Deliverable D1.1

Air traffic and fleet modelling for 2050

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Abstract

For work package 1 of the MINIMAL project, we present future aircraft fleet compositions that are developed on the basis of two building blocks: Economic scenario development and technological improvements aiming at reducing the total global fuel consumption. These fleet compositions will feed into estimating the overall climate impact of aviation. Over a time horizon until 2050, we conduct simulations of the global transport effort distributed over 34 route groups, operated by up to 13 different aircraft types for five different scenarios.
The results of these simulations show that the overall global fuel burn is foremost influenced by the demand, and the technological improvements in this work can only offer a short respite, despite a steady efficiency gain of the entire fleet on an ASK level.

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Nature of the deliverable [1]

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Dissemination level

PU	Public, fully open. e.g., website	✔
SEN	Sensitive, limited under the conditions of the Grant Agreement	
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DEM: demonstrator, pilot, prototype, plan designs.
DEC: websites, patent filings, press and media actions, videos, etc.
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Abbreviations

AF	Africa
AS	Asia
ASK	available seat kilometre
ATAG	Air Transport Action Group
BADA	Base of aircraft data
BAU	business as usual
BHL	Bauhaus Luftfahrt
BL / bl	baseline aircraft
CAGR	compound annual growth rate
DEPA	Development Pathways for Aviation
EIS	entry-into-service date
EU	Europe
FCECT	fuel-consumption and emissions calculation tool
FSDM	Fleet System Dynamics Model
IATA	International Air Transport Association
kg	kilogram
km	kilometre
L	medium-to-long-haul routes
LA	Latin America
ME	Middle East
MINIMAL	MInimum enviroNmental IMpact ultra-efficient cores for Aircraft propuLsion (project)
NA	North America
nm	nautical miles
OD	origin–destination
RA / ra	reference aircraft
RPK	revenue passenger kilometre
S	short-haul routes
S1, S2,…	Scenario 1, Scenario 2,…
SAF	sustainable aviation fuel
UNFCCC	United Nations Framework Convention on Climate Change
WP	work package

Executive summary

This document forms part of work package (WP) 1 of the MINIMAL project. We present future aircraft fleet compositions up until 2050 that are developed on the basis of two building blocks: Economic scenario development and technological improvements aiming at reducing the total global fuel consumption. Within the MINIMAL project, the future fleet compositions will feed into estimating the overall climate impact and mitigation potential for key technology scenarios, policy measures and operational procedures.

We develop five different MINIMAL scenarios that take into account different factors, scenarios and forecasts, which serve as input parameters for the modelling framework. The purpose of including different potential development paths of the global aviation sector is to anticipate the effects and uptake of new aircraft technologies within existing aircraft fleets. Future demand trends can account for modifications in travel behaviour and affect passengers' propensity to fly. Furthermore, supply side developments may also influence the future air transport sector.

Based on demand trends, the in-house BHL fleet model allocates existing commercial aircraft fleets and estimates the need for additional aircraft. Further, it accounts for production capacities and aircraft life cycles in order to draw realistic pictures of fleet turnovers. Ultimately, estimates will be given for fleet compositions, aircraft allocation, air traffic volumes and fuel.

Over a time horizon until 2050, we conduct simulations of the global transport effort distributed over 34 route groups, operated by up to 13 different aircraft types for five different scenarios. The results of these simulations show that the overall global fuel burn is strongly influenced by demand, and the technological improvements in this work can only offer a short respite. Over the simulation period, we observe a decrease in fuel burn for scenarios with low demand or medium demand where advanced technology has been introduced. In comparison, in the business-as-usual scenario or the scenario with high demand, fuel-burn numbers increase steadily. This emphasises the need for early introduction of new technology and more efficient propulsion systems (like the MINIMAL CCE concepts) in order to reduce global fleet fuel burn by 2050. Going into more detail allows us to differentiate further. On routes below 1000 nm, the technological advances, i.e. the introduction of baseline aircraft, mean that the trend of fuel-burn decrease is more strongly pronounced even with medium RPK growth rates, compared to longer routes. In our scenarios, new aircraft are readily accepted into the fleet mix, since they provide better efficiencies compared to what was previously available. This is also facilitated through the ambitious production capacity, that need to be in line with the RPK growth rates, in order to meet the various demand increases. This leads to steady efficiency gains of the entire fleet on an ASK level.

It is important to stress, that the current model uses fuel burn as an optimisation parameter, which is suitable to estimate the potential of fuel-burn reduction, however, it does not accurately reflect how aircraft are allocated in the market. Typically, there we see a behaviour aimed at maximising profits of single airlines or alliances, rather than minimizing the global fuel used.

1. Introduction

With this document, we present future aircraft fleet compositions up until 2050 that are developed on the basis of two building blocks: Economic scenario development and technological improvements aiming at reducing the total global fuel consumption.

We start with an overview of the objectives and the tripartite modelling approach to determine future fleet compositions, see in Section 2. Then we describe the process of scenario development in Section 3 and the modelling framework in Section 4. We conclude with a discussion of the results in Section 5. With Section 7, we provide an appendix that contains raw data on flights for the different scenarios.

2. Objectives

This document forms part of work package WP1 of the MINIMAL project. The aim of WP1 is to quantify the climate impact in terms of global temperature rise concerning novel engine configurations in future (e.g., the MINIMAL concept) and alternative fuels (e.g., SAF and hydrogen) under different scenarios, policy measures and operational procedures.

As a first step, we model potential compositions of future aircraft fleets and make use of a tripartite approach, see Figure 2-1.

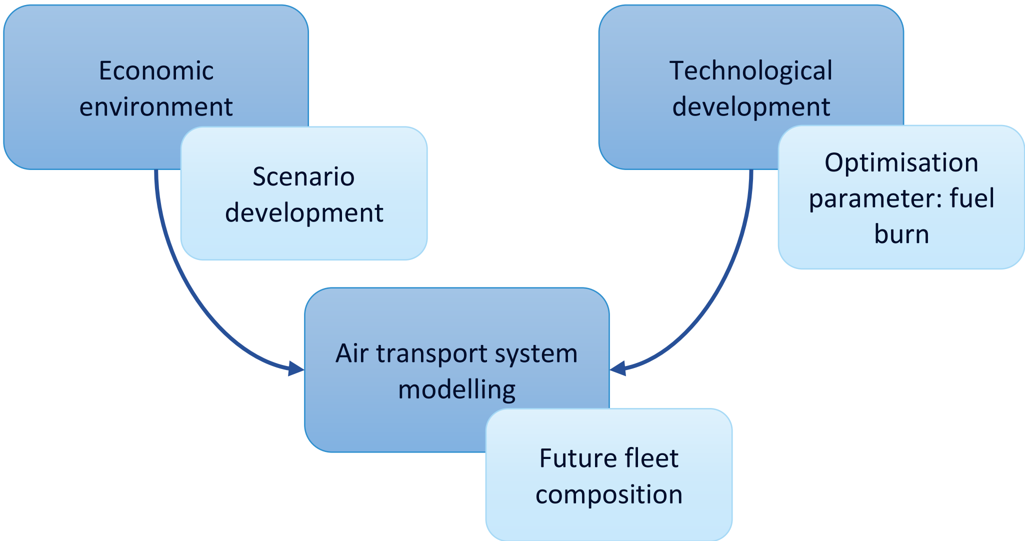

Figure 2-1 Tripartite modelling approach to determine future fleet compositions.

To this end, we create scenarios depicting a range of demand trends and estimate technological developments, in particular the evolution of fuel requirements, in the aviation sector. We then incorporate the outcome into a modelling framework for estimating fleet developments up to 2050. The results show us—per scenario—what types of aircraft constitute the global fleet, how these aircraft are allocated to different regions, what air traffic volumes to expect and how much fuel is burnt.

In the following, we give a detailed description of the scenario-building process, the nature of the different scenarios and their key differentiation points. We then explain the framework that is used to model the air transport system and what assumptions are being made.

3. Scenario development

The purpose of including different potential development paths of the global aviation sector is to anticipate the effects and uptake of new aircraft technologies within existing aircraft fleets. Future demand trends can account for modifications in travel behaviour and affect passengers' propensity to fly. Furthermore, supply side developments may also influence the future air transport sector. The work within MINIMAL WP1 therefore included a literature review of various studies that consider factors with a possible influence on aviation demand and supply as well as the collection of a multitude of scenario studies and forecast (see Section 3.1).

Taking these different factors, scenarios and forecasts into account, five different MINIMAL scenarios have been derived (Section 3.2) which serve as input parameters for the modelling framework established in Section 4.

3.1. Scenario and forecast review

As a starting point, different scenario studies and forecasts have been assessed in regard to their geographical focus and coverage, the air transport market segments being covered (e.g. short-, medium-, long-haul), publicly available data of e.g. RPK growth rates, and other factors of relevance for the MINIMAL project. These different studies are depicted in Table 1: Airbus (2023) and EUROCONTROL Aviation Outlook 2050 (2022) are considered most appropriate in terms of number presentation and their association to route groups, see Section 4.2.2

Table 1 Overview scenario studies and air transport forecasts

Reference	Geographical focus	Forecast	Scenarios	Market segments	Data publicly available	MINIMAL relevance
Modus (2021)	Europe	x	x	Short-/ medium-haul	Partly, no RPK growth rates on detailed route level	
DEPA2050	Global	x	x	All	Partly, no RPK growth rates on detailed route level	
Airbus (2023)	Global	x		All	RPK growth rates on detailed route level	X
Boeing (2023)	Global	x		All	RPK growth rates on detailed route level	
EUROCONTROL Challenges of Growth (2018)	Detailed European focus, global	x	x	All	Growth rates on detailed route level available	
EUROCONTROL Aviation Outlook 2050 (2022)	Detailed European focus, global	x	x	All	Growth rates on detailed route level available	X

3.2. MINIMAL scenario development

The different scenarios, parameters and respective assumptions have been discussed and validated within an internal MINIMAL expert workshop. Each scenario is currently described by three distinctive parameters: (1) the revenue passenger growth (RPK) rate per year over the considered time period, (2) the production capacity of the aircraft, and (3) the route uptake of these particular market segments.

Furthermore, the modelling framework distinguishes different world regions such as Europe or Asia, see Section 4.2.2Network assumptions. For further analysis, it may be possible to assume different uptake rates of new aircraft across these regions in order to test the impact of e.g. subsidies in specific world regions. However, within the scope of the analysis in this deliverable, providing the input for the consecutive analysis within the MINIMAL project, uptake rates that further differentiate a high and low uptake are assumed to be the same across regions but can differentiate within a region on long and short routes. Another factor which can be used to distinguish scenarios from each other is the introduction of sustainable aviation fuel (SAF) across the entire aircraft fleet. This may also be an aspect for future considerations. These factors have been discussed within the internal expert workshop, for the assessment of the baseline aircraft it was decided to opt for lower complexity in order to assess the effects of this aircraft introduction equally on a global level.

(1) RPK growth

The RPK growth indicates the assumed growth rate per route and per year for the different scenarios. A route in this context denotes the connections within or between particular global regions, such as within Europe or between Europe and North America (and vice versa). An overview of these routes can be found in Section 4.2.2. The ranges in growth rates depict the lowest and highest value across the different regions; three RPK growth pathways have been assumed (low, medium and high) to account for potential futures of the air transport sector.

(2) Production capacity of the aircraft

The production capacity indicates the capacity of different aircraft manufacturers to produce a certain amount of aircraft per year. Historical values are available and big manufacturers also project future numbers of aircraft. For the scenarios we use an ambitious production capacity, derived from Boeing, Airbus, Embraer, Bombardier and ATR. A comprehensive study was also produced by Leeham[2] which served as input.

