denser air traffic network in recent years. Improvements in connectivity can mainly be achieved over very short distances, to remote locations or through intermodal approaches. For this reason, further research in this area would be appropriate to tailor improvements to the needs of the users. For small air transport and short distance routes this has already been in the following section in relation to the European situation and with regard to the ACARE 4-hour-goal.

5.1.2. Small air transport

European focus: ACARE 4-hour-goal

For small air transport the same methodology as in the case of mainliner/regional aircraft was applied to estimate the accessible population with a four-hour time frame by assuming at the same time an introduction of new SAT routes throughout Europe to improve connectivity. Consistent with the approach for mainliner and regional aircraft this indicator is not based on actual or potential demand but shows general options to increase the degree of the accessible population in Europe in comparison to the existing mainliner and regional air traffic network.

To analyse the concrete improvement potential the population in the EEA area including Switzerland and United Kingdom was again regarded on the level of NUTS-3 regions. For each of these 1,385 NUTS-3 regions the nearest airport/airfield capable to handle small air transport was identified in a next step.[310] In a further step new "theoretical" SAT routes were introduced assuming that SAT technology allows to perform ranges of 800 kilometers with a cruise speed of 300 km/h and 400 km/h for comparison. To assess the complete performance under the four-hour time constraint airport processes (incl. taxi-out, climb, descent and taxi-in) were assumed to take 15 minutes in total. In case of distances above the 800 kilometers' range 35 additional minutes were added to this calculation for a refuelling stop. Finally, the total travel time was calculated by considering the airport access and egress times (by car) from/to the geographic center of each NUTS-3 region to/from the identified individual airport/airfield, the airport-to-airport flight time and the passenger handling process times at the airport.

Based on these modelling parameters the final results were related to the findings from the mainliner and regional aircraft analysis in order to compare the existing connectivity degree with conventional transport mode choice (car as airport access/egress mode and scheduled air transport in between) and the potentials of SAT to improve connectivity especially with regard to regions that are not so well connected to the existing scheduled aviation network. In this respect, it has to be said that SAT has indeed benefits to offer for improving the accessibility of the population throughout Europe. SAT traffic can be handled from smaller and, therefore, from more airports/airfields. In addition, the size of SAT aircraft is optimised for less passengers to address low demand routes more efficiently. Finally, SAT aircraft can be used more flexibly by operations on demand and can also quicker respond to demand fluctuations over time. Furthermore, in the scope of the DEPA 2050 scenarios especially electric propulsion of SAT aircraft, which is quite probable up to the year 2050, also includes further benefits in the environmental domain (i.e. reduction of CO_2 emissions during the flight stage). Additional connectivity improvements are also probable, if air taxis as airport access/egress modes would be combined with SAT traffic in another enhancement step.

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[310] Suitable airports/airfields were selected on base of the available airport/airfield data from https://ourairports.com/.

For the time being, SAT potentials are, however, already evident. On base of the conducted analysis 29.9% of the European population could be accessed in a four-hour time span, if a SAT network with a cruising speed of 300 km/h would become available. If the cruise speed is increased up to a level of 400 km/h this value might even be improved by 6.7% resulting in a total degree of 36.6%. This means a significant improvement compared to 10% of the total European population that can currently be reached within a four-hour time span with regard to existing mainliner and regional aircraft travel options. Anyhow, it has to be pointed out, that the connectivity potentials of SAT depend strongly on the regarded regions. While regions that are already served by higher volumes of scheduled air traffic through the existence of bigger hubs in close distance profit less, relatively centrally located regions with worse connections to bigger airports benefit more. This is outlined in the following figure.

Accessible population in EEA from NUTS-3 regions <4h (Top 20)
Comparison of scheduled air/car transport (base case 2014) and additional theoretical SAT; sorted by highest gain in percentage points for SAT air traffic with 400km/h speed in reference to the base case 2014
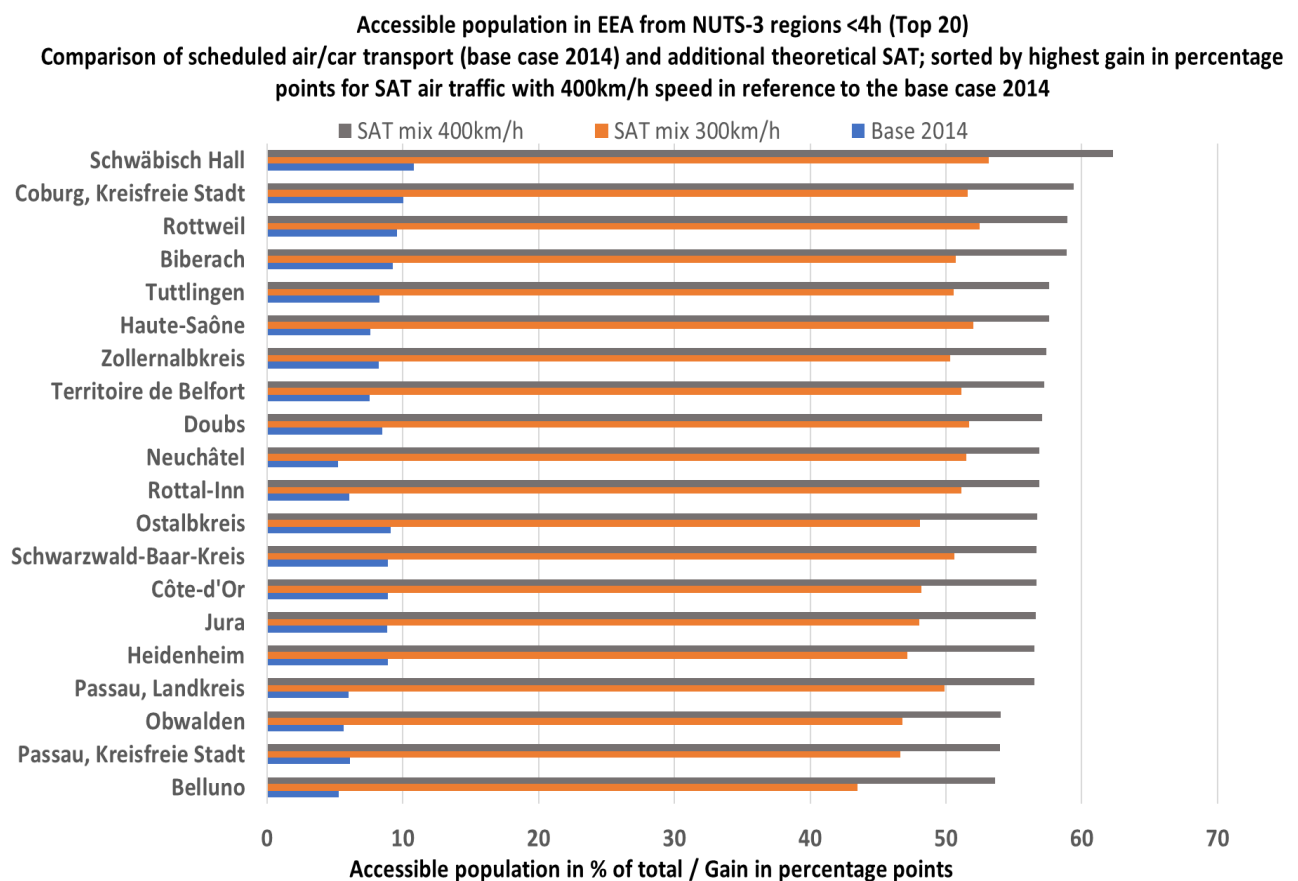
Figure 95: Accessible population in EEA from NUTS-3 regions <4h ("Top 20") in comparison of "air/car" transport and additional theoretical SAT connections, sorted by highest gains (in %)

In general, the degree of the accessible population within the given four-hour time frame and for the presented regions can be improved by up to 40%, if a SAT system with a cruise speed of 400 km/h would be in place. For Coburg in Germany, for example, this share would be even higher with an improvement of nearly 50% for a SAT system with a cruising speed of 400 km/h. The added value for many parts in Southern Germany and smaller cities in Switzerland is given this

way, as this is a relatively SAT-convenient area with closer distances to important metropolitan areas and economic centers in central Europe such as Paris, Milan and Munich. Thus, with a relatively low number of additional SAT flights a relatively high share of the population in Europe could easier be reached as with given conditions including car and scheduled aviation as only travel option. Meanwhile, for European capitals the connectivity is in general already high due to the close distance to central hubs. Additionally, for remote regions the benefits to be expected from SAT are rather limited, as only a smaller share of the European population could be accessed quicker. For instance, additional SAT flights from Northern Norway or Northern Finland can only improve access into the Southern direction with the bigger cities of Stockholm and Oslo. To expand SAT traffic into other directions would not mean a significant improvement as only a small share of the Scandinavian population is living outside of the bigger capitals in the South of the respective countries. In addition, the distance to the central European capitals and their population is generally exceeding the SAT flight distance of 800 kilometers, which means that additional stopovers would become necessary meaning a significant increase of the total travel times.

Finally, it has to be concluded that an extended future SAT system can surely contribute to an improvement of connectivity throughout Europe as no other transport mode might increase the share of the accessible population in shorter time frames as they are given today in case of scheduled air traffic. Mainliner and regional aircraft are too big to operate low demand routes in an economically efficient manner and for high speed railway the challenge would be to connect also remote regions with a high number of origin and destination stops in between, which contradicts the idea of bundling traffic demand with less stops to assure time advantages. In contrast, SAT aircraft is more flexible, can be operated on demand and shows in the context of the DEPA 2050 scenario assumptions also better options for a complete switch to electrical propulsion over the long-term with a corresponding additional benefit in terms of CO_2 emissions' savings.

Although the situation for SAT was only outlined for Europe in this study due to data gaps for other world regions, it can be assumed that benefits for other regions are partially similar. While the U.S. is traditionally a country with a high share of low-distance air traffic similar conditions as in Europe might also be given in South America and Africa. Meanwhile, in Asia and Australia distances are partially larger and the population is unequally distributed with a higher concentration around the megacities. Thus, as also found for Europe, connectivity improvements of introducing additional SAT flights will strongly depend on the conditions in a specific region. However, further connectivity improvements through future SAT air traffic, as it was outlined in the scope of the DEPA 2050 scenarios and in the SAT forecast, can surely be assumed. On the one hand, there is additional demand potential even in densely populated regions as in Europe. On the other hand, the extension of flight distance for SAT aircraft, as it was described and assumed for the SAT forecast (cf. section 3.3), will also improve the vehicle productivity and the overall attractiveness of this type of air traffic.

5.2. Results on Emissions and Climate Impact

5.2.1. Methodology of Emission Inventories

Based on the individual aircraft performance characteristics per seat category and in relation to the DEPA 2050 scenarios the first step in the calculation of emissions and in preparation of the climate impact assessment for mainliner and regional aircraft (i.e. scheduled air traffic) was conducted with the run of DLR's emission inventory tool "4D-Race". The model is capable of delivering the exact place, time, amount and composition of emissions caused by air traffic in relation to given flight plans. Thus, based on the outcome of the modelling of future air traffic demand and the future fleet mix air traffic emission inventories could be generated for the conservative-evolutionary and for the progressive scenario in a first step. In a second step, the estimated ATM efficiency improvements as outlined in section 4.5 were embedded in form of correction factors as "4D-Race" typically operates with great circle distances and not with real flight routes. For this purpose, the estimates for horizontal flight efficiency improvements and for potential future changes in relation to probable additional flight times at loaded airports (cf. section 4.5) were added in a post-processing step with a separate tool developed for this use case. This allowed also to compare the emission inventory results with and without consideration of ATM improvements to assure the validation of the corresponding findings.

As a third step an additional "Do Nothing" scenario in the field of the emissions-related impact analysis was defined and calculated. The basic idea was to have a further base for comparison to the two DEPA 2050 scenarios assuming that no technological progress in aircraft technology is made from the year 2014 onwards. Finally, in a fourth step, the emission inventory calculations were extended by assuming a steadily increasing usage of SAF in the global fleet to show potential effects of the switch from conventional jet fuels to alternative fuels in the emissions and climate impact modelling dimension. The basic assumptions for this modelling approach are outlined in section 4.7.4. Due to the remaining uncertainty with regard to future SAF usage in aviation (i.e. availability, price development and market penetration rates) this analysis was similar to the ATM consideration also done as a post-processing step to the overall emissions assessment in order to be able to compare the results with and without SAF usage in form of a "what-if" study. With regard to the emission inventories the corresponding results for jet fuel consumption, CO_2 and NO_x are given in the next section. The results of the climate impact modelling in relation to the two DEPA 2050 scenarios and the "Do Nothing" scenario are presented in section 5.2.3. A short outlook on the potential CO_2 emissions of supersonic air transport in relation to the DEPA 2050 scenarios is finally concluding the overall emission analysis (cf. section 5.2.4).

5.2.2. Emission Inventory Results

Specifically important in regard of aviations' emissions and climate impact are CO_2 and NO_x emissions. Both depend on the overall fuel consumption which is also an important criterion to

analyse environmental effects of aviation. Based on the scenario calculations the results for the overall fuel consumption of the global fleet are outlined in the following.
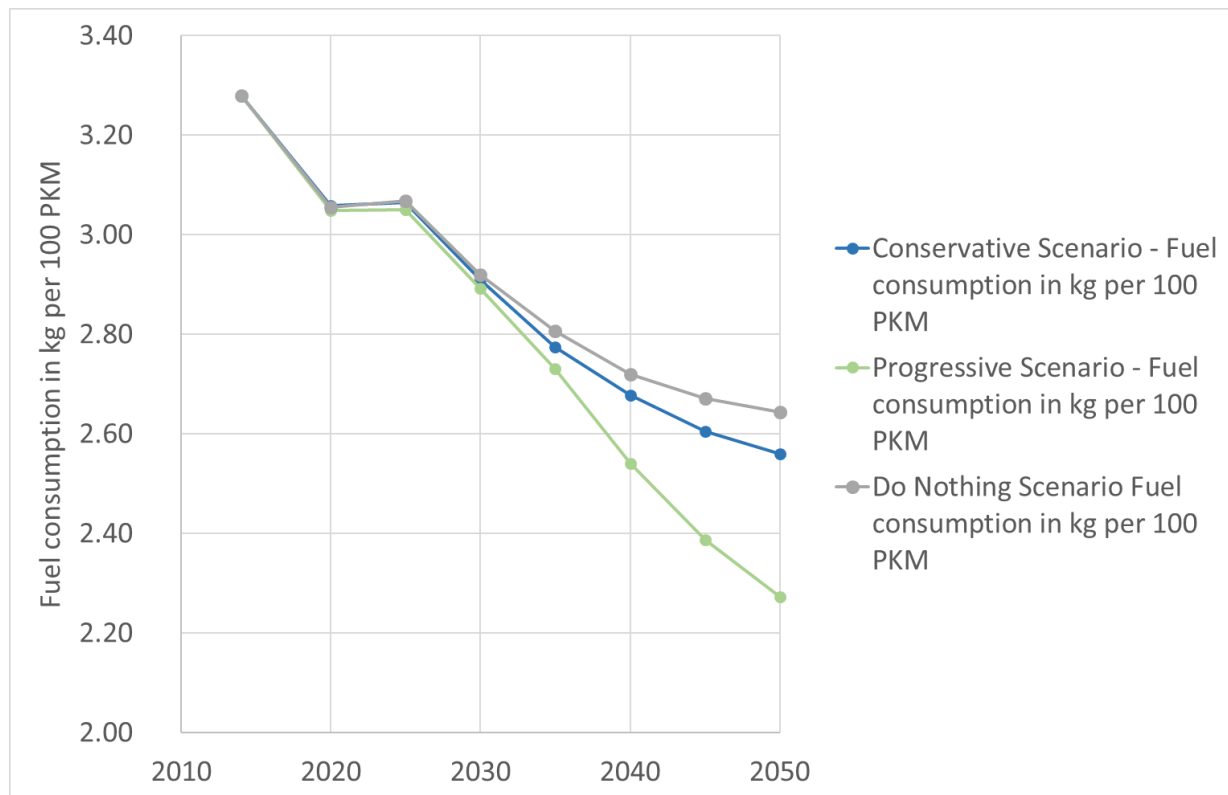
Figure 96: Future fuel consumption in kg per 100 PKM in the DEPA 2050 scenarios

The consumption of fossil fuels (in kg) per 100 PKM is decreasing significantly in the DEPA 2050 scenarios. Especially for the progressive scenario a decrease of 31% can be expected up to 2050 due to improved aircraft technology in all seat categories and due to improved ATM processes. The improvement in the conservative-evolutionary scenario is lower due to less advanced aircraft technology in this scenario. Thus, from an environmental point of view a clear preference should be given to aircraft technology development as illustrated in the progressive scenario.

Further improvements can be reached through the introduction of SAF. Compliant with the storylines of the DEPA 2050 scenarios different market penetration rates were assumed in this respect for the progressive and the conservative-evolutionary development pathway. For both scenarios SAF usage in the global fleet starts in the year 2025. Thus, by 2030 the share of SAF insertion in the progressive scenario will already reach a level of 15% in terms of total fuel consumption while in the conservative-evolutionary scenario the share is assumed to be at a level of 10%. Up to the year 2050 the SAF admixture degree is assumed to increase up to 80% in the progressive scenario and up to 40% in the conservative-evolutionary scenario respectively. With regard to the SAF calculations a life cycle estimation for the CO_2 impact of SAF was considered[311] while for the fossil fuels only CO_2 emissions from fuel burn were analysed. This has to be

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[311] 80% of the CO_2 emissions from SAF were regarded as climate-neutral.

