Technical, logistical and economic challenges associated with the practical introduction and implementation of 100% SPK SAF in aviation

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Date of publication: 21 July 2026

Responsibility for the content of this publication lies with the authors.

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Summary

In addition to the CO_2 emissions from aviation, there is an increasing focus in science, politics and the aviation industry on non-CO_2 effects, which are principally caused by contrails. The use of sustainable aviation fuel (SAF) can deliver a significant reduction in soot and ice particles during combustion and therefore also in these non-CO_2 effects. Given that the proportion of aromatic hydrocarbons in the fuel is a key factor in the formation of soot particles, it makes sense to use aromatic-free fuel in order to reduce the non-CO_2 effects of aviation. However, aviation fuel must have a minimum aromatic content in order to ensure the leak-tightness of the fuel system in modern aircraft and fuel infrastructure on the ground. Whereas aromatics are naturally present in fossil kerosene, a lower limit of 8 vol% of aromatics has been defined for SAF.

This study investigates whether and how there could be a successful future transition to the use of an aromatic-free fuel known as synthetic paraffinic kerosene (SPK) at German airports. To this end, stakeholder surveys were first carried out in order to ascertain relevant aspects of modern fuel logistics (the status quo) and identify key challenges for a transition to 100% SPK-SAF. In the process, we explored the elements of SAF production and distribution, airport infrastructure and refuelling, aircraft and engine certification, airline operations, and market and regulatory aspects.

As well as the qualitative analysis of challenges and potential solutions, the study also focuses on determining the cost and benefit of using 100% SPK-SAF. It develops multiple introduction and usage scenarios, which differ in terms of the distribution of aircraft that are compatible with 100% SPK-SAF within the fleet and the means of concrete implementation (physical supply vs book and claim[1]).

[1] The term “book and claim” describes a model in which sustainability certificates (claims) are handled independently of the physical product (e.g., here, the SPK-SAF) so that a company can claim the environmental benefits of sustainable production without having received the physical product.

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The findings of the qualitative and quantitative analysis are used to derive different courses of action, which are intended to help pave the way for the use of 100% SPK-SAF and thus to make aviation more sustainable. The analyses show that the non-CO_2 effects of flights from German airports are strongly concentrated at a small number of airports – particularly Frankfurt Main and Munich. Given these framework conditions and assumptions, it therefore seems sensible to target the physical supply of 100% SPK-SAF at these airports. Meanwhile, the assumption- and model-based analyses show that fuel for flights from the other airports could be integrated via a book-and-claim system, for example. Accompanying measures to create incentives for the use of 100% SPK-SAF could help to make the introduction as competitively neutral as possible while also maximising the reduction of non-CO_2 effects. Before the introduction of 100% SPK-SAF, there are considerable challenges to overcome in various areas. These include defining the fuel standard, the (re)certification and potential retrofitting of aircraft, the creation of suitable infrastructure and supply chains, and adjustments to the regulatory framework.

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1 Introduction

International aviation is responsible for approx. 3% to 5% of global anthropogenic climate impact (Lee et al. 2021). Flights from and to Germany also make a corresponding contribution to the environmental impact of aviation. With a view to reducing this impact, the sector has been subject to the Emissions Trading System of the European Union (EU ETS) since 2012. As well as falling caps on emissions of carbon dioxide (CO_2), the system of free allowances for aviation is to be eliminated by 2026. In addition, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was initiated by the International Civil Aviation Organization (ICAO) and is administrated by the participating member states, is intended to compensate for the CO_2 emissions from international aviation. Emissions exceeding a defined base figure (85% of the emissions from the year 2019) must be compensated for by offsetting in the form of CO_2 emissions reductions in projects that largely relate to other sectors.

In addition to direct CO_2 emissions, aviation also contributes through what are known as non-CO_2 effects. These include aerosols, which lead to the formation of contrails and cirrus clouds, and nitrogen oxide (NO_x) emissions, which promote the formation of ozone (Lee et al. 2021). Although non-CO_2 effects can have both warming and cooling effects, the net effect is warming. Non-CO_2 effects make up around half (Lee et al. 2021) to two-thirds of the overall climate impact of aviation (Niklaß et al. 2019) but are not currently included in the surrender obligation as part of CORSIA or the EU ETS. Since 2025, aircraft operators have been required to report their non-CO_2 effects as part of the annual emissions report for the EU ETS. This reporting obligation fundamentally covers the same geographical delimitation as the EU ETS (Deutsche Emissionshandelsstelle 2026).

Besides the EU ETS, the European Union also adopted the ReFuelEU Aviation regulation in 2023, stipulating mandates for the use of sustainable aviation fuel (SAF) for all flights departing from airports in the European Union. In accordance with this regulation, SAF includes both biogenic fuels produced from raw materials defined according to the Renewable Energy Directive (RED III) and synthetic fuels produced from green hydrogen (H_2) and CO_2 (renewable fuels of non-biological origin, RFNBOs). SAF is not used in pure form but rather as a blend with fossil fuel. In the documents of the American Society for Testing and Materials (ASTM International), sustainable aviation fuels are referred to as

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synthetic blending components (SBCs) in order to create a clear distinction between the premixed fuel and the synthetic components (ASTM D7566 - 23b; ASTM D1655 - 24).

In the ReFuelEU Aviation regulation, the quotas for the use of SAF relative to the overall quantity of fuel used rise from 2% in 2025 to 70% in 2050 (Figure 1). These percentages refer to the unblended proportion of SBCs.[2] From 2030, there is additionally a subquota for the use of electricity-based fuels, which rises to a share of 35% by 2050. The biggest technological and economic challenges for the use of SAF relate to scaling up production and reducing production costs, as SAF is currently significantly more expensive than fossil kerosene (Braun et al. 2024; EASA 2026).

SAF, as a mixture of SBCs and fossil jet fuel (Jet A-1), can be integrated directly into today's fuel infrastructure and logistics chains and used with modern aircraft and engines, as it meets the specifications for aviation fuels. Such fuels are therefore referred to as drop-in fuel. The ASTM defines global standards for the use of SAF in aviation. According to ASTM D7566, there are currently eight approved production processes for SAF, in addition to three others for co-processing. The current maximum blending limits of SAF as an SBC to conventional fuel (Jet A-1) depend on the feedstock as well as on the SAF production process but must not exceed a maximum of 50%.

[2] The shares or quantities of SAF indicated below in this study always refer to the unblended SBC in accordance with the system set out in the ReFuelEU Aviation regulation.

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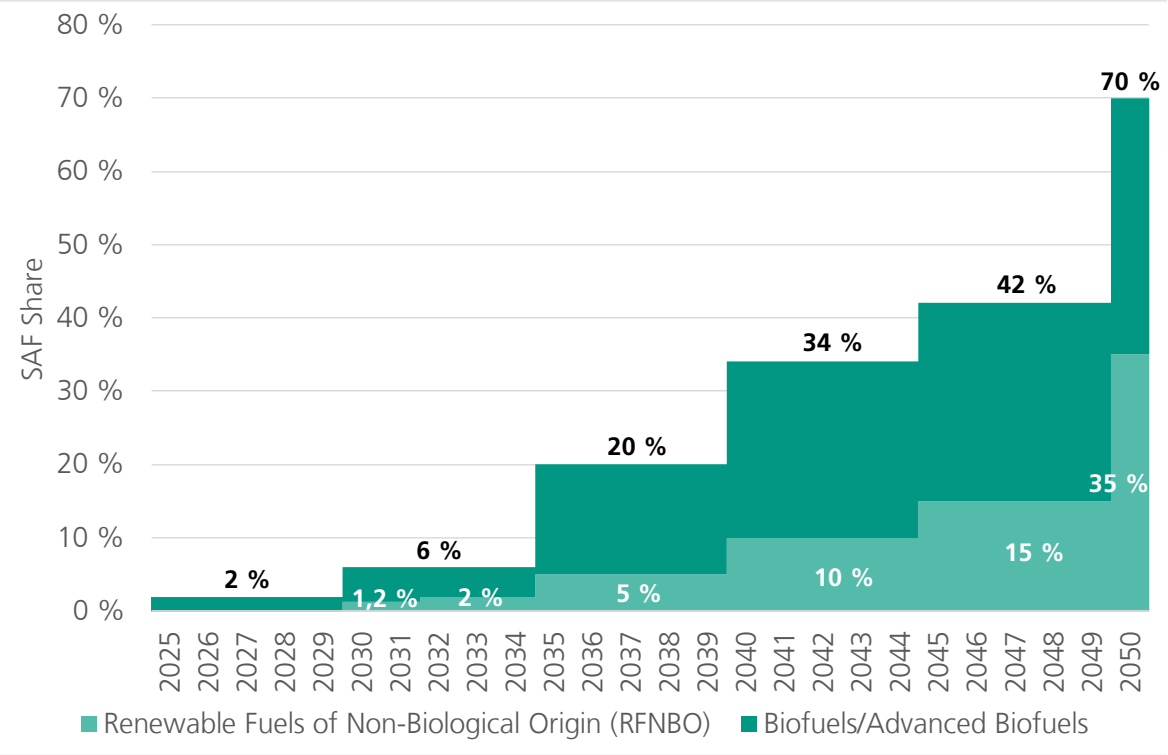


Figure 1: Change in SAF blending requirement in accordance with Regulation (EU) 2023/2405 (source: own graphic, data: European Parliament and Council of the European Union (2023))

Through the use of alternative fuels, it is possible to reduce not only the CO_2 effects but also the non-CO_2 effects. Measurements by the DLR in the ECLIF3 study in collaboration with Airbus, Rolls-Royce and Neste showed that the lower emissions of soot particles and a lower number of ice crystals during contrail formation can reduce the climate impact of contrails by 26% when using pure SAF (Märkl et al. 2024). The emissions of soot particles can be reduced by decreasing the amount of aromatics needed in the fuel. Although it is theoretically possible to produce SAF without aromatics, the presence of aromatics in fuels is necessary in today's commercial aircraft in order to maintain the elasticity of seals, for example. For this reason, aromatics are in some cases added to drop-in SAF artificially. ASTM D7566 stipulates a minimum share of 8 vol% of aromatics in approved fuels mixed with SAF (SAF blends).

A future use of 100% SPK-SAF, also referred to by some aviation industry stakeholders as "Jet X", in the style of the current fuel standard Jet A/A-1 (Ahrens et al. 2025), could therefore further reduce the climate impact of aviation compared with the use of aromatic-containing fuels. The use of 100% SPK-SAF could reduce pollution in the vicinity of airports

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thanks to the reduction of soot particles. However, current models of commercial aircraft are not yet approved for the use of SAF with a lower share of aromatics.

This study develops and examines workable concepts and therefore scientifically sound courses of action for the transition to a potential 100% supply with aromatic-free SAF in aviation in Germany. The focus is on the identification and analysis of technical, logistical, economic and regulatory challenges, as well as the evaluation of individual scenarios depending on the availability of SPK-SAF, as well as the compatibility of the fleet. The study also seeks to consider and evaluate the impact of allocating SAF to particularly climate-intensive flights. Based on a series of models and assumptions, the scenario analysis additionally includes a scientific examination of the efficiency, costs and feasibility of different approaches to the distribution of SPK-SAF to German airports – for example, duplicate physical infrastructure or centralised flexibility solutions such as book and claim.

The study is structured as follows:

Section 2 defines the study's terms of reference, scope and system boundaries. Section 3 provides an overview of fuel logistics at airports, the regulatory environment in relation to SAF use, and the environmental effects of 100% SPK-SAF. Section 4 derives challenges for the use of 100% SPK-SAF based on a literature study and stakeholder survey. Section 5 includes the quantitative analysis, in which scenarios are used to analyse the cost and benefit of using 100% SPK-SAF. Section 6 discusses the qualitative and quantitative results and derives scientifically sound courses of action. The study ends with a conclusion and outlook in section 7, exploring prospects for further analyses with a view to promoting the use of 100% SPK-SAF.

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2 Terms of reference, scope and system boundaries

The scope of this study relates to the theoretical impact of using 100% SPK-SAF on flights from German airports. The entire functional chain is considered, including production, distribution, storage, refuelling and flight operations. Outstanding questions around certification and regulatory affairs are addressed and subsequently used to derive scientifically sound courses of action. This approach serves to identify relevant differences in the use of 100% SPK-SAF compared with the status quo, as shown in Figure 2.