(3) Route uptake

This factor describes whether the RPK growth rates differ by market segment (short- vs. long-haul air traffic).

Five scenarios have been derived which differ with respect to these factors. As the reference case for the modelling framework, the '**Business as usual (BAU)**' scenario is introduced. Here, medium RPK growth rates between 1.1% and 3.4% compound annual growth (CAGR) are assumed, and reference aircraft with state-of-the-art technology are included in the modelling framework.

'Scenario 1' ("Fast Tech") assumes the same growth path as the BAU scenario and differs in regard to the aircraft technologies considered: an evolutionary technology uptake is assumed with an entry into service goal of 2040, thus implying a fast technology implementation.

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[2] Leeham, Production rates by Airbus and Boeing. http://leehamnews.com/2015/02/03/airbusboeing-production-rates-forecast-through-2020/

Compared to this, **'Scenario 2'** ("Slow Tech") also assumes an evolutionary aircraft technology uptake but with an entry into service goal of 2045, thus implying a slower technology uptake.

'Scenario 3' ("Fast Uptake"), on the other hand, assumes much higher RPK growth rates than the previous scenarios. Across the various world regions, the rates range from 1.7% up to 5.3%. This also aligns with a faster uptake of evolutionary aircraft technologies, and hence an assumed entry into service of 2040. A further differentiation of this scenario is the higher growth rates and therefore assumed uptake of aircraft technologies on short-haul market segments.

'Scenario 4' ("Slow Uptake") depicts the future path with the lowest growth rates, ranging between 0.4% and 1.0% for the various world regions. This also implies that the uptake of evolutionary aircraft technologies is slower, hence leading to an assumed entry into service in 2045. Furthermore, it is assumed that long-haul routes experience higher growth rates than short-haul ones.

Table 2 MINIMAL scenarios

Factor	Business as usual (BAU)	Scenario S1	Scenario S2	Scenario S3	Scenario S4
RPK growth	Medium 1.1%-3.4% CAGR[3]	Medium 1.1%-3.4% CAGR[4]	Medium 1.1%-3.4% CAGR[5]	High 1.7%-5.3%[6]	Low 0.4%-1.0% CAGR[7]
Availability of aircraft types	Reference aircraft (state-of-the-art technology)	Baseline aircraft EIS 2040 (evolutionary technology uptake)	Baseline aircraft EIS 2045 (evolutionary technology uptake)	Baseline aircraft EIS 2040 (evolutionary technology uptake)	Baseline aircraft EIS 2045 (evolutionary technology uptake)
Route uptake				Higher demand on short-haul v. long-haul routes	Lower demand on short-haul v. long-haul routes
Regional uptake	No further self-tailored regional differentiation in uptake values; based on distinct regional growth rates as assumed in 'demand development'.				
SAF introduction	No impact in the aircraft/ fleet choice in this part.				

The drop in passenger numbers during the COVID-19 pandemic was not modelled in detail but a flattening of passenger numbers has been introduced during that period, picking up at current levels. This is due to the fact that the fleet model introduced in the following section does not assume a renewal of the fleet during periods of negative demand up until the "original" demand is surpassed again.

[3] EUROCONTROL Aviation Outlook 2050 (2022) (base scenario)
[4] EUROCONTROL Aviation Outlook 2050 (2022) (base scenario)
[5] EUROCONTROL Aviation Outlook 2050 (2022) (base scenario)
[6] Airbus General Market Forecast 2023-2042 (2023)
[7] EUROCONTROL Aviation Outlook 2050 (2022) (low growth scenario)

4. Modelling framework

Based on demand trends, the in-house BHL fleet model will allocate existing commercial aircraft fleets and estimates the need for additional aircraft. Further, it will account for production capacities and aircraft life cycles in order to draw realistic pictures of fleet turnovers. Ultimately, estimates will be given for: fleet compositions, aircraft allocation, air traffic volumes and fuel consumption.
The BHL fleet model is under development since 2012, in cooperation with the Technical University in Munich. It has been used in various studies for a time horizon until 2050 (Randt et al., 2015; Ploetner et al., 2017; Ploetner et al., 2018) and for a time horizon until 2100 (Habersetzer et al., 2020) and took inspiration from e.g. Jimenez et al. (2012), Schaefer (2012) and Tetzloff and Crossley (2014). The results have been validated against aviation specific as well as global aims for reducing emissions, such as Flightpath 2050 (The European Commission, 2011), ATAG Goals (ATAG (Air Transport Action Group), 2011), or the Paris Agreement (UNFCCC (The United Nations Framework Convention on Climate Change), 2015), and compared to current market forecasts (see Section 3.1).

4.1. Model description

At the heart of modelling the air transport systems lies the Fleet System Dynamics Model (FSDM), the flow of which is depicted in Figure 4-1.

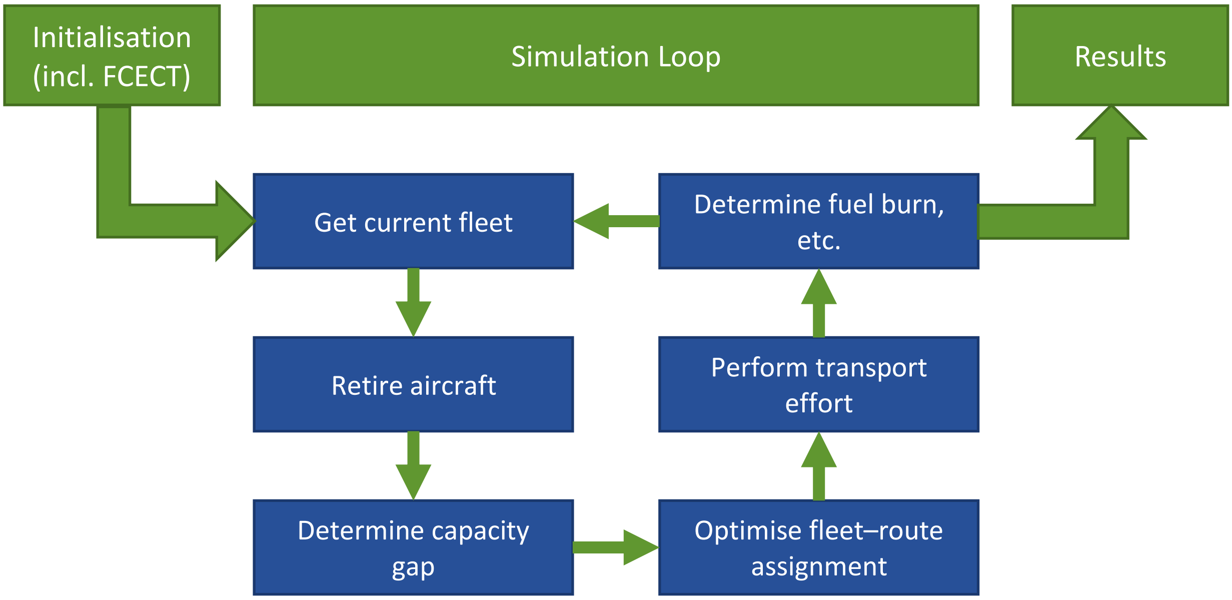

Figure 4-1 Flow of the Fleet System Dynamics Model (FSDM)

The modelling sequence starts with an initialisation phase, in which all user input is processed and prepared for the simulation. Details on this can be found in Section 4.2. In the following, we are describing each part of the simulation loop in turn. Note that the simulation begins from the year after the base year, since the data for the base year is already provided in the input files.

4.1.1. Get current fleet

In the first year of the simulation, the fleet is read from the input files. For all subsequent years, the fleet at the start of the year is carried forward from the previous year including all changes that happened throughout that year.

4.1.2. Retire aircraft

Aircraft retirement is performed on every aircraft based on the retirement curves for that aircraft. These retirement curves provide the probability of survival of an aircraft of a certain age. The logistic S-curve function form derived by (Morrell & Dray, 2009) given as follows can be used in calculating the probability of survival (POS):

$$POS = \frac{1}{1 + e^{(-\beta_I - \beta_{II})}}$$

Where β_I and β_{II} are retirement coefficients specific for each type of aircraft. This probability is fed into a randomised approach in order to make the retirement non-deterministic.

4.1.3. Determine capacity gap

To determine the capacity gap, the first step that is performed is the calculation of the total ASKs required on every route based on the input data and data from the simulation of previous year. The following formula is used to calculate the required ASK for the current year:

$$ASK_{req} = ASK_{prev} \cdot lf_{prev} \cdot RPK_{curr}/lf_{curr}$$

Where ASK_{prev} is the ASK calculated from the fleet of the previous year, lf_{prev} is the passenger load factor of the previous year (determined via the input), RPK_{curr} is the demand growth of the current year (read from input) and lf_{curr} is the passenger load factor of the current year (from input). These ASKs might not always be satisfied exactly. This could occur due to rounding errors, since the aircraft fleet size is always an integer, or in scenarios where the aircraft production in a certain year is not high enough to fulfil the capacity gap. This would result in an under-satisfied ASK in that year, which would also be carried forward into future years. To ensure that this doesn't occur, the above formula is slightly modified:

$$ASK_{req} = (ASK_{prev} - ASK_{oversatisfied} + ASK_{undersatisfied}) \cdot lf_{prev} \cdot RPK_{curr}/lf_{curr}$$

The capacity gap is then calculated as the difference between the required ASKs and the ASKs satisfied by the fleet remaining after retirement. As a result, the capacity gap takes into account both the market growth gap and the retirement gap, as shown in Figure 4-2:

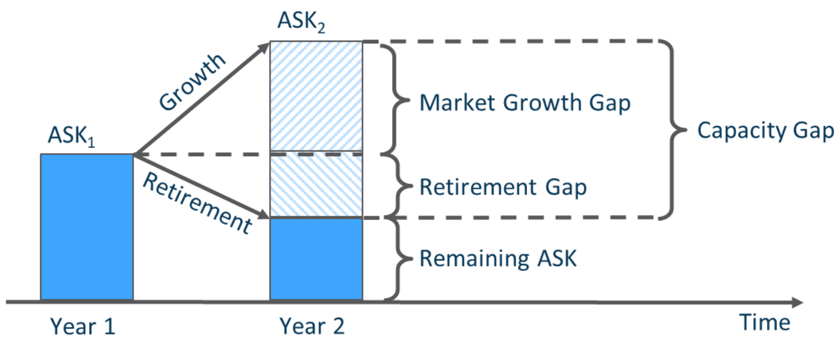

Figure 4-2 Illustrating the capacity gap, see Randt (2013)

4.1.4. Optimise fleet–route assignment

Once the capacity gaps have been calculated, new aircraft are introduced into the fleet. To ensure that the allocation of aircraft onto routes is optimal, a ranking algorithm is used in the fleet model. The algorithm employs the use of a ranking parameter, which is calculated for every aircraft-route pair. Since one the aims of the current project is to minimize the fuel burn, across the fleet, the specific fuel burn is chosen as the ranking parameter, calculated as follows:

$$SFB_{i,j} = FB_{i,j}/(dist_j \cdot seats_{i,j})$$

Where $SFB_{i,j}$ is the specific fuel burn of aircraft i on route j, $FB_{i,j}$ is the fuel burn (in kg) of aircraft i on route j, $dist_j$ is the distance of route j and $seats_{i,j}$ is the seating capacity of aircraft i on

route j. The aircraft are then allocated based on their efficiency, until either the ASKs of all routes have been satisfied or no more aircrafts are remaining to be allocated.
We tested this approach against a non-linear optimisation algorithm, based on the interior-point method, which showed improvements only in the per-mill region, whilst taking considerably longer to run. In view of the number of simulations we carried out, this second approach was dismissed.