considered with regard to the corresponding assessment results. The following figures provide on base of the outlined modelling approach an overview of the increasing SAF usage in both DEPA 2050 scenarios according to the described assumptions. For the "Do Nothing" scenario SAF usage was not considered.
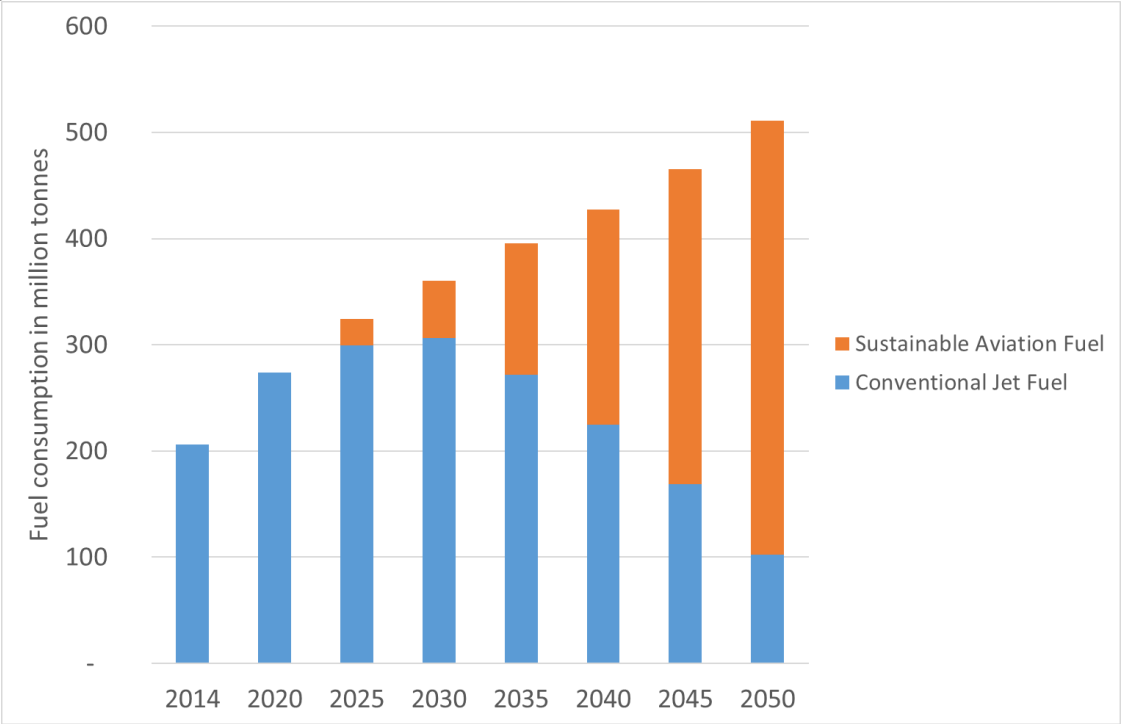
Figure 97: Future fuel consumption and fuel mix in the progressive scenario including SAF share
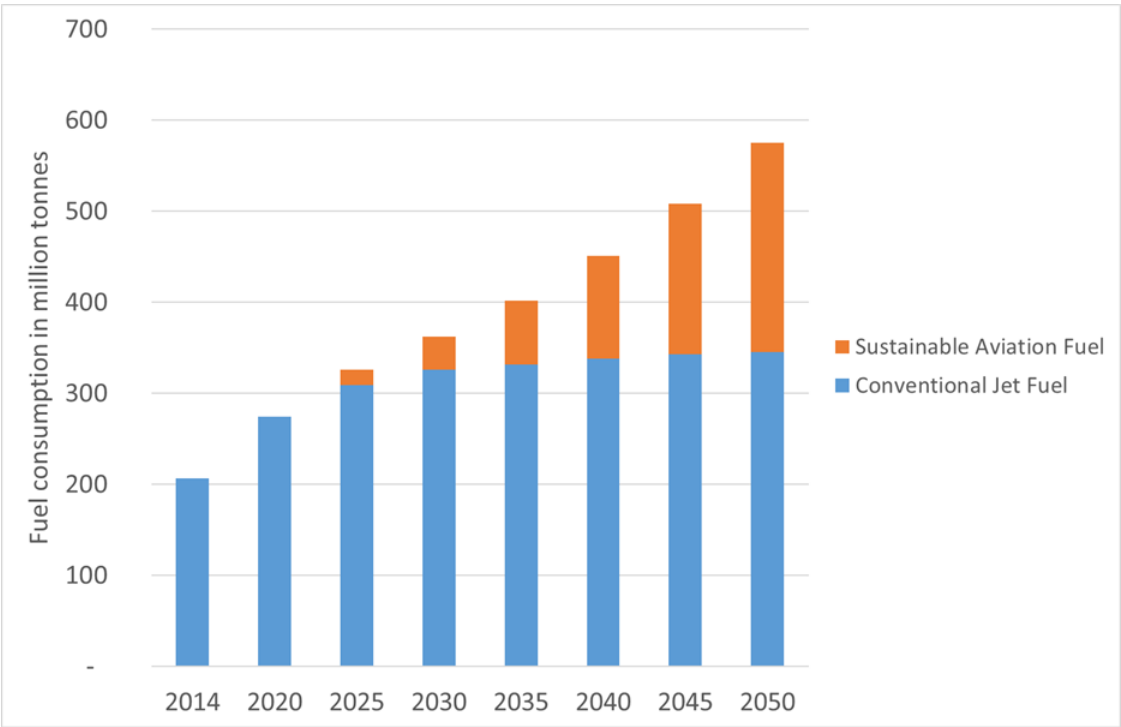
Figure 98: Future fuel consumption and fuel mix in the conservative scenario including SAF share
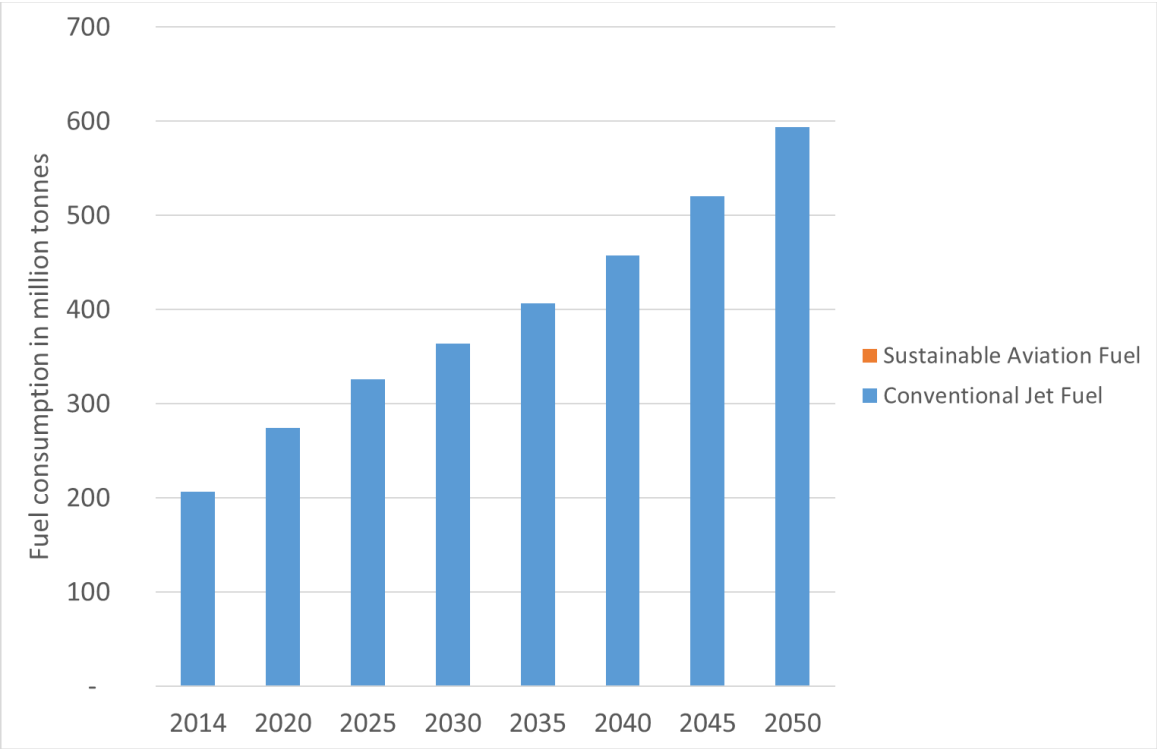
Figure 99: Future fuel consumption and fuel mix in the "Do Nothing" scenario without SAF

Based on the fuel consumption calculations the emission inventories delivered results for the development of the overall CO_2 emissions from 2014 to 2050 as presented in the following figure. The post-integration of SAF is illustrated in form of the dashed lines (blue and green).
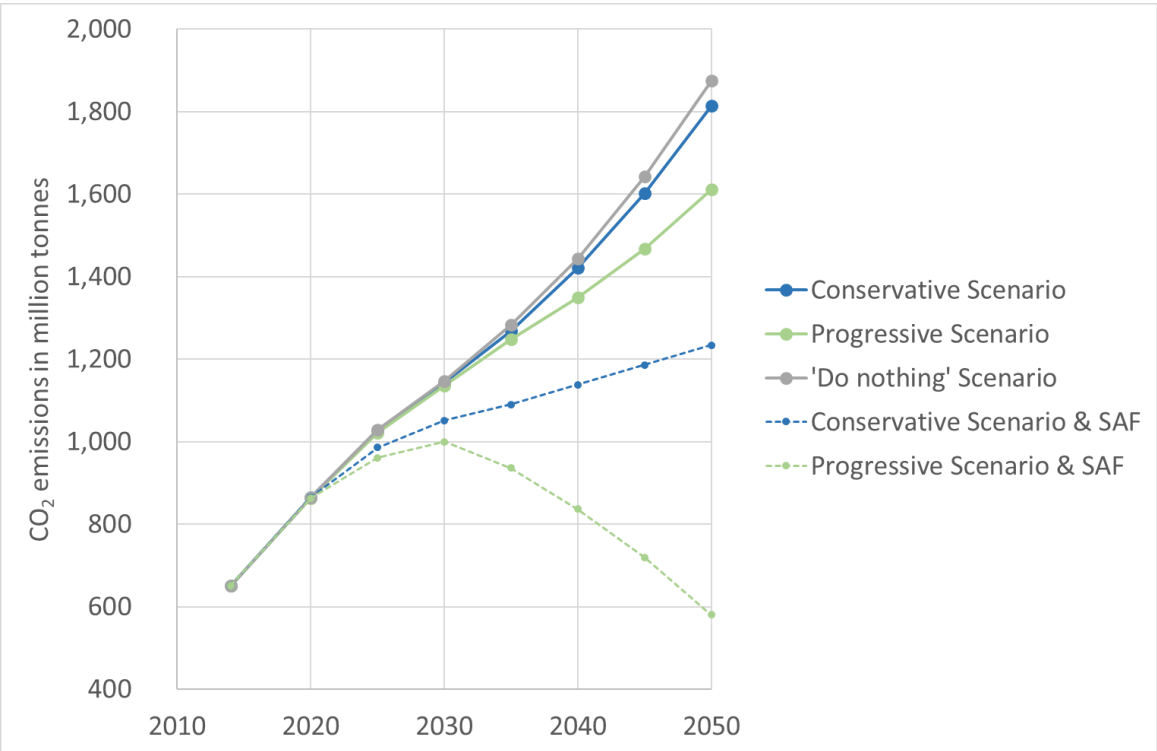
Figure 100: Development of CO_2 emissions in the DEPA 2050 scenarios (with and without inclusion of SAF)

In general, the consideration of the DEPA 2050 concept aircraft and ATM efficiency improvements without the calculations for SAF shows an increase of the overall CO_2 emissions in all of the three scenarios which is caused by more or less a doubling of air traffic demand between 2014 and 2050. As a result, the CO_2 emissions in the "Do Nothing" scenario will reach a level of nearly 1,871 million tonnes in 2050 compared to 651 million tonnes in 2014. For the conservative-evolutionary scenario approximately 1,812 million tonnes of CO_2 emissions are probable for 2050. Again, the progressive scenario shows the most preferable development with 1,609 million tonnes of CO_2 emissions in 2050.

If SAF is considered additionally under the given assumptions as outlined above, the CO_2 emissions reduction potential increases. However, in terms of total CO_2 emissions also the integration of SAF in the conservative-evolutionary scenario has not the effect to stabilise them on a constant level nor to decouple it from the predicted air traffic growth. This is only possible in the progressive scenario in which the peak of CO_2 emissions is reached in 2030. Afterwards, the trend develops vice versa and in the year 2050 the overall CO_2 emissions reach indeed a level below the value of 651 million tonnes as in 2014. Despite of the successful reduction rate of CO_2 emissions based on improved aircraft technology, increasing ATM efficiency and extended usage of SAF in the global fleet, the results have to be interpreted very carefully. As pointed out before, uncertainty factors remain to date in the field of SAF usage in relation to final prices. Thus, the assumed SAF usage rates are quite ambitious. For instance, in order to reach an admixture rate of 10% SAF as it is assumed in the conservative-evolutionary scenario for the year 2030 as most conservative estimation in the given scenario set production capacities for 34 million tonnes of SAF would be needed. From a technical point of view this supply might be delivered partially even by a single country to satisfy global jet fuel demand,[312] but the concrete way forward is not clear yet considering also geopolitical issues. Even more, it is a question of final prices. Anyhow, the outcome of the emission inventories within the scope of the DEPA 2050 study shows clearly the need for further action to influence the course of aviation towards a climate-neutral development as important objective of the major aviation stakeholders (e.g. ICAO and IATA). Without a mixture of improved aviation technologies, operational improvements and a mixture of energy sources for aviation (especially with higher usage rates of SAF and hydrogen) this will surely not be possible.

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[312] Cf. Falter et al. (2020).
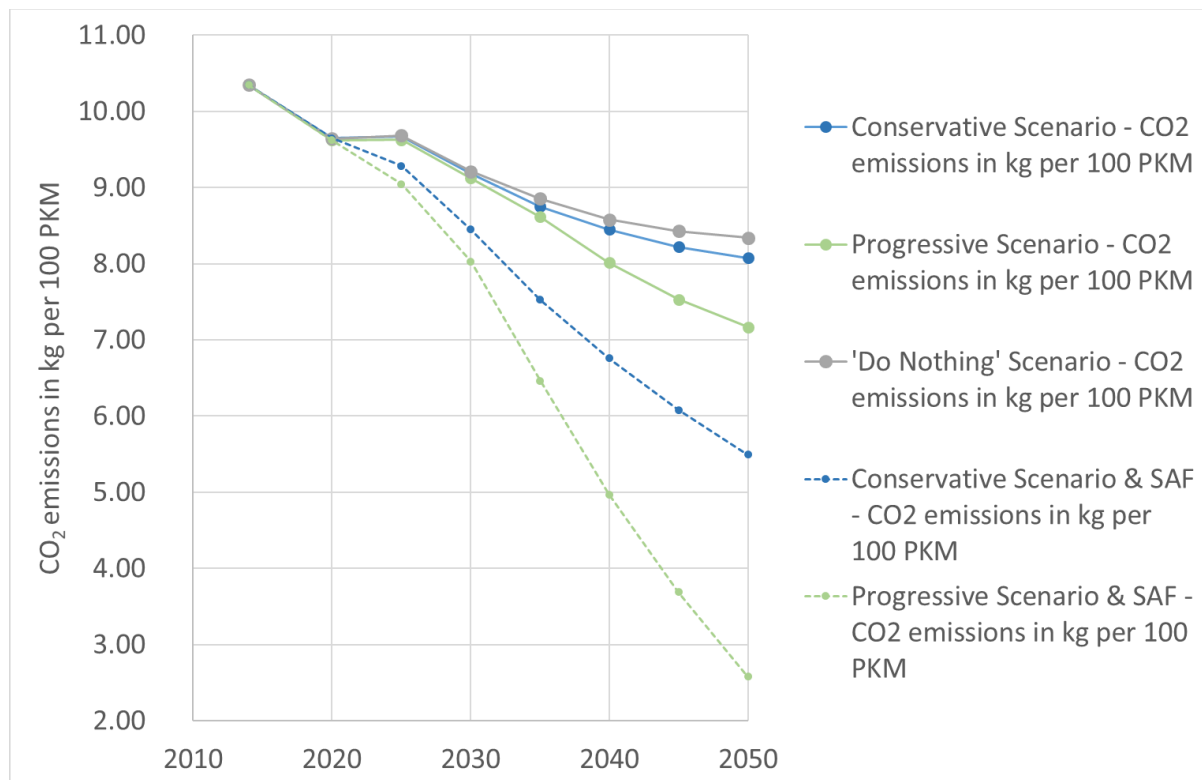
Figure 101: Development of CO_2 emissions in kg per 100 PKM in the DEPA 2050 scenarios (with and without inclusion of SAF)

The added value of the usage of SAF becomes also visible when the relative development of CO_2 emissions is regarded in relation to the air traffic development. However, the advanced aircraft technologies and the assumed improvements in ATM efficiency show also stand-alone positive effects. For instance, within the conservative-evolutionary scenario the CO_2 emissions (in kg) per 100 PKM will be reduced by 22% and the progressive scenario shows a decrease of nearly 31% from 10.35 kg CO_2 emissions per 100 PKM in 2014 to 7.17 kg CO_2 emissions per 100 PKM in 2050.

If SAF usage is considered additionally, the CO_2 emissions per 100 PKM shrink in the conservative-evolutionary scenario from 10.35 kg in 2014 to 5.49 kg in 2050 and with regard to the progressive scenario to 2.58 kg in 2050. For the conservative-evolutionary scenario this equals a reduction of approximately 47% of the 2014 value and for the progressive scenario a reduction rate of 75% is the final outcome. Again, SAF usage besides aircraft technology and operational improvements is a major factor to decouple air traffic growth from the CO_2 emissions development.

For NO_x emissions the emission inventories delivered also some interesting findings on the future development. The overall development of the NO_x emissions in the DEPA 2050 scenarios is outlined in the following figure.

Again, the progressive and the conservative-evolutionary scenario results were used to put them into comparison to a "Do Nothing" base case.[313]
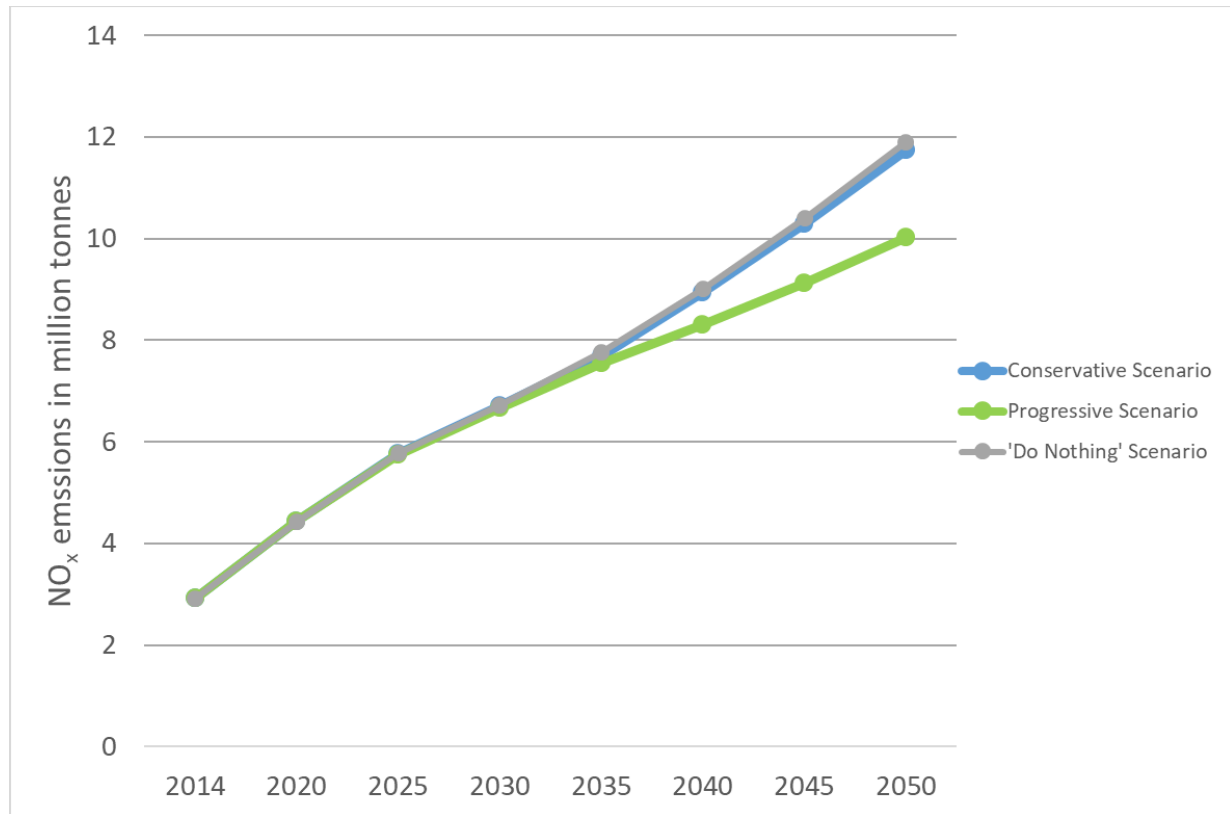
Figure 102: Development of NO_x emissions in the DEPA 2050 scenarios

From 2014 to 2050 the NO_x emissions increase in total from 2.9 million tonnes to around 11.8 million tonnes in the conservative-evolutionary scenario and to around 10 million tonnes in the progressive scenario. Thus, in the progressive scenario the NO_x increase is around 59% lower than in the conservative-evolutionary scenario and around 64% lower than in the "Do Nothing" scenario which shows a total growth of NO_x emissions up to 11.9 million tonnes for the year 2050. Despite of these differences all of the three development pathways indicate corresponding to the development of the absolute CO_2 emissions also an overall growth of NO_x emissions. Thus, independent from improved aircraft technology and expected changes in the ATM efficiency a decoupling from the predicted air transport growth is accordingly also not possible for NO_x emissions in the conservative-evolutionary scenario and in the progressive scenario.

If the relative NO_x emissions are regarded the picture changes to same extent.