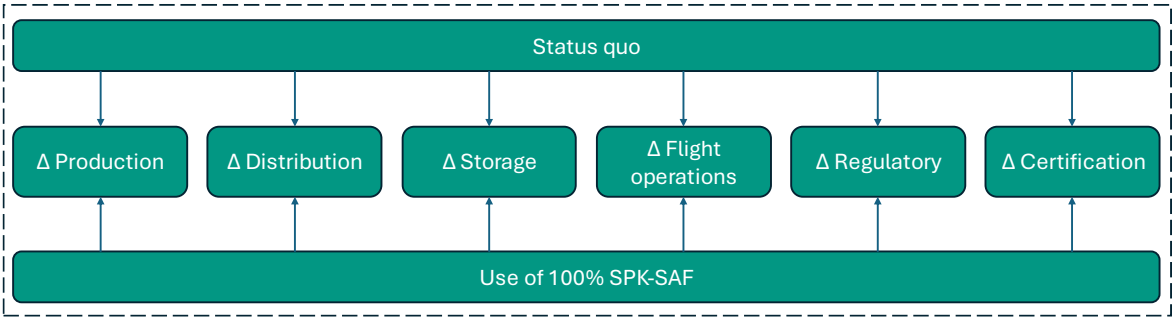


Figure 2: System boundaries/components of quantitative analysis (source: own graphic)

The impact on the stated elements of the functional chain is evaluated qualitatively in order to assess the relative advantage of specific measures. A quantitative evaluation is carried out with regard to the analysis of the potential fuel demand for the nationwide and targeted use of 100% SPK-SAF. Furthermore, the relative advantage of targeted use – based on, for example, refuelling for maximum climate benefit – is estimated based on the quantitative analysis.

The estimation of fuel demand (fossil kerosene and SAF) is based on the currently applicable legal framework established by the blending quota in the ReFuelEU Aviation regulation. It is assumed that the quantities of SAF stipulated by ReFuelEU will continue to be met in the future, albeit wherever possible by 100% SPK-SAF. In order to estimate the usability of 100% SPK-SAF by compatible aircraft, fleet modelling is carried out for the future fleet mix of aircraft at German airports.

The study does not include a more detailed examination of aspects relating to civil–military cooperation, e.g. the compatibility of military aircraft with non-drop-in fuels or mutual dependencies in the supply of fuel at shared airfields.

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3 Framework and background

3.1 Status quo of fuel logistics and demand

The supply of aviation fuels is a vital part of reliable and safe aviation. Turbofan and turboprop aircraft are approved for the use of jet fuel (kerosene), whose properties are defined in ASTM Standard D1655 or Def Stan 91-091 (for fossil kerosene) and ASTM Standard D7566 (for fuels with synthetic components). In Europe, the fuel is sold as Jet A-1.

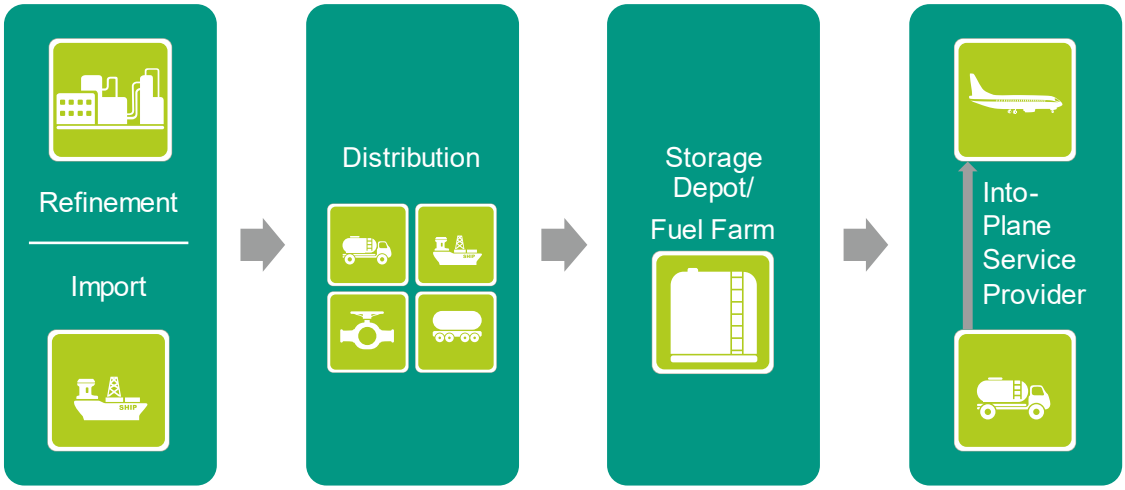


Figure 3: Logistics chain for the supply of aviation fuel (source: own graphic)

The logistics chain for the supply of fuel is complex from a regulatory and organisational perspective and encompasses various different stakeholders (Figure 3). Most refineries are operated by the major oil companies. However, current refinery production of jet fuel in Germany, at approx. 4.5 to 4.8 million t per year, only meets just under half of domestic demand (Wirtschaftsverband Fuels & Energie e.V. 2025). Germany is becoming increasingly dependent on imports for the supply of jet fuel. Whereas over 60% of the fuel needed in Germany was still produced at German refineries in the early 2000s, this value is now less than 50% in the 2020s. Overall, refinery capacity in Germany has decreased in recent years, including due to the closure or conversion of plants in Wilhelmshaven (2011), Hamburg-Harburg (2022) and Wesseling (2025) (Hedvat 2023; Westerhoff 2010; Shell Deutschland GmbH 2025).

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Jet A-1 fuel is supplied to German airports by pipeline, inland waterway vessel, or rail or road tanker depending on the airport's location and infrastructure connections. In many cases, different modes of supply are also used at a single airport, partly for reasons of redundancy against disruptions and partly due to variability in the sources of supply.

The Central Europe Pipeline System (CEPS) is an important piece of infrastructure for Western Europe and Germany, connecting refineries, depots and airports in Belgium, France, Germany, Luxembourg and the Netherlands to one another through over 5,000 km of pipeline (NATO 2021). The pipeline system was conceived for military purposes but is approved for supplying fuel to civilian airports. The sections in Germany are operated by Fernleitungs-Betriebsgesellschaft, a company in which the federal government holds a majority stake (Fernleitungs-Betriebsgesellschaft mbH 2023). The airports of Köln Bonn, Frankfurt Main, Stuttgart and Memmingen are predominantly supplied by this pipeline. Other pipeline systems also play a key role in supplying German airports, such as the direct line between the OMV refinery in Burghausen and Munich Airport.

At other airports, the main supply route is by rail tanker. These airports include Berlin Brandenburg, which principally receives its fuel by rail from the refineries in Schwedt and Leuna.

For airports located close to navigable inland waterways, inland vessels are also a common mode of transport. For example, there is a port for tank vessels in the immediate vicinity of Frankfurt Main Airport, providing another supply route in addition to the pipeline connection. The connection to the airport again relies on a pipeline for the last few kilometres.

Airports that lack a pipeline, inland waterway or rail connection are supplied by road tankers. This supply route is used at Düsseldorf and Hamburg airports as well as at other airports if, for example, the pipeline supply is not available due to maintenance work.

On the airport grounds or in their immediate vicinity, there are storage depots whose function is essentially to buffer fuel demand in the short term and distribute the fuel across the site. The intermediate storage capacities in the vicinity of the airport typically only cover fuel demand for a few days (IATA 2008), and alternative supply capabilities must therefore be implemented in a short space of time in the event of disruption in order to ensure smooth operation. The storage depot and distribution facilities are operated by specialist companies (e.g. Hydranten-Betriebs OHG (HBG) in Frankfurt am Main), which are often jointly owned by the oil companies.

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At the end of the supply chain come the “into-plane” services providers, which carry out the actual refuelling of the aircraft. Depending on the infrastructure available, refuelling is carried out primarily using pump trucks fed from an underground hydrant system (Berlin Brandenburg, Frankfurt Main and Munich airports) or using tankers (all other airports). The two market leaders among the into-plane service providers in Germany are Skytanking and AFS Aviation Fuel Services GmbH. Skytanking is a subsidiary of PrimeFlight Aviation Services, which is in turn owned by two private-equity companies (The Sterling Group and Capitol Meridian Partners) (PrimeFlight Aviation Services 2023). AFS Aviation Fuel Services GmbH is two-thirds owned by Swissport International Ltd., one of the largest providers of ground services, and one-third by DLH Fuel Company mbH, the fuel company of the Lufthansa Group.

A series of industry standards are in place to ensure the quality of the fuels. In addition to the fuel standards of the ASTM, these standards address the correct handling of fuels along the supply chain in order to avoid contamination (e.g. with water or microorganisms) and the mixing of different fuels, which could mean that the fuels no longer meet specifications. Another key part of quality assurance are the specifications for testing and sampling the fuel along the supply chain.

An overview of the applicable regulations can be found in ICAO Doc 9977 “Manual on Civil Aviation Jet Fuel Supply” (ICAO 2012). The key standards for the quality assurance of refuelling processes include the documents of the industry organisation known as the Joint Inspection Group (JIG). The two most important sets of rules in relation to fuel logistics and refuelling are JIG 1 (Aviation Fuel Quality Controls and Operating Standards for Into-Plane Fuelling Services) and JIG 2 (Aviation Fuel Quality Controls and Operating Standards for Airport Depots and Hydrants).

Statistics on the production, sale, and import and export of jet fuel in Germany are published by the trade association Fuels und Energie e. V. (en2x). Domestic deliveries to aviation increased from 6.4 to 8.3 million tonnes between 2001 and 2024, with the highest consumption so far, at 9.4 million t, reached in 2019 (Figure 4). Given the relatively weak development in air traffic compared with other European countries in recent years and the use of increasingly fuel-efficient aircraft, figures have not yet returned to the peak values recorded before the COVID-19 pandemic.

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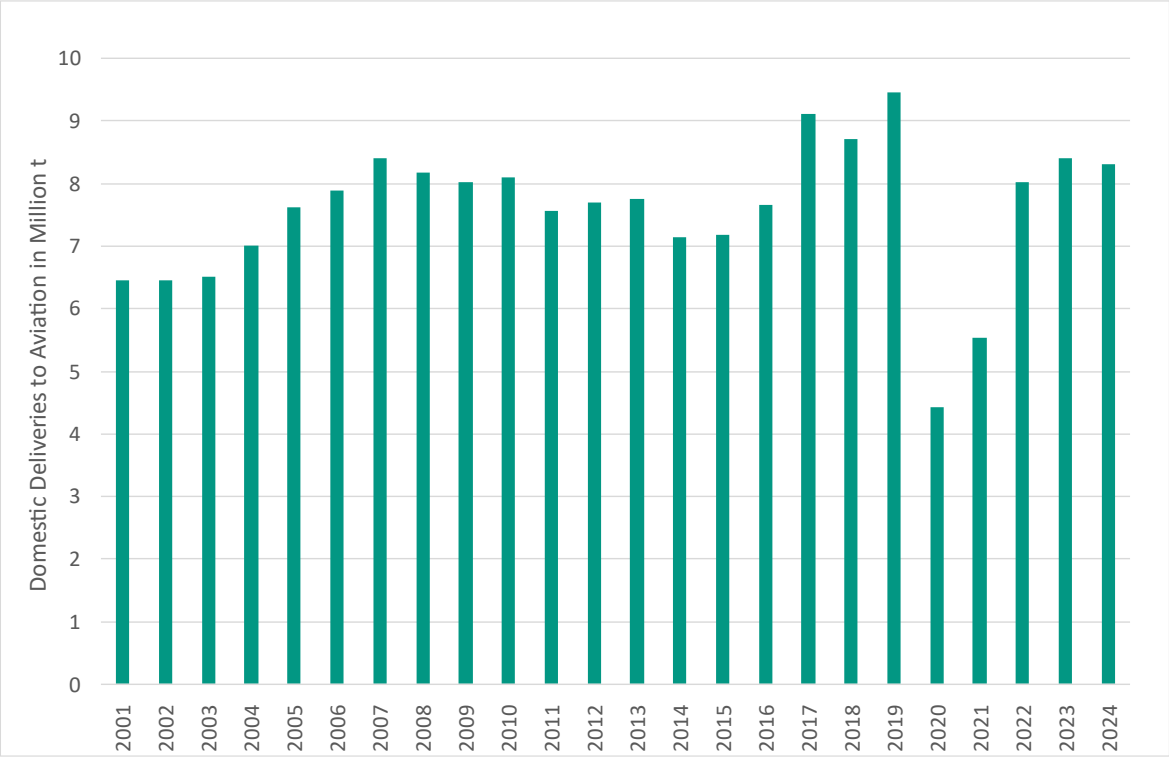


Figure 4: Domestic deliveries of jet fuel to aviation in Germany, 2001–2024 (source: Wirtschaftsverband Fuels & Energie e.V. 2025)

Although the consumption of jet fuel is not broken down by airport in the official oil statistics, it is possible to estimate the proportional consumption to be allocated to each airport fairly precisely from the flights in the official aviation statistics (complete with the departure and destination airport and model of aircraft) and from flight performance modelling[3]. However, this does not account for the practice of tankering, whereby airlines take on more fuel than is directly needed for the next flight. In any case, this practice has been restricted since 2025 by the rule in the ReFuelEU Aviation regulation that at least 90% of the annual fuel requirement must be taken on at the respective departure airport. Figure 5 shows the distribution of fuel demand in Germany in 2024 estimated according to this method.

[3] Master Emissions Calculator of the European Environment Agency (2023).