4.1.5. Perform transport effort

This is the step where the aircraft essentially fly according to the fleet model allocations. In this step, the ASKs satisfied by the updated fleet (after introduction) are calculated and the tracking of under- or over-satisfied ASKs for every route is performed, to be used for determining the capacity gap in the next simulation year.

4.1.6. Determine fuel burn and other factors

As a final step of the simulation loop, the fuel that is used by the fleet is determined and the important statistics are written to an external file, which are then used for post-processing the simulation results. Fuel burn at a fleet level is modelled using the in-house fuel-consumption and emissions calculation tool (FCECT), see section 4.2.4.

4.2. Modelling assumptions and runs

As a base year, from which to start the simulations, we choose the year 2018. Further assumptions on technology, network and operations are given in the following sections.

4.2.1. Technology assumptions

OAG[8] reports 238 different names of specific aircraft in their global air travel database of 2018. In order to reduce this complexity, we cluster the aircraft into separate groups; taking into account the average distances flown, number of seats, payload capacities and propulsion types. We cluster the current fleet into the seven types shown in Table 3.

Table 3 Seven initial aircraft types.

Cluster no.	Aircraft type	Typical no. of seats	Average age [years]	Initial fleet size	Typical range [km]	FB/ASK on typical range[9] [kg/seat-km]
AC1	19 Seater	19	9.5	192	145	0.1030
AC2	Turboprop Commuter	63	9.5	1086	343	0.0363
AC3	Jet Commuter	76	12.0	2449	657	0.0470
AC4	Short-Medium Range	165	12.0	16741	1133	0.0234
AC5	Medium Range	261	12.5	1631	2329	0.0247
AC6	Long Range	297	5.7	2738	3919	0.0275
AC7	Long Range Heavy	419	9.9	613	4672	0.0277

On top of the aircraft available in the base year, we offer six further types of aircraft to reflect technological advancements over the simulated period, see Table 4. The availability and entry-into-service date (EIS) of the baseline aircraft depends on the chosen scenario. Note that BL1 is hydrogen powered. The yearly growth in production capacity ranges on average from 4.6 % to 5.9 %, depending on the aircraft type. When a new aircraft is introduced to substitute an existing

[8] A global travel data provider; see https://www.oag.com (accessed 31 Aug 2023)
[9] The passenger load factor was assumed to be 0.8 with 100 kg/PAX but without additional freight and a taxiing time of 10 min for each in and out; same for Table 4.

type, production of the new and old types are gradually ramped up and down respectively, so that a complete switch to the new aircraft is completed after six years.

Table 4 Additional aircraft types available during the simulation period.

Cluster no.	Aircraft type	Typical no. of seats	EIS	Typical range [km]	FB/ASK on typical range [kg/seat-km]
R150 / RA1	Short-range reference aircraft	150	2020	926	0.0196
R200 / RA2	Medium-range reference aircraft	200	2020	2222	0.0159
R330 / RA3	Long-range reference aircraft	330	2020	6482	0.0182
B150 / BL1	LH_2 Short-range baseline aircraft	150	2040/2045	926	0.0056
B200 / BL2	Medium-range baseline aircraft	200	2040/2045	2222	0.0127
B330 / BL3	Long-range baseline aircraft	330	2040/2045	6482	0.0144

These aircraft types have been specified by the MINIMAL consortium as part of WP 4, important technological specifications are provided in D4.2, more detailed information will be reported in D4.3 (engine characteristics) and D4.1 (final MINIMAL aircraft designs and performances). Current results are based on latest preliminary results on future aircraft performance from WP 4.

4.2.2. Network assumptions

OAG reports flights from over 4,000 airports and nearly 70,000 different origin–destination (OD) pairs in their global air travel database of 2018.

Our modelling framework cannot handle this amount of routes; hence, we are clustering those OD pairs into route groups. We define six regions—Asia (AS), Africa (AF), Europe (EU), Latin America (LA), Middle East (ME), North America (NA)—and all the combinations of arrival and departure from and within these regions form 21 route groups, compare Figure 4-3.

Figure 4-3 Six fully connected regions (including loops) forming 21 route groups

For modelling the fine-grained demand structure presented in the scenarios in Chapter 3, we further divide those routes into short-haul routes (S) and medium-to-long-haul routes (L). As the threshold between S and L, we choose 1000 nm (1852 km), which also constitutes the 95-percentile of the distances flown by our short-range aircraft classes.

Aggregating all flights present in the OAG data (after the appropriate cleaning steps) into these route groups, gives as a good overview of the average activity on that network throughout the year. Table 5 shows the average route lengths associated with these routes, split into long and short.

Table 5 Average route lengths of the 34 route groups in km in 2018.

AFAF_L	AFAF_S	AFLA_L	AFNA_L	ASAF_L	ASAS_L	ASAS_S	ASLA_L
3099	532	7084	8581	6905	2990	832	10800
ASME_L	ASME_S	ASNA_L	EUAF_L	EUAF_S	EUAS_L	EUAS_S	EUEU_L
4058	1491	10037	3996	1240	6156	1157	2440
EUEU_S	EULA_L	EUME_L	EUME_S	EUNA_L	EUNA_S	LALA_L	LALA_S
801	8400	3655	1227	6653	1110	2698	620
LANA_L	LANA_S	MEAF_L	MEAF_S	MELA_L	MEME_L	MEME_S	MENA_L
3121	1196	3697	1245	11992	2057	790	11153
NANA_L	NANA_S						
2842	775						

4.2.3. Operational assumptions

The operational assumptions on average initial fleet size, age distribution and seat capacity have been added to the tables on technology assumptions, see Table 3 and Table 4. In terms of passenger load factor, we assume a constant value of 80%, staying 1.9 percentage points under the 2018 value by IATA[10] to account for the shift in load factor during and after COVID-19. Also, the utilisation (how many hours an aircraft can be used for operation, taking into account e.g. night curfews and maintenance periods) is assumed to be constant, see Randt (2016). From the utilisation, the flight frequency on a certain route can be determined.
One important assumption is that the allocation of new aircraft to particular routes is based on the fuel burn of these aircraft. The objective is to minimize the global fuel burn, the mechanism of which is described in Section 4.1.4. On any route, one aircraft is preferable over another depending on the distance and required routes, but this is subject to change with the demand. Depending on the production capacity (see Section 4.2.1), a global optimal allocation can mean that a certain route is not allocated the aircraft that is performing most efficiently on that route for closing a capacity gap, but a second or even third best aircraft.

4.2.4. Further initialization assumptions

In order to initialise a simulation, we have already given details on most the following:

- Fleet (i.e. different aircraft types)
    - Age distribution
    - Production capacity
    - Passenger load factor / utilisation
    - Retirement rates
    - Start and end of service
- Routes
    - Distances
    - Demand
- Initial allocation of fleet to routes (derived from OAG)
    - Aircraft types
    - Flight frequency

[10] IATA Annual Review 2019 https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2018.pdf (accessed 20 Aug 2023)

- Fuel burn

As an input to the optimisation algorithm, we need to establish how much fuel is burned by an aircraft on a specific route, carrying a specific load. To that end, we are using the in-house fuel-consumption and emissions calculation tool (FCECT) for AC1–AC7, see Randt (2016).

The FCECT determines two major performance characteristics (fleet-wide fuel burn and fleet-wide emission quantities of CO_2 and water vapour) of all current and future aircraft types that are part of the global aircraft fleet simulated by the FSDM. As inputs, we require details about the initial fleet size, route distances and route frequencies (derived from OAG), details about aircraft parameters, and further operational parameters such as load factors and cruise altitudes. The FCECT uses BADA aircraft performance modelling as the fundamental technique for simulating aircraft performance. The technical parameters of the current aircraft types are generated on the basis of BADA data (version 3.16).
The technical parameters of the future types and the fuel burn on the respective routes for the respective types are provided by the partners from work package 4 of the MINIMAL project.

5. Results and discussion

The presented results are based on the input parameters described in the previous section. In order to avoid strong variations in the outcome of the simulation due to the non-deterministic nature of the model, we executed 20 runs per scenario, obtaining the width of the 95% confidence interval below 0.1% of the mean fuel burn.

As a recap, we mention the five scenarios and their most important markers here again.

- **BAU** (Business as usual) with medium RPK growth and reference aircraft with state-of-the-art technology.
- **Scenario 1** ("Fast Tech") with medium RPK growth rates, an evolutionary technology uptake and entry into service in 2040.
- **Scenario 2** ("Slow Tech") with medium RPK growth rates, an evolutionary technology uptake and entry into service in 2045.
- **Scenario 3** ("Fast Uptake") with high RPK growth rates (higher on short than on long routes), an evolutionary technology uptake and entry into service in 2040.
- **Scenario 4** ("Slow Uptake") with low RPK growth rates (lower on short than on long routes), an evolutionary technology uptake and entry into service in 2045.

5.1. Global fuel burn comparison by scenario and route length

For a first overview, we look at the total global fuel burn of the specified 34 routes, i.e. the long and short routes combined, see Figure 5-1.

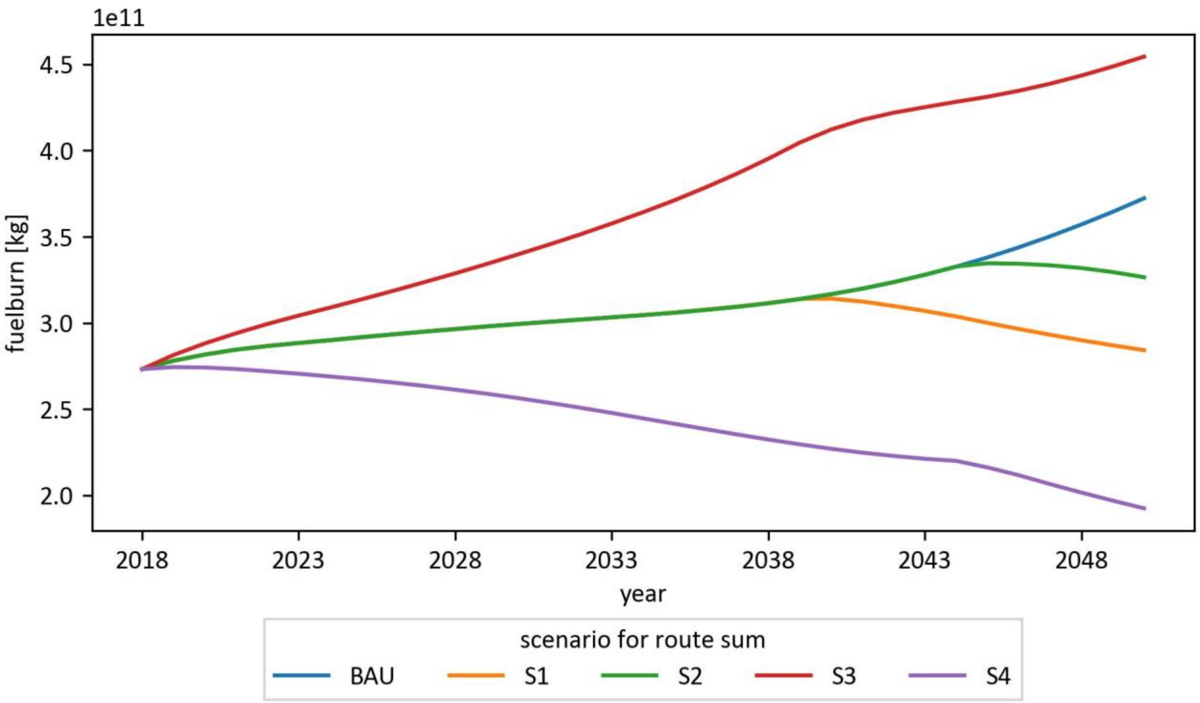

Figure 5-1 Fuel burn in kg for all routes combined per year for the five scenarios