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[313] SAF usage was not considered in the following analysis as only some types of SAF lead to smaller reductions of the overall NO_x emissions but the effect is not completely investigated yet (cf. Braun-Unkhoff et al. (2017)).
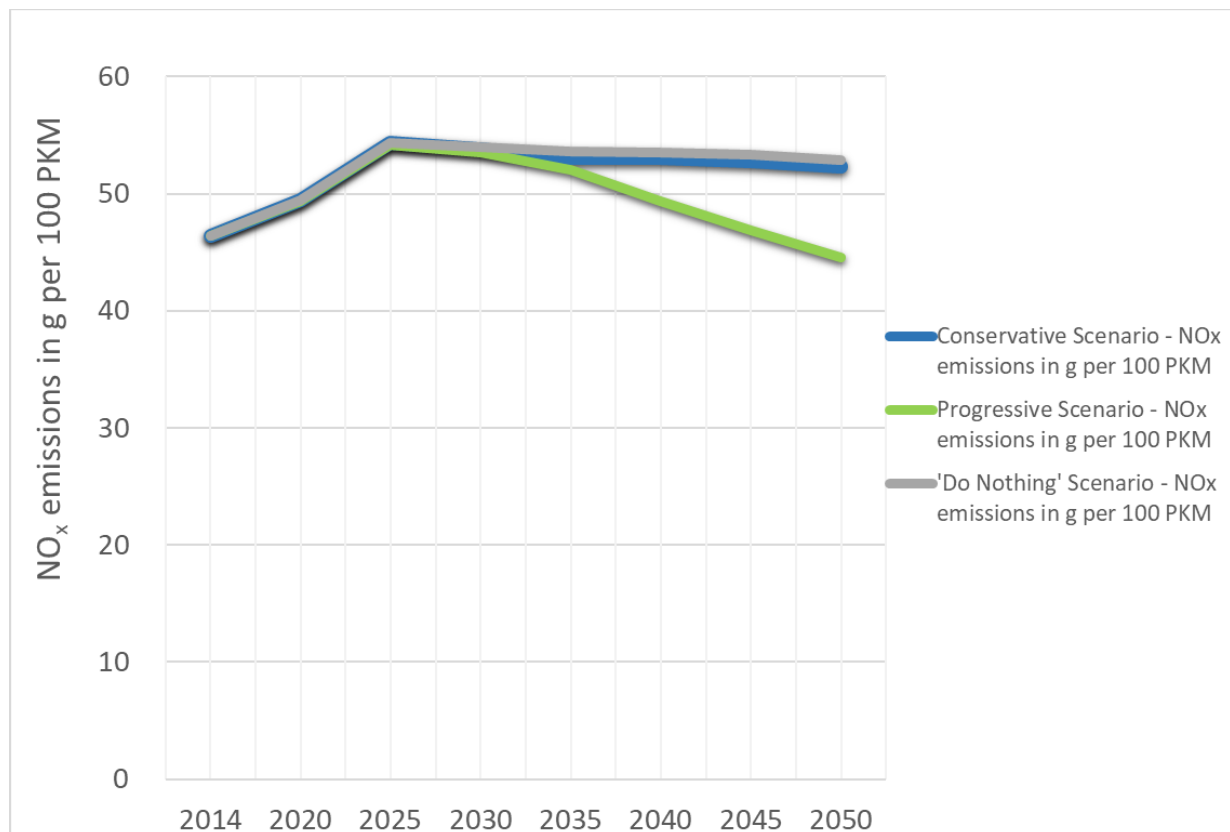
Figure 103: Development of NO$_x$ emissions in gram per 100 PKM in the DEPA 2050 scenarios

Corresponding to the predicted fuel efficiency improvements as an outcome of improved aviation technology and changes in the horizontal flight efficiency the NO$_x$ emissions per 100 PKM fell in the progressive scenario from 46.4 gram to 44.6 gram between 2014 and 2050. From the year 2045 onwards, the increasing traffic performance reflected in the significant growth of passenger kilometers is to some extent overcompensating the absolute growth in NO$_x$ emissions. However, this effect is not observable for the conservative-evolutionary scenario and the "Do Nothing" scenario. In both scenarios absolute NO$_x$ emissions were predicted to be higher in 2050 with 11.8 and 11.9 million tonnes respectively. This leads to nearly identical courses of the blue and grey curves in the diagram above and a nearly identical development of the relative NO$_x$ emissions following the absolute ones.

Taking into account the outcomes of these emission inventory results, the corresponding effects on climate impact are discussed in the following section.

5.2.3. Outcome on Climate Impact

5.2.3.1.   Climate Impact of Aviation

For assessing aviation's climate impact, it is important to consider beside CO$_2$ also non-CO$_2$ effects. CO$_2$ and the various non-CO$_2$ climate species contribute in very different ways to the

climate impact of aviation. An overview of these different effects was published in Dahlmann et al., 2020a as part of a UBA project. Here we give a short summary of that overview: The greenhouse gases carbon dioxide (CO_2) and water vapour (H_2O) have a direct impact on the radiative balance of the atmosphere. Nitrogen oxide (NO_x) influence the atmosphere only indirectly by increasing ozone (O_3) production and methane (CH_4) destruction. Aerosol emission indirectly influence the atmosphere by forming particles and influencing contrails characteristics.

In addition to the different ways of influencing the atmosphere, also the lifetimes vary widely: while CO_2 emissions partly remain in the atmosphere for several thousand years contrails only remain for a few hours. The lifetime of water vapour lies between hours at the ground and months and years in the stratosphere. The lifetime of ozone perturbations due to NO_x emissions is in the order of weeks while the CH_4 perturbation caused by these NO_x emissions has a lifetime of about 12 years. The decline of the methane concentration leads to a decrease in ozone concentration, since methane is also a precursor for ozone, with a lifetime equal to the methane lifetime.

Contrails and contrail cirrus (contrail induced cloudiness, CiC) form when the hot and humid exhaust gets saturated during the mixing with the dry and cold air in the environment. The lifetime of these contrails depends on atmospheric conditions and is between minutes and hours. Aerosols have a direct effect on radiation trough absorption and scattering as well as an indirect radiation effect through influencing clouds with a lifetime of days to weeks.

The climate impact of a species depends, beside the amount of emissions, also on other factors like atmospheric lifetime or background conditions (e.g. temperature, humidity). For example, the impact of H_2O strongly increases with increasing emission altitude as a lack of degradation mechanism (chemistry) and rain out in the stratosphere result in clearly longer lifetimes than in the lower troposphere. The formation of contrails and CiC, significantly depend on the surrounding temperature and humidity. Particularly the conditions near the tropopause where it is cold and not too dry are favorable for contrail formation. The impact of CH_4 is less dependent from the emission location due to the relatively long CH_4 lifetimes.

Between radiative forcing (RF) and global near surface temperature change a linear relation exist via the climate sensitivity parameter λ. This climate sensitivity parameter depends on feedback mechanism which differ in-between climate agents. The relation between λ of a climate agent and the λ of CO_2 is called efficacy. If this efficacy is larger than 1, e.g. for aviation induced O_3, the same value of RF leads to larger temperature changes when it results from O_3 than for CO_2. For CiC this efficacy is significantly lower than 1, which was recently confirmed by Bickel et al. (2020). Recently Lee et al. (2020) published an updated assessment report about the climate impact of aviation. In comparison to the previous assessment from Lee et al. (2009) they provide now additionally to radiative forcing also effective radiative forcing (ERF). ERF accounts for the different efficacies and is therefore a better indicator for temperature change as RF.

Lee et al. (2020) gives an RF of CO_2 emissions until 2018 of about 34 mW/m². The net RF of NO_x emissions is about 8 mW/m², as the warming effect of ozone increase (36.0 mW/m²) is partly compensated by the cooling effect of decreasing methane concentration (-18 mW/m²),

decreasing longtime ozone concentration (-9 m W/m^2) and stratospheric water vapour decrease (-3 mW/m^2). The warming effect of CiC was given as 111 W/m^2 in Lee et al. (2020), which is two time more than the value given in Burkhard and Kärcher (2011) for the year 2002. The warming effect of H$_2$O and the direct effect of soot are relatively small with 2.0 and 0.9 mW/m^2. The direct effect of sulfur aerosols is negative with -7.4 mW/m^2. For the indirect aerosol effect on clouds large uncertainties exit. First sensitivity analyses (e.g. Righi et al (2016)) indicate negative RF, but no best estimate is given by Lee et al. (2020).

5.2.3.2.   Results from DLR Project Eco2Fly

Eco2Fly is a DLR project which started in 2019 focusing on eco-efficient aviation. This project already achieved scientific results, which are also relevant for DEPA 2050.

The indirect aerosol effects on clouds has large uncertainties and Lee et al. (2020) does not give a best estimate for this effect. In Grewe et al. (2017) already results were presented for the indirect aerosol effects on warm clouds. The RF is between –69.5 and +2.4 mW/m2 in the year 2000, depending mainly on the assumed size distribution of emitted particles (Grewe et al., 2017). In Eco2Fly Righi et al., (2020) implemented a new cloud microphysical scheme including a detailed parameterization for aerosol-driven ice formation in cirrus clouds in the global ECHAM/MESSy Atmospheric Chemistry (EMAC) model to additionally analyse the indirect aerosol effect on ice clouds. It shows that this effect leads to cooling of the atmosphere. Nevertheless, large but unquantified uncertainties exist for this effect. Therefore, this effect is not yet addressed in DEPA 2050.

Grewe et al. (2019) published an updated calculation method of NO$_x$ climate impact of aviation. The inclusion of two additional physical processes of the NO$_x$ photo-chemistry and an updated radiation calculation for NO$_x$-induced perturbations of atmospheric background CH$_4$ concentrations in previous publications lead to the impression that NO$_x$ impact is very small. Nevertheless, two further published methodological shortcomings have not been fully considered in earlier studies which leads to a considerable underestimation of the contribution of aviation's NO$_x$ emissions to climate change as explained in Grewe et al. (2019). First, for methane concentration change calculations implicitly assume steady-state instead of an adequate transient development. Second, most studies use in order to calculate ozone changes the so-called perturbation method, where the O$_3$ response results from switching off or reducing aviation NO$_x$ emissions, instead of calculating aviation contributions to the ozone. Such methodological simplifications largely underestimate the contribution of the aviation NO$_x$ emissions to climate change. Note that the contribution of an emission to climate change and the climate impact of a mitigation option require different calculation methods.

DEPA 2050 concentrated more on the technological pathway of aviation with a focus on longtime impact. Therefore, here we used AirClim for climate assessment of our DEPA inventories and scenarios as it accounts for climatological climate impact. Operational measures comprising

weather optimised flight trajectories or flying in formation could provide additional mitigation options, which are not accounted for in DEPA 2050. Grewe et al. (2017) showed that climate optimised flight planning can reduce the climate impact by about 15% with only little increase in direct operating costs. Another operational measure with promising mitigation potential is flying in formation. Recent studies by Dahlmann et al. (2020b) and Marks et al. (2020) showed that flying in formation reduces both the fuel consumption by 5% and the climate impact by about 20% when comparing to two independent flights. This concept is also now as wake-energy retrieval. Note, that the mitigation potential that is evaluated there, only applies for those flights that have a potential for formation flight and not for the whole air traffic. For the analysis with global flights about 20% of all analysed flights could be performed as formation flight. That means globally about 4% climate mitigation would be possible.

5.2.3.3.   Methodology

In DEPA 2050 the non-linear climate response model AirClim was used to calculate the development in temperature change caused by the different emission pathways. AirClim combines precalculated atmospheric impact data with spatially resolved air traffic emission data to calculate e.g. aviation climate impact for a multitude of emission inventories (Grewe and Stenke, 2008; Dahlmann et al., 2016). For the precalculated data, climate-chemistry simulations for different idealized emission regions were performed, employing normalised emissions of nitrogen oxides and water vapour to obtain the chemical response. The results of these detailed simulations constitute the precalculated atmospheric input data for AirClim. AirClim combines these precalculated, altitude and latitude dependent responses with 3-dimensional emission data in order to calculate atmospheric composition changes, radiative forcing and near surface temperature changes caused by these emissions.

AirClim is applicable to evaluate numerous air traffic scenarios, including different routings and technological options. AirClim was used for climate assessment of different aircraft technologies and operations (e.g. Grewe et al., 2010; Grewe et al., 2016; Dahlmann et al., 2016; Hepting et al., 2020; Dahlmann et al., 2020). It includes the climate impacts of the climate agents CO_2, H_2O, CH_4 and O_3 (latter two are aviation indirect impacts resulting from photochemical transformation of NO_x-emissions) and contrail cirrus (contrail induced cloudiness, CiC). The climate impacts of direct and indirect aerosol effects are not considered here, as the uncertainties are considerably large (Righi et al., 2020; Lee et al., 2020).

Using SAF influences the climate on two different ways. As SAF is produced from renewable resources a large part of the CO_2 emissions can be assumed as climate neutral. In DEPA 2050 we assumed that 80% of the CO_2 emissions are climate neutral. Using SAF instead of conventional kerosene has additionally an impact on the optical properties of CiC. From simulations of Burkhardt et al. (2018) we received a functional dependency between the change in radiative forcing and the reduction of particulate matter (PM) (cf. the following figure). Reducing the

number of aerosol particle emissions leads to reduced radiative forcing. Note, this is only valued for reductions less than 90% (i.e. PM of 0.1). As for larger reductions the ambient aerosols become important the radiative forcing is reduced by a maximum of 70%.
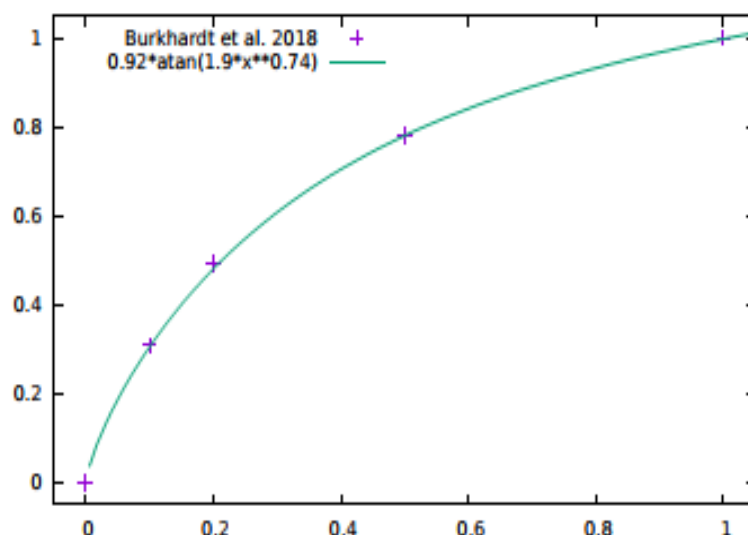
Figure 104: Functional dependency of relative change in radiative forcing (RF) from CiC on the relative change in the number of PM emission

For the DEPA 2050 scenarios we assumed that no SAF is used in the "Do Nothing" scenario. As outlined above, we assumed for the conservative-evolutionary scenario that the fraction of SAF increases from zero in the year 2020 to 10% in 2030 and 40% in 2050. For the progressive scenario we assumed a blend of 15% in 2030 and 80% in 2050. The fraction of SAF is assumed constant after 2050.

When calculating temperature changes within the AirClim model emission pathways and background concentrations are considered. For analysing the climate impact of DEPA 2050 scenarios we assumed historical emissions before 2020 and constant emissions after 2050. The climate impact of CO_2 and CH_4 is also dependent on the background concentration of these greenhouse gases. Increased CO_2 background leads to smaller impact of CO_2 emissions due to saturation effects. In contrast a larger CH_4 concentration leads to larger impact of CH_4 as the lifetime change impacts a larger amount of CH_4. In DEPA 2050 we applied RCP2.6 for defining the background concentrations, which assumes a strong mitigation scenario (Meinshausen et al., 2011).

5.2.3.4. Results

The climate impact in terms of near surface temperature change in the year 2100 ($\Delta T(2100)$) for the "Do Nothing" scenario is about 156 mK and increases up to 176 mK in the year 2120 (Figure

107). In the year 2100 CO_2 contributes to 43% to the climate impact, NO_x to 34%, CiC to 21% and H_2O only to 2%.

The change in $\Delta T(2100)$ of the conservative-evolutionary scenario compared to the "Do Nothing" scenario is shown in Figure 108a for the total impact and the individual species. In Figure 108b the individual changes relative to the total impacts are presented, to show which species contribute most to the total change in temperature. In total the temperature change is reduced by about 11%, although the fuel consumption and the flown distances are quite similar. The climate impact of CO_2 is reduced by 23% and the climate impact of CiC by 6% due to the 40% replacement of kerosene with SAF, which influence radiative properties of CiC and reduces the impact of CO_2 as we assumed 80% of the used SAF CO_2 as climate neutral. The change in $\Delta T(2100)$ of 11% is mainly caused by CO_2 (10%) and to a lower degree by CiC (1%). The climate impact of NO_x is slightly increased due to increased NO_x emissions in the conservative-evolutionary scenario, but this has only a very small impact on the total temperature change.
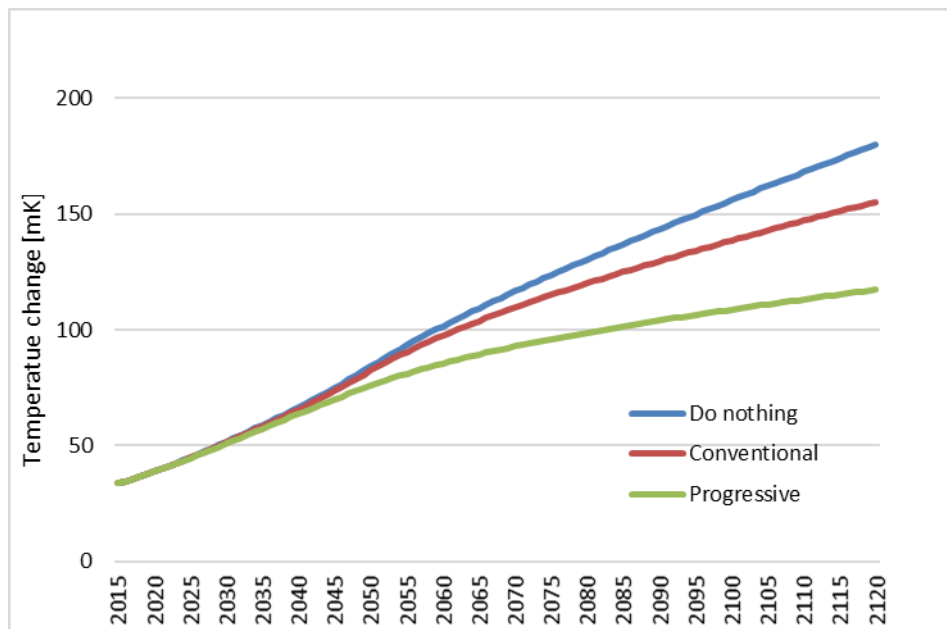
Figure 105: Temporal development of temperature change for the three different scenarios 'Do Nothing' (blue), 'conservative-evolutionary' (conventional, red) and 'progressive scenario' (green)

The $\Delta T(2100)$ for the progressive scenario is about 30% lower than for the "Do Nothing" scenario. The impact of CO_2 is reduced by 45% due to emission reduction of 11% and 80% replacement of kerosene by SAF. The usage of SAF also reduces the impact of CiC by 22%. The reduced NO_x emission of 17% causes a 15% change in NO_x induced climate impact. The reduced fuel consumption of 11% and a slightly lower flight altitude reduces the impact of H_2O by 13%. The largest contributions to the 30% reduction in $\Delta T(2100)$ are from reduction of impacts of CO_2 (19%), CiC (5%) and NO_x (6%).

a)

b)

Figure 106: Relative differences of ΔT(2100) of the conservative-evolutionary and progressive scenarios in comparison to the 'Do Nothing' scenario for the total impact and for the different climate species (a) and individual changes relative to the total impacts (b)

Although aviation emissions are assumed to be constant after 2050, temperature change further increases for all analysed scenarios (Figure 105), as the CO_2 emissions accumulate in the atmosphere due to the long lifetime of CO_2. That means that even for constant emissions the climate impact of aviation would increase over the next decades without further mitigation measures.

5.2.4. Estimation of CO_2 Emissions of Supersonic Air Transport

Since no concrete performance data with regard to fuel consumption are yet available for supersonics, currently only rough estimates for probable emissions for these vehicle types can be made. Based on the assumption that supersonics will probably have 3-4 times higher fuel consumption than conventional subsonic aircraft and with the knowledge that current subsonic aircraft have an average fuel consumption of 3.4 liters per passenger kilometer[314] as well as 3.16 kilogrammes of CO_2 per kilogramme of burned fuel are emitted,[315] rough estimates can be given. Thus, in the conservative-evolutionary scenario in 2030 all 25,149 flights would emit around 2.7 megatons of CO_2 in total. In the progressive scenario, in the same year 75,615 flights would result in around 9.9 megatons of CO_2 emissions. The comparison with the total CO_2 emissions of mainliner and regional aircraft in 2030 shows that the CO_2 emissions from the progressive supersonic scenario are not insignificant, but would represent only a small share of global aviation emissions.