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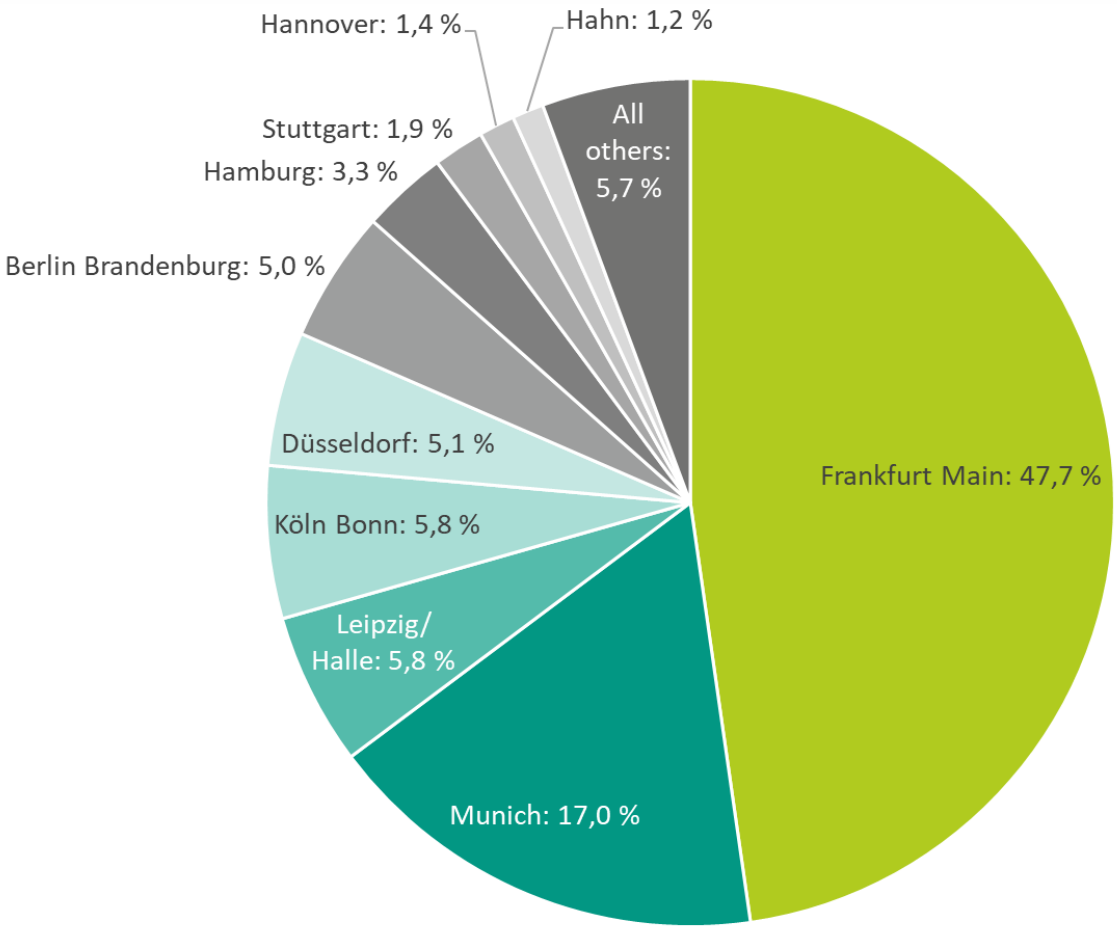


Figure 5: Geographical distribution of demand for jet fuel in Germany, 2024 (source: own calculations based on official German aviation statistics)

Frankfurt Main Airport accounts for a good 48% of total German demand. This corresponds to some 4 million t of fuel in 2024. Meanwhile, Munich Airport accounts for 17% of total German consumption (approx. 1.5 million t), followed by the airports of Leipzig/Halle, Köln Bonn, Düsseldorf and Berlin Brandenburg, which each account for 5% to 6% of total demand (some 500,000 t in each case). Next in the list are Hamburg (3%), Stuttgart (2%), Hannover (1%) and Hahn (1%). All other airports together account for less than 6% of total demand.

3.2 Regulatory framework

Recent years have seen increasingly significant use of SAF in aviation. The treaty states of the International Civil Aviation Organization (ICAO) have set themselves the target of reaching net zero CO_2 emissions for global aviation by 2050 (ICAO 2022). In addition to offsetting mechanisms, alternative propulsion systems and operational efficiency

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improvements, the aim is for SAF to make up the biggest share of the planned reduction in the climate impact of aviation (ICAO CAEP 2022). At the Third Conference on Aviation and Alternative Fuels (CAAF/3), the ICAO treaty states agreed that global CO_2 emissions from aviation are to be reduced by 5% by 2030 through the use of SAF (ICAO 2023).

The aim is to increase demand for SAF through national and supranational incentive systems or the establishment of minimum quantities of SAF. In the EU, the blending requirement set out in Regulation (EU) 2023/2405 has since 1 January 2025 stipulated the binding use of increasing shares of SAF on flights from airports with over 800,000 passengers or 100,000 t of freight per year (Europäisches Parlament and Rat der Europäischen Union 2023). In this context, it is the suppliers who are obliged to provide the fuel. A requirement was imposed on airlines to take on at least 90% of their annual fuel demand at the respective airport. For a transitional phase until the end of 2034, suppliers can meet the quota as an average across all of the supplied airports, i.e. there may be considerable differences in the quantity of SAF physically supplied to the airlines. This represents a logistical simplification, on the one hand, but also leads to unequal treatment of airlines, as they can only claim credit in the EU Emissions Trading System for CO_2 emissions that they have reduced themselves with physically refuelled SAF, whereas a SAF surcharge is levied as standard for all refuelling processes in the EU (personal communication with Condor/Lufthansa). Airlines that operate at airports with high shares of SAF therefore require fewer emission rights in the EU ETS than airlines departing from airports where less or no SAF is provided. Airlines report not only that the unequal provision of SAF is problematic but also that there are considerable deficits when it comes to the provision of the required documentation of SAF use, which are necessary for the recognition of CO_2 savings in the EU ETS (personal communication with Condor/Lufthansa).

In the USA, no minimum requirement for SAF use has been imposed in law; rather, the fuel producers receive a tax credit currently amounting to one US dollar per gallon of SAF (U.S. Government 2025). This represents a significant decrease relative to the original version of the Inflation Reduction Act in the USA (117th Congress of the United States of America 2022), which provided for a tax credit of 1.75 US dollars per gallon.

The production processes for SBCs, or rather their maximum blending proportions, are defined by ASTM standards. ASTM D7566 sets out the standard specifications for jet fuels containing synthetic hydrocarbons (ASTM D7566 - 23b). The standard includes the

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currently approved production processes for SBCs, their characteristics and their maximum proportion in a SAF blend (Table 1). In addition, three further types of SAF, which are produced by co-processing, are also approved pursuant to ASTM D1655 (ASTM D1655 - 24).

At present, the minimum share of 8 vol% of aromatics in the premixed fuel according to ASTM D7566 is necessary for safety reasons, as the effects of these substances include that they cause the swelling up of sealing rings, thereby preventing fuel leakages.

As SPK-SAF is almost aromatic-free, the use of 100% SPK-SAF in modern commercial aircraft is not permitted according to the applicable ASTM standards. Accordingly, it will first be necessary to develop a fuel standard of this kind, which will involve extensive testing and certification efforts. As only certain models of aircraft would therefore be approved for the use of 100% SPK-SAF, the fuel types would have to be segregated for refuelling at the aircraft.

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Process	Maximum blending proportion	ASTM standard
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	50%	ASTM D7566
Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	50%	ASTM D7566
Synthetic Iso-Paraffin (SIP)	10%	ASTM D7566
Fischer-Tropsch Synthetic Kerosene with Aromatics (FT-SKA)	50%	ASTM D7566
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	50%	ASTM D7566
Catalytic Hydrothermolysis Jet fuel (CHJ)	50%	ASTM D7566
Hydroprocessed Hydrocarbons-HEFA (HHC-HEFA)	10%	ASTM D7566
Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	50%	ASTM D7566
Co-processing of mono-, di-, and triglycerides, free fatty acids, and fatty acid esters	5%	ASTM D1655
Co-processing of hydrocarbons derived from synthesis gas via the Fischer-Tropsch process	5%	ASTM D1655
Co-processing of hydrocarbons derived from hydroprocessed mono-, di-, and triglycerides, free fatty acids, and fatty acid esters	24%	ASTM D1655

Table 1: SAF production processes and maximum blending proportions (source: own graphic based on ASTM D1655 - 24 and ASTM D7566 - 23b)

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3.3 Contribution of SAF to reduction of climate impact and to local air quality

In recent years, the climate impact of aviation has received greater attention from regulatory authorities, the aviation industry and society as a whole. On the one hand, the focus is on the reduction of CO_2 emissions. These can be reduced by the use of SAF, as this fuel's life cycle emissions are significantly lower than those of fossil aviation fuel, depending on the different feedstocks used.

On the other hand, increasing emphasis is now being placed on the reduction of non-CO_2 effects of aviation. Having been the subject of ongoing research in recent years, these effects can be determined with increasing accuracy. The determination of non-CO_2 effects is a highly complex process, and their climatological influence depends on a series of factors, including environmental conditions (temperature, air pressure, humidity), the place where the emissions are formed (altitude, latitude), the characteristics of the engines used, and the composition of the fuel. The effect of contrails and of the resulting cirrus clouds also depends on the time of day and the optical characteristics of the earth's surface (albedo). Depending on the chosen climate metric, the non-CO_2 effects account for about half to two-thirds of the total climate impact of aviation.

The use of SAF can reduce contrail formation and particulate emissions. Non-CO_2 effects are negatively correlated with the share of SAF in the fuel used, i.e. a high share of SAF has a positive impact in terms of avoiding non-CO_2 effects. The positive effects of SAF result from the low proportion of aromatics, which tend to form soot (non-volatile particulate matter, nvPM) on combustion, and from the low proportion of sulphur particles, which contribute to the formation of volatile particulate matter (vPM).

As part of the Emission and Climate Impact of Alternative Fuels (ECLIF3) campaign, in situ measurements were taken of the emissions from an Airbus A350-941 during combustion of 100% HEFA-SPK. The results showed a 56% reduction in ice particles and a 35% reduction in soot particles compared with conventional Jet A-1, which can lead to a 26% reduction in radiative forcing in global modelling (Märkl et al. 2024). Analyses by Rolls Royce on a Pearl engine for business jets found that the use of 100% SPK-SAF can reduce the number and mass of particles in the landing and take-off (LTO) cycle by 60% (Ahrens et

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al. 2025). From 2025, further investigations into this topic are being conducted as part of the Horizon Europe project PACIFIC (Particle Emissions, Air Quality and Climate Impact related to Fuel Composition and Engine Cycle) under the leadership of Airbus and in collaboration with Rolls Royce and the DLR (CORDIS 2025).

Teoh et al. (2022b) investigated the effects of allocating SAF to individual flights over the North Atlantic with a high climate impact. They found that the targeted use of SAF on 2% of flights, which are principally responsible for the formation of warming contrails, can achieve a 6% reduction in the overall climate impact in the affected region. The study's authors also conclude that radiative forcing from contrails could be reduced by 44% if 100% SAF were used across the entire fleet.

Although uncertainties remain as to the exact quantification of non-CO_2 effects due to the use of SAF, it is still possible to deduce from the findings of the recent studies that the benefits of SAF can be maximised if it is used on the flights with particularly high non-CO_2 effects. However, this represents a deviation from the current regulations, which provide for general blending of SAF without prioritising specific flights.

The particulate emissions from aviation not only make a significant contribution to the non-CO_2 effects but also affect local air quality in the vicinity of the airport through the formation of nvPM and vPM. According to one current study by CE Delft, the use of 100% aromatic- and sulphur-free fuels would reduce particulate matter emissions by over 70% and therefore the occurrence of serious respiratory and cardiovascular diseases to the same extent (van Seters et al. 2024). The targeted use of fuels with a high share of SAF or 100% SPK-SAF at airports near city centres could therefore have benefits for local air quality in addition to the aforementioned benefits in terms of reducing non-CO_2 effects.

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4 Challenges for the use of SPK-SAF and appropriate solutions

4.1 Methods

The introduction of 100% SPK-SAF would lead to considerable changes in how commercial aircraft are supplied with fuel compared with the situation today. To identify these challenges and derive possible solutions, this study included both a literature review and a consultation of various stakeholders. The information from the stakeholders was used to gain additional knowledge but is also intended to reflect the different positions and priorities of the aviation sector, industry, regulatory authorities and the world of science.

Contact was established with the stakeholders through the InnoFuels project team. The individual stakeholders were then each asked about the impact of introducing the use of 100% SPK-SAF in aviation in interviews lasting approximately one hour over a video-conferencing system. In preparation for the interviews, a list of questions was drafted that included questions on the introduction of 100% SPK-SAF along the entire functional chain. This list of questions can be found in the appendix.