We can see that in only two scenarios (BAU and S3—fast uptake), the fuel burn is rising continuously. In the other three scenarios (S1—fast tech, S2—slow tech and S4—slow uptake), the fuel burn reaches its peak in 2039, 2044 and 2020 respectively. The introduction of reference aircraft from 2020 contributes to the decreasing rate of change in fuel burn for BAU, S1 and S2 until 2034, however from then on, the rate of change picks up again due to rising demands. Depending on the introduction date of the baseline aircraft, a fall in fuel burn is experienced from 2040 or 2046 onwards. For Scenario S3 (high uptake), the rate of change in fuel burn decreases until 2024 and then increases until 2039. With the introduction of baseline aircraft, the rate of change decreases steeply until 2045 from when on the high demand leads to another increase. For S4, a different picture emerges. After an initial short increase in fuel burn, it decreases with the introduction of reference aircraft. Although the decreasing rate of change slows down in 2035, the introduction of baseline aircraft leads to a second, steeper period of fuel-burn decrease from 2045 onwards. The fuel-burn growth rates at the end of the simulation period for the five scenarios are 2.16% for BAU, -0.97% for S1, -0.91% for S2, 1.27% for S3 and -2.27% for S4.
We can compare the fuel burn to the DEPA 2050 study (Leipold et al., 2021), where three scenarios were analysed with a range of technology and policy options, but always the same growth rate which is in line with our high growth scenario. By 2050, the global fuel burn of their scenarios (from “do nothing” over “conservative evolution” to “progressive”) ranges from 5.9 e^{11} kg to 5.1 e^{11} kg, which we undercut here due to a more efficient aircraft portfolio.

We now differentiate this global fuel burn according to route length and a different picture emerges.

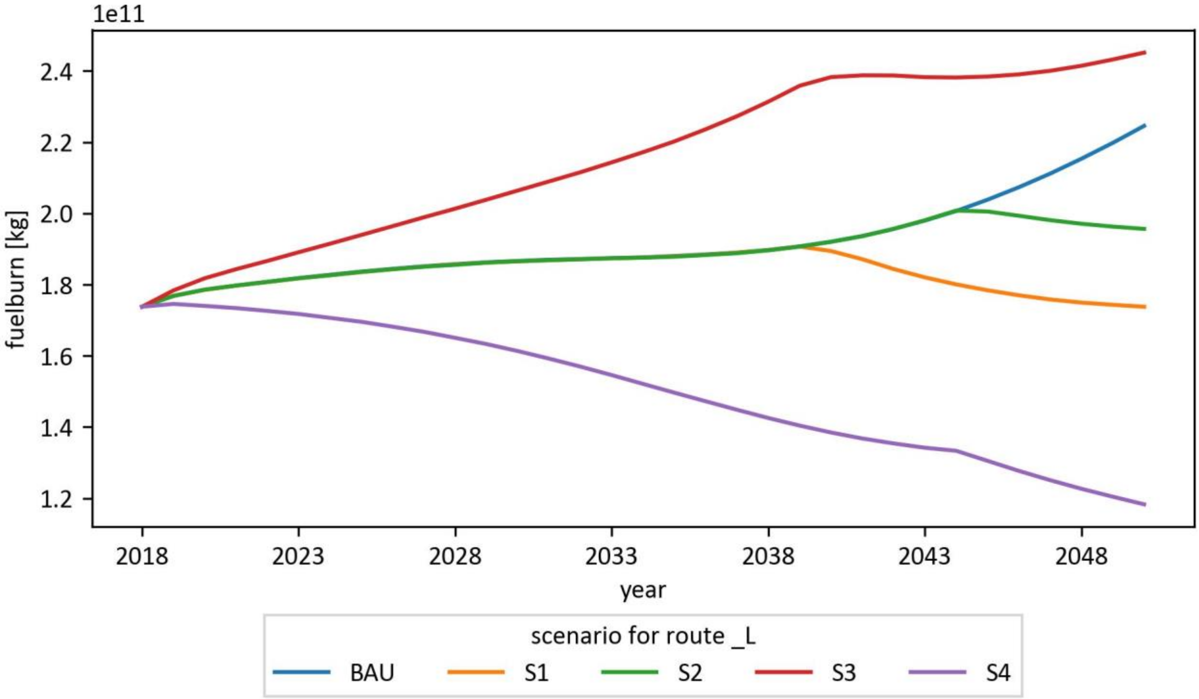

Figure 5-2 Fuel burn in kg for long routes (>= 1000 nm) per year for the five scenarios

On long routes (>= 1000 nm), see Figure 5-2, the behaviour of fuel-burn increase and decrease closely follows the development of the overall global fuel burn, but with a smaller range of changes in the fuel burn and only until the introduction of baseline aircraft. Notably, the fuel burn in S3 plateaus from 2042–2044, however, the rate of change in fuel-burn decrease flattens out towards 2050 for S1 and S2. The fuel-burn growth rates at the end of the simulation period for the five scenarios for long routes are 2.17% for BAU, -0.31% for S1, -0.32% for S2, 0.79% for S3 and -1.78% for S4.

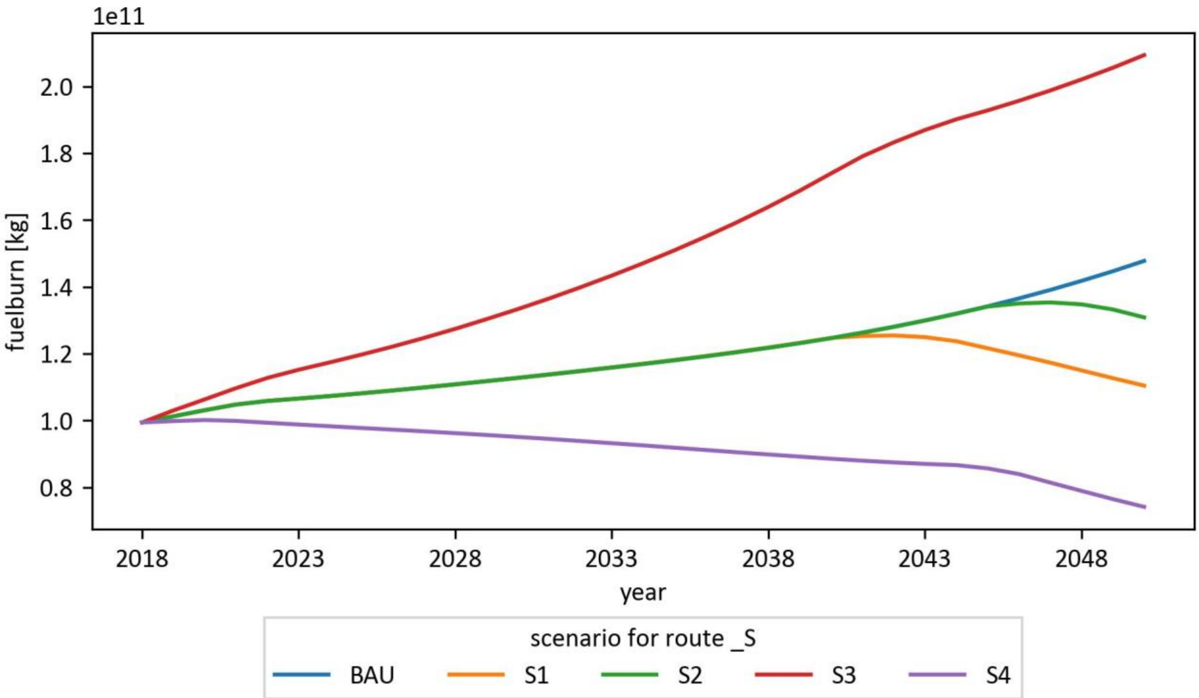

Figure 5-3 Fuel burn in kg for short routes (< 1000 nm) per year for the five scenarios

On short routes, the slopes of fuel-burn decrease and ensuing increase are flatter than in the two previous cases. We can see that, for medium growth scenarios, the rate of change in fuel burn starts to decrease again once baseline aircraft are introduced, resulting in a decrease of fuel burn from 2043 and 2048 onwards only. The fuel-burn growth rates at the end of the simulation period for the five scenarios for short routes are 2.13% for BAU, -1.99% for S1, -1.77% for S2, 1.84% for S3 and -3.04% for S4.

Overall, we can say that the introduction of baseline aircraft manages to reverse the increase in fuel burn for medium and low growth scenarios on shorter and longer routes, but when demand increases, in a high growth scenario or towards the end of the simulation period, the effect of technological advances is quickly eradicated.

5.2. Global number of aircraft in different scenarios

The number of aircraft required in a given year to fulfil the necessary transport effort is steadily increasing, very much like the growth rates in demand that were specified in the different scenarios. Figure 5-4 shows the size of the fleet throughout the simulation period for all types of aircraft.

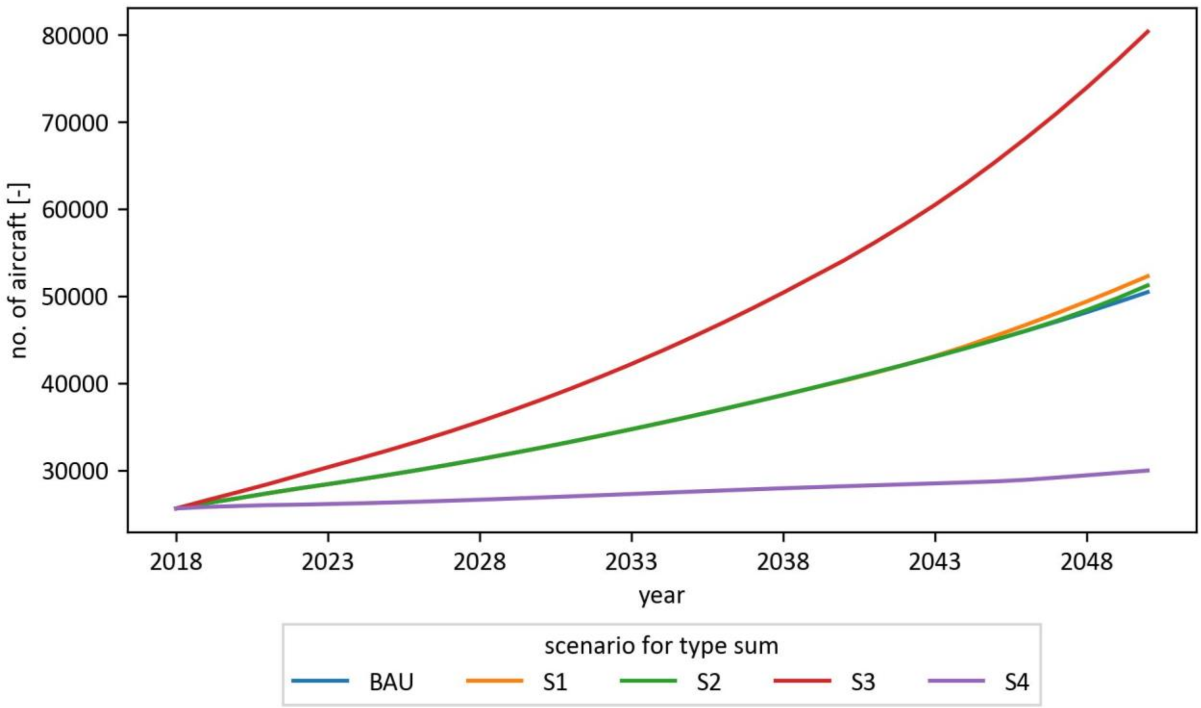

Figure 5-4 Number of aircraft of all aircraft types combined per year for the five scenarios

For 2042, Airbus forecasts 43,330 passenger aircraft above 100 seat assuming the same level of growth as in S3[11]. Subtracting the smaller aircraft classes from our figures gives us a range between 41,280 and 57,355 aircraft for all medium and high growth scenarios. Boeing offers slightly different numbers with an estimate of 44,830 aircraft (discounting freighters) for 2042[12]. We assume that our numbers are higher because we do not have capacity constraints at airports and we do not increase the payload factor over the simulation period. The biggest factor might be due to the fact that in S3, the short-haul market grows faster than the long-haul market, so

[11] Airbus General Market Forecast 2023-2042 (2023)
[12] Boeing Commercial Market Outlook 2023

that the increased demand has to be covered by more aircraft, since they offer fewer seats compared to long-haul aircraft.