However, it is well established[316] that the climate impact from supersonic aviation is predominantly arising from the high-altitude water vapour emissions. While for subsonic aviation the total climate impact is roughly 3 times that of the mere CO_2 climate impact, the respective factor for supersonic transport might be as large as 10 for cruise altitudes of around 17 to 20 km. And the enhancement of the climate impact when flying supersonic with respect to a subsonic fleet with the same transport volume is around 3 times for cruise altitudes of 15 to 16 km and rises to 14 times at around 17-20 km.[317]

5.3. Results on Aircraft Noise

Concerning the aircraft noise prediction it should be noted, that the corresponding studies conducted in preparation of this report concentrated primarily on the modelling and prediction of engine noise with a special focus on novel configurations, such as BLI propulsors, for example. Although the engine is an important source of aircraft noise compared to other sources (e.g. landing gear, flaps, slats, fuselage, etc) other sources may dominate the overall noise at certain flight stages. This depends strongly on the operating point (e.g. take-off/sideline or approach). The description of these other mentioned sources, as well as the propagation of the totality of all sources, e.g. to create a noise carpet, goes beyond the scope of research that could be covered in the DEPA 2050 project. Therefore, the following conclusions refer to engine noise exclusively. However, the findings as illustrated in section 5.3.1 to 5.3.3 served as important starting point to identify future potentials for the overall aircraft noise reduction in relation to the DEPA 2050 scenarios. Section 5.3.4 was additionally added to present the latest status on noise assessments

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[314] EASA (2019).
[315] Cf. ICAO (2019).
[316] Cf. IPCC (1999); Grewe et al. (2007,2010).
[317] Cf. Grewe et al. (2010).

and to propose a set-up for a more holistic future noise study that can use the presented findings as base case for running extended noise impact assessments.

5.3.1. Preliminary Analytical Investigation of Rotor-Stator Interaction (RSI) Noise for a Distributed Propulsion System

In a first study a continuous increase of the propulsor number for an engine meeting the thrust requirements of an A320-sized aircraft was investigated. The fan pressure ratio was assumed to be 1.3. Note that no assumptions concerning the detailed placement of the propulsors were made. In addition, it was assumed that all noise sources are uncorrelated, i.e. the noise prediction for one propulsor can be multiplied by the total number of propulsors to obtain the overall noise. In a first study the rotor-stator interaction (RSI) noise was investigated. The noise mechanism of this source is shown in Figure 108: due to the wall friction the rotor blades cause wakes mainly characterized by a mean velocity deficit. In addition, turbulence is also carried in this kind of shear flow. Therefore, the interaction of the turbulent wakes with the stator vanes leading edges downstream of the rotor established a tonal and broadband interaction noise source. For a subsonic rotor this interaction noise source is usually dominating other engine noise sources, such as self-noise. Therefore, this source is a reasonable representative engine noise source for the investigation of a distributed propulsion system.
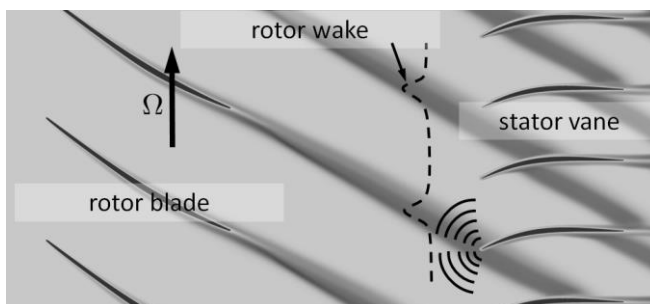
Figure 108: RSI noise mechanism.

Figure 107 shows results of the sound power level (PWL) for the tonal RSI noise at 1st to 5th blade passing frequency (BPF). First, it can be seen that the PWL is proportional to the considered operating point (PWL Sideline > PWL Cut-Back > PWL Approach). In addition, the PWL is decreasing from 1st to 5th BPF. For approach (AP) operating conditions the 1st BPF is suppressed by the cut-off design for the considered RSI noise source. This effect results from the modal composition of the sound field constituted by the described RSI noise mechanism. An increase of the propulsor number yields a
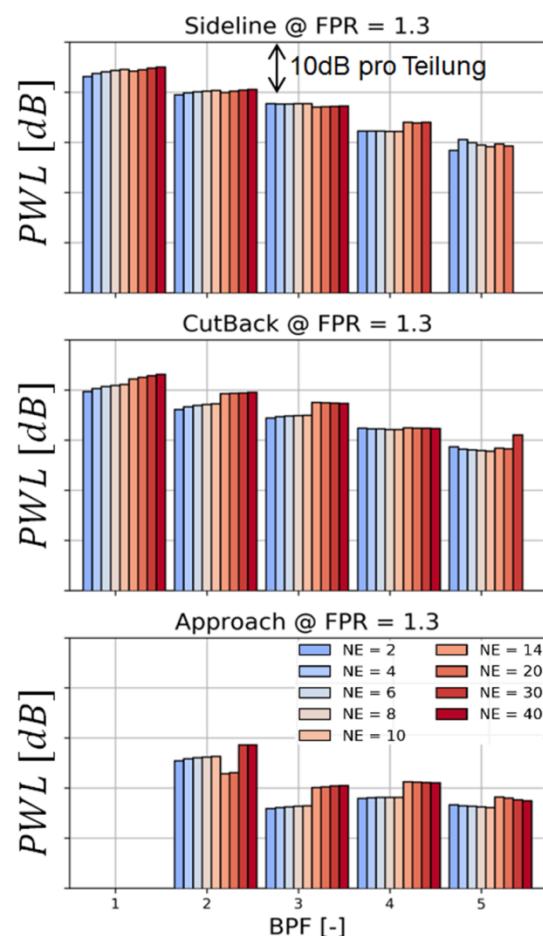
Figure 107: Tonal RSI noise predictions for different numbers of propulsors.

continuously but slightly increase of the PWL at every BPF. This effect can be associated with the increasing Reynolds number and results from the sharper forming of the rotor wakes, for smaller propulsors which better excite the tonal RSI noise.

To validate the preliminary analytical findings, Reynolds averaged Navier-Stokes (RANS) simulations have been performed. For the computational fluid dynamics (CFD) study DLR's in-house flow solver "TRACE" has been used. The investigated geometry is the ASPIRE-Design of DLR and Airbus. This ultra-high bypass ratio (UHBR) engine is shown in Figure 109. The mentioned design features a bypass ratio (BPR) of 16 and is representative for a next generation turbofan engine (usable in aircraft seat categories 8 to 13 as regarded in DEPA 2050). The fan stage has 16 rotor blades and 36 stator vanes. A cut-off design for the first BPF is achieved for all operating points. The fan pressure ratio (FPR) of the fan stage is 1.3. For the CFD study a structured mesh was generated with the DLR meshing tool "PyMesh". The new designed mesh ensures an adequate resolution of the rotor wake region, which is an important requirement for reasonable CFD-informed RSI noise predictions. An example for the used mesh topology and mesh resolution is shown in Figure 110. The used turbulence model is the isotropic Menter-SST-k-ω model. Due to the azimuthal symmetry of the computational domain, only one rotor and one stator passage was needed to be computed. This was realized by the use of a periodic boundary condition in circumferential direction and results in a significant reduction of computational time and cost. Required boundary conditions for the computation are the total pressure and temperature at the inlet (upstream), the static pressure or alternatively the mass flow at the outlet (downstream) and the fan rotational speed for the investigated operating point. Note that all walls, as well as the rotor blades and stator vanes, are modelled as viscid walls. Since the moving rotor block group, shown in Figure 110, is connected to the fixed stator block group by a so-called mixing plane, an extrapolation of the mean and turbulent quantities of the rotor wakes becomes necessary. This extraction of the rotor wakes at the mixing plane and its extrapolation to the stator vanes leading edges is also performed by DLR's in-house tool "PropNoise".
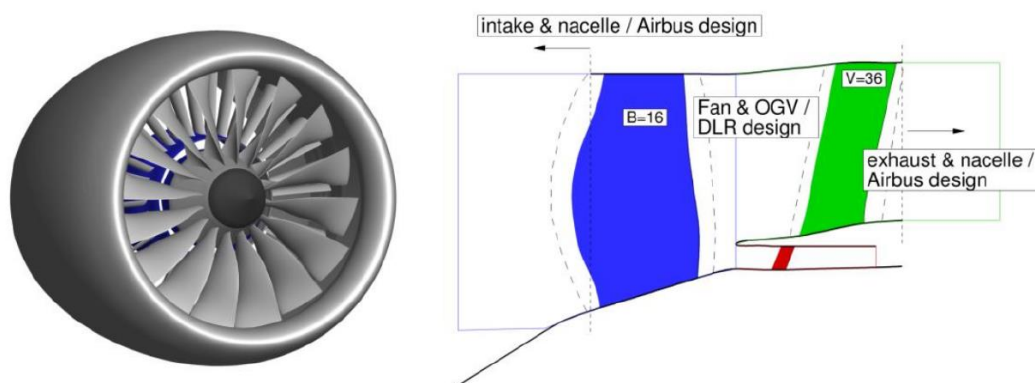
Figure 109: Aspire design used for the CFD study.
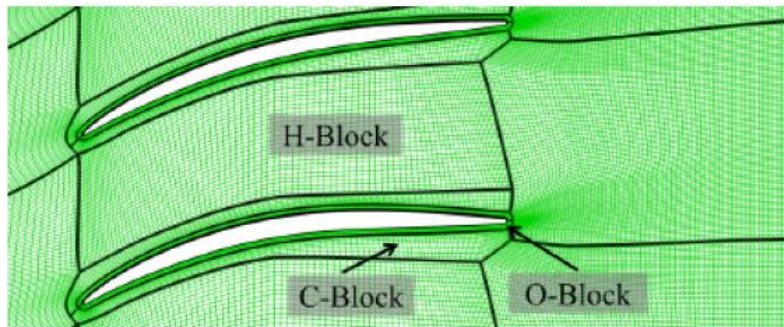
Figure 110: Example of mesh topology of rotor block group for the CFD study.

Figure 111 (left) compares analytical predictions for the ASPIRE design, similar to the study shown in Figure 107, with RANS-informed tonal RSI noise predictions (right) at sideline/take-off operating conditions. The analytical and RANS-informed PWL prediction shows a reasonable agreement with each other. For the 2nd to 3rd BPF the observed trend of an increasing PWL with the number of propulsors, as predicted by the preliminary studies for tonal RSI noise, is confirmed.
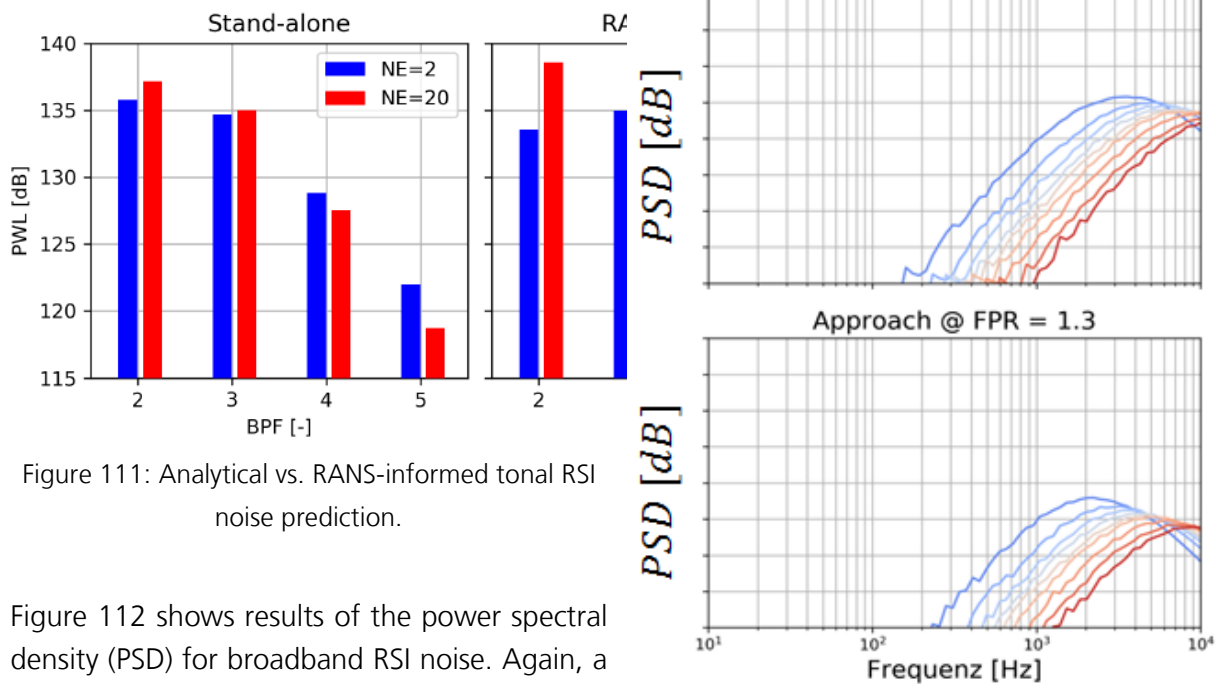
Figure 111: Analytical vs. RANS-informed tonal RSI noise prediction.

Figure 112 shows results of the power spectral density (PSD) for broadband RSI noise. Again, a distributed engine, fulfilling the thrust requirements of an A320, is assumed for this

Figure 112: Broadband RSI noise predictions for different numbers of propulsors.

preliminary design study. Again, the PSD is proportional to the considered operating point (PSD Sideline > PSD Cut-Back > PSD Approach). An increase of the number of propulsors is accompanied by an increase of the rotational speed of the fans. This in general results in a shift of the PSD spectrum towards higher frequencies for large numbers of propulsors. While the number of propulsors increases, the geometrical dimensions of the fan stage decreases. Beside the aforementioned sharper wakes, the size of turbulent structures within the rotor wakes is also decreasing. The reduction of this turbulent length scale also results in an additional shift of the PSD spectra towards higher frequencies but also in a reduction of the PSD amplitude. This amplitude reduction can be seen in Figure 112.

To validate the preliminary broadband RSI noise findings, Figure 113 compares predictions for the before discussed ASPIRE design. A comparison of amplitudes reveals a good agreement between the preliminary analytical prediction and the RANS-informed prediction. As before, the increase of fan rotational speed, accompanied by a reduction of turbulent length scale, leads to a shift of the PSD to higher frequencies with slightly reduced peak amplitude if the propulsor number is increased. This amplitude reduction cannot be reproduced by the RANS-informed broadband RSI noise prediction. The reason for this discrepancy is an increased turbulence intensity or turbulent kinetic energy (TKE) in the RANS-flow solution for an increase of propulsor number.
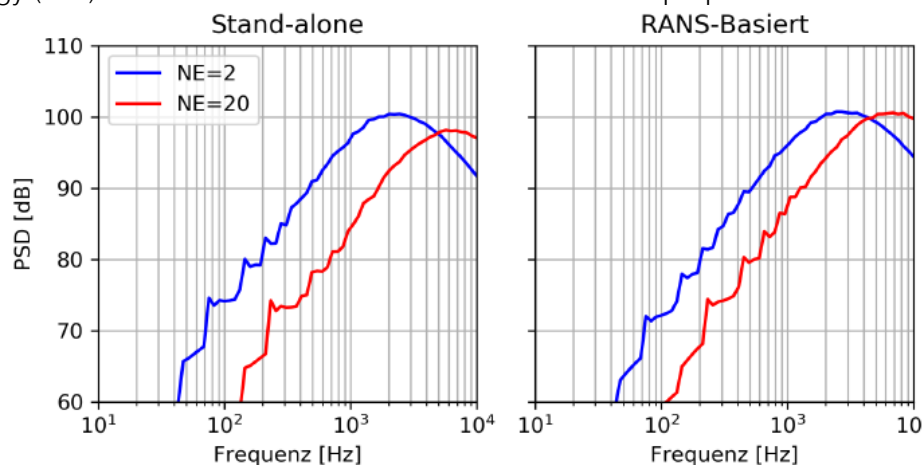
Figure 113: Analytical vs. RANS-informed broadband RSI noise predictions.

5.3.2. Analytical Prediction of Boundary Layer Ingestion (BLI) Noise

Another aspect concerning a distributed propulsion concept is the detailed distribution of several propulsors along the fuselage of an aircraft. A possible option could be the distribution of several propulsors atop of the wings. However, also a circumferential distribution of the propulsors at the rear of an aircraft is discussed. For the BLI noise study, a boundary layer with a thickness of $\delta_{99} = 0.2m$ was assumed. This thickness roughly corresponds with the theoretical boundary layer thickness at the rear fuselage of an A320 (38m) at cruise conditions. In addition, a neutral boundary layer with a shape factor of $H_{12} = 1.3$ was assumed. This factor is strongly linked to the pressure gradient and implies that the boundary layer is not accelerated or decelerated.

Figure 115 shows results at 1st to 5th BPF for a continuously increasing number of propulsors from 2 to 14 for tonal BLI noise. A FPR of 1.3 was assumed. Again, similar to the tonal RSI noise results, the tonal BLI noise is proportional to the considered operating point (PWL Sideline > PWL Cut-Back > PWL Approach). For sideline operating conditions an increase of the propulsor number is accompanied by an increase of PWL. The PWL is continuously decreasing with the BPF harmonic. However, results are not as clear for cut-back and approach operating conditions. Due to the modal structure of the resulting sound field, caused by the tonal BLI noise mechanism (boundary layer – rotor interaction noise), a cut-off design is not possible anymore. The reason is the excitation of all cut-on acoustic modes. This is a significant difference compared to tonal RSI noise.
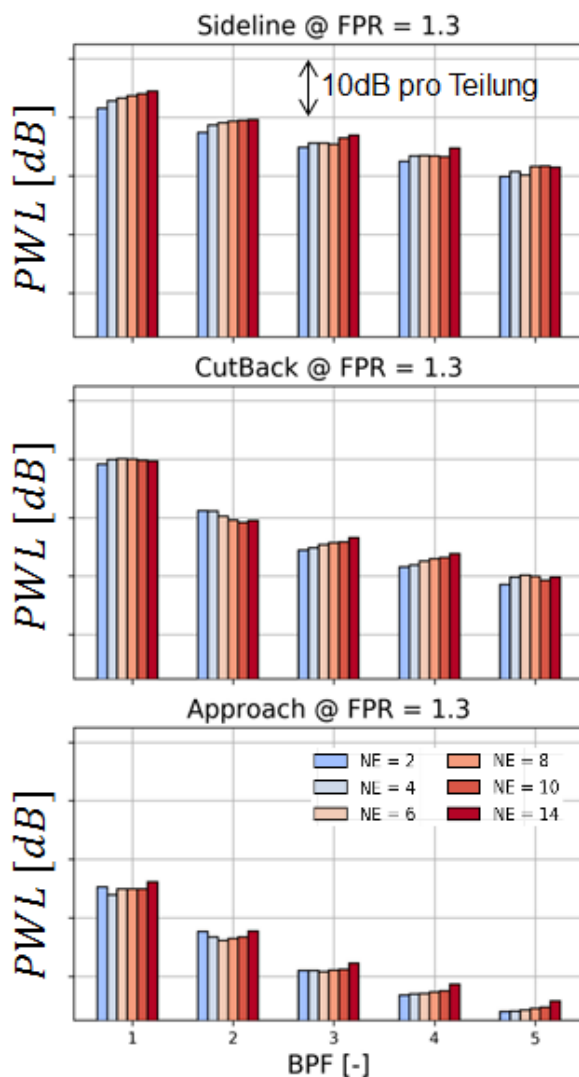
Figure 115: Tonal BLI noise predictions for different numbers of propulsors.
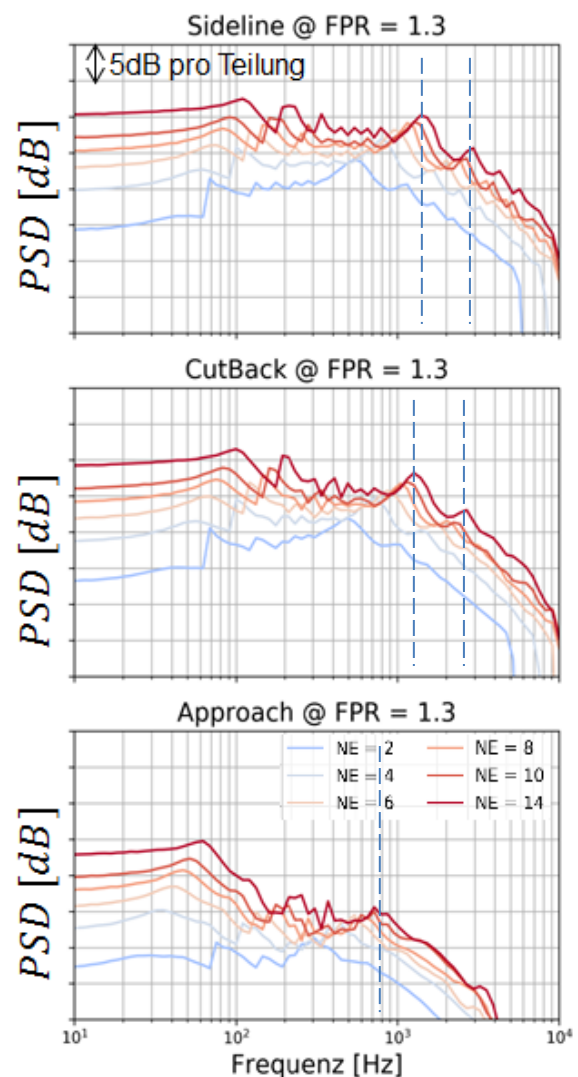
Figure 114: Broadband BLI noise predictions for different numbers of propulsors.