Before the interviews began, the questions and stakeholders were divided into different categories so that the stakeholders could answer questions specifically from their own industry segment. A total of 14 stakeholder interviews were conducted. The categories and the surveyed stakeholders are set out in Table 2.

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Category	Stakeholder
SAF production	SkyNRG Karlsruhe Institute of Technology, IKFT DLR Institute of Combustion Technology
Distribution, airport infrastructure and refuelling	Düsseldorf Airport Köln Bonn Airport Skytanking AFS Aviation Fuel Services BSAF Blue Sky Aviation Fuel
Aircraft and engine manufacturers	Airbus Pratt & Whitney
Airlines	Deutsche Lufthansa Condor Flugdienst
Market & regulatory	Federal Environment Ministry Hochschule RheinMain – University of Applied Sciences and Arts

Table 2: Stakeholder consultation: categories and contacted stakeholders

4.2 SPK-SAF production

Two key challenges in relation to the use of SPK-SAF (and SAF in general) are availability and price. In the view of the aviation industry, greater support measures are needed in order to achieve the large-scale implementation of SAF production. At present, it is expected that demand for SAF will be covered – at least in the short and medium term – by used cooking oils and fats by means of the HEFA process. However, the availability of cooking oils and plant and animal fats as waste materials is limited, and rising demand means there are unlikely to be significant drops in SAF prices with this production process, despite new installations and the resulting economies of scale. At present, the production capacities for HEFA-SAF are being expanded (CENA Hessen 2025). In the long term, the sharp rises in blending quotas and the RFNBO subquota will mean that other processes aimed at using a

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broader feedstock base must be further developed and scaled up to meet growing demand. Many stakeholders therefore see the primary challenge as being the sufficient medium- and long-term provision of SAF and the associated regulatory aspects, such as the sustainability criteria for feedstocks (e.g. CO_2 and hydrogen), particularly in the case of imports from outside the EU.

There is a prospect that costs could be reduced through economies of scale, the improvement of production processes, and a broader feedstock base. At present, according to the EASA report on fuel reference prices, these costs are higher than those for fossil kerosene by a factor of approximately three (market prices of HEFA-SAF) to ten (production costs of PtL-SAF) (EASA 2026). However, price parity of SAF with fossil fuels is not expected to be achievable.

The production of SPK-SAF as non-drop-in fuel is similar to the production of SBCs, which are used for blending with conventional Jet A-1 as drop-in fuels in accordance with ASTM D7566. The technical and economic challenges of scaling up and economies of scale therefore barely differ from the production of drop-in fuels. So far, most of the known production processes can produce SAF with a small amount of aromatics or none at all – including, for example, the HEFA process, the only process that can produce SAF in large quantities. In order to reach the minimum content of 8 vol% according to ASTM D7566, these aromatics must therefore be added. The 100% SPK-SAF considered in this study as non-drop-in fuel should contain no aromatics. This means that the disadvantage of current processes such as HEFA or FT-SPK, which do not contain aromatics, could represent an advantage for the production of 100% SPK-SAF. Accordingly, no or only minor adjustments are to be expected in production. This should also mean that the production costs of 100% SPK-SAF as non-drop-in fuel do not differ significantly from those of SBCs used in drop-in fuels. However, as larger quantities of SAF are to be produced in the long term, there is likely to be a need for processes in which conversion involves significantly greater effort. This is likely to result in a significant increase in costs (in relative terms).

As the 100% SPK-SAF fuels have the same sustainability criteria, this study assumes that the SAF requirements due to ReFuelEU Aviation can in future be fully or partially met by using 100% SPK-SAF as a non-drop-in fuel.

As yet, no fuel standard has been defined for 100% SPK-SAF as a non-drop-in fuel, and the corresponding working groups are not expected to reach a conclusion until after 2028. Two aims are being pursued by the aviation industry: on the one hand, a standard model is to be

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developed that allows the use of 100% SAF as a drop-in fuel in order to raise the limits for the maximum shares of SAF shown in Table 1. This is also important when it comes to compatibility with the stipulated blending quotas in ReFuelEU Aviation, which provide for 70% SAF use in 2050. However, this fuel would provide a minimum level of aromatics and would therefore not achieve the optimum combustion characteristics of aromatic-free 100% SPK-SAF.

On the other hand, a standard is to be defined for 100% SPK-SAF as a non-drop-in fuel whose characteristics are to be specifically optimised. The particular challenge here is to harmonise different target values and find an optimum balance. Account must be taken not only of the properties and characteristics of the fuel but also of its interaction with the aircraft technology and of the properties of the source materials and the production techniques. For example, these properties and characteristics include:

- gravimetric and volumetric energy density
- conductivity
- lubricity
- thermal capacity
- viscosity
- surface tension
- combustion characteristics (particle formation)
- restart behaviour (in the event of engine failure during cruise flight)
- effects on seals/pipes in aircraft and ground infrastructure.

In particular, the fuel's behaviour during atomisation in the combustion chamber is a key factor in the behaviour in the event of restarting during cruise flight. At extremely low ambient temperatures, it is noted in the literature that 100% SPK-SAF behaves less favourably than fuels that meet the specifications under Jet A/A-1 (Ahrens et al. 2025).

Before a standard is adopted, the scope for deriving details of specific challenges relating to production and use is very limited. Accordingly, assumptions are made at many points in this study with a view to the qualitative and quantitative analyses.

4.3 Fuel logistics

One of the biggest challenges for the introduction of a fuel that does not meet the specifications of the Jet A-1 used today is the need to segregate it from other fuels. This is

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necessary because, after a fuel standard is introduced for the use of 100% SPK-SAF, it can currently be assumed that only part of the fleet at a commercial airport will be certified for this fuel and also that a (decreasing) proportion of fuel demand will continue to be served by Jet A-1. One key challenge is therefore the duplication of the necessary infrastructure. Given the need to segregate the fuel, these challenges affect the entire supply chain, from the refinery to the respective airports and the refuelling of aircraft.

Account must also be taken of the different routes for distributing fuel to the airports. If an airport is supplied via a pipeline system, there is very limited scope for segregation. Accordingly, these airports would need to be given a regularly used, additional distribution line for the supply of 100% SPK-SAF on a lasting basis.

For reasons of redundancy, airports that are connected to pipeline systems already have alternative supply routes that are used when the pipeline is undergoing maintenance, for example. However, these alternative supply routes are frequently associated with higher logistics costs (e.g. for handling, vehicles and personnel) if delivery takes place via inland navigation or rail or road tanker.

As some airports are not directly connected to ports, railways or the CEPS, there is often a need for combined distribution routes in order to supply the airport with fuel. The challenges for airports that are not connected to the CEPS may be slightly smaller due to the introduction of 100% SPK-SAF, as it may be possible to repurpose current means of transport. Here, it is nevertheless vital to maintain complete segregation in all circumstances in order to avoid contamination of the fuel. Whatever the case, however, greater complexity can be expected due to the additional transport routes for the distribution of 100% SPK-SAF.

One can therefore assume that the logistics costs of supplying fuel will increase significantly for many airports. This is particularly likely over time if the stipulated SAF quantity increases and more aircraft are compatible with 100% SPK-SAF. Alternative supply routes would therefore become more significant than the current system of supplying fuel by pipeline. This would simultaneously reduce the degree of utilisation of the CEPS if the fuels were supplied via other channels. This is a crucial issue for the airlines when it comes to the acceptance of 100% SPK-SAF, as higher costs could put them at a competitive disadvantage, particularly on long-haul routes. Competitively neutral financing mechanisms will therefore also be important for the successful introduction of 100% SPK-SAF.

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4.4 Airport infrastructure and refuelling

The introduction of a new fuel also brings challenges in terms of airport infrastructure and refuelling. There are essentially three aspects that must be considered here:

- duplication of refuelling infrastructure (storage depots)
- prioritisation of flights for refuelling with 100% SPK-SAF
- organisation of the refuelling process.

As is the case in the upstream supply chain from the producers to the airport, the supply of 100% SPK-SAF also requires separate fuel logistics at the airport.

The consulted stakeholders observed that the use of 100% SPK-SAF is associated with significant challenges for refuelling and for the airport infrastructure in general. The necessary segregation of fuel types results in a need for dedicated storage depots. Given the required settling periods, at least two or three new fuel tanks may be needed in order to take on the functions of receiving, settling and supplying the fuel, depending on the required volume. One major challenge in this regard is the space requirement at airports due to the new storage depots. Indeed, the repurposing of existing tanks is only possible to a very limited extent. At Köln Bonn Airport, for example, there are only a total of three tanks that supply the airport with fuel. This corresponds to the IATA recommendation, which envisages that one tank be designated for receiving fuel, one tank for a several-hour settling phase after receipt or as a reserve in the event of maintenance work, and another tank from which fuel is extracted for refuelling (IATA 2008).

Switching over to 100% SPK-SAF would therefore require the construction of several new tanks and the associated receipt and refuelling infrastructure (pumping stations and areas for delivery by road tankers and the filling of airport refuelling trucks). The key challenge lies in the rising demand for 100% SPK-SAF over the course of time if more aircraft are available to use the fuel. This would mean building facilities with almost all of the current storage capacity in order to convert the system to 100% SPK-SAF over the coming decades while simultaneously making Jet A-1 available for old models of aircraft.

Given the low availability of SAF in the short to medium term, it is also important to clarify which flights should be refuelled with SPK-SAF. The key situations here are those in which the quantity of SPK-SAF is not sufficient to meet the requirements of all compatible aircraft

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at the airport. In such cases, it may be necessary to prioritise the flights with the greatest climate impact.

Various studies have looked at the possible effects of the targeted use of SAF or SPK-SAF in terms of climate impact and at the necessary prerequisites in terms of physical infrastructure at airports. Quante et al. (2024) evaluated the feasibility and operational impact of segregated fuel infrastructure in Northern Europe. To this end, tankers were used to refuel 84 flights on the Stockholm to Copenhagen route with an increased blending quota of SAF. While the expansion of existing hydrant systems currently appears impracticable, Quante et al. (2024) state that refuelling via tankers is realistic for short- and medium-haul flights. The climate impact of the contrails caused by the flights could be reduced by over 20% with blending quotas of 50%. Quante et al. (2025) carried out simulations in which they examined the targeted use of 100% SPK-SAF on flights departing from five major airports. They found that the targeted use of SPK-SAF could reduce the climate impact by up to 55% if the fuel were used only on segments of a flight in which warming contrails form due to atmospheric conditions. Quante et al. (2025) also remarked on the necessary infrastructure measures at airports as well as the necessary modifications of aircraft. Woeldgen et al. (2025) examined three different strategies for the targeted use of SAF in aviation for flights departing from airports in the EU and the United Kingdom in 2019. As well as considering the climate impact, they also quantified directly incurred costs and used these as the basis for determining marginal abatement costs for the individual strategies. The research also analysed the possibility of only allocating SAF to flights taking off from 16:00 local time onwards. These flights were prioritised because climate research has found that contrails have a particularly warming effect at night (Stuber et al. 2006). The study also modelled an option in which only flights that cause long-lived contrails with a length of over 250 km were refuelled with higher SAF blending quotas. Both options reduced effective radiative forcing by 9% to 17% compared with the use of purely fossil Jet A-1. On the other hand, additional costs arose for the segregation of the fuel system. In contrast, another strategy for seasonally uniform distribution of the total SAF from October to February leads to approx. 12% to 13% lower radiative forcing but, given the uniform distribution of the fuel, only results in slight additional costs, making this the study's most cost-effective measure for avoiding climate-relevant emissions.

During refuelling of the aircraft fleet, care must be taken to ensure that only aircraft that are compatible with the new fuel are refuelled in order to avoid contamination of incompatible

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aircraft. This can create additional complications for flight operations and refuelling. At larger airports in Germany (e.g. Frankfurt Main or Munich), aircraft are primarily refuelled using hydrant fuelling systems. Given the need for segregation and to avoid contamination, it would be essential to create an additional refuelling option – in other words, the existing hydrant fuelling system could not be used for 100% SPK-SAF.

The quantity of 100% SPK-SAF at airports may be limited by the low availability of compatible aircraft, particularly in the early phase of its introduction. Depending on how these factors develop, larger quantities of the fuel are expected in the following years due to increased demand from compatible fleets. Due to the rising blending quotas in the ReFuelEU Aviation regulation, it can be assumed that the ramp-up of SAF or of 100% SPK-SAF will rise steeply towards 2050 following the introduction of compatible aircraft models. Given the high investment costs, it appears impracticable to introduce an additional hydrant fuelling system for this period, including from the point of view of stakeholders. Refuelling with 100% SPK-SAF would therefore have to switch over to airport refuelling trucks at the three largest German airports of Frankfurt, Munich and Berlin Brandenburg, which have a hydrant fuelling system and are responsible for a total of almost 70% of fuel demand in Germany. A switchover of this kind would be very costly at these airports, as new tankers would need to be purchased and crewed. In operational terms, this would mean a considerable increase in traffic on the apron as well as additional local and global climate emissions, unless electrically operated tankers were used. At the other airports in Germany, where refuelling is currently carried out using airport refuelling trucks, the switchover would lead to relatively smaller changes in the refuelling process.