In addition to the number of aircraft globally, we now show a few more results of either specific aircraft types or routes. The first example is the uptake of baseline aircraft, see Figure 5-5.

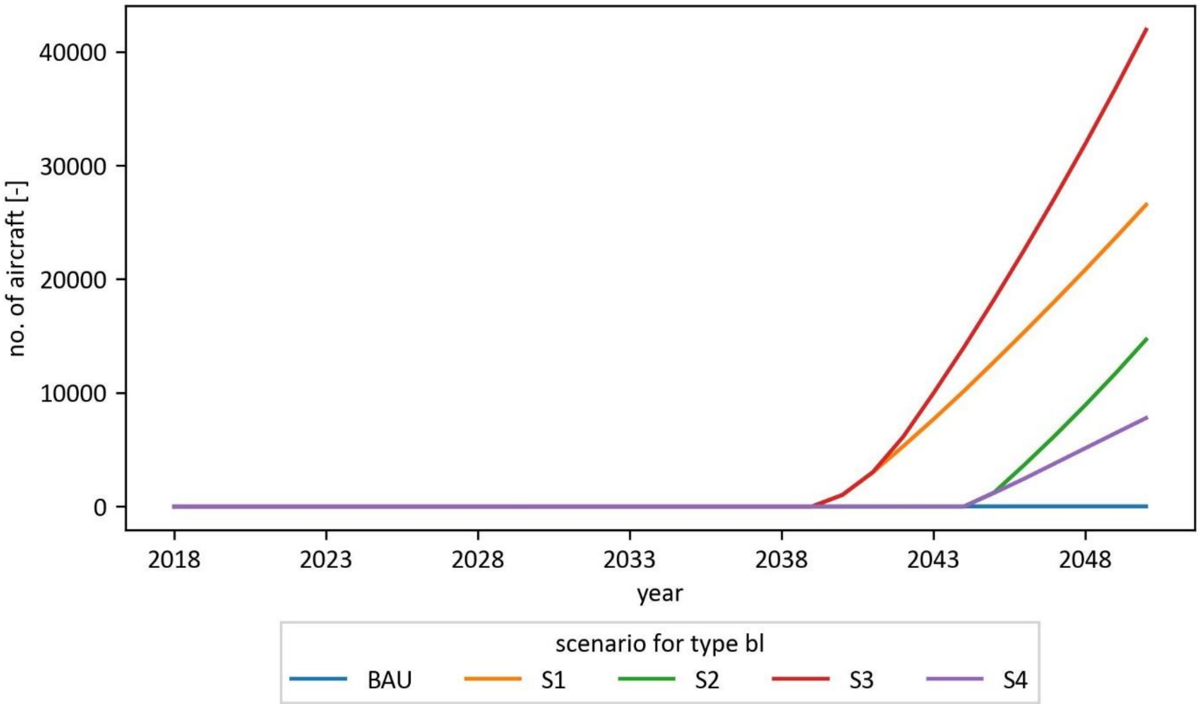

Figure 5-5 Number of aircraft of baseline aircraft types combined per year for the five scenarios

We can see that the different demand patterns of the different scenarios also induce different rates of uptake of these aircraft. A medium uptake rate for S1 and S2 where the introduction date is five years later for S2, and a high and low rate for S3 and S4, respectively, again with different introduction dates. For BAU, these aircraft types were not on the market, hence no uptake occurs.

Zooming in on a specific baseline aircraft—BL1 which is hydrogen powered—we can see that approximately the same number of aircraft is present in the market, scooping up nearly all produced aircraft over that time period, compare top graph in Figure 5-6. On the bottom, the corresponding hydrogen consumption (in kg) is presented. In a study on potential hydrogen demand, (Grimme & Braun, 2022) project an amount of 19.2 Mt for 2050, based on a medium growth rate and hydrogen aircraft on routes up until 1500 nm. This can be best compared to scenario S1, where we project a more optimistic hydrogen demand of 30.7 Mt, albeit for routes up until 2000 nm.

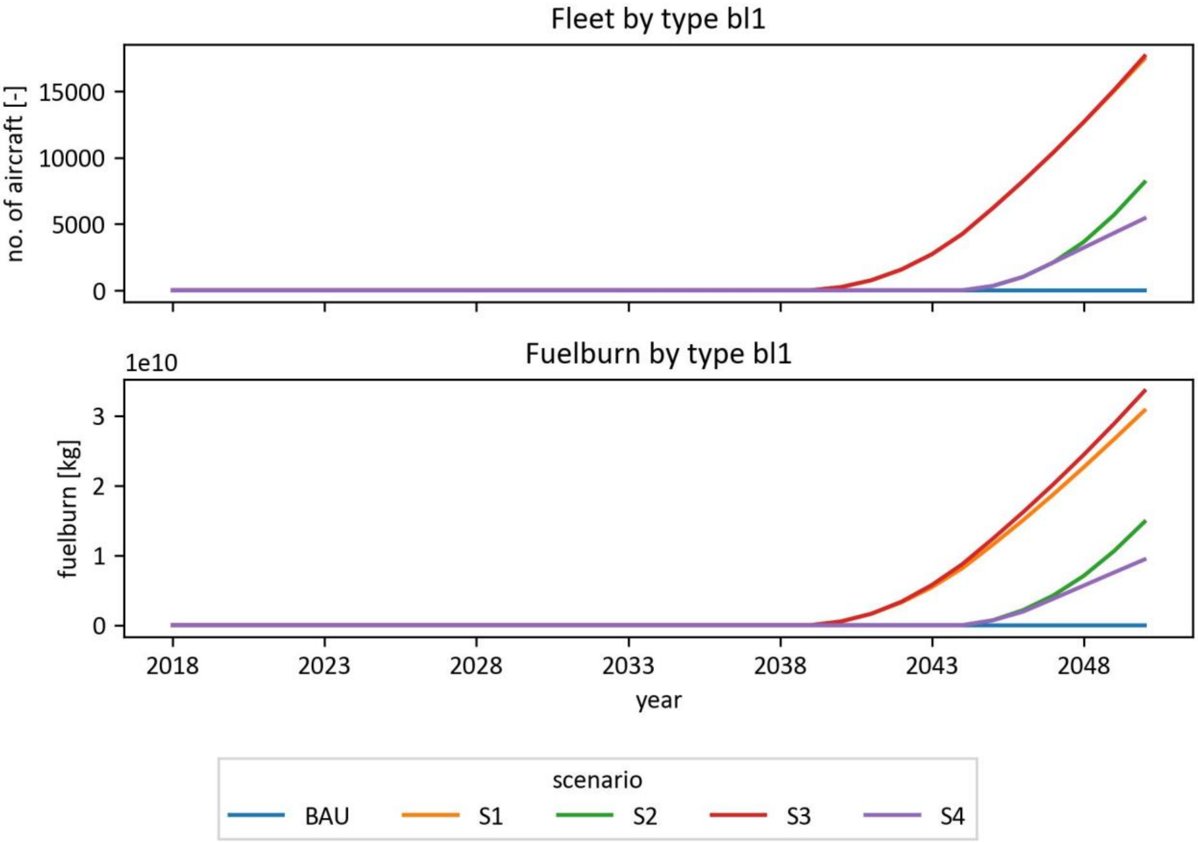

Figure 5-6 Aircraft numbers and hydrogen consumption by baseline aircraft BL1 for the five scenarios

We would now like to showcase the fleet mix of two different scenarios, S3 and S4, see Figure 5-7 and Figure 5-8 respectively.