Figure 114 shows results for the preliminary broadband BLI noise predictions. Note that the predicted PSD considerably differs from the parabola shaped broadband RSI noise shown in

Figure 112. The reason is the notably larger turbulence length scale and anisotropic character of the coherent structures of the ingested boundary layer, compared to the small scale and isotropic turbulence within the rotor wakes. As a result, the PSD spectra are shifted to much lower frequencies compared to broadband RSI noise. These structures interact with the moving rotor blades. Since the coherent structures are considerably large, consecutive rotor blades may be exhibit to the same statistical turbulence if the rotational speed of the rotor is large enough. This result in peaks in the PSD spectra centred at the BPF and its higher harmonics. The BPF peaks for the 1st and 2nd harmonic are tagged in Figure 114 by blue dashed lines for the highest set of propulsors (NE = 14). If the propulsor number is decreased, the rotational speed of the rotor decreases and the peaks are shifted to lower frequencies. For approach operating conditions the rotational speed of the fan is too low and the correlation of consecutive rotor blades, resulting in a BPF peak, is lost.

To compare the preliminary RSI noise predictions with RANS-informed predictions CFD computations of the full annulus domain of the turbomachinery would be necessary. The reason is the circumferentially non-symmetrical boundary condition at the inlet for the total pressure. This would result in exhaustive computation times. Alternatively, the situation of an inflow distortion with a mean velocity gradient at the tip wall, as shown in Figure 116, is investigated.
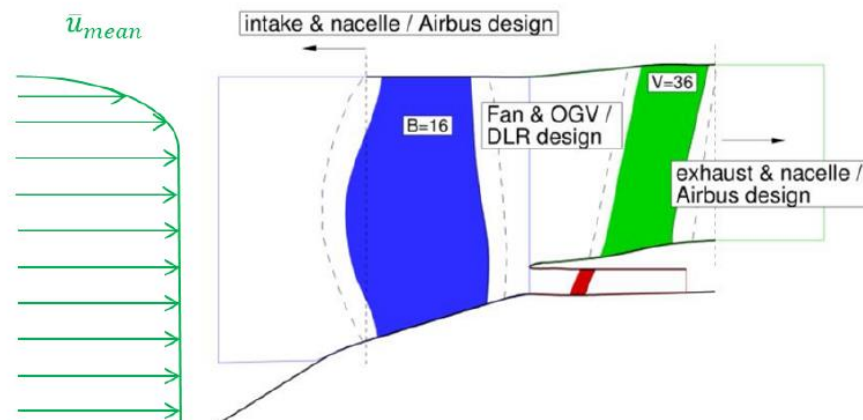
Figure 116: Illustration of investigated inflow distortion.

Results for the tonal RSI noise are shown in Figure 117. In case of a non-uniform inflow (del99 = 0.25R) a lower PWL for the tonal RSI noise is predicted. On the one hand the decreased noise level results from a decrease of the amplitude of the excitation in the tip region. On the other hand a destructive interference (phase effect of excitation) has been verified. Again the cut-off design of the fan stage avoids any tonal RSI noise at the 1st BPF.
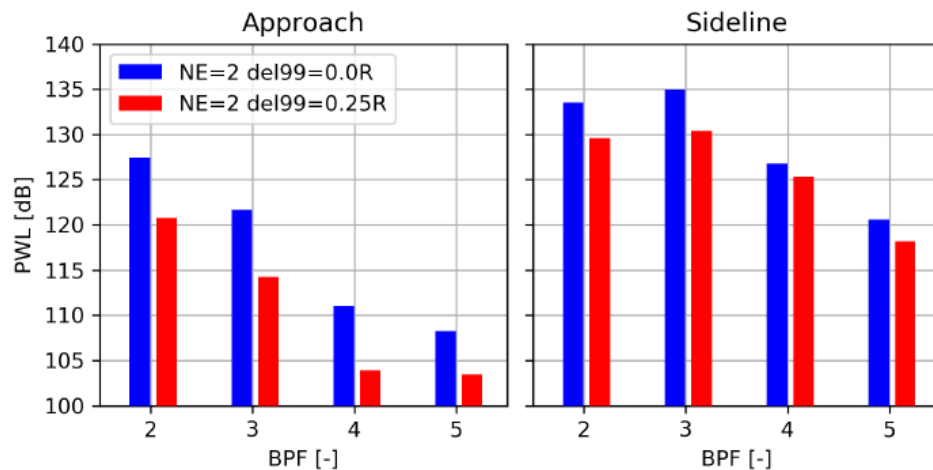
Figure 117: RANS-informed tonal BLI noise prediction for two operating conditions.

Finally, Figure 118 illustrates results for the broadband RSI noise. Here the presence of the inflow distortion clearly increases the PSD levels for both operating conditions. The reason is the additional TKE within the turbulent boundary layer that enters the engine and interacts with the stator vanes. The peak of the PSD is also shifted towards lower frequencies for both operating points since in the tip region the turbulent length scale is increased by the additional large scale turbulence within the boundary layer.
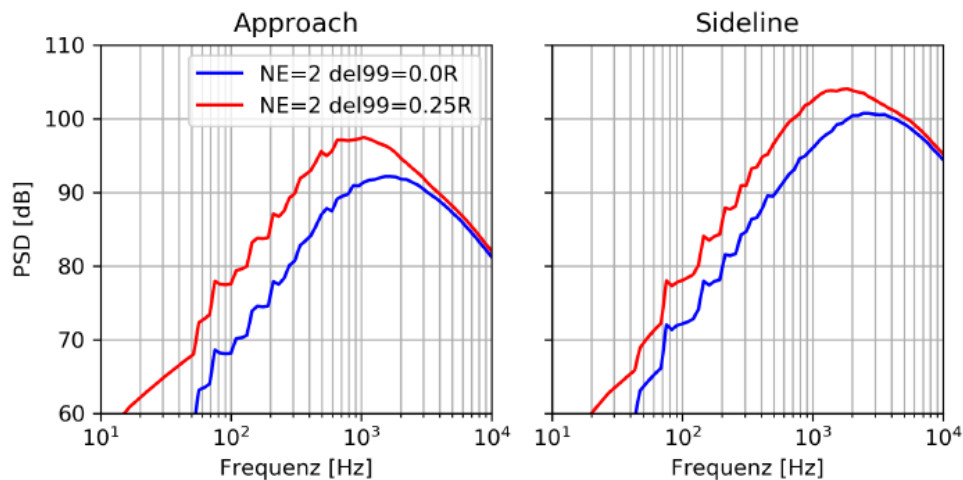
Figure 118: RANS-informed broadband BLI noise prediction for two operating conditions.

5.3.3. Literature Review

In addition to the presented analytical and numerical studies on the assessment of engine noise with distributed propulsion and boundary layer ingestion, a literature review was carried out in order to obtain as comprehensive an overview as possible of the expected development of aircraft noise over the time period and seat categories considered by DEPA. This review also tries to extend the view from the pure consideration of engine noise to the entire aircraft. The literature

review focuses on the topics "distributed propulsion", "electric (distributed) propulsion" and "air taxi" to address implications for UAM. Table 24 gives an overview of major past research programmes and the key findings concerning engine and aircraft noise.

Table 24: Overview of aircraft noise studies

Research program	Major findings
NASA & Boeing: SUGAR High and SUGAR Volt Figure 119: SUGAR High Credit: NASA, Boeing.	• Noise reduction of electric propulsion is widely claimed but literature does not present many quantitative noise prediction • Comparison of SUGAR High (high-tech turbofan) and SUGAR Volt reveals only a noise reduction of 1EPNdB • Noise savings from electric propulsion are expected primarily due to an enlarged design space which enables more effective shielding • 1MW electric motor's contribution to external sound power is small compared to the noise of a low pressure ratio fan
Silent Aircraft Initiative: SAX-40 Figure 120: SAX-40 Credit: Silent Aircraft Initiative.	• Low stall-speeds require no flaps and allow low noise take-off and landings • Airframe centerbody provides shielding of forward radiated engine noise • Gear fairing • Variable nozzles allow high mass flows at lower velocities to reduce jet noise • Long bypass and exit duct to apply multi-segment liners • Optimization of take-off profile for jet, fan and airframe noise • Elimination of tonal turbine noise by increase of shaft speed and careful choice of turbine blade and vane count, minimized mass flow through combustor • Designed approach trajectory with engines at idle thrust

University of Southampton
CTOL DEP, e-A320 concept

Figure 121: e-A320
Credit: Synodinos et al.

- A320 like dimension, payload, mission
- Concept studies with hybrid electric (turbo-electric distributed propulsion) and full electric propulsion
- Variation of engine number
- Turbo-electric concept with 6 propulsors has the highes noise reduction potential
- All-electric propulsion is less benefitial due to increased aircraft weight (batteries)
- Both electric concepts off noise reduction compared to a conventional A320

NASA
CTOL NASA N+3

Figure 122: N+3 Credit: Dae & Berton et al.

- Low-noise concept with aggressive shielding of the distributed electric propulsion system atop the fuselage

NASA
D8 Subsonic Transport

Figure 123: D8 Subsonic Transport
Credit: Clark et al.

- High efficient BLI engines
- Simplified flap system with porous flap side edge, slat leading edge
- Partial main gear fairing
- Engine noise shielding by fuselage
- Additional noise risk by turbulence ingestion and mean flow distortion due to BLI

e.SAT
Silent Air Taxi

Figure 124: Silent Air Taxi
Credit: e.SAT

- Use of a ducted rotor-stator configuration instead of open propellers
- Cut-off design for 1st blade passing frequency (15 rotor blades / 28 stator vanes)
- Large diameter fans for low rotational speed, no shock regions at blades
- Mitigation of tip vortex system by a very small tip gap
- Sound absorbers for internal combustionengine
- Noise reduction potential of 20dB(A)

5.3.4. Conclusion of Aircraft Noise Studies

As mentioned and explained above the aircraft noise impact analysis was limited to the prediction of engine noise. Here, the impact of the technology of distributed propulsion on engine noise was examined in detail. Such a concept is considered likely especially with regard to the electrification of aircraft engines and could be used by small aircrafts (e.g. an air taxi) up to larger airliners. It is therefore pointed out that the study carried out does not yet allow any final conclusions to be drawn regarding the development of the noise level of future aircraft.

Concerning the tonal RSI noise a slightly increase of PWL can be expected with increasing propulsor number due to the sharper formed rotor wakes. Concerning the broadband RSI noise a shift of the PSD towards higher frequencies has to be expected with increasing propulsor number due to the increased rotational speed. The analytical predicted RSI noise trends are in reasonable agreement with high-fidelity CFD-informed noise predictions. The CFD computation also suggests that an inflow distortion, i.e. the ingestion of a turbulent boundary layer, decreases the tonal RSI noise but increases the broadband RSI noise. The reason for the former is the reduction of sharply pronounced rotor wakes, whereas the latter is caused by the additional turbulence. Finally, noise predictions for a new tonal and broadband BLI noise source, resulting from the boundary layer – rotor interaction, have been presented. Due to the modal structure of the resulting sound field no cut-off design, as for RSI, is possible. Additional tonal noise is added at all BPF harmonics. The noise trends seem to be strongly dependent on the operating point considered. Concerning broadband BLI noise, an increase of the special extension of the inflow distortion leads to an increase of PSD since additional turbulence is added.

In order to focus on a wider range of noise than engine noise only, a literature study covering all seat categories as regarded in the DEPA 2050 study, was performed. It turned out that the acoustically previously detailed investigated scenarios of distributed propulsion and BLI are considered important technologies in achieving the noise reduction goals. The new technologies - and here mainly the electrification of aircraft engines that leads to distributed engines - offer great potential to continue the steady reduction of aircraft noise in the future for all existing and new seat categories (e.g. the air taxi).

5.3.5. State of Research in Aircraft Noise Impact Assessments

A huge variety of research and industry projects as well as public concerns indicate that the reduction of the overall aircraft noise remains an important issue for the future. This results in justifiable expectations that the overall aircraft noise will surely be reduced in the time frame up to 2050. However, a concrete estimation on the dimension of aircraft noise reduction over the long-term is quite difficult taking into account the different sources of noise, the high effort needed to derive from noise measurements to noise impact assessments taking into account that noise awareness is a subjective phenomenon and adequate and detailed data to address this topic from a global point of view is typically not publicly available.

Thus, to draw some general conclusions despite of those difficulties external noise analyses have been reviewed in the scope of the DEPA 2050 project. ICAO, for instance, uses a multidisciplinary approach to reduce the aviation impact in terms of noise with regard to all vehicles and by considering different measures.[318] In terms, of aircraft technology development and the future noise impact the latest extended analysis stems from 2019. It delivered a projection of the possible development of the total contour area and the population that lives inside the area with yearly average day-night level (DNL) higher than 55 dB contours. The corresponding trend analysis was conducted on base of four different aircraft technology scenarios assuming different technological progress and included a set of 315 global airports which cover a total share of global air traffic of 80% in total.[319]
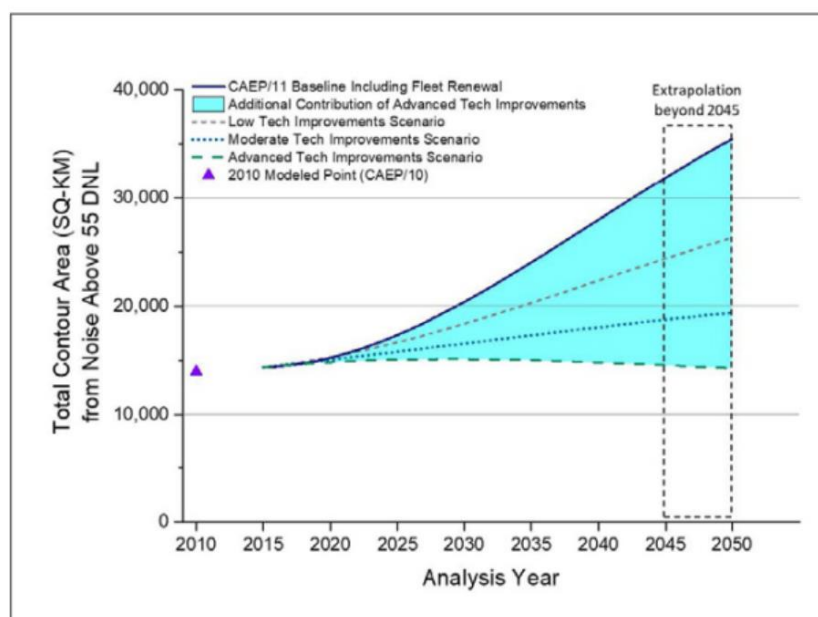
Figure 125: Total aircraft noise contour area above 55 dB DNL for 315 airports, 2010 to 2050.[320]

In general, there is an increase in the size of the noise contour area over time visible. In dependence of the aircraft technology scenario and as a result of increasing air traffic this area will grow between 100% and 220% up to the year 2045. A contrary trend can only be found for the most advanced aircraft technology scenario. From 2035 onwards, it is possible to decouple air traffic growth from the increase of the noise contour area which leads to the result that in 2050 the noise contour area is 10% lower compared to prior trend projections. In total, this is caused by a combination of significantly less noisy aircraft and a reduction of air traffic demand.[321]

Based on aircraft noise levels of selected existing aircraft and estimations of experts from ICAO CAEP the European Aviation Safety Agency (EASA) has also published a projection on the

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[318] Cf. ICAO (2019).
[319] Cf.: https://www.icao.int/environmental-protection/Pages/Noise_Trends.aspx .
[320] Cf. Ibid.
[321] Cf. Ibid.

potential development of the aircraft noise levels in relation to aircraft technology.[322] The following figure presents the assumed development for heavier aircraft and maximum engine thrusts ratings including also a consideration of new aircraft noise levels that EASA has certified from 2016 to 2018 as well as estimations for the A380 and a representative small/medium range aircraft with two counter-rotating open rotor (CROR) engines. In reference to the chosen indicator of cumulative noise margins in relation to Section 3 aircraft (EPNdB) the analysis shows also a general decline in overall aircraft noise levels.

Figure 126: Estimated aircraft noise development over time based on most current jet aircraft families[323]

Taking research initiatives like the Clean Sky 2 programme with separate goals for noise reduction and the huge variety of other research and technology activities into this field into account, it is highly probable that all vehicle types in aviation will become less noisy over the next decades. In addition, the overall noise reduction is supported by additional measures in the field of operational and policy measures. However, as outlined before a concrete prediction on the reduction of noise for concrete future years is quite problematic and depends on various factors that increase the uncertainty. Further research especially in the field of holistic noise assessments is therefore needed. This topic is discussed in more detail in section 6.2.

5.4. Results on Economy

5.4.1. Overview

Besides the important role of air transport as connector of world regions and enabler of fast transportation in the globalised world of today the air transport sector is also an essential contributor to economic growth and prosperity. This has become never more obvious than in the current Covid-19 pandemic. The dramatic fall in air traffic demand has a severe impact on the overall air transport industry. Specifically, for airlines besides other air transport actors (e.g. aircraft manufacturers, airports, etc.) dramatic job cuts as well as financial losses became reality in a very short time span.

In line with all results presented in this report the Covid-19 impact has not further been considered with regard to the estimated short- and medium-term effects. As pointed out earlier in relation to DLR's air traffic forecast used in this study a rebound effect for the global air traffic development is likely meaning that also the employment situation and financial stability of airlines will most probably recover up to the year 2050. Thus, the general growth tendency for air transport's economic effects can be regarded as similarly valid for the long-term although smaller uncertainties with regard to the future development remain. However, these uncertainties are also given in form of other developments that may influence the long-term future of aviation and especially the employment conditions (e.g. artificial intelligence, digitalisation, automatisation, unpiloted systems, etc.). Over the long-term these factors may lead to even more incremental changes in society and in the overall economy while the resulting effects are not fully understood yet.

In contrast, the following analyses have been conducted by assuming a stable structure of the overall economy on global scale excluding the impact of potential future disruptions. In general, for sector-specific analyses of economies the direct, indirect and induced effects of a specific sector are of special interest. The following figure provides a definition of the coverage of those effects.

Direct Effects	Employment and Gross Value Added (directly generated by the air transport industry)
Indirect Effects	Employment and Gross Value Added (indirectly generated along the upstream supply chain)
Induced Effects	Employment and Gross Value Added as result of income spent by direct and indirect employees

Figure 127: Economic impact of air transport activities on global scale (2014 vs. 2050)

Direct effects in air transport originate from the air transport activity or airlines' business activities respectively. They cover the employment and gross value added that is directly generated on the airline company level. Meanwhile, indirect effects originate also from the airlines' business activities but appear on the level of suppliers in terms of job and value creation through requested deliveries from the airlines' side. The third type of effects, induced effects, are generated by the income that is spent by the direct employees of the airlines and those employees of other sectors whose jobs are supported by the air transport industry. Thus, the wider economic impact of air transport does not only cover the air transport sector itself. There is a wider and very important impact on all sectors in a specific economy (the so-called "multiplier effect").