As the segregation of 100% SPK-SAF and Jet A-1 must also be ensured when refuelling with tankers, there would be a need for dedicated tankers to refuel aircraft that were compatible with 100% SPK-SAF – and these tankers would only be used for 100% SPK-SAF in everyday operations. Here, the possibility of repurposing the existing fleet of tankers at airports should also be examined. On the one hand, the required amount of fuel for individual flights poses a challenge, as two or three full tankers would generally be needed to supply long-haul flights. On the other hand, the availability of tankers presents an additional layer of complexity. The into-plane service providers would have to keep relatively large sub-fleets of tankers in reserve that could meet the demand for both Jet A-1 and 100% SPK-SAF at any given time. Given that the increased climate impact of long-haul flights means that these flights should be prioritised for 100% SPK-SAF, peak phases could emerge as a

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function of the flight plan. These peak phases could mean that many tankers were tied up at the same time, while the utilisation would be very low in other phases of the daily cycle. It is therefore essential that operational limitations and challenges be taken into account when evaluating the introduction of the new fuel.

Given the high concentration of long-haul traffic in Germany at the airports of Frankfurt Main and Munich, the greatest benefit at these two airports would presumably be achieved in the event of limited availability of 100% SPK-SAF. However, the airports would also present the biggest logistical challenges because the existing hydrant fuelling system, as described above, cannot be used for 100% SPK-SAF – and, for cost reasons, it is also highly unlikely that it can be duplicated.

4.5 Aircraft and engine manufacturers

The key challenge in terms of aircraft and engines is compatibility with the use of 100% SPK-SAF. With their approval in the type certificate data sheet (TCDS), commercial aircraft receive a list of fuels that can be used. An example of this can be seen in Figure 6 for the Airbus A320.

Fuel Specification

ENGINES	KEROSENE DESIGNATION
CFM56: Installation document CFM 2026 or CFM 2129)	JET A, JET A-1, JP5, JP8, N°3 Jet Fuel, JET B**, JP 4**, TS-1, RT(GOST), F44, F34, AVTUR, AVTUR/FSII, AVTAG/FSII, AVCAT/FSII
IAE V2500: IAE Standard Practices and processes Manual IAE 0043	JET A, JET A-1, JP5, JP8, N°3 Jet Fuel, JET B**, JP 4**, TS-1*, RT(GOST), F44, F34, AVTUR, AVTUR/FSII, AVTAG/FSII, AVCAT/FSII
IAE PW1100G-JM: (Service Bulletin PW1000G - 100-73 00-0002-00A930AD)	JET A, JET A-1, JP5, JP8, N°3 Jet fuel, TS-1(GOST), RT(GOST), AVTUR, AVTUR/FSII, AVCAT/FSII
CFMI LEAP-1A: Service Bulletin LEAP-1A S/B 73-0001	JET A, JET A-1, JP5, JP8, N°3 Jet fuel, TS-1(GOST), RT(GOST), AVTUR, AVTUR/FSII, AVCAT/FSII

The above-mentioned fuels are also suitable for the APU.
Refer to Consumable Material List (CML) for details on approved fuel specifications

* For IAE V2500 engines, TS-1 is cleared for transient use (less than 50% of operations)
** JET B and JP 4 fuels are not authorized for use in aircraft fitted with jet pumps (modification 154327)

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Figure 6: Excerpt from type certificate data sheet EASA.A.064 for the Airbus A320 (source: EASA 2025)

The fuels that are approved for use in modern aircraft meet the ASTM D7566/Def Stan 91-091 and ASTM D1655 standards. One key factor is the aromatic content, which today aids the swelling of seals and thereby helps to keep the fuel system leak-tight. According to reports in the literature, fuel leaks have occurred in aircraft fitted with nitrile seals and refuelled with aromatic-free fuels (Hamilton et al. 2024). Given that fossil kerosene generally has a sufficient minimum aromatic content, the fuel standard does not define a minimum level. For SAF, as mentioned in section 3, ASTM D7566 stipulates a minimum content of 8 vol%.

To be able to use an aromatic-free fuel, aircraft and engines would require new or additional certification and would have to be retrofitted in order to meet the high aviation safety standards. This would mean replacing nitrile seals with other materials, such as fluorosilicone, which are more expensive and also have different properties, such as lower abrasion resistance (Hamilton et al. 2024). The fuel measurement system would also have to be designed for the new fuel, including due to differences in viscosity and specific energy content. This is, in principle, possible from a technical perspective. In collaboration with Deutsche Aircraft, the DLR retrofitted a type-Do328 turboprop regional aircraft for trial operation with an aromatic-free fuel (DLR 2024). Test flights by the DLR in collaboration with Airbus have in principle shown that type-A350 and -A320neo aircraft can also be operated with low-aromatic 100% HEFA kerosene without significant modifications (Märkl et al. 2024). However, approval has not been granted for regular commercial operation – and there is a lack of experience with the long-term use of aromatic-free fuel. The test flights were also carried out under restrictive conditions that would not be practicable in commercial operation.

Stakeholders from aircraft and engine manufacturers consider the costs of recertification for commercial flight operations to be substantial. After all, every single model of aircraft would need to be recertified. This is, in principle, conceivable for current models of aircraft that are still in production, as it may make economic sense for aircraft and engine manufacturers to seek additional certification while the fleet is growing and long production periods are still planned. This would be a necessary prerequisite for the use of 100% SPK-SAF, as Airbus is not currently planning any successor models to the long-haul A350 and A330neo aircraft. The market entry of a successor to the A320 family is planned for after

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2035 (Eiselin 2025), before which several thousand aircraft are still likely to be delivered. For aircraft models that are no longer in production, the business case for recertification is considered to be significantly worse. The introduction of 100% SPK-SAF is unlikely until after 2030 due to the lack of standards and infrastructure. By then, the number of common aircraft models from recent years/decades (e.g. A320ceo, A330/340, Boeing 747, 757, 767) in the active fleets will have decreased significantly, and recertification therefore makes little economic sense if it is very costly.

In addition to the costs of recertification, there would also be costs for retrofitting the individual aircraft. In many cases, the retrofitting of aircraft models from the existing fleet in order to use 100% SPK-SAF would require extensive interventions into the fuel system and engines. If such scope for retrofitting exists, it therefore seems sensible to carry out the work as part of large maintenance events (e.g. a D check).

During (re)certification or retrofitting, care should also be taken to ensure “backward compatibility”. Aircraft that are approved for the use of 100% SPK-SAF will also need to be compatible with conventional Jet A-1, as 100% SPK-SAF is unlikely to be available at all airports in the global aviation system. This may mean that engines cannot be optimised exclusively for the combustion of 100% SPK-SAF nor can they achieve optimum combustion of either 100% SPK-SAF or Jet A-1. The effect on fuel consumption and local pollutant emissions would need to be examined in detail once the fuel standard for 100% SPK-SAF is available. In principle, however, it is clear that no negative aspects of the use of 100% SPK-SAF have been observed with current engines on the test stand so far, at least in short-term operation. For example, Rolls Royce demonstrated on the test stand in 2023 that all of their current production engines were compatible with the use of 100% SAF (Ahrens et al. 2025). It may be that combustion with fewer soot particles and the absence of sulphur in the fuel could even lead to positive effects, e.g. reduced deposit build-up, longer use of components before inspection or replacement, and therefore lower maintenance costs. However, this assumption should also be verified in long-term testing, which is yet to be carried out.

The high level of complexity and the associated costs of recertifying current or discontinued aircraft models led aircraft and engine manufacturers to remark, within the framework of the stakeholder survey, that compatibility with 100% SPK-SAF may only come with new aircraft models that reach the market in the future. This would have a considerable impact on the demand for 100% SPK-SAF and the expected environmental effects, particularly as

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Airbus does not anticipate putting the successor to the A320 into service until after 2035. This impact is quantified in various different scenarios in section 5.

4.6 Airlines

The introduction of 100% SPK-SAF is also associated with various challenges for the airlines. As fuel costs can make up around a third of direct operating costs depending on the business model, usage scenario and framework conditions, airlines are generally very sensitive to changes in fuel prices. In this context, one particular challenge with all types of SAF are the significantly higher costs compared to conventional Jet A-1. According to EASA (2026), the average reference prices for biobased sustainable aviation fuel in Europe in 2025 were 1,925 €/t, compared with 640 €/t for conventional Jet A-1. Market prices for synthetic fuels were not available to EASA. However, at an average of 7,520 €/t, the production costs were estimated at over ten times the market price for fossil kerosene.

Given that the blending quotas for SAF are still low, the effects on the total cost of fuel have so far been limited. In the present study, it was assumed that the blending requirements under the ReFuelEU Aviation regulation can be met not only by drop-in SAF but also in future by 100% SPK-SAF. However, the selective use of 100% SPK-SAF by a few airlines with compatible aircraft would necessitate a financial compensation mechanism. Otherwise, the operators of aircraft flying with 100% SPK-SAF would face a significant, unilateral financial burden.

The current incentive systems for the use of SAF are not, however, designed for the particular challenges associated with the use of 100% SPK-SAF. One possibility would be to encourage airlines to purchase and actively use 100% SPK-SAF through financial incentives, provided they had compatible aircraft in their fleet. For example, one conceivable option would be a levy scheme in which all passengers, or senders of air freight, pay a surcharge on ticket prices or freight tariffs or on conventional fuel. The proceeds could serve to benefit users of 100% SPK-SAF in order to avoid distortions of competition due to high fuel costs. In an incentive system of this kind, it is important to ensure that flights with a high climate impact would have greater incentives to use the fuel so as to make optimum use of the limited amount of SPK-SAF available. At the same time, it could be ensured through the regulatory framework that there were no disadvantages for airlines that forewent the use of 100% SPK-SAF because they had no compatible aircraft, for example.

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Should competitive advantages lead to a gain in market share for airlines from third countries where there are no obligations in terms of SAF blending or the surrender of emission rights, this leads to a risk of carbon leakage, i.e. the relocation of emissions to unregulated third countries. This problem not only arises with the surrender obligation for CO_2 emission rights but would presumably also be exacerbated in the event of potential levy requirements for non-CO_2 effects.

A system of this kind would need to be comprehensive enough to fairly resolve the existing challenges for crediting the use of SAF in the EU ETS. There would also be a need for a reliable monitoring, reporting and verification (MRV) system for non-CO_2 effects in order to reflect the incentives in a scientifically sound manner. A first step in this direction is the MRV system for monitoring non-CO_2 effects as part of the EU ETS, which was introduced with the amendment of implementing regulation (EU) 2018/2066 in 2024 and is currently being set up.

Another option would be the compulsory use of 100% SPK-SAF on routes with high climate impact, provided that appropriately certified aircraft are used on this route. The advantage of such a measure lies in achieving maximum effectiveness when it comes to reducing climate impact. However, the practical implication is that these flights would have to be supplied with 100% SPK-SAF, which would present significant challenges in terms of fuel logistics (and, where applicable, fleet and network planning). In addition, accompanying measures such as a compensation mechanism for the different costs of fuel would have to be implemented in order to avoid distortions of competition. It is clear not only from stakeholder interviews as part of this study but also from press releases or position papers from associations that the aviation industry takes a critical view of the compulsory use of 100% SPK-SAF, as the implementation of the ReFuelEU Aviation regulation is already seen to be distorting competition (Bundesverband der deutschen Luftverkehrswirtschaft 2026). Without a compensation mechanism of this kind, operators of mixed fleets of compatible and incompatible aircraft would have an incentive to use incompatible aircraft on particularly climate-sensitive flights in order to avoid an obligation to use 100% SPK-SAF on those flights.

In the stakeholder consultation, representatives of airlines also pointed to the logistical challenges of prioritised 100% SPK-SAF use on flights with particularly large non-CO_2 effects. Flights that are to be supplied with 100% SPK-SAF would have to be identified sufficiently far in advance in order to plan the refuelling logistics. In the interviews, the

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representatives pointed out that flexibility in refuelling could be lost if only a limited number of tankers with 100% SPK-SAF are available.

4.7 Market & regulatory

There are also a number of challenges to overcome in terms of the availability of 100% SPK-SAF and the regulatory approach to this fuel. On the one hand, the low production quantities of SAF are the result of low production capacities and barriers to demand from airlines due to the high price of SAF. For the time being, the key driver is therefore likely to be the blending quota stipulated by the ReFuelEU Aviation regulation. In addition, measures such as the eligibility of SAF for the EU ETS could create potential incentive systems. According to stakeholders, however, these measures do not go far enough. To boost demand for the use of 100% SPK-SAF in particular, one plausible course of action from a scientific perspective would be to introduce additional offsetting mechanisms. On the one hand, as already discussed in section 4.6, there are many reasons why it makes sense to provide airlines with incentives to use expensive 100% SPK-SAF. The same applies to incentives for airports, fuel suppliers and refuelling service providers to make investments in infrastructure. Here, there are presumably significant differences depending on the size and route network of the airport in question.