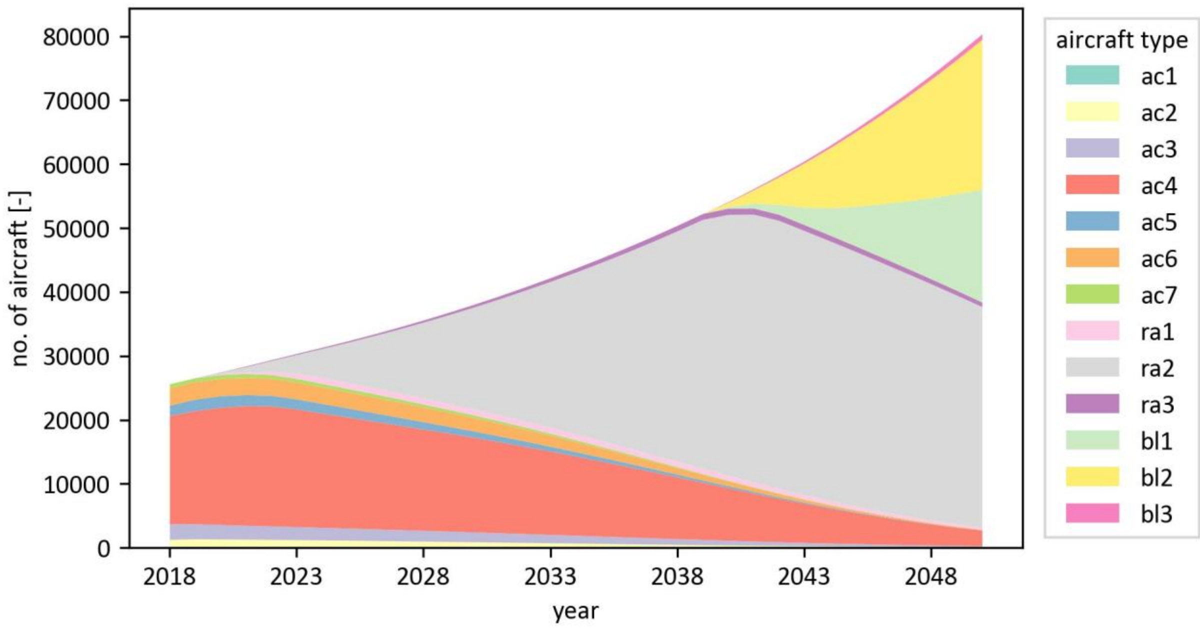

Figure 5-7 Number of aircraft per type for scenario S3

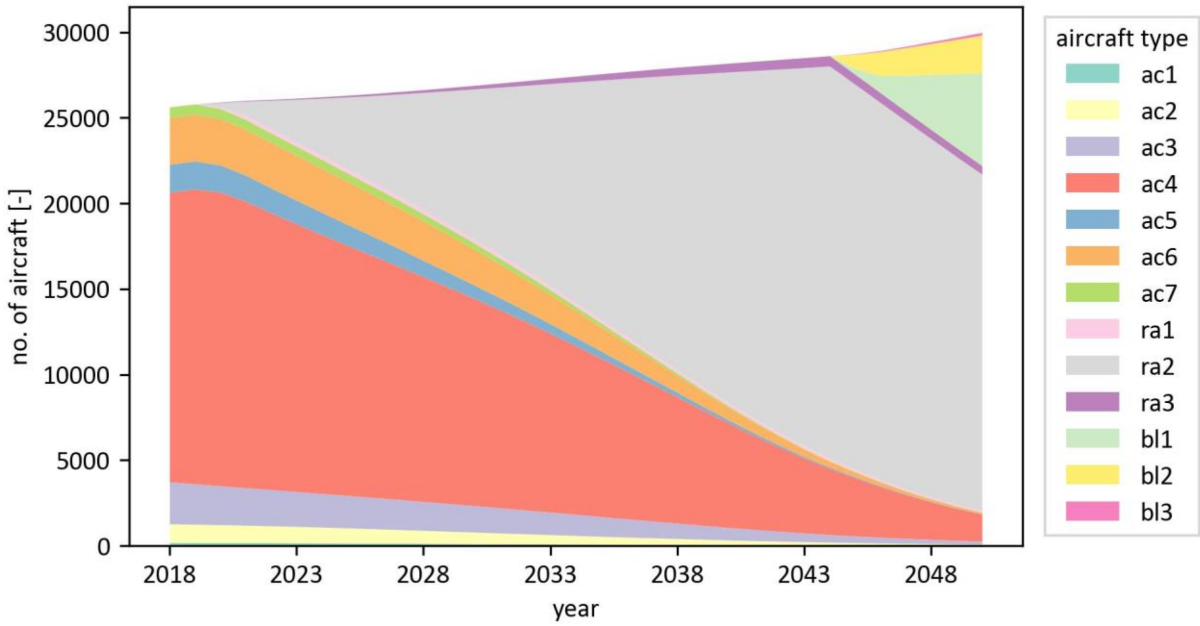

Figure 5-8 Number of aircraft per type for scenario S4

These two figures show that, with the higher demand and faster technology introduction in S3, the share of aircraft types AC1 to AC7 drops a couple of years later compared to S4, but the uptake of baseline aircraft compared to the total number of aircraft is about twice as high by the end of the simulation. In both cases, the share of RA1 aircraft is very low. This is due to the fact that RA2 outperforms RA1 in terms of fuel burn per ASK on the deployed routes and is hence used when there is a shortage of RA2 aircraft.

5.3. Efficiency gains and fleet mixes in the different scenarios

The introduction of more efficient aircraft effects the fuel burn per ASK on a route level. These efficiency gains are shown in Figure 5-9 to Figure 5-11.

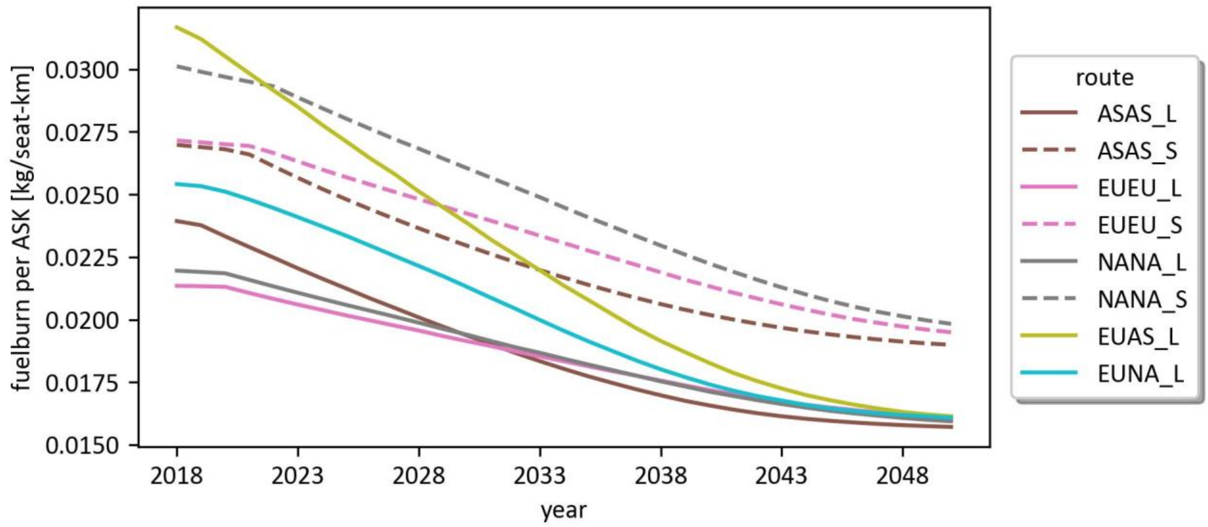

Figure 5-9 Fuel burn per ASK in kg for selected routes for scenario BAU

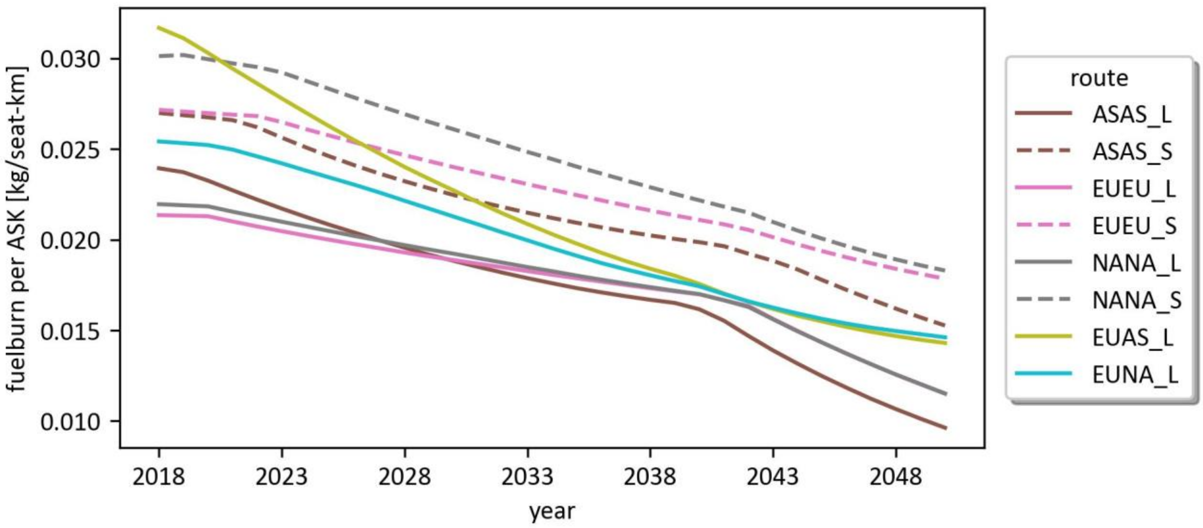

Figure 5-10 Fuel burn per ASK in kg for selected routes for scenario S3

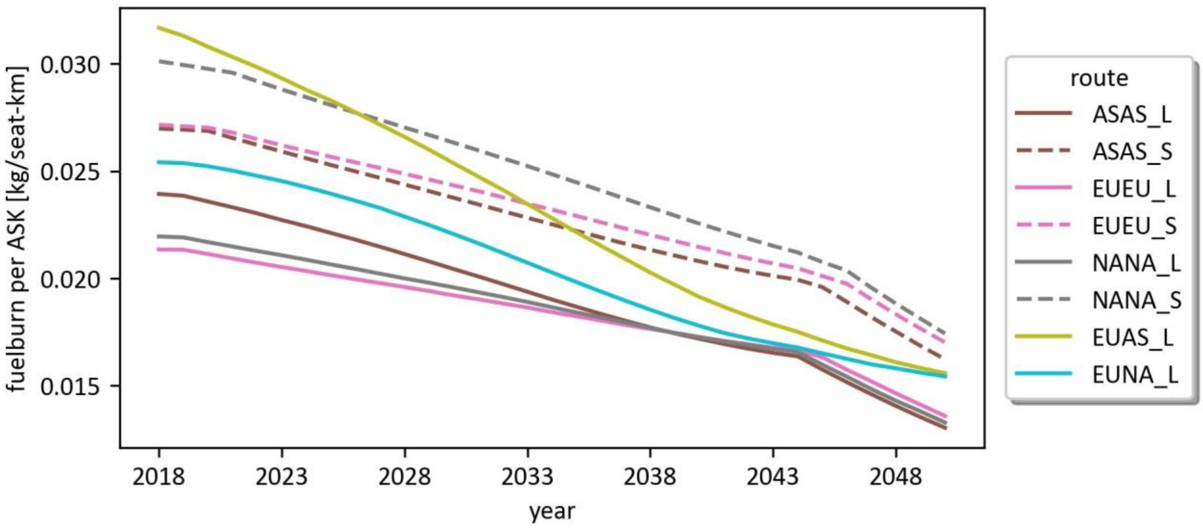

Figure 5-11 Fuel burn per ASK in kg for selected routes for scenario S4

We can see that the longest routes from EU to AS or NA do not benefit as heavily from the new technology, whereas the comparably shorter routes (which for this purpose also includes the long intra-regional routes) do so to a greater degree. This is very much driven by the introduction of hydrogen aircraft, which leads to a steep decrease in fuel burn per ASK.

EU–AS long performs better than EU–NA long, due to the fact that a steeper increase in demand on that route led to a higher share of more efficient aircraft in that fleet, see Figure 5-12. The effect of optimising aircraft allocation is particularly visible in the right-hand side of the plot where in the first years of introducing baseline aircraft (from 2040), production capacities of BL2 are not high enough to cover the demand, and hence BL3 are introduced on that route instead as second best option. From the small plateau, we can also see that fewer BL3 aircraft are needed to cover the demand since they have more available seats compared to BL2.

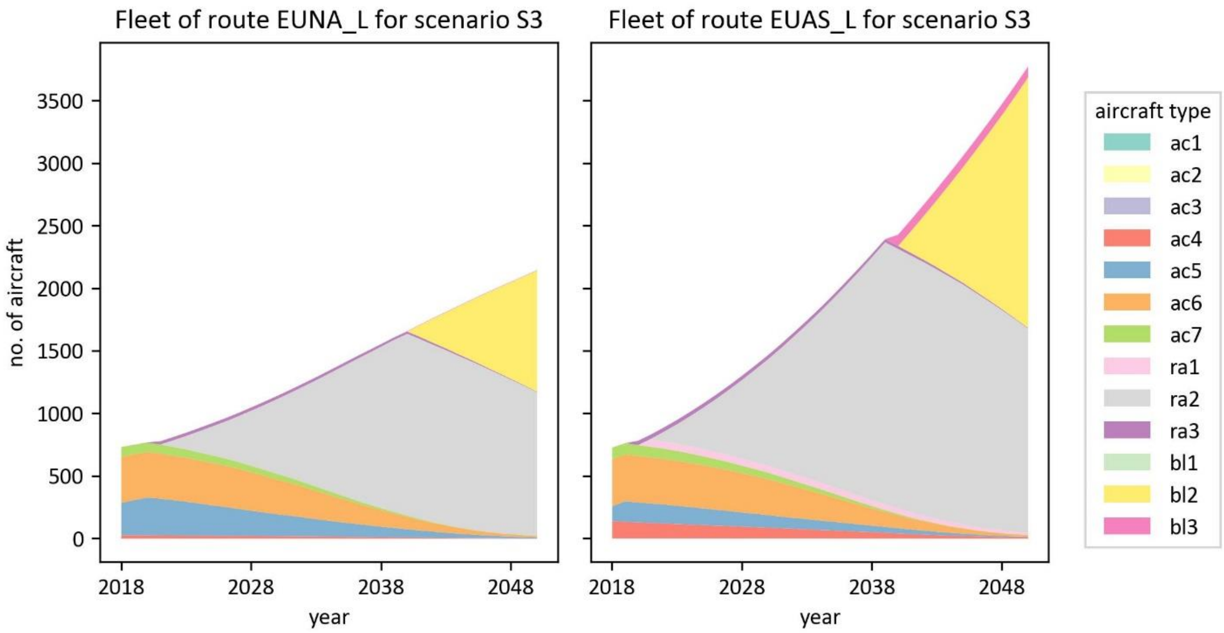

Figure 5-12 Fleet mix on routes EU–NA long and EU–AS long for scenario S3

Another example where a fleet was able to uptake new technology more readily is intra-AS short, compared to intra-EU short, in the fast-uptake scenario S3, see Figure 5-13. BL2 was allocated to both routes, whereas BL1, the hydrogen-powered aircraft, was allocated to intra-AS short only due to a favourable specific fuel burn on that route and general production limits.