To calculate these effects for the DEPA 2050 reference year 2014 data from the "World Input Output Database" (WIOD) had been used. The WIOD data set covers 56 industry sectors in total for 43 of the biggest national economies.[324] In combination with an input-output modelling approach the indirect and induced effects can be calculated by the analysis of cross-sectoral relationships along the supply chain. This allows to conclude on the total economic impact of an economic sector (e.g. for the air transport sector) and to extract the most important indicators given by created jobs and generated gross value added along the supply chain. Based on this analysis for the reference year 2014 estimates for the long-term development of the direct, indirect and induced effects of air transport on the economic development were conducted. Results were separately analysed for the global scale and the European member states.

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[324] In total these economies cover around 90% of global air traffic in terms of flights. Thus, a large part of the global aviation industry and corresponding economic effects are captured on this basis.

5.4.2. Results on global scale
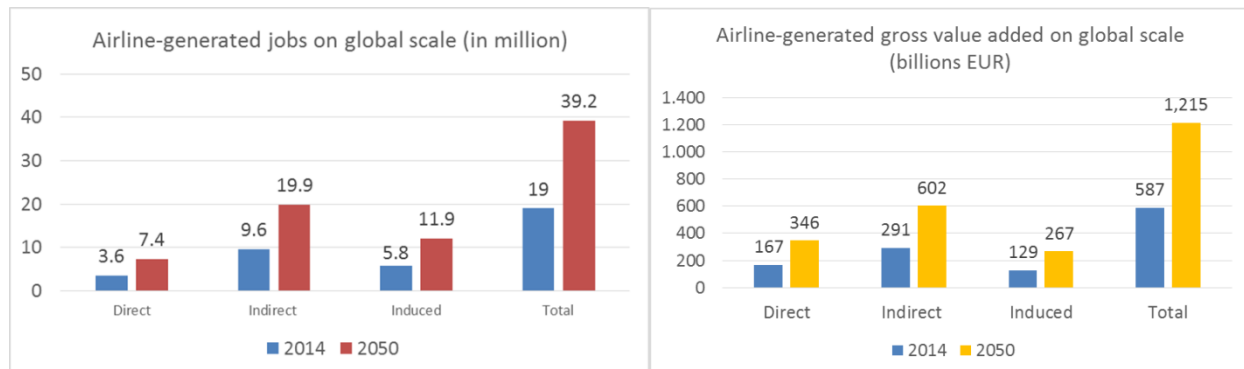
Figure 128: Economic impact of air transport activities on global scale (2014 vs. 2050)

On global scale about 3.6 million direct jobs at airlines could be reported for the year 2014. This equals 0.8% of all jobs on global scale. In addition, more than 9.6 million jobs were generated through the demand of airlines for requested deliveries along the supply chain. The spending of the direct and indirect employees in the same year contributed further to 5.8 million induced jobs in the overall global economy. Thus, in total 19 million jobs depended directly or indirectly on air transport activities in the year 2014. Driven by the expected growth in air transport (cf. section 3.3) these values might significantly increase over the next decades. For the direct employment it can be estimated that the number of jobs in the air transport industry will increase up to a level of 7.4 million (+105.6%). Indirect employment will grow by approximately 10.3 million jobs over the regarded period of 36 years. This means nearly a doubling of the 2014 base value and reflects the important role of air transport as catalyst of further job creation. Given the fact that the air transport industry deliveries typically stem from a highly diversified and globalised supply chain it is also evident that air transport activities and air transport growth have a high importance for all major economies in the world.

Taking furthermore induced employment effects into account it can be estimated that those will also increase from 5.8 to 11.9 million jobs between 2014 and 2050. In total, the overall employment generated by air transport activities will grow in the same time span from 19 to 39.2 million jobs. In line with the estimated growth of flights this will also mean a doubling over the next decades. Compared to other industries air transport will therefore clearly be a job engine in the future although some jobs might be replaced by the effects of automatisation and artificial intelligence. Similar tendencies can also be seen for the development of air transport's gross value added. In the year 2014, air transport activities were responsible for more than 1.2% of the global GDP. The direct gross value added created by the air transport industry amounted to 167 billion euro in this year and will increase up to 346 billion euro by the year 2050 (+107.2%). Meanwhile, for the indirect gross value added which will be created among the airline suppliers a growth from 291 billion to 602 billion euro can be expected which equals a rise of 106.9%. The calculation for the induced gross value added shows a similar trend from 129 billion to 267 billion

euro over the next decades. In summary, the air transport growth on global scale might turn out into 1,215 billion euro of gross value added in the year 2050 (+107% compared to 2014).

As an outcome of this analysis it can be concluded that the air transport sector plays a very important role for the creation of gross value added and employment by contribution to welfare and economic development in the major economies in the world. This is also reflected in the national tables for job creation and gross value added that are provided in the annex of this report. However, with regard to the long-term some changes in the rankings of countries in relation to air transport's role in the overall economy can be expected. Those are mainly driven by the significant air transport growth that in specific countries in Asia. For example, in terms of total direct, indirect and induced employment Taiwan will pass the United Kingdom and Turkey in 2050 as outlined in the following table.

Table 25: Top ten countries in terms of air transport's overall employment effects (2014 vs. 2050)

Country	2014	Country	2050
China	5,881,894	China	16,298,866
Indonesia	3,301,169	Indonesia	7,703,882
India	2,181,462	India	5,561,703
United States	1,824,764	United States	3,282,917
Russia	926,483	Russia	1,564,887
Brazil	647,925	Brazil	1,233,398
Germany	421,031	Germany	778,259
United Kingdom	402,699	Taiwan	733,009
Turkey	312,211	United Kingdom	722,874
Taiwan	302,583	Turkey	713,295

Ascending countries   **Descending countries**

Similar conclusions can be drawn for the development of air transport's overall gross value added. While the countries listed on rank 1-4 are assumed to be able to keep their positions between 2014 and 2050, the second part of the list shows higher dynamics. In this respect, Indonesia is the clear winner of the given ranking. It is predicted that this country will be able to improve its position from place number 7 to place number 5 in terms of air transport-related gross value added. Similarly, also driven by rising air traffic demand over the long-term Australia might be able to change the position with France up to the year 2050. In contrast, Japan and Russia will most probably lose their former positions ending up at place number 6 and 7 in the 2050 ranking. The resulting snapshot for the years 2014 and 2050 is given in the following table.

Table 26: Top ten countries in terms of air transport's overall gross value added (2014 vs. 2050)

Country	2014	Country	2050
United States	186	United States	334
China	69	China	192
United Kingdom	32	United Kingdom	58
Germany	29	Germany	53
Japan	24	Indonesia	51
Russia	23	Japan	42
Indonesia	22	Russia	39
France	21	Australia	37
Australia	18	France	37
Canada	17	Canada	30

Ascending countries   Descending countries

5.4.3. Results for EU level

With regard to the European scale air transport demand plays also an important role for the national economies as outlined in the following figure.
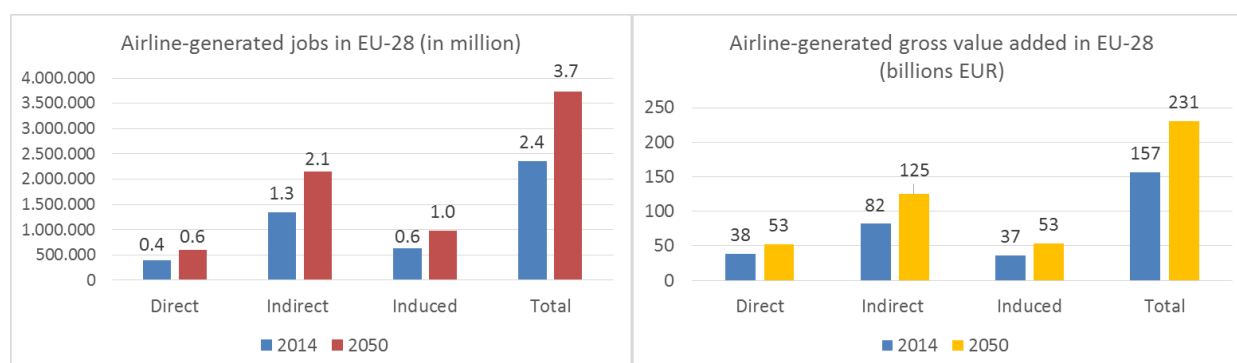
Figure 129: Economic impact of air transport activities on within EU-28 (2014 vs. 2050)

In the year 2014 the airlines' business activities generated approximately 400,000 direct and 1.3 million indirect jobs within the EU member states.[325] For the year 2050 it is estimated that those

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[325] For the long-term statistical analysis United Kingdom was regarded as part of the European Union also up to the year 2050.

figures will grow by additional 200,000 direct jobs (+50%) and 800,000 indirect jobs (+61.5%). Correspondingly, the induced jobs will increase from 600,000 in the year 2014 to 1 million in the year 2050. In total, the overall air transport-related employment within the EU will grow from 2.4 million jobs to 3.7 million jobs in the time span between 2014 and 2050. Given the fact, that the air transport sector is already today responsible for about 1% of all jobs within the economy of the EU-28 the important role of airlines business' activities is evident.

Similarly, the gross value added directly generated by air transport will increase from 38 billion to 53 billion euro between 2014 and 2050. For the indirect gross value added a growth from 82 to 125 billion euro can be assumed over the long-term (+52.4%). With regard to the induced gross value added the airlines' business activities generated about 37 billion euro throughout the economy of the EU. This value might increase to 53 billion euro up to 2050. In total, the overall gross value added created by the air transport activities throughout the European member states will rise from 157 billion to 231 billion euro in 2050 (+1.3% p.a.). Based on these analyses it can be concluded that air transport plays a very important role for the creation of benefits for economy and society. As outlined air transport is an essential contributor to economic growth and prosperity especially expressed by being an enabler of employment growth and a catalyst of value creation. Although the current impact of the current Covid-19 pandemic has led dramatic job cuts and financial losses of airlines a long-term recovery is probable as soon as air traffic demand itself recovers. This stresses the direct linkage between air transport growth and air transport's economic impact. Also mega trends like automatisation or artificial intelligence might therefore not significantly reduce the demand for highly-skilled employees over the long-term as the air transport sector is generally growing and traditionally a sector with a significant share of employees with higher education levels and diversified skills that are needed to guarantee safe and efficient transport and to contribute to innovation within the air transport supply chain.[326]

5.5. Evaluation of Results

This section summarises the results of the preceding impact assessments in the scope of the DEPA 2050 study with regard to the dimensions of mobility/vehice productivity, emissions and climate impact as well as noise and economy. Due to the different types and reliability of assessments that have been performed the main results are given for each dimension separately without an overall weighting of the individual results. This facilitated also the provision of cross-references to existing goals from industry and politics for the future aviation development, if it has been appropriate to underpin the findings of the DEPA 2050 study.

Results on mobility/vehicle productivity
The analysis for the assessment dimension of mobility and vehicle productivity allows to draw several conclusions in dependence of the regarded vehicle market segments. For mainliner,

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[326] Cf. https://aviationbenefits.org/social-development/developing-skills/.

regional and small air transport the ACARE four-hour-goal goals was a starting point to analyse the connectivity situation in the course of this study based on the DEPA 2050 assessment scheme. For this purpose two different indicators were used to assess the status quo for mainliner and regional aircraft: 1) the percentage of the accessible population within a four-hour time frame in comparison of "car traffic only" and "car/scheduled aviation" and 2) the percentage of theoretically completed air trips within four hours. In relation to the first indicator the impact analysis was rather disillusioning. It showed that the share of the overall population in the EEA region that can theoretically be reached in a four-hours' time frame is relatively low with 10%. For the second indicator real air traffic data for the year 2018 was used and results have been quite similar. It was found that only 88.1% of all European passengers had been able to realise their journey throughout in a four hours' time span with a theoretical flight distance of 2,060 kilometers not to be exceeded and very optimistic airport access/egress and processing times of 45 minutes in total. As the European airport and scheduled aviation network is already very dense within Europe and the airport processing times cannot be optimised anymore, the ACARE 4-hour can therefore be seen as not fulfilled at the moment. For the future it is also unlikely that the restricting parameters will improve meaning that also over the long-term the fulfillment of the ACARE 4-hour goal remains a challenging task.

Anyhow, the analysis on global scale for mainliner and regional aircraft including the top 200 city pairs in terms of GDP/capita has shown that the degree of connectivity on global scale has significantly improved over the last 20 years. Especially the number of direct connections, which is the preferred travel option for a clear majority of passengers due to significant travel time savings, has drastically grown from 2000 to 2019 (e.g. by 81% in Europe and by 27% in the Asia-Pacific region).[327] However, also connections with 1 or 2 stops between the selected city pairs have increased. For the long-term future this could also mean that further improvement potential – as shown with regard to the ACARE 4-hour-goal – might rather be limited or further connectivity growth might at least slow up in relation to mainliner and regional air traffic.

The situation looks a little bit different for small air transport. In general, SAT aircraft can serve low-demand and limited distance routes in all world regions efficiently and especially if other transport modes (e.g. high-speed rail) do not provide adequate alternatives.[328] For Europe, the conducted analysis in relation to the ACARE 4-hour-goal showed that the percentage of the accessible population within a four-hour time frame can substantially be increased. By assuming a flight speed of 300 km/h for SAT aircraft the share can grow from 10% (on base of the findings from the mainliner and regional aircraft analysis) to 29.9% and up to 36.6% by assuming a flight speed of 400 km/h. The connectivity gains for SAT differ in this context from region to region, but show on average a high potential to improve the current situation especially over the short- to medium-term. As the sensitivity analysis in regard of different flight speeds has shown, the

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[327] The variety depends on the number of airports regarded in a certain region as part of the "Top 200" city pairs' dataset. For example, in Europe the value is automatically higher given the high number of capitals with corresponding population figures and GDP generation.

[328] For example, New Zealand or all countries in South America offer good conditions for establishing new SAT connections over the next years.

vehicle productivity and technological conditions represent a further crucial factor in this respect if SAT potential shall be fully exploited.

Over the long-term the connectivity improvement potentials of supersonic aircraft and with regard to UAM have to be further included in corresponding analyses on connectivity and vehicle productivity. Due to a higher uncertainty with regard to the final EIS and the market prospects for both segments they have been excluded from the impact analysis in the scope of this study. However, the vehicle-specific scenarios and the demand forecast for commercial supersonic air transport and for UAM (cf. section 3.1.5 and 3.3.) indicate that both transportation concepts will be game changers in the global aviation network. Over long- and ultra-long distances supersonic aircraft will significantly reduce travel times and on smaller geographical scale UAM will have a disruptive effect on intra- and intercity travel especially in comparison to other transportation modes. In addition, travel chains combining supersonic and subsonic air travel and UAM will further contribute to travel time savings and will also change underlying travel behavior. Although these impacts could not be quantified yet, the following figure tries to provide a qualitative prediction of the connectivity impact of all vehicle segments up to 2050. While more detailed investigations of the illustrated trends are needed, this could serve as a starting point for further discussions.
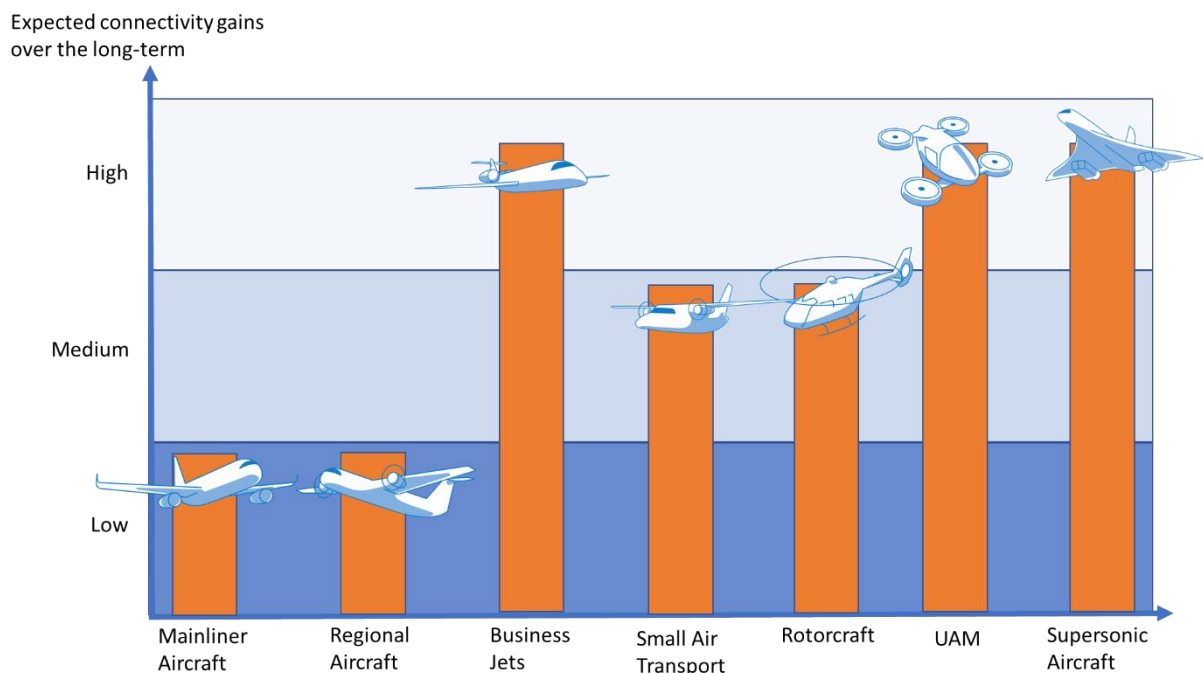
Figure 130: Estimation of potential connectivity benefits from the DEPA 2050 vehicle segments

Results on emissions and climate impact

The broad scope of the DEPA 2050 study with its impact assessment on emissions, the definition of long-term scenarios and the development of aircraft technology and ATM roadmaps allows to

draw several links to existing environmental goals for the aviation sector. In this respect, a brief overview of major goals is given in the following.

IATA goal:
The air transport industry itself has launched a set of goals in the year 2009 to address the issue of climate change. Besides a short-term goal on improving fuel efficiency these goals cover two major aspects:[329]

- Carbon-neutral growth from the year 2020 onwards by stabilizing the net CO_2 emissions at the 2020 level
- A 50% reduction of aviations' net CO_2 emissions by 2050 in comparison to the year 2005

To meet these goals a so-called "four pillar strategy" was defined based on the following components:

- Improved technology (including sustainable aviation fuels)
- More efficient aircraft operations
- Infrastructure improvements (including modernized ATM systems)
- Market-based measures, to fill the remaining emissions gap

The estimated contribution of each of these components to achieve this goal of a 50% CO_2 emissions reduction is outlined in the following figure.
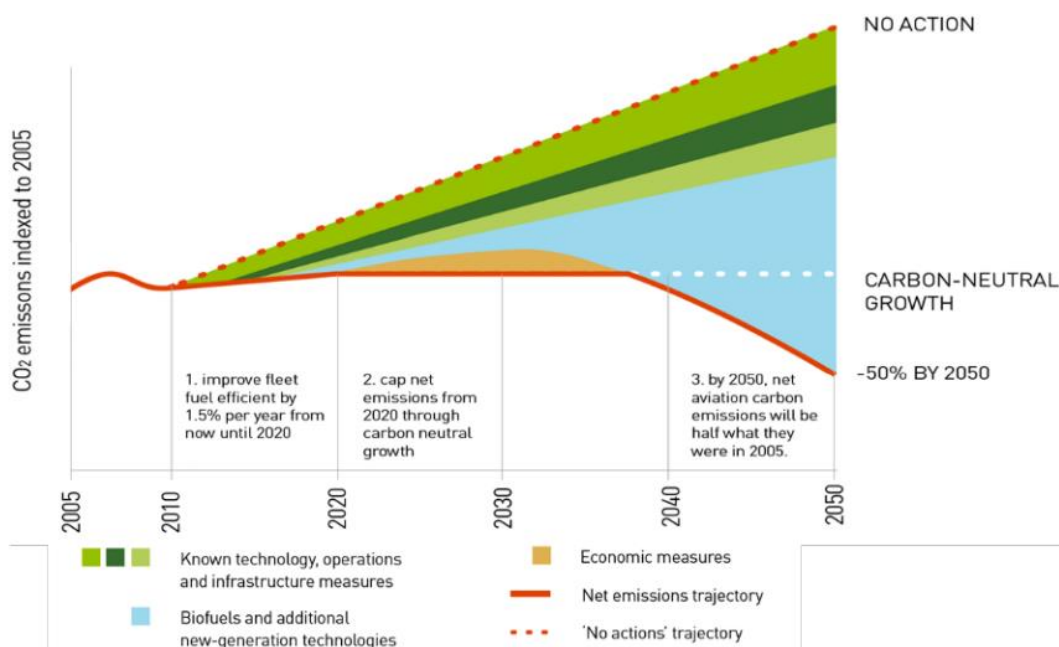
Figure 131: CO_2 goal until 2050[330]

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[329] Cf. IATA (2020).