One significant challenge would be the potential adaptation of the ReFuelEU Aviation regulation in order to incentivise targeted SAF use on flights with high non-CO_2 effects, which is advisable from a scientific perspective. The representatives of the aviation industry and authorities who were consulted as part of the stakeholder survey consider that a complete reform of the ReFuelEU Aviation regulation does not appear to be realistic, at least in the short term. It was pointed out that the current status quo is the result of lengthy negotiations and that a reform of the regulation carries the risk of weakening the ambitious quota rules.

In addition to the availability of SPK-SAF, it is also vital to take account of regulatory challenges in terms of the fuel's use. At present, as described in section 3.2, ASTM D7566 and D1655 only allow SAF blending quotas of up to 50%, depending on the production process. However, as the mandates of ReFuelEU Aviation stipulate the use of 70% SAF on departing flights within the EU by 2050, it has to be expected that the maximum permitted blending quotas will be adapted in future in order to meet these quotas. In this context, both

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Airbus and Boeing have committed to being able to produce aircraft from 2030 that are certified for the use of 100% SAF (non-aromatic-free) (Airbus 2026; Boeing 2020).

Within the ASTM, therefore, there is currently a task force for the development of a new fuel standard for both drop-in and non-drop-in fuels. When it comes to the development of a new fuel standard for 100% SPK-SAF, necessary measures will include reducing the minimum aromatic content in the fuel as well as eliminating maximum blending quotas. The current expectation is that a new fuel standard will first be developed for drop-in fuels. This may mean that it could take a number of years to introduce a fuel standard for non-drop-in fuels, which may delay the market ramp-up of potential aircraft that are certified for this fuel.

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5 Scenarios and economic assessment

5.1 Scenarios

A scenario analysis is carried out below in order to model the impact of different future developments in terms of the availability of SPK-SAF and the compatibility of current and future generations of aircraft, and therefore to estimate the demand for 100% SPK-SAF at German airports. These scenarios can be used to model uncertainties with regard to the underlying assumptions and to take account of relevant influencing factors.

Given the high costs and low availability of SAF in general, it can be assumed that 100% SPK-SAF will also only be available to a limited extent. Internationally, some countries have begun stipulating the use of SAF in law or encouraging airlines to use it via incentive mechanisms. In the EU, blending quotas in the ReFuelEU Aviation regulation have required fuel suppliers to provide a minimum proportion of SAF at European airports since 2025. This proportion is set to rise to up to 70% by 2050. Assuming that the availability of SAF in the EU and Germany will be limited but that the mandates in the ReFuelEU Aviation regulation must be met, it can be assumed for the purposes of the quantitative analysis that the availability of SPK-SAF will be in line with these mandates. Here, it is also assumed that SPK-SAF will cover the mandates for the use of synthetic fuels.

One key element of this study is the analysis of the availability of SPK-SAF at airports in Germany. This analysis entails the definition of three scenarios that differ from one another in terms of the compatibility of commercial aircraft:

The **“ReCert Fleet” scenario** assumes that, in addition to new aircraft that will be delivered from 2035 onwards, a recertification of the fleet is also possible. The aim is to be able to replace required system components that would be necessary for using 100% SPK-SAF as part of a regular D check from 2035 onwards. Given not only that the retrofitting process is more complex from a technical perspective but also that the economic incentives are weak, it will not be possible to recertify aircraft generations whose production ended before 2025. It is assumed that, in light of the high certification costs and decreasing number of aircraft from older generations over time, the aircraft and engine manufacturers will refrain from certifying these aircraft for 100% SPK-SAF for economic reasons.

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The **"NextGen 2035" scenario** assumes that only commercial aircraft supplied from 2035 onwards will be certified for the use of 100% SPK-SAF. Aircraft delivered earlier than that will therefore not receive certification, i.e. there will be no retrofitting of the existing fleet.

The **"Late Adoption" scenario** assumes that the introduction of aircraft generations that are compatible with 100% SPK-SAF will be delayed until 2040. In this scenario, the recertification of the existing fleet is also ruled out. The individual scenarios and their characteristics are summarised in Figure 7.

The assumptions regarding the market entry and market ramp-up of aircraft compatible with 100% SPK-SAF is a key factor in the scenario analysis with a view to identifying the limiting factors. The times assumed in the three scenarios for market entry of the 100% SPK-SAF aircraft generation are based on the estimates of aircraft and engine manufacturers as part of the stakeholder consultation (section 4).

	ReCert Fleet	NextGen 2035	Late Adoption
Recertification of Existing Fleet	✓	✗	✗
Successor Generation, 2035	✓	✓	✗
Successor Generation, 2040	✓	✓	✓
Duplicate Physical Infrastructure	*1A*	*1B*	*1C*
Flexibility Mechanism	*2A*	*2B*	*2C*

Figure 7: Scenarios for fleet compatibility with 100% SPK-SAF (source: own graphic)

In addition to the entry into service of the fleet of aircraft compatible with 100% SPK-SAF and the retrofitting of the existing fleet, the study also examines the availability of SPK-SAF at airports. Here, two approaches are examined in greater detail in each of the scenarios: on the one hand, the establishment of duplicate physical infrastructure with simultaneous supply of Jet A-1 and 100% SPK-SAF at all German airports (1A, 1B and 1C) and, on the other hand, the possibility of flexibility mechanisms (2A, 2B and 2C). In addition, the study analyses the allocation of the available SPK-SAF to individual airports in Germany. With potential flexibility mechanisms such as "book and claim" and offsetting mechanisms or levy schemes, the aim is to scientifically analyse and discuss the possible incentive systems in this approach as well as the advantages and disadvantages of the different

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approaches. Optimising the use of 100% SPK-SAF, which will be in short supply, at least in the market ramp-up phase, is also viewed through the prism of the flexibility mechanisms.

5.2 Fleet and fuel modelling

To evaluate the future impact of using 100% SPK-SAF at German airports, this section aims to describe the approach used to model the actually usable quantity of SPK-SAF in this study. On the one hand, this quantity is predetermined by the minimum quantities of SAF in the EU due to ReFuelEU Aviation, but it may also be limited by the availability of compatible aircraft, depending on the scenarios under consideration. In that case, the remaining quota would be met by drop-in SAF. An overview of the approach to modelling is provided in Figure 8.

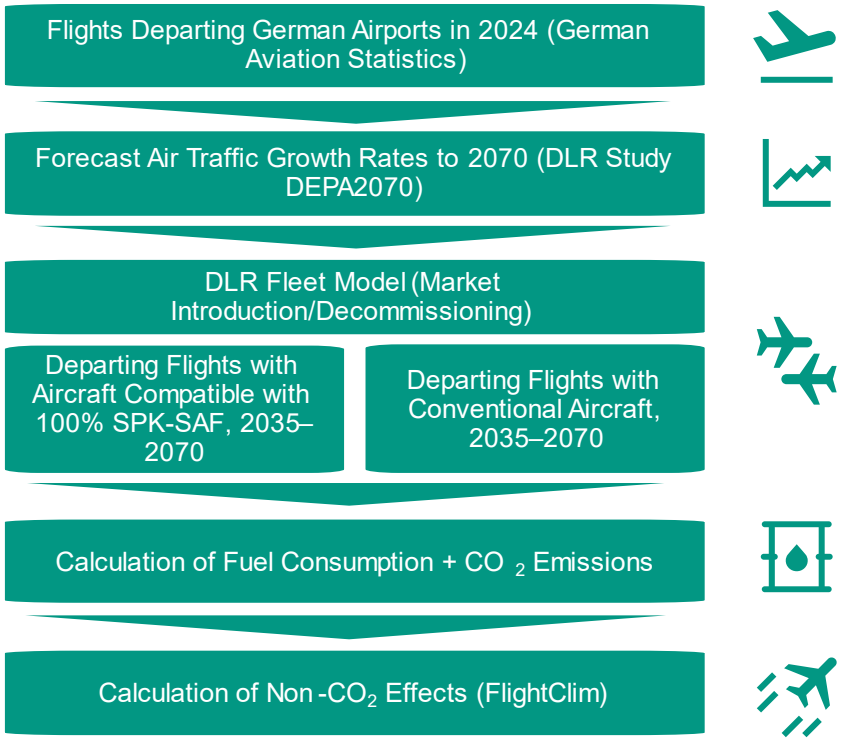


Figure 8: Modelling of fleet development, fuel demand and non-CO_2 effects in the different scenarios (source: own graphic)

The current and future fuel demand are calculated based on data from the German aviation statistics (Fiplan GmbH), which document, among other things, all flights departing in 2024 from aerodromes in Germany that are subject to reporting requirements. The aviation

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statistics include information not only on the take-off and landing airfields, the aircraft type used, and the flight type (e.g. passenger or cargo flight) but also on the total flights operated, the payload carried and the average seating capacity of the flights.

Future fleets and flight movements are modelled using the route-specific growth rates from the DLR project Development Pathways for Aviation up to 2070 (DEPA 2070, Leipold et al. 2024). This project models the future aircraft movements, the total number of passengers transported, and the average number of available seats per flight at route level up to the year 2070. In flight types without passenger volumes (e.g. cargo flights, general aviation), only the number of future flights is considered.

The operated flights are then divided into two categories in line with the scenarios. One category is made up of all flights with aircraft certified for the use of 100% SPK-SAF, while the other category contains all other flights, on which fuel of this kind cannot be used. Taking account of fleet growth, it is assumed that additional flights on a route from 2035 onwards (from 2040 in the late adoption scenario) will be operated using aircraft models that are compatible with 100% SPK-SAF. Likewise, it is assumed that aircraft that are also certified for this fuel will gradually replace the existing fleet, so that 5% of flights operated with the existing fleet will be substituted with aircraft that are compatible with 100% SPK-SAF each year. In addition to the replacement of the fleet, the ReCert Fleet scenario also assumes that it will be possible to retrofit 8% of aircraft from the existing fleet each year and then to use these aircraft with 100% SPK-SAF. This is in keeping with the assumption that retrofitting will be carried out in the course of D checks, which must be conducted at a maximum interval of 12 years. As set out in the different scenarios, only aircraft generations that were still in production after 2025 are eligible for retrofitting.

The next step models the fuel demand, or rather the need for 100% SPK-SAF, in Germany. This modelling is carried out using the tool FlightClim v1.0, which was developed by the DLR. FlightClim can be used to estimate the climate impact of individual flights but also allows the simplified calculation of fuel consumption for individual flights based on information about the operated flight's departure and destination airports and number of seats (Bruder et al. 2025). Specific seating categories (20–50, 51–100, 101–151, 152–201, 202–251, 252–301 and 302–600 seats) are therefore first assigned to the modelled flights in accordance with FlightClim. Given their lack of passenger volumes, cargo flights are assigned to the highest seating category and general aviation flights are assigned to the lowest seating category.

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For each pair of airports, FlightClim then calculates the distance between them (great circle distance + 95 kilometres) and the required quantity of fuel based on the specific seating category and the number of flights operated. An estimate is also made of CO_2 emissions and non-CO_2 effects.

The calculated quantity of fuel is then corrected by an average efficiency increase for the fleet of 1.5% per year. The total quantity of fuel and the total fleet growth depend on the chosen scenarios. These scenarios do not account for the potential introduction of hydrogen-powered or (hybrid) electric aircraft. Nor do they account for a growth-hampering effect due to potentially higher ticket prices to reflect cost increases from the use of growing quantities of SAF or rising carbon prices. In particular, the use of new energy sources could have a substantial impact on demand for hydrocarbon-based fuels in the long term. It is possible to derive the discrepancy between the actually available quantity of 100% SPK-SAF and the required amount for compatible aircraft in the individual scenarios by taking account of the applicable quotas from ReFuelEU Aviation by 2050. Here, it is assumed, on the one hand, that the quantity of available 100% SPK-SAF is capped by the quotas of ReFuelEU Aviation and, on the other hand, that there will be no further increase in the required quotas beyond 2050. If insufficient aircraft that are compatible with 100% SPK-SAF are available in the scenarios to cover the available 100% SPK-SAF, the specified quotas are to be met by adding additional drop-in SAF to the conventional fuel.

Given the potential shortage of 100% SPK-SAF, it is also possible to estimate the climate impact of individual flights for individual scenarios using FlightClim in order to separately prioritise individual flights with a particularly large climate impact when allocating the fuel. The CO_2 emissions are calculated using the efficacy-weighted absolute global warming potential over a 100-year time horizon ($EAGWP_{100}$). This includes an assumption of recurring emissions, as the flights take place annually. The flights are sorted by ascending ratio of climate impact to consumed quantity of fuel, allowing the most climate-intensive flights to be filtered out and prioritised in the allocation of 100% SPK-SAF.

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6 Results and discussion

6.1 Results of modelling

Figure 9 shows graphs of the market ramp-up of aircraft compatible with 100% SPK-SAF in the three scenarios ReCert Fleet, NextGen 2035 and Late Adoption. The indicator used is the number of flights operated with compatible aircraft.