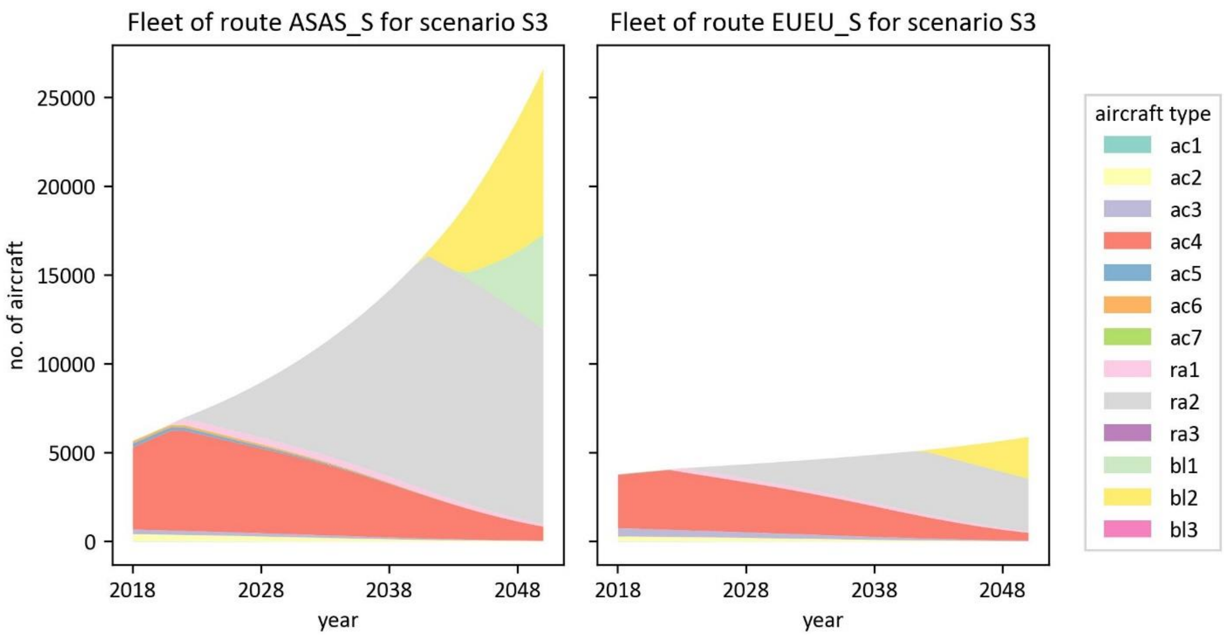

Figure 5-13 Fleet mix on routes AS–AS short and EU–EU short for scenario S3

In contrast, when we look at the slow-uptake scenario S4, both are equally able to accrue baseline aircraft in their fleet, see Figure 5-14.

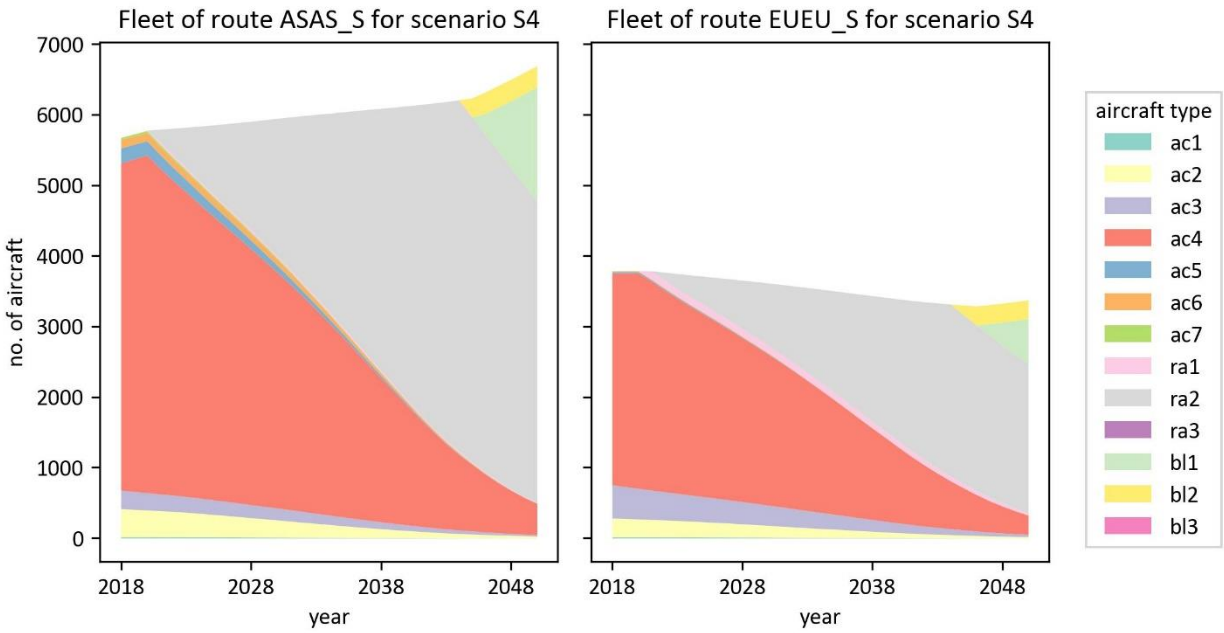

Figure 5-14 Fleet mix on routes AS–AS short and EU–EU short for scenario S4

5.4. Discussion and conclusion

Summing up the above results, we can say that the overall global fuel burn is strongly influenced by the demand, and the technological improvements in this work can only offer a short respite, compare Figure 5-1. Over the simulation period, we observe a decrease in fuel burn for scenarios with low demand or medium demand where advanced technology has been introduced. In comparison, in the business-as-usual scenario or the scenario with high demand, fuel-burn numbers increase steadily. This emphasises the need for early introduction of new technology and more efficient propulsion systems (like the MINIMAL CCE concepts) in order to reduce global fleet fuel burn by 2050. Going into more detail allows us to differentiate further. On routes below 1000 nm, the technological advances, i.e. the introduction of baseline aircraft, mean that the trend of fuel-burn decrease is more strongly pronounced even with medium RPK growth rates, compared to longer routes.

In our scenarios, new aircraft are readily accepted into the fleet mix, since they provide better efficiencies compared to what was previously available. This is also facilitated through the ambitious production capacity, that need to be in line with the RPK growth rates, in order to meet the various demand increases. This leads to a steady efficiency gain of the entire fleet on an ASK level.

We have compared the results to several scenario studies and market forecasts, see Sections 5.1 and 5.2, and see that our findings are in line with the current literature. We would like to stress that this work does not exhaust all possible technological measures. We did not, for example, consider the possibility of retrofitting an aircraft with new technology when it is still in service. The current model only allows for the same technology of an aircraft throughout its lifetime. We also do not take into account operational improvements, that could lead to higher utilisation rates and payload factors, which would affect the overall fuel burn.

It is also important to stress, that the current model uses specific fuel burn as an optimisation parameter, which is suitable to estimate the potential of fuel-burn reduction, however, it does not accurately reflect how aircraft are allocated in the market. Typically, we see a behaviour that aims at maximising profits of single airlines or alliances, rather than minimising the global fuel used.

The results we have highlighted above attempt to show the rich picture that emerges from simulating the global transport effort distributed over 34 route groups, operated by up to 13 different aircraft types for five different scenarios up until 2050. The interested reader is invited to look at Section 7, where we have appended the flight numbers per aircraft type and year for each single scenario. Within the MINIMAL project, the future fleet composition will feed into estimating the overall climate impact and mitigation potential for key technology scenarios, policy measures and operational procedures.

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7. Appendix

The appendix contains the data on the flights operated by each type of aircraft per year for the five different scenarios. These flights represent the basis for calculating different markers, such as fuel burn or ASK.

7.1. Operated flights [in 1000] per aircraft type for Scenario BAU

year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	RA1	RA2	RA3
2018	258	1727	5114	26648	1584	2306	433	0	0	0
2019	253	1701	4919	27635	1573	2292	432	0	0	0
2020	248	1663	4728	28365	1521	2278	426	65	198	19
2021	242	1623	4554	28681	1463	2258	413	387	611	28
2022	235	1575	4377	28223	1400	2235	399	919	1537	35
2023	227	1526	4220	27395	1325	2205	383	1053	3112	44
2024	218	1469	4071	26559	1250	2167	367	1051	4827	53
2025	210	1413	3921	25762	1168	2124	351	1048	6548	63
2026	200	1358	3778	24976	1083	2070	335	1045	8292	73
2027	191	1295	3633	24175	998	2009	318	1040	10089	85
2028	183	1225	3489	23377	916	1940	301	1034	11914	97
2029	174	1156	3338	22572	828	1861	282	1027	13800	110
2030	163	1082	3182	21736	747	1770	263	1020	15742	124
2031	154	1011	3026	20880	664	1668	244	1012	17746	139
2032	144	941	2865	19977	586	1558	223	1001	19824	154
2033	134	875	2706	19031	517	1441	202	990	21963	170
2034	123	804	2534	18052	453	1317	180	977	24167	187
2035	113	736	2360	17035	394	1196	159	957	26427	204
2036	103	674	2187	16020	340	1075	137	935	28705	220
2037	94	613	2014	14963	288	954	116	911	31048	237
2038	86	555	1839	13892	241	835	97	883	33423	254
2039	78	498	1666	12797	202	722	79	849	35835	271
2040	71	447	1494	11715	167	619	64	817	38239	287
2041	64	399	1338	10654	137	525	51	778	40637	301
2042	57	354	1185	9636	111	438	40	741	43016	316
2043	50	314	1043	8629	91	363	31	697	45395	330
2044	44	275	911	7695	70	294	22	649	47741	344
2045	38	244	792	6775	55	240	17	601	50080	356
2046	33	213	679	5951	43	194	13	546	52364	367
2047	29	185	581	5195	33	155	9	493	54615	378
2048	26	160	496	4507	25	123	7	443	56830	388
2049	22	138	419	3880	19	96	5	399	59021	398
2050	19	118	354	3337	14	76	4	354	61174	408