ICAO goal:

During its 37th Assembly in 2010 ICAO has committed itself to two goals to address the challenge of climate change.[331] The first one foresees an annual fuel efficiency improvement of 2% up to the year 2050 and the second one foresees a carbon neutral growth of international aviation in the time span between 2020 and 2050. Similar to ATAG a so-call "basket of measures" shall contribute to the fulfillment of these goals including the following measures:

- Aircraft technology improvements
- Operational improvements
- Sustainable aviation fuels (SAF)
- Market-based measures (i.e. CORSIA)

In reference to this goal framework the following figure provides an overview of the expectation of ICAO to meet this goal and the contribution of the individual components of the basket of measures.
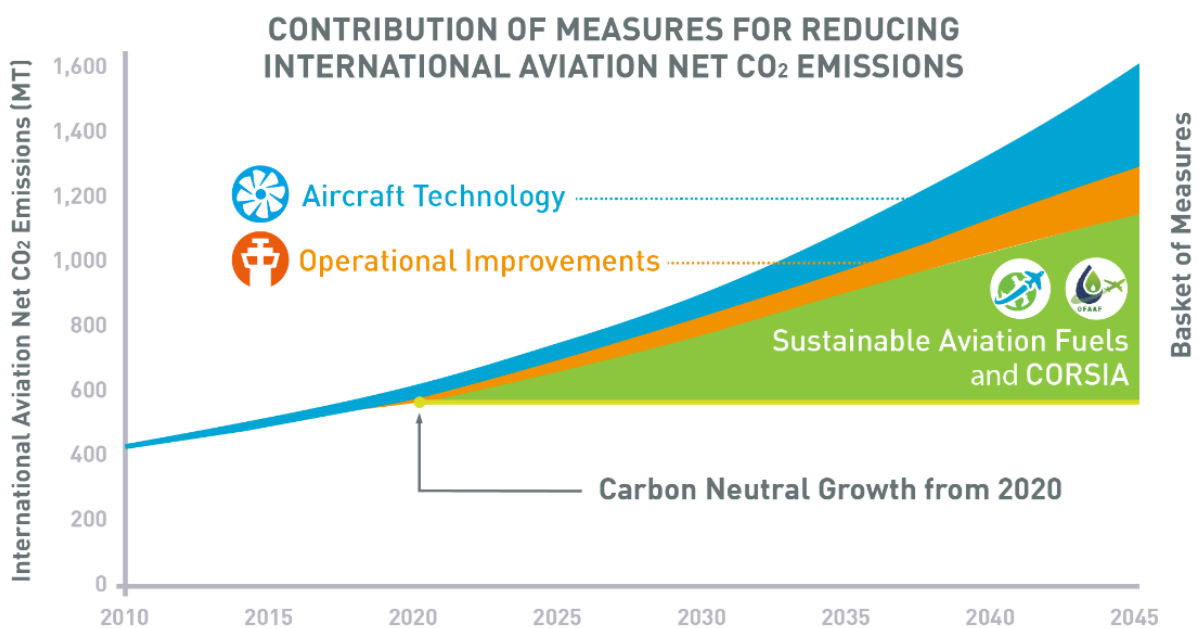
Figure 132: CO_2 goal and contributing measures until 2045[332]

European Green Deal:

By approving the European Green Deal the European Commission has also set own ambitious target for European air transport stakeholders as part of the transport industry. The basic

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[330] IATA (2013).
[331] Cf. https://www.icao.int/environmental-protection/pages/climate-change.aspx.
[332] ICAO (2019).

objective is to reduce greenhouse gas emissions from transport by 90% up to the year 2050 to assure that also the transport sector contributes significantly to the overall goal of climate-neutrality by 2050. In addition, as a medium-term goal for the year 2035 the introduction of the first zero-emission large aircraft is foreseen.[333]

Core elements to achieve these goals are referring to ICAO's basket of measures and include e.g.:

- The development of disruptive technologies
- Fostering research and innovation
- Adequate carbon pricing policies
- Improvement of air traffic management (Singe European Sky)
- Deployment of renewable and low carbon fuels including the set-up of the necessary supply infrastructure[334]

Within the scope of these important goals the DEPA 2050 study has addressed the majority of the mentioned measures and instruments to achieve the diverse environmental goals for the aviation sector. On the component level the DEPA 2050 study has investigated the potential of promising technologies to increase fuel efficiency and reduce emissions by selecting them for further consideration in the DEPA 2050 concept aircraft models. In addition, operational improvement potential in the field of ATM was identified and incorporated into the scenario-specific calculation of emissions and climate impact. Furthermore, the potential of sustainable aviation fuels (SAF) and hydrogen was assessed with different granularity.

Although different reference cases and metrics were used in the goal frameworks that are described above, which makes direct comparisons to DEPA 2050 results difficult, some general conclusions can be drawn. In order to meet the given goals for the aviation sector in all cases high efforts will be needed. It is also evident that only a mixture of measures will lead to successful results while a concentration on one or two categories of measures will not be sufficient to decouple aviation's' emissions from the predicted air transport growth. Among all discussed measures SAF will furthermore play a very important role. This is one major finding in relation to the development pathways for aviation as investigated in this study (cf. section 5.2) and is also supported by the estimations of ICAO (cf. figure 134) and ATAG (cf. figure 133).

However, for the future a continuous monitoring and analysis of the overall development in terms of greenhouse gas emissions will remain important to track changing conditions (e.g. in relation to the Covid-19 pandemic) as well as to check the impact of (newly introduced) policies in relation to the discussed measures. Typically, over the long-term and especially on global scale priorities in the political agenda-setting might change. Furthermore, different propulsion concepts and the necessary infrastructure behind might develop differently over time with changing impacts on emissions and consequences for the degree of fulfilment of the presented goals.

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[333] Cf. European Commission (2020b).
[334] Cf. Ibid.

Finally, also the market diffusion and environmental performance of new vehicle types and transportation concepts (i.e. supersonic aircraft and UAM) have to be considered for a complete impact assessment when the uncertainty about corresponding EIS dates becomes lower. In addition, the growth of multimodal transportation chains and a potential switch to other transportation modes (e.g. high-speed rail, long-distance coaches) might also become an important factor over time that change the degree of fulfilling the presented goals.

Results on noise

Besides the development of greenhouse gas emissions further noise reduction is one of the top priorities for aviation with regard to the environmental domain of sustainability. Important guidance on how to achieve this goal is given by ICAO's "Balanced Approach" which is presented in the following figure:
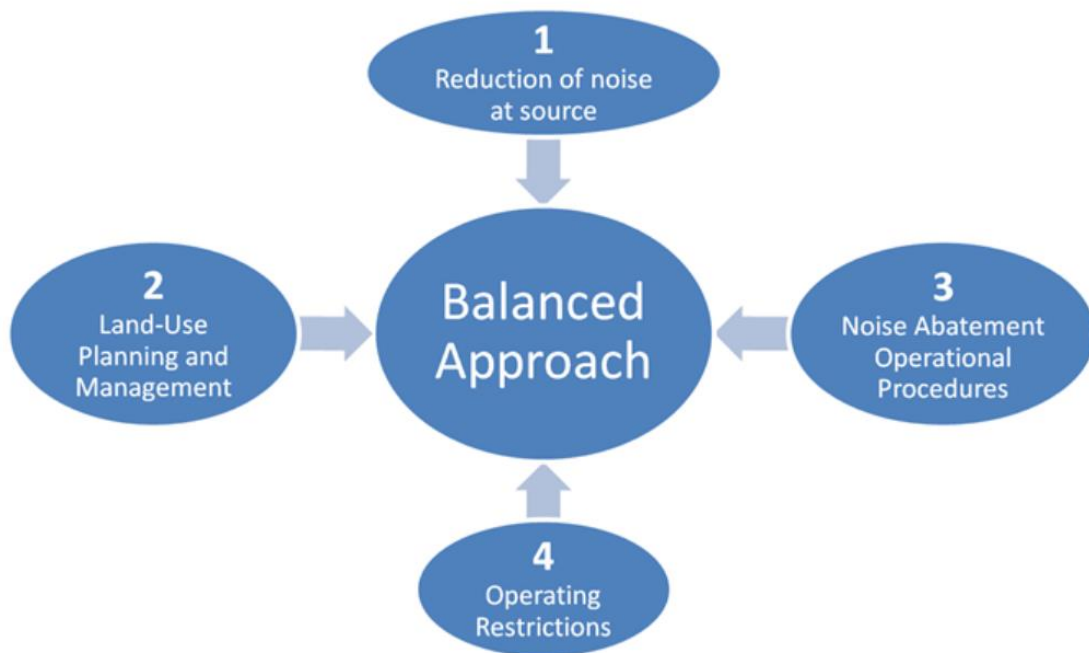
Figure 133: "Four pillar" strategy of ICAO's balanced approach[335]

In the scope of the DEPA 2050 study the pillar of "reduction of noise as source" was addressed. Furthermore, the primary focus was put on the modelling and prediction of engine noise with a special focus on novel configurations, such as BLI propulsors. For this purpose, as a first step a continuous increase of the propulsor number for an engine meeting the thrust requirements of an A320-sized aircraft was analysed. The corresponding outcome in terms of RSI and BLI noise

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[335] Cf. https://www.icao.int/environmental-protection/Pages/noise.aspx.

was investigated to model and validate a specific design and its impact on the engine noise. In general, the findings from this technology modelling of a next-generation engine show, that the analysed engine design can be integrated in the majority of all aircraft seat categories in the range from category 8-13 and can contribute to the reduction of noise at source as outlined in ICAO's "four pillar" strategy as part of the "balanced approach". However, due to the complexity of noise generation and impact modelling an integration into the DEPA 2050 aircraft models had not been possible in the scope of this study. The findings indicate, however, that there is still a potential for the reduction of aircraft noise at its source.

This tendency is also supported by the findings from a conducted literature review on external projects that deal with the reduction of engine noise but also with noise-optimised aircraft. A specific focus was put on the topics "distributed propulsion", "electric (distributed) propulsion" and "UAM vehicles". The outcome of this desk research supports in line with other studies the general estimation that aircraft noise might further be reduced over the next decades. Anyhow, according to ICAO this will mainly be possible through novel aircraft configurations and a mixture of optimisations in the field of noise from the fan but also from the airframe.[336]

Results on economy

Most recently, the drastic outcome of the Covid-19 pandemic has shown that the air transport sector plays an undisputable important role for the global economy. This is also stressed by the results of the economic impact analysis which was conducted in pre-Covid-19 times with regard to the gross value added and with regard to employment effects that are generated by airlines on base of air transport activities.

The following figure summarises the main findings for the current and future economic footprint of air transport for the years 2014 and 2050 as a direct result of air traffic demand.[337]

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[336] Cf. ICAO (2019).

[337] The analysis is based on the air transport demand forecast for mainliner/regional aircraft, SAT and business jets, which was calculated in pre-Covid-19 times. Thus, the economic impact of aviation in the short-term might be lower. However, if a full recovery in air transport demand will take place, the figures for the year 2050 are relatively reliable.
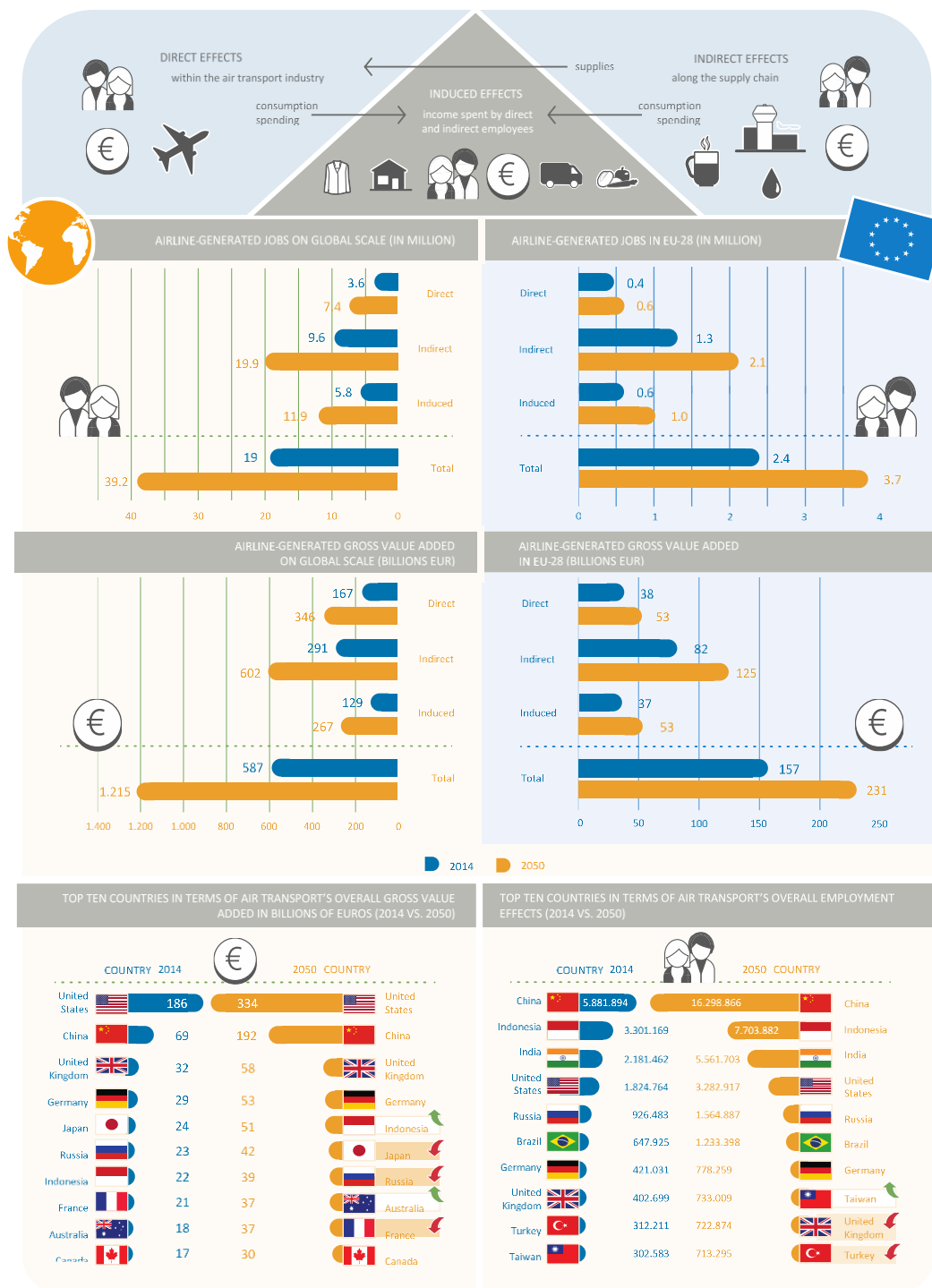
Figure 134: Air transport economic footprint on global and European scale (2014 vs. 2050)

On global scale the gross value added will increase from 587 billion euro to 1,215 billion euro. For the overall employment effect also approximately a doubling of total jobs from 19 million to 39.2 million employees can be expected. Similarly, on the level of the EU-28 member states the gross value added will grow from 157 billion euro to 231 billion euro over the next decades. The employment benefit will be in the range of additional 1.3 million jobs meaning that the number

of 2.4 million jobs in 2014 will rise to 3.7 million total jobs in 2050. However, on a more detailed level not all countries in Europe and on global scale will profit from this development in the same degree. As the top ten country ranking above shows, there are some countries that will lose their relative position in terms of air transport-related gross value added or in terms of total employment in linkage to the forecasted air transport demand growth in the respective countries. This holds for Indonesia, Japan, Russia, Australia, France, Taiwan, United Kingdom and Turkey in particular.

Anyhow, the analysis shows that there is generally a strong growth tendency for air transport-related economic effects expectable. Although no concrete target values for the development of aviation-related economic benefits exist, this is in line with the intention and partly goals of diverse initiatives from politics and industry to support aviation's overall development as an enabler of economic development and social prosperity. For example, the European Commission just recently propagated in its "Sustainable and Smart Mobility Strategy" to make the transport sector as a whole "more attractive for workers".[338] ACARE is also following a similar intention by making air transport careers more attractive for students in the scope of the goal of "prioritising research" and by strengthening the competitiveness of the European aviation industry with regard to the goal of "industrial leadership".[339] ATAG, which conducts regularly similar analyses for the economic benefits of the whole aviation industry (including e.g. aircraft manufacturers, airports, air navigation service providers) is also stressing the importance of aviation for the overall economic development, which contributes at the same time to the UN sustainability goals and has diverse linkages to the environmental and social dimension of sustainability.[340] Although the Covid-19 pandemic has affected the air traffic development and the economic performance of the aviation industry dramatically, a recovery will over the long-term improve the situation. This means there will also be recovery of the strengths of the air transport sector in terms of innovation, job and value creation as well as hit enabler of social exchange and foreign trade.

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[338] European Commission (2020b).
[339] Cf. ACARE (2011).
[340] Cf. ATAG (2020, 2018, 2016).

6. Conclusion

6.1. Final Results

With regard to the overall project objectives as outlined in section 1.3 it can be concluded that the DEPA 2050 study has fulfilled the requirements that were defined at the beginning of the project.

To cover the current state of research projects, studies as well as existing technology roadmaps were reviewed to evaluate the full technology potential of existing aviation technologies and further technologies in the development stage. This included the definition, description and classification of candidate technologies for the DEPA 2050 scenarios as well as the estimation of corresponding TRL levels and the most probable EIS of each technology up to the year 2035. The latter was a major requirement to consider technologies for the scenario quantification in the mainliner and regional aircraft segment. Additional qualitative assessments of technology potentials were separately conducted for the other vehicle segments (i.e. supersonic aircraft, UAM vehicles, business jets, rotorcraft and small air transport). This allowed to describe wider implications for MRO and ATM requirements (cf. section 4.6 and section 4.5). Finally, further analyses of future technologies were conducted for airports and for the description of a more detailed future development pathway of synthetic fuels and alternative fuels usage. While for those analyses a wider definition of the term "aviation technology" as originally intended had been used, this broader scope was of additional value to complete the planned roadmap elaboration. To deliver coherent and consistent estimations on the future vehicle configurations corresponding framework conditions had to be analysed in parallel.

The DEPA 2050 scenarios itself represented a major element of the DEPA 2050 study. The investigation of aviation external and internal studies on the future development up to the year 2050 allowed to draw general conclusions on the operating conditions for the aviation sector over the long-term. Hence, this analysis was an important starting point to specify the seven vehicle-specific scenarios for the "progressive" and the "conservative-evolutionary" pathway within the DEPA 2050 scenario taxonomy and with regard to the technology and vehicle roadmaps. The main intention behind was to elaborate development pathways for each vehicle type as unique and innovative feature of the DEPA 2050 study. The advantage of the scenario approach allowed in this respect to concentrate not only on two diverging pathways. As scenarios imply always the analysis of a broad variability of different trends they provide a better understanding of many different alternative developments that may be close to the scenario assumptions, but do not necessarily conform to them completely. In reality, future developments always differ from initial predictions, but the elaboration of scenarios allow this way to get a better idea, how the future could like look.

In this respect, the DEPA 2050 scenarios provide a general orientation on trends that are relevant for all air transport vehicle types and thus, present a good starting point for further research. This is linked to two essential strategic objectives of the project: 1) to deliver an agreed and

upgradable estimation of the possible future development in air transport and 2) to develop a consistent and permanent aviation technology modelling and assessment framework for DLR.