In the ReCert Fleet scenario, over 50% of flights can already be operated with 100% SPK-SAF some ten years after the introduction of aircraft that are compatible with this fuel. Likewise, in the NextGen 2035 scenario, the ramp-up of compatible aircraft is relatively fast. It is clear that, although the existing fleet is not retrofitted, a high degree of compatibility with 100% SPK-SAF can be achieved within a few years due to growth in air traffic and gradual replacement of the existing fleet. Moreover, it can be concluded from this finding that retrofitting the existing fleet is not a necessary condition for the successful introduction of 100% SPK-SAF, or rather that retrofitting the existing fleet should only be considered if it can be achieved cost-effectively. It may be that retrofitting of the existing fleet is not strictly necessary even if the quantity of 100% SPK-SAF is limited and is consumed in full due to the use in new aircraft.

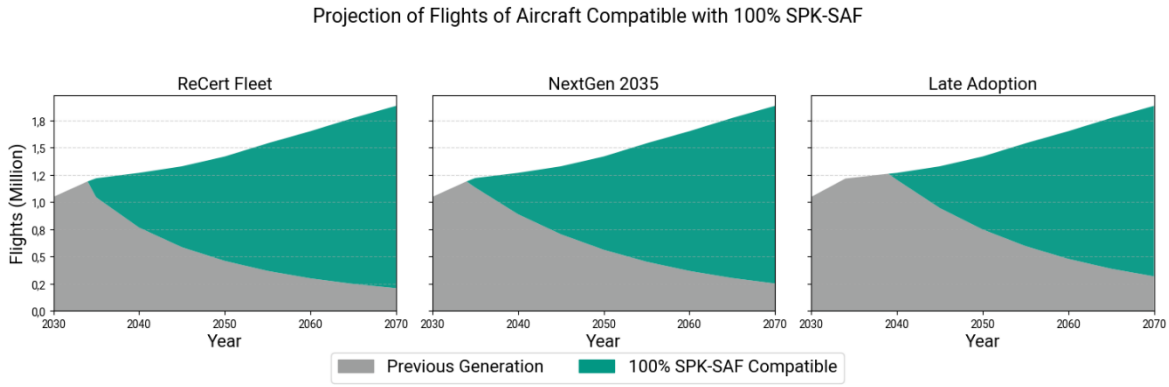


Figure 9: Change in the proportion of flights operated with aircraft compatible with 100% SPK-SAF in the ReCert Fleet, NextGen 2035 and Late Adoption scenarios (source: own graphic)

Figure 10 shows how demand is impacted by assumptions relating to the evolution of fuel consumption efficiency. Due to the assumption of an annual efficiency increase of 1.5%, the fuel consumption is around 50% less in 2070 than without efficiency improvements. In

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the long term, the efficiency improvements in aircraft technology and operating procedures are of considerable importance in terms of future fuel demand. Figure 11 a, b and c show the total amount of fuel required for flights from German airports and the distinction between 100% SPK-SAF, drop-in SAF and conventional fossil Jet A-1 in the period from 2025 to 2070, taking account of the annual efficiency improvements. Given the assumed efficiency increase of 1.5% p.a. across the fleet, total fuel demand increases from a current figure of approx. 8.3 million t (March 2026) to slightly over 10 million t. This corresponds to an annual growth rate (CAGR) in fuel demand of approximately 0.4%, which is roughly in line with the historical trend in Germany. Efficiency improvements in the fleet have significantly reduced the growing demand for fuel due to growth in air traffic. For example, the demand for aviation fuel in 2024 was approximately the same as in 2007.

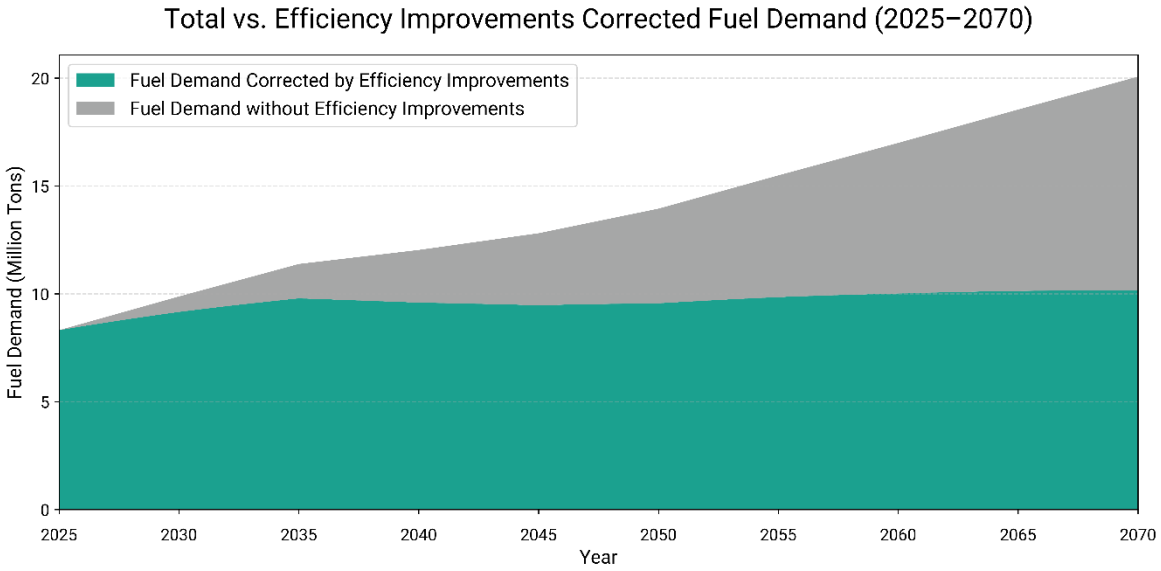


Figure 10: Impact of assumptions regarding efficiency improvements on fuel consumption of flights departing from German airports, 2025–2070 (source: own graphic)

In the ReCert Fleet scenario (Figure 11a), the relatively fast influx of aircraft that are compatible with 100% SPK-SAF means that the market can take up the entire supply of SAF (approx. 2 million t) in the form of 100% SPK-SAF from as early as 2036. In subsequent years, the fleet compatible with 100% SPK-SAF grows faster than the maximum quantity of SPK-SAF available. In the long term, the entire quantity of SAF stipulated by ReFuelEU Aviation can therefore be used in the form of 100% SPK-SAF, so there is only a temporary need for drop-in SAF.

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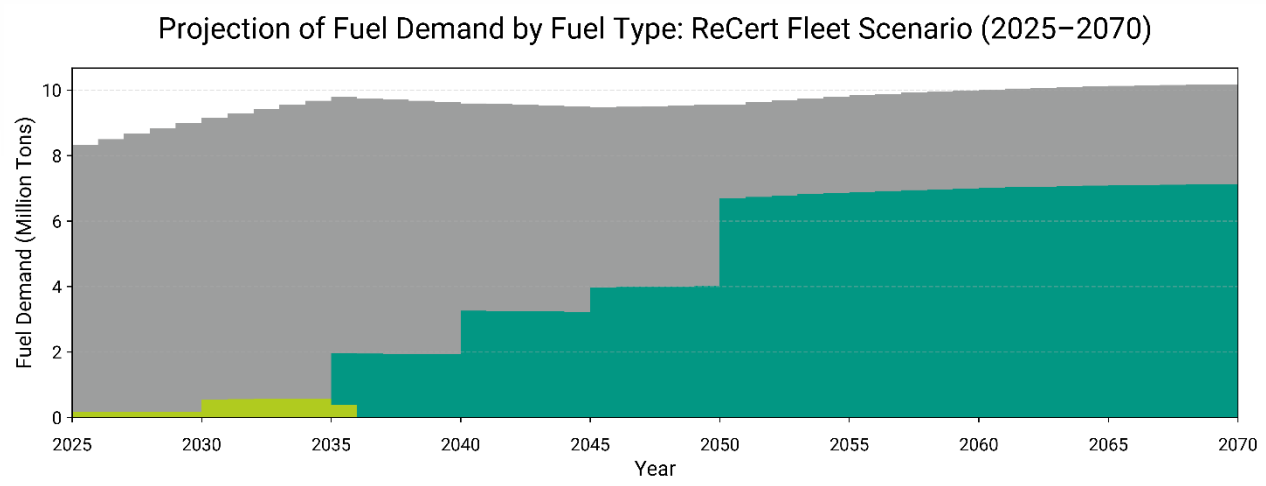
In the NextGen 2035 scenario (Figure 11b), the distribution of aircraft compatible with 100% SPK-SAF is much slower initially, as reflected in the corresponding demand for 100% SPK-SAF. In 2035, there will only be demand for just under 1 million t of 100% SPK-SAF, although the entire quantity of SAF can also be used as 100% SPK-SAF from approx. 2038 in this scenario. The delivery of new aircraft that are compatible with 100% SPK-SAF due to the growth in air traffic and as a replacement for decommissioned aircraft occurs at a relatively high rate before 2040, such that the total quantity of SAF stipulated by ReFuelEU Aviation can be used in the form of 100% SPK-SAF. It is only in 2050, due to the jump to a SAF quota of 70%, that a small amount of drop-in SAF is once again required for a short period of time.

In the Late Adoption scenario (Figure 11c), the situation is quite different: given that the SAF quota from ReFuelEU Aviation will rise to 34% of total fuel demand by 2040 but that it is only at this point that the first aircraft that are 100% compatible with SPK-SAF will be available on the market, most SAF will need to be used as drop-in fuel until after 2040. Between 2046 and 2049, the consistent SAF quota and the growth in the compatible aircraft fleet mean it is now possible to meet the demand for SAF entirely as 100% SPK-SAF. Between 2050 and 2054, the increase in the SAF blending quota from 42% to 70% from 2050 onwards means that a disparity can once again be observed between the available quantity of 100% SPK-SAF and the compatible aircraft fleet. The reason for this is that the available quantity of 100% SPK-SAF grows much faster, due to the increased SAF blending quota, than the corresponding fuel demand for compatible aircraft in this period.

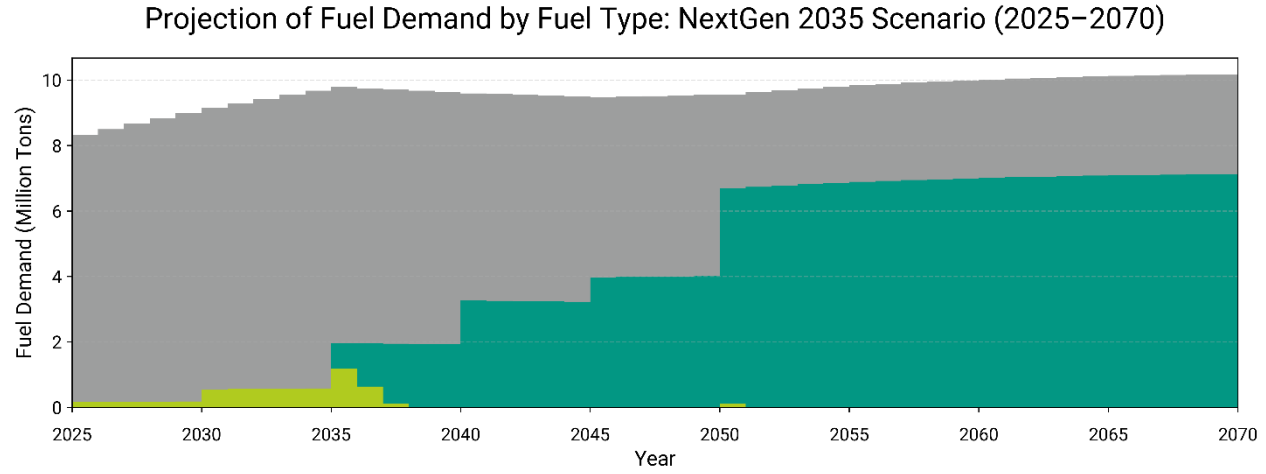
In the long term, however, fleet renewal and the entry into service of new aircraft to serve growing demand mean that the aircraft fleet is not a limiting factor in terms of the potential demand for 100% SPK-SAF.