7.2. Operated flights [in 1000] per aircraft type for Scenario S1

year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	RA1	RA2	RA3	BL1	BL2	BL3
2018	258	1727	5114	26648	1584	2306	433	0	0	0	0	0	0
2019	253	1691	4919	27637	1572	2293	432	0	0	0	0	0	0
2020	248	1655	4730	28363	1522	2278	426	66	197	19	0	0	0
2021	243	1612	4553	28679	1466	2257	413	387	610	29	0	0	0
2022	236	1565	4378	28223	1401	2234	398	918	1537	37	0	0	0
2023	229	1513	4220	27382	1328	2205	383	1060	3113	46	0	0	0
2024	223	1457	4065	26558	1250	2168	368	1056	4820	55	0	0	0
2025	213	1398	3923	25748	1170	2125	351	1054	6546	66	0	0	0
2026	205	1338	3776	24957	1084	2073	336	1051	8295	76	0	0	0
2027	195	1273	3629	24173	999	2012	319	1046	10081	87	0	0	0
2028	188	1208	3486	23390	914	1941	303	1041	11895	99	0	0	0
2029	177	1143	3333	22586	827	1860	284	1034	13778	113	0	0	0
2030	167	1068	3182	21752	743	1769	264	1026	15724	127	0	0	0
2031	158	1001	3028	20882	666	1664	245	1017	17736	141	0	0	0
2032	148	931	2873	19990	591	1556	226	1007	19792	157	0	0	0
2033	138	860	2711	19053	522	1441	204	994	21926	173	0	0	0
2034	129	794	2548	18065	456	1319	183	980	24132	189	0	0	0
2035	117	729	2377	17061	393	1199	161	963	26383	206	0	0	0
2036	108	667	2203	16021	339	1080	140	942	28676	223	0	0	0
2037	98	606	2021	14972	290	962	118	920	31011	240	0	0	0
2038	89	544	1849	13891	244	842	99	893	33389	257	0	0	0
2039	82	492	1681	12809	202	729	83	864	35783	273	0	0	0
2040	74	443	1504	11725	165	623	67	831	37459	284	236	496	46
2041	66	397	1336	10647	134	529	53	793	37559	279	752	2431	65
2042	57	351	1181	9618	108	436	41	753	37053	273	1675	4644	86
2043	50	311	1033	8621	88	362	31	708	36470	267	3295	6388	106
2044	45	272	907	7685	69	295	23	664	35795	260	5679	7615	125
2045	39	240	782	6780	54	235	18	612	35037	252	8918	8284	144
2046	34	209	674	5961	40	188	13	562	34206	243	12387	8795	163
2047	29	182	579	5198	31	150	10	512	33280	233	16086	9195	184
2048	25	160	491	4503	24	119	7	462	32273	224	20051	9447	204
2049	22	138	416	3880	19	94	5	416	31162	213	24189	9641	225
2050	19	121	350	3318	14	75	4	366	29967	201	28411	9839	246

7.3. Operated flights [in 1000] per aircraft type for Scenario S2

year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	RA1	RA2	RA3	BL1	BL2	BL3
2018	258	1727	5114	26648	1584	2306	433	0	0	0	0	0	0
2019	252	1693	4911	27640	1574	2293	431	0	0	0	0	0	0
2020	247	1656	4722	28371	1524	2278	424	65	198	19	0	0	0
2021	241	1613	4554	28680	1467	2257	410	388	614	29	0	0	0
2022	235	1567	4386	28235	1403	2232	397	919	1529	37	0	0	0

2023	228	1515	4226	27374	1332	2201	382	1086	3102	46	0	0	0
2024	220	1458	4069	26560	1253	2165	367	1083	4799	55	0	0	0
2025	212	1400	3925	25755	1174	2122	351	1081	6519	65	0	0	0
2026	201	1338	3777	24970	1091	2071	334	1077	8264	76	0	0	0
2027	192	1272	3642	24176	1002	2010	316	1072	10059	88	0	0	0
2028	182	1210	3502	23381	915	1934	302	1068	11887	100	0	0	0
2029	171	1141	3360	22559	832	1854	284	1062	13773	112	0	0	0
2030	160	1075	3210	21731	749	1764	264	1054	15709	127	0	0	0
2031	149	1007	3055	20867	670	1663	243	1046	17719	142	0	0	0
2032	138	935	2899	19967	591	1553	223	1037	19790	157	0	0	0
2033	127	869	2727	19030	523	1438	204	1025	21921	173	0	0	0
2034	116	801	2551	18044	457	1320	182	1009	24123	191	0	0	0
2035	107	735	2373	17036	394	1195	159	991	26391	207	0	0	0
2036	100	670	2197	15991	339	1073	139	971	28693	223	0	0	0
2037	91	610	2015	14945	286	952	119	945	31030	241	0	0	0
2038	81	553	1839	13878	240	835	100	919	33396	257	0	0	0
2039	75	500	1663	12783	198	724	81	886	35811	273	0	0	0
2040	67	443	1500	11709	164	620	64	852	38216	288	0	0	0
2041	60	397	1336	10647	133	521	50	813	40626	304	0	0	0
2042	52	354	1185	9607	108	437	39	775	43018	318	0	0	0
2043	46	309	1042	8609	86	362	31	731	45395	331	0	0	0
2044	41	271	903	7678	70	295	23	682	47737	344	0	0	0
2045	36	240	784	6778	55	238	18	633	49205	335	321	613	21
2046	31	207	674	5958	43	192	13	577	48323	327	1018	3253	41
2047	28	177	578	5190	33	155	10	523	47349	317	2440	5416	62
2048	24	153	490	4485	25	125	8	473	46284	307	4782	6954	83
2049	21	131	420	3873	18	100	6	422	45111	295	8152	7779	104
2050	18	113	355	3315	14	79	4	376	43832	284	12451	8001	125

7.4. Operated flights [in 1000] per aircraft type for Scenario S3

year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	RA1	RA2	RA3	BL1	BL2	BL3
2018	258	1727	5114	26648	1584	2306	433	0	0	0	0	0	0
2019	252	1875	4911	27577	1891	2295	433	0	0	0	0	0	0
2020	247	1830	4733	28809	1854	2279	431	77	193	21	0	0	0
2021	242	1784	4560	29724	1796	2260	419	306	629	50	0	0	0
2022	236	1737	4399	30115	1730	2236	405	830	1371	60	0	0	0
2023	229	1685	4242	29625	1658	2204	391	1589	2736	72	0	0	0
2024	223	1634	4089	28799	1582	2166	377	1905	4780	83	0	0	0
2025	214	1576	3944	27994	1498	2123	360	1897	7130	97	0	0	0
2026	204	1515	3795	27180	1411	2071	343	1891	9563	110	0	0	0
2027	195	1448	3652	26371	1326	2008	327	1885	12072	124	0	0	0
2028	185	1381	3502	25553	1242	1934	309	1878	14672	140	0	0	0
2029	176	1312	3356	24740	1158	1854	290	1869	17351	155	0	0	0
2030	166	1239	3204	23890	1075	1763	271	1858	20152	173	0	0	0

2031	155	1168	3045	23002	994	1665	251	1844	23074	192	0	0	0
2032	145	1096	2887	22082	915	1557	231	1828	26119	211	0	0	0
2033	133	1026	2720	21119	842	1442	211	1809	29291	231	0	0	0
2034	122	958	2558	20107	767	1323	190	1789	32599	252	0	0	0
2035	112	888	2378	19063	697	1200	168	1761	36047	273	0	0	0
2036	102	816	2212	18001	629	1078	147	1730	39600	294	0	0	0
2037	92	751	2035	16895	565	956	125	1693	43294	316	0	0	0
2038	84	685	1863	15767	501	842	105	1651	47106	337	0	0	0
2039	74	623	1687	14602	443	730	88	1602	51054	358	0	0	0
2040	67	561	1526	13453	387	626	72	1542	54333	378	231	503	53
2041	58	504	1358	12311	335	529	57	1484	56777	372	739	1821	80
2042	51	453	1192	11187	285	443	43	1416	57303	365	1557	4931	107
2043	45	405	1047	10101	235	367	33	1338	56518	356	2759	9153	134
2044	39	360	917	9062	195	298	25	1255	55617	347	4691	13025	161
2045	35	315	800	8062	158	239	19	1168	54621	336	7441	16474	190
2046	30	278	689	7128	124	193	13	1076	53501	325	10371	19997	219
2047	26	244	588	6246	100	155	10	987	52244	312	13494	23601	249
2048	23	215	501	5452	79	124	7	897	50866	301	16837	27249	278
2049	20	186	426	4725	62	99	6	806	49353	286	20397	30982	309
2050	17	161	359	4067	49	77	4	716	47696	272	24163	34830	342

7.5. Operated flights [in 1000] per aircraft type for Scenario S4

year	AC1	AC2	AC3	AC4	AC5	AC6	AC7	RA1	RA2	RA3	BL1	BL2	BL3
2018	258	1727	5114	26648	1584	2306	433	0	0	0	0	0	0
2019	253	1690	4923	27072	1561	2294	430	0	0	0	0	0	0
2020	248	1651	4732	27183	1514	2278	416	83	208	19	0	0	0
2021	241	1610	4560	26595	1456	2257	404	420	843	24	0	0	0
2022	234	1565	4400	25698	1390	2232	391	436	1987	28	0	0	0
2023	227	1518	4235	24864	1321	2202	375	435	3113	34	0	0	0
2024	217	1461	4080	24057	1243	2166	360	434	4233	40	0	0	0
2025	208	1400	3932	23256	1163	2120	342	433	5375	46	0	0	0
2026	198	1339	3790	22477	1081	2067	327	431	6498	53	0	0	0
2027	189	1274	3648	21712	992	2003	310	428	7644	61	0	0	0
2028	177	1207	3497	20918	906	1929	292	426	8829	69	0	0	0
2029	169	1142	3350	20114	821	1850	274	423	10030	78	0	0	0
2030	159	1075	3200	19287	740	1756	255	419	11267	88	0	0	0
2031	149	1005	3043	18446	659	1658	235	415	12529	98	0	0	0
2032	139	938	2881	17581	585	1546	215	410	13820	109	0	0	0
2033	129	869	2718	16671	513	1429	195	406	15157	121	0	0	0
2034	121	801	2551	15730	448	1313	174	399	16517	133	0	0	0
2035	111	737	2381	14774	387	1190	153	391	17893	145	0	0	0
2036	101	676	2209	13789	330	1071	132	380	19288	156	0	0	0
2037	92	616	2032	12803	281	951	111	369	20677	168	0	0	0
2038	84	559	1861	11804	236	833	93	359	22059	180	0	0	0

2039	75	500	1686	10798	199	724	77	344	23434	190	0	0	0
2040	67	448	1514	9809	162	617	61	329	24788	200	0	0	0
2041	60	396	1359	8834	131	523	48	309	26100	209	0	0	0
2042	52	354	1205	7904	105	440	36	292	27351	217	0	0	0
2043	47	313	1057	7016	84	361	28	273	28548	224	0	0	0
2044	41	276	920	6211	67	297	21	255	29646	230	0	0	0
2045	36	244	797	5465	53	243	16	233	29132	225	332	1292	11
2046	32	212	689	4768	41	192	12	211	28531	219	1365	2094	21
2047	28	184	591	4123	32	152	9	189	27864	213	3264	2249	31
2048	24	163	508	3538	25	121	6	168	27141	205	5214	2347	42
2049	20	140	427	3021	19	95	5	150	26343	199	7177	2447	51
2050	18	122	358	2561	14	75	4	132	25510	191	9106	2544	62