The documentation of the corresponding working steps and results, as presented in this report, finally also allowed to deviate further recommendations how a future-oriented, efficient and sustainable air transport system should be designed. Anyhow, taking the huge dynamics in the air transport market and in technology development into account, further research is needed to fully identify and exploit the identified technology potentials over the long-term. The following section presents some of the most relevant research fields in this respect.

6.2.   Further Research Needs

The DEPA 2050 study aimed at delivering a first consistent and coherent set of future aviation scenarios covering innovative technologies and new vehicle concepts with a system-wide approach. In addition, an extended impact analysis was conducted to illustrate the possible consequences in the field of sustainability by estimating diverse effects on mobility and vehicle productivity, the environment in terms of emissions and noise as well as on the overall economic development up to the year 2050.

By interpreting the corresponding results, it has to be considered that they represent a state-of-the-art snapshot. Changing circumstances as, for instance, the Covid-19 pandemic has shown, justify a regular update of the conducted analyses to address new trends that may evolve over time. This allows to conclude on possible consequences for the development of the aviation sector and, vice versa, the meaning for society. In this respect, there might be a need to extend the time horizon of the study analysis over the next years. Especially for climate research extended time scales are needed to predict the long-term impact of aviation on climate change and to have broad set of scenarios available in order to investigate and compare different potential developments. Taking the DEPA 2050 study as a starting point, an appropriate update over the next years could cover a time span until 2070 or beyond. However, this approach also comes along with higher uncertainties (e.g. with regard to aviation policies, technological developments and many other scenario factors). In this respect, one solution to overcome this issue might be to increase the number of regarded scenarios to cover more alternatives for future developments. Furthermore, diverse sensitivity analyses might reduce the level of uncertainty. Following the DEPA 2050 scenario framework such sensitivity analyses could address, for instance, the choice of single aviation technologies or technology bundles and their individual impact on vehicle and fleet level. Additional sensitivity analyses could concentrate on possible changes of the modal split within the air transport sector to testify varying market shares with special regard of more innovative transport concepts (i.e. urban air mobility, supersonic air transport).

An additional approach in the field of scenario conceptualisation could consider normative scenarios to address requirements from politics and society. For instance, the European Green Deal – besides other objectives for aviation – might be a useful starting point to question and to define, which technologies and which vehicle concepts as well as which type of market

conditions are needed and preferable to fulfil given goals. Another option might also deal with free-chosen obligations. For example, normative scenarios could also be defined in a way that only one pillar of sustainability is improved to the most possible extent. Within the environmental pillar of sustainability this could for example refer to a scenario in which aircraft noise reduction has the highest priority and determines the choice of aviation technologies and the overall air transport market development.

Besides the scenario development also intensified research in the field of technology and vehicle modelling is needed in the future. This requirement is mainly referring to the need of improving a system-wide and realistic focus on possible TRL levels and the EIS of aviation technologies, which is even among experts controversially discussed. To support the achievement of this goal the recognition of unified performance metrics for technologies and vehicle concepts could be a first important step. Another one is an intensified conduction of sensitivity analysis have to be conducted to assure a higher reliability in the results of technology assumptions and choices. In addition, a stronger orientation towards market requirements is needed meaning that in the most extremely way a promising technology will not necessarily conquer a specific market if, for instance, its costs exceed an acceptable limit from a user's point of view. Thus, for future research especially the production and direct operating costs of technologies as well as follow-up costs (e.g. with regard to MRO) are important criteria to improve the estimation of TRL levels and EIS for aviation technologies. Anyhow, the investigation of those factors and the prediction of their importance over the long-term is a complex and challenging task that goes beyond the scope of a single study as conducted in the context of the DEPA 2050 project. In addition, data and information especially with regard to costs is sensitive data and not publicly available meaning that this information can only be estimated in ranges and therefore only partially improve the technology and vehicle modelling results.

In relation to the conducted vehicle-specific forecasts the most important question for future research is, to what extent the Covid-19 pandemic, but also other wild card effects, will influence the air transport demand over the medium- and long-term. While different external scenarios exist for the recovery of air transport demand over the next decade in relation to the Covid-19 pandemic travel behaviour might eventually change over the long-term, if a larger share of society considers air travel as not necessary anymore. This holds for the market segment of business travellers, which might replace air travel more and more by virtual meetings, but also for private travellers that consider an active abdication of air travel as essential contribution to reduce the negative impact of climate change. The development of those drivers is not fully predictable yet, but changes in this field might be a direct outcome of the Covid-19 pandemic and may first evolve over the next years.

Finally, there is additional research needed in the field of the presented impact analyses in the scope of the DEPA 2050 study. In relation to the impact category of "mobility and vehicle productivity" this holds especially for the investigation of the further market share development of new transportation concepts in the field of urban air mobility and supersonic air transport. Both types of air transport are "game changers" and will significantly influence the competition

and modal split within the air transport sector itself and with regard to other transportation modes. Resulting consequences are hardly to predict yet completely. Thus, to improve the reliability of the findings of this study further investigations of potential user groups and regional demand for supersonic air transport and urban air mobility are needed. The same holds for the further analysis of chances and challenges linked to those types of air transport (e.g. with regard to ATM restrictions, safety and security requirements, etc.). Finally, a holistic and complete comparison of connectivity improvements and travel time savings between different modes of air transport and other modes of transport would be a valuable topic for further research especially guided by the question to what extent urban air mobility and supersonic air transport will provide additional benefits for the society. However, the analysis for mainliner and regional aircraft has already shown that even for Europe adequate data is missing as only scheduled air transport is covered by official statistics in a needed granularity for such analyses. In addition, passenger survey data to determine the concrete origin and destination of passengers is not available meaning that real travel chains from door-to-door cannot be analysed and have to be investigated on base of diverse assumptions. Thus, system-wide connectivity analyses dealing with new transportation concepts are currently not feasible and can only be conducted in form of "what-if" studies.

In relation to the assessment dimension of "emissions" further research is also needed. For instance, the effect of soot aerosols on cloud formation is not fully understood yet similar to the effects of sulphate aerosols. Furthermore, the effects of the DEPA 2050 scenarios and the respective fleet development has not been investigated in relation to the consequences of local air quality. The general development of future emissions especially in regard of CO_2 emissions depends finally also on concrete climate policies and their enforcement and success, which was excluded from the scope of this study to concentrate on the pure technology impacts as a first approach. However, in relation to given goals for the aviation sector and the political and industrial willingness to foster disruptive change in aviation technologies (e.g. by hydrogen-powered aircraft and SAF usage) the whole impact assessment becomes significantly more complex. For instance, in relation to SAF the composition and properties and hence the emissions of conventional jet fuels vary and have significant regional and also temporal variations. Also, the composition and properties and hence the emissions of SAF varies between the different production pathways, but also between different facilities due to varying process parameters. This has implications on the emissions of the blends. In addition, the available volumes of SAF in the future will vary from region to region and hence the achievable blending ratio at each airport. Emission reduction from SAF usage in further studies should therefore be assessed with these regional differences.

Similarly, for SAF but also for all other fuels (conventional jet fuels and H2) availability and costs will decide about their individual market shares and thus, finally about the related emissions. The problem here is that especially the cost development is complex and hardly predictable taking also the future competition with users from other industries into account. To overcome these uncertainties further scenario specifications and sensitivity analyses are needed. On base of the

general hydrogen sub-scenario that was part of the DEPA 2050 study further analyses should at this base concentrate more on infrastructure conditions at airports but also on the requirements of airlines in terms of short turn-around times, low costs and higher aircraft productivity.

Finally, in relation to the impact analysis conducted in the DEPA 2050 study further research on aircraft noise is needed. Due to the complexity of this topic and the clear focus of industry and politics on CO_2 emissions reductions the development pathways of the DEPA 2050 study concentrated mainly on greenhouse gas emissions in relation to the choice of promising aircraft technologies for the DEPA 2050 scenarios. Proceeding research could therefore focus on the design and modelling of noise-optimised vehicles to testify the overall impact by populating the global fleet with corresponding technology.

Anyhow, specific obstacles remain. A noise impact assessment is difficult due to the subjective awareness of aircraft noise. In addition, a unique measure and a single, commonly accepted metric to evaluate aircraft noise does not exist as in the case of greenhouse gas emissions. While some measures focus more on the aircraft noise itself, others concentrate on the affected population or the number of noise events. Furthermore, local conditions may differ significantly from airport to airport (e.g. depending on the size of an airport and potential curfews). This makes a general judgement about the status-quo noise situation on global scale hardly feasible and for long-term projections this gets even more difficult. Anyhow, a specific analysis of aircraft noise reduction potentials for specific vehicles in form of scenarios may be a first step to estimate these potentials more concretely and to compare it with predictions of external studies that typically analyse the noise development over the past to draw conclusions for future noise development. Finally, an intensified trade-off analysis between technological noise reduction potentials and the benefits for society in terms of human health is also a precious field for future research.

With regard to the impact analysis in the field of economy which was conducted in the scope of the DEPA 2050 study, future research is especially needed to investigate long-term trends. Besides the impact of the Covid-19 pandemic especially aviation-related employment will surely be affected by further digitalisation and automatisation. As in other sectors this might eventually lead to job cuts or a higher demand for highly-skilled personnel. At the same time the added value generated by the aviation sector might further increase, if digitalisation and automatisation lead to productivity increases and cost savings. Such effects are partially already discussed (e.g. for the automotive sector) while for the aviation sector detailed studies about those effects are rarely available.

7. Annex

Appendix A: Overview scenario publications

No.	Publication / Project	Year	Author	Time horizon	Thematic focus	No. Scenarios
1	Future of the airline industry 2035	2018	IATA	2035	Aviation	4
2	Three Scenario Narratives for a Resource-Efficient and Low-Carbon Europe in 2050	2018	Schanes, K. et al.	2050	Environment	3
3	European aviation in 2040 - Challenges of Growth	2018	EUROCONTROL	2040	Aviation	4
4	Aviation benefits beyond borders	2018	ATAG	2050	Aviation	2
5	Forecasting Air Passenger Demand between settlements worldwide based on Socio-Economic Scenarios	2017	Terekhov, I.	2050	Aviation	4
6	Energy Technology Perspectives	2017	IEA	2060	Energy / Environment	3
7	Mobility4EU - D3.1, Report on MAMCA scenario descriptions	2017	Vrije Universiteit Brussel (VUB)	2030	Transport / Mobility	4
8	DATASET2050 - D 4.2 "Future Supply Profile"	2017	University of Westminster	2050	Aviation	3
9	ITF Transport Outlook	2017	OECD/ITF	2050	Aviation / Transport	3
10	Global Trends	2017	NIC	2035	General	3
11	2050 Global Work/Technology Scenarios	2016	The Millenium Project	2050	Technology / General	3
12	Air traffic growth, energy and the environment 2040: drivers, challenges and opportunities for aviation	2015	Randt, N. et al.	2040	Aviation	3
13	Zukunft der Mobilität- Szenarien für Deutschland in 2035	2015	ifmo	2035	Transport / Mobility	2
14	ET2050 Territorial Scenarios and Visions for Europe	2014	Ulied, A. et al.	2030 / 2050	European territory	3
15	CECILIA 2050 - Macroeconomic routes to 2050	2014	Meyer, B. et al.	2050	Environment / Policy	3
16	RACE 2050 - Responsible innovation Agenda for Competitive European transport industries up to 2050	2014	TU Berlin	2030 / 2050	Transport	6
17	2050 Scenarios for Long-Haul Tourism in the Evolving Global Climate Change Regime	2013	Vorster, S. et al.	2050	Aviation	4
18	Applied scenario planning as a basis for the assessment of future aircraft technologies	2013	Randt, N. et al.	2050	Aviation	3
19	Global Europe 2050	2012	European Commission	2050	General	3
20	Delivering tomorrow - Logistik 2050	2012	DHL	2050	General / Logistics	5
21	Global Environment Outlook (GEO 5)	2012	UNEP	2050	Environment	2
22	OPEN:EU Scenario Storylines, Report: Scenarios for a One Planet Economy in Europe	2011	Gardner, L. et al.	2050	Economy / Environment	4
23	Global Transport Scenarios 2050	2011	WEC	2050	Transport	2
24	TOSCA - D 8 Scenarios of European Transport Futures in a Global Context	2011	Schäfer, A.	2050	Transport	3
25	Towards the future generation of Air Transport System	2010	EREA	2050	Aviation	4
26	Airport 2030 - Szenarioerstellung im Rahmen des Leuchtturmprojektes „Effizienter Flughafen"	2010	Phleps, P.	2030	Aviation / Airport	3
27	Zukunft der Mobilität- Szenarien für das Jahr 2030	2010	ifmo	2030	Transport / Mobility	3
28	TRANSvisions - Report on Transport Scenarios with a 20 and 40 Year Horizon	2009	Petersen, M. et al.	2050	Transport	4
29	Shell energy scenarios to 2050	2008	Shell	2050	Energy	2
30	STOA - The Future of European long-distance transport	2008	ETAG	2050	Transport	3
31	Aviation in a low-carbon EU	2007	Tyndall Centre for Climate Change Research	2050	Aviation	4
32	CONSAVE 2050	2005	Berghof et al.	2050	Aviation	4

No.	Publication / Project	Year	Author	Time horizon	Thematic focus	No. Scenarios
33	Ecosystems and Human Well-being: Scenarios, Volume 2	2005	Millenium Ecosystem Assessment	2050	Environment	4
34	Quantifying Four Scenarios for Europe	2003	Lejour, A.	2040	General	4
35	Great Transition	2002	Global Scenario Group	2050	General	6
36	Special report on emission scenarios (SRES)	2000	IPCC	2050	General / Environment	4 [6]

Appendix B:

Estimated total gross value added created by the air transport sector up to 2050 on national, European and global scale (in million Euro)

Country	2014	2020	2030	2040	2050	% GVA economy
Australia	17,998	21,210	25,933	30,601	36,967	1.8%
Austria	3,562	3,970	4,683	5,302	6,164	1.2%
Belgium	3,986	4,700	5,460	6,147	6,919	1.1%
Brazil	12,437	12,818	15,989	19,226	23,675	0.8%
Bulgaria	604	842	1,008	1,185	1,408	1.6%
Canada	17,477	19,584	23,091	26,526	30,465	1.4%
China	69,131	96,367	126,289	154,915	191,564	0.9%
Croatia	336	447	532	613	690	0.9%
Cyprus	219	301	363	409	485	1.4%
Czech	1,232	1,546	1,838	2,086	2,389	0.9%
Denmark	2,559	3,032	3,535	4,038	4,668	1.1%
Estonia	213	269	327	377	404	1.2%
Finland	2,764	3,113	3,708	4,259	4,924	1.6%
France	21,124	24,745	28,882	32,700	36,796	1.1%
Germany	28,931	34,298	40,505	46,335	53,478	1.1%
Greece	2,734	3,666	4,249	4,729	5,269	1.7%
Hungary	1,054	1,376	1,672	1,926	2,223	1.2%
India	6,649	9,898	13,307	15,039	16,952	0.4%
Indonesia	21,701	31,769	38,855	44,192	50,662	3.3%
Ireland	5,604	7,393	8,524	9,400	9,606	3.3%
Italy	12,157	14,383	16,514	18,477	20,535	0.8%
Japan	23,932	28,453	33,130	37,571	42,157	0.7%
Korea	11,033	13,936	17,098	19,957	23,390	1.1%
Latvia	416	505	600	676	757	2.0%
Lithuania	328	433	533	614	716	1.0%
Luxembourg	429	549	640	710	794	1.0%
Malta	131	173	200	217	243	1.8%
Mexico	9,617	12,010	14,689	17,451	20,220	1.0%
Netherlands	12,567	15,804	18,646	21,401	24,880	2.1%

Country	2014	2020	2030	2040	2050	% GVA economy
Norway	5,268	5,680	6,731	7,660	8,693	1.6%
Poland	2,768	3,732	4,676	5,339	6,269	0.8%
Portugal	3,570	4,885	5,663	6,375	7,166	2.4%
Romania	1,303	1,885	2,306	2,692	3,179	1.0%
Russia	22,848	26,444	31,094	34,806	38,592	1.9%
Slovakia	407	694	809	963	1,176	0.6%
Slovenia	281	330	385	443	562	0.9%
Spain	11,069	14,041	16,464	18,616	21,291	1.2%
Sweden	4,344	5,293	6,249	7,050	8,043	1.1%
Switzerland	11,257	12,796	14,796	16,686	19,047	2.2%
Taiwan	6,501	9,143	11,224	13,185	15,749	1.7%
Turkey	8,523	11,529	14,110	16,309	19,472	1.6%
United	32,176	39,228	44,953	50,546	57,758	1.6%
United States	185,762	209,200	248,621	289,208	334,203	1.4%
World	587,005	721,728	881,680	1,029,406	1,214,572	1.2%
EU28	156,868	152,405	178,970	203,077	231,034	1.3%

Appendix C

Estimated total employment created by the air transport sector up to 2050 on national, European and global scale

Country	2014	2020	2030	2040	2050	% Jobs economy
Australia	187,999	221,554	270,880	319,646	386,139	1.6%
Austria	46,500	51,826	61,134	69,210	80,465	1.1%
Belgium	48,329	56,984	66,204	74,526	83,885	1.1%
Brazil	647,925	667,791	832,966	1,001,612	1,233,398	0.6%
Bulgaria	49,516	69,058	82,609	97,132	115,414	1.4%
Canada	203,423	227,952	268,763	308,754	354,596	1.1%
China	5,881,894	8,199,255	10,745,097	13,180,707	16,298,866	0.7%
Croatia	13,908	18,507	22,033	25,358	28,568	0.9%
Cyprus	5,951	8,170	9,860	11,107	13,177	1.7%
Czech Republic	39,262	49,265	58,578	66,482	76,140	0.8%
Denmark	24,680	29,239	34,090	38,943	45,016	0.9%
Estonia	5,770	7,295	8,854	10,208	10,955	0.9%
Finland	33,243	37,444	44,597	51,224	59,220	1.3%
France	243,471	285,211	332,886	376,890	424,102	0.9%
Germany	421,031	499,138	589,469	674,309	778,259	1.0%
Greece	46,734	62,657	72,632	80,839	90,071	1.2%

Country	2014	2020	2030	2040	2050	% Jobs economy
Hungary	35,795	46,734	56,798	65,422	75,488	0.8%
India	2,181,462	3,247,292	4,365,738	4,934,181	5,561,703	0.3%
Indonesia	3,301,169	4,830,892	5,908,534	6,720,066	7,703,882	2.0%
Ireland	40,241	53,089	61,210	67,502	68,977	2.1%
Italy	216,503	256,150	294,091	329,056	365,713	0.9%
Japan	240,772	286,256	333,314	377,986	424,132	0.4%
Korea	209,698	264,870	324,964	379,303	444,567	0.9%
Latvia	14,621	17,733	21,078	23,758	26,606	1.6%
Lithuania	9,226	12,193	14,987	17,263	20,148	0.7%
Luxembourg	3,766	4,818	5,620	6,231	6,972	0.9%
Malta	3,640	4,818	5,565	6,022	6,743	1.9%
Mexico	198,596	248,005	303,327	360,369	417,547	0.5%
Netherlands	155,642	195,727	230,926	265,050	308,135	1.8%
Norway	30,948	33,371	39,545	45,000	51,067	1.1%
Poland	109,871	148,117	185,621	211,916	248,842	0.7%
Portugal	80,728	110,474	128,047	144,166	162,054	1.8%
Romania	63,871	92,416	113,014	131,967	155,824	0.7%
Russia	926,483	1,072,310	1,260,874	1,411,397	1,564,887	1.2%
Slovakia	10,929	18,632	21,727	25,853	31,581	0.5%
Slovenia	7,221	8,477	9,905	11,393	14,446	0.8%
Spain	179,211	227,327	266,554	301,400	344,716	1.0%
Sweden	48,154	58,669	69,267	78,146	89,154	1.0%
Switzerland	122,742	139,524	161,334	181,938	207,679	2.4%
Taiwan	302,583	425,560	522,392	613,689	733,009	1.5%
Turkey	312,211	422,320	516,877	597,410	713,295	1.0%
United Kingdom	402,699	490,964	562,615	632,606	722,874	1.3%
United States	1,824,764	2,055,001	2,442,239	2,840,923	3,282,917	1.2%
World	18,933,182	23,278,314	28,437,334	33,202,037	39,174,316	0.8%
EU28	2,360,512	2,430,170	2,867,356	3,261,375	3,730,672	1.0%

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