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a)



b)



c)

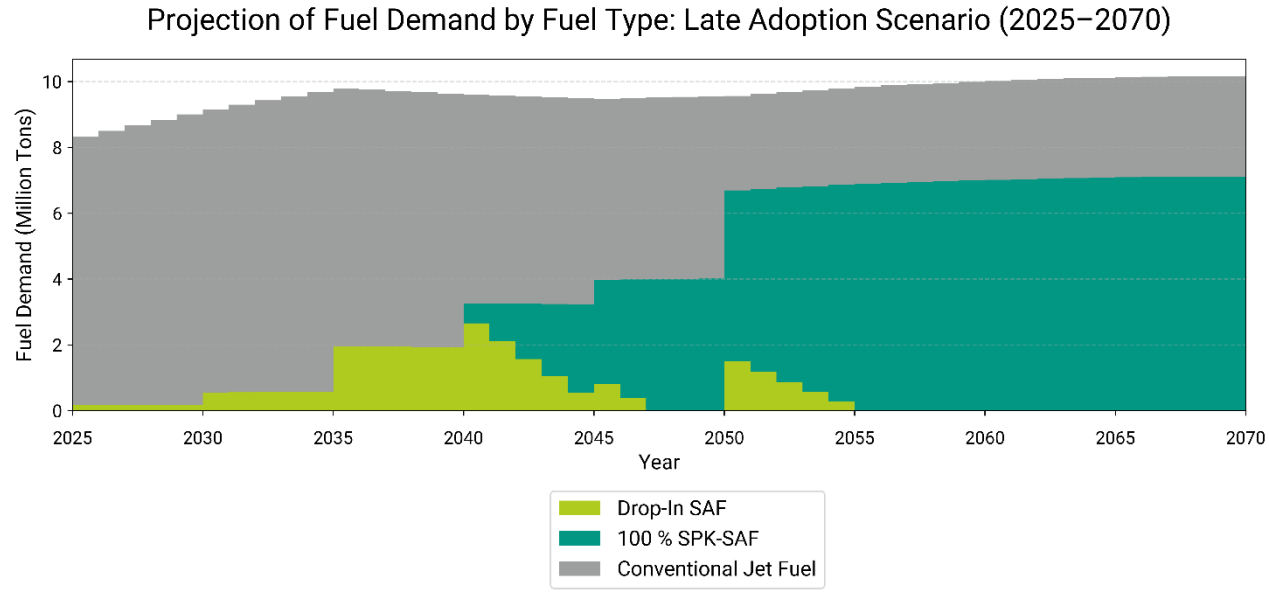


Figure 11: Fuel consumption in the ReCert Fleet (a), NextGen 2035 (b) and Late Adoption (c) scenarios (source: own graphic)

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6.2 Cost-benefit analysis

The use of 100% SPK-SAF at German airports results in various benefit and cost dimensions. The benefits include the reduction of non-CO_2 effects in terms of climate impact, the improvement of local air quality through lower particulate matter emissions, the potential reduction of maintenance costs through lower deposit build-up in engines, and improved fuel efficiency thanks to a higher energy content per kilogram of fuel. On the cost side, the largest items are the expenditure on infrastructure measures in the storage depot and the increased logistics costs during refuelling. Account must also be taken of the costs of (re)certifying aircraft models for the use of 100% SPK-SAF and the retrofitting of the existing fleet.

As no exact information is currently available on the fuel characteristics of 100% SPK-SAF (e.g. specific energy content/energy density, combustion characteristics, production costs, aircraft adaptation requirements), the quantitative analyses are subject to significant uncertainties. More precise quantitative information on the costs and benefits could not be provided either by the literature review or by the stakeholder survey. The cost-benefit analysis is therefore carried out based on the best possible estimates according to the available information. It is at least possible to represent the orders of magnitude and sensitivities of the cost and benefit in order to assess the use of 100% SPK-SAF.

6.2.1 Investment and logistics costs

The most significant cost components in the introduction of 100% SPK-SAF are the necessary modifications to storage depots in order to ensure a segregated supply of the fuel regardless of the existing supply of Jet A-1, as well as the logistics costs for aircraft refuelling.

For the adaptation of storage depots, an amount in the mid tens of millions appears to be realistic in the case of a large commercial airport. The planned construction of the new storage depot at Düsseldorf Airport, with a storage capacity of 9,000 cubic metres, is budgeted at €70 million (Flughafen Düsseldorf 2025a). The EU-funded project ALIGHT examined the targeted use of SAF at Copenhagen Airport, which would also require a segregated fuel supply and therefore an expansion/modification of the storage depot. The surveyed stakeholders estimate the costs of expanding the storage depot at some €40 million (Müller et al. 2025). The problem here is the availability of land at large

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commercial airports. This is either because there is not unlimited scope for expansion of the storage depot in order to accommodate the supply of 100% SPK-SAF and/or because of the opportunity costs attached to the rezoning of land. Another challenge from a business perspective is that investments in a 100% SPK-SAF storage depot are generally lumpy, or rather indivisible: large up-front investment is needed in order to build a corresponding storage depot, which is oversized and underused in the initial phase. Utilisation only increases over time, with greater availability of 100% SPK-SAF and a larger number of compatible aircraft. This presents a significant problem in terms of the amortisation of such an investment.

The amortisation of a one-off investment can be calculated using the annuity method. The inputs to this calculation include the capital cost in the form of interest on the invested capital and the term (typically the useful life of a capital asset). The weighted average cost of capital (WACC) of Fraport AG, currently at 8%, is used as the representative capital cost rate (Fraport 2025a). A period of 30 years is assumed as the economic life. For an investment of €50 million in a sufficiently large 100% SPK-SAF storage depot that allows growth in the use of 100% SPK-SAF over time, this would mean annual financing costs and depreciation expenses of €4.44 million. That is in addition to the operating and maintenance costs of the duplicated storage infrastructure.

The refuelling of aircraft with 100% SPK-SAF would require an additional investment in airport refuelling vehicles at airports that currently have a hydrant fuelling system. Conventionally powered vehicles (with a combustion engine) cost in the region of €500,000, and electric vehicles cost significantly more. At airports without a hydrant fuelling system, existing refuelling vehicles could potentially be retrofitted or earmarked for refuelling with 100% SPK-SAF in order to reduce additional investment costs.

If annualised investment costs for storage depots and vehicles, as well as the potentially increased logistics costs (operating costs for vehicles, maintenance, staffing costs, etc.) are added up, the benefit from using 100% SPK-SAF would have to be at least in the order of €6 million for a major commercial airport in order to outweigh the cost. That is in addition to the costs faced by airlines for retrofitting aircraft, certification costs and potentially greater operational complexity if only certain flights are to be refuelled with 100% SPK-SAF.

For building up **duplicate physical infrastructure**, the findings obtained here mean that a critical view should be taken of the cost-benefit ratio. The benefit, which stems particularly from the reduction of non-CO_2 effects, is focused very closely on a few airports. However,

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the creation of duplicate physical infrastructure would lead to high investment and operating costs at each airport. Even if smaller and cheaper infrastructure could be built at smaller airports due to the lower fuel demand, it is estimated that the total Germany-wide costs would run to the mid hundreds of millions. This contrasts with the relatively low non-CO_2 effects of flights taking off from smaller airports. In addition, given the low number of available aircraft that are compatible with 100% SPK-SAF, it is uncertain whether these aircraft could also take off and land at all airports, at least in the initial phase – i.e. there is an investment risk that 100% SPK-SAF infrastructure would be created and then potentially not used intensively for several years.

One difference between scenarios 1A, 1B and 1C (Figure 7) essentially lies in the times when the investments must be made. The difference in demand for 100% SPK-SAF between scenarios 1A and 1B is not particularly large, meaning that infrastructure of an approximately similar scale would have to be built for both scenarios, including with a view to growth over time. If aircraft compatible with 100% SPK-SAF are only introduced from 2040 (Scenario 1C), drop-in SAF would also be needed until 2055 in order to meet the SAF quotas. The infrastructure for the distribution of 100% SPK-SAF could therefore be built up later, although the benefit dimensions would also not be realised until a later stage.

Assuming backward compatibility of SPK-SAF-certified aircraft, it therefore seems sensible from a scientific perspective to focus the use of 100% SPK-SAF on a few airports and that stakeholders be able to implement the most competitively neutral and simultaneously climate-optimal solution for the use of 100% SPK-SAF through a **book-and-claim** system. Here, too, the requirements in the different scenarios 2A, 2B and 2C (Figure 7) also relate to the dimensioning of the infrastructure at the respective airports. If the use of 100% SPK-SAF is focused on a few airports, the infrastructure at those airports would have to be on a larger scale, but that is likely to result in lower overall costs than duplicating the physical infrastructure, as it would allow economies of scale and mean that certain fixed costs (e.g. for planning and approval) would only arise at a few airports rather than at all of them.

6.2.2 Benefit dimension "climate"

The most significant component of the benefit of using 100% SPK-SAF is the reduction of non-CO_2 effects. Using the DLR tool FlightClim, it is possible to quantify the non-CO_2 effects of aviation originating from Germany according to various climate metrics. For better comparability, it is often useful to represent the non-CO_2 effects as CO_2 equivalents. As part

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of an economic evaluation, this approach also allows these effects to be monetised by means of the damage cost per tonne of CO_2, which is widely used in the literature, and their comparison with other benefit and cost categories, which are also represented in monetary terms.

Figure 12 shows the CO_2 equivalents for flights departing from Germany in 2024, broken down into direct CO_2 emissions and non-CO_2 effects, expressed in terms of the climate metric $EAGWP_{100}$. The total CO_2 emissions amount to 26.3 million t and the non-CO_2 effects to 67.8 million t of CO_2 equivalents. The non-CO_2 effects are therefore equivalent to some 2.6 times the CO_2 effects. The graph shows a significant concentration of both direct CO_2 emissions and CO_2 equivalents of non-CO_2 effects at Frankfurt Main and Munich airports. One can also see the relatively high climate significance of the airports of Leipzig/Halle, Köln Bonn and Hahn as a result of the high proportion of air cargo traffic at each.

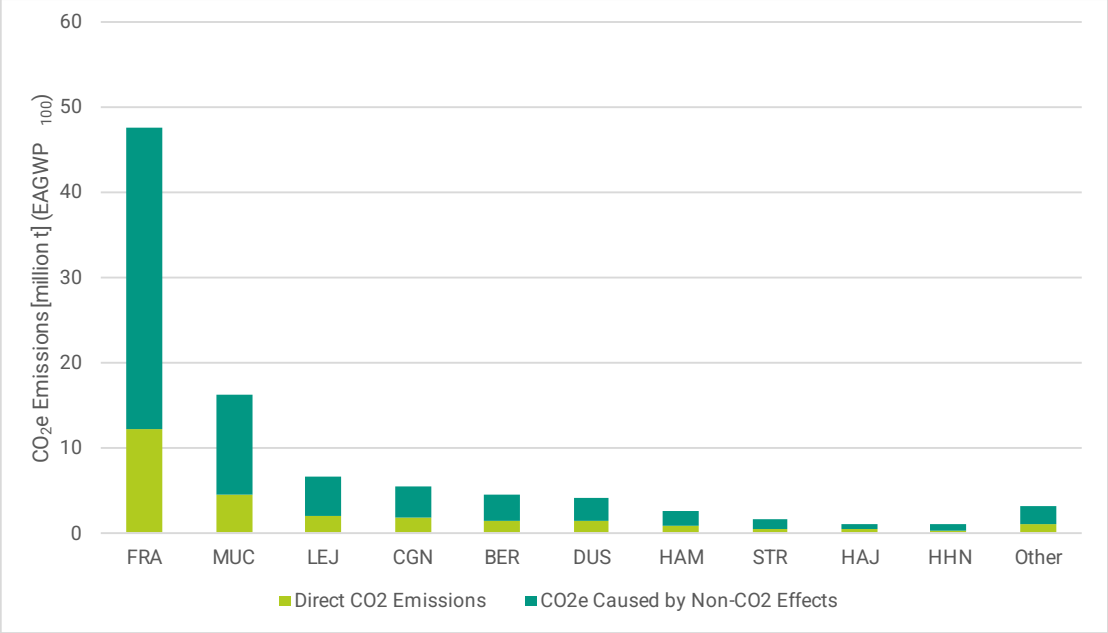


Figure 12: CO_2e emissions in million tonnes ($EAGWP_{100}$) based on FlightClim for flights departing from German airports in 2024 (source: own graphic)

The ratio of non-CO_2 effects to CO_2 effects essentially depends on the methodology chosen for retrofitting non-CO_2 effects into CO_2 equivalents. If a shorter time horizon is chosen, for example, the short-lived effects (e.g. formation of cirrus clouds from contrails) would be weighted more strongly relative to long-lived effects (CO_2). In the scientific literature, the efficacy-weighted global warming potential over a 100-year time horizon ($EAGWP_{100}$) is

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seen as a sensible measure for assessing the impact of new aircraft or fuel technologies (Megill et al. 2024), although there is no clear, objectively correct choice of climate metric at this point.

In terms of the potential to reduce non-CO_2 effects by using aromatic- and sulphur-free fuel, the ECLIF3 study showed that a 26% reduction in non-CO_2 effects can be achieved across global air traffic (base year 2018) compared with the use of fossil fuel (Märkl et al. 2024). From these results, it is therefore possible to determine the economic utility of using 100% SPK-SAF in a first approximation based on the degree of usage (proportion of flights) and assumptions regarding the damage cost of the emissions (CO_2 or CO_2 equivalents). Figure 13 shows the level of economic utility of reducing non-CO_2 effects versus the degree of utilisation of 100% SPK-SAF and the assumption

ns of CO_2 damage costs per unit of emissions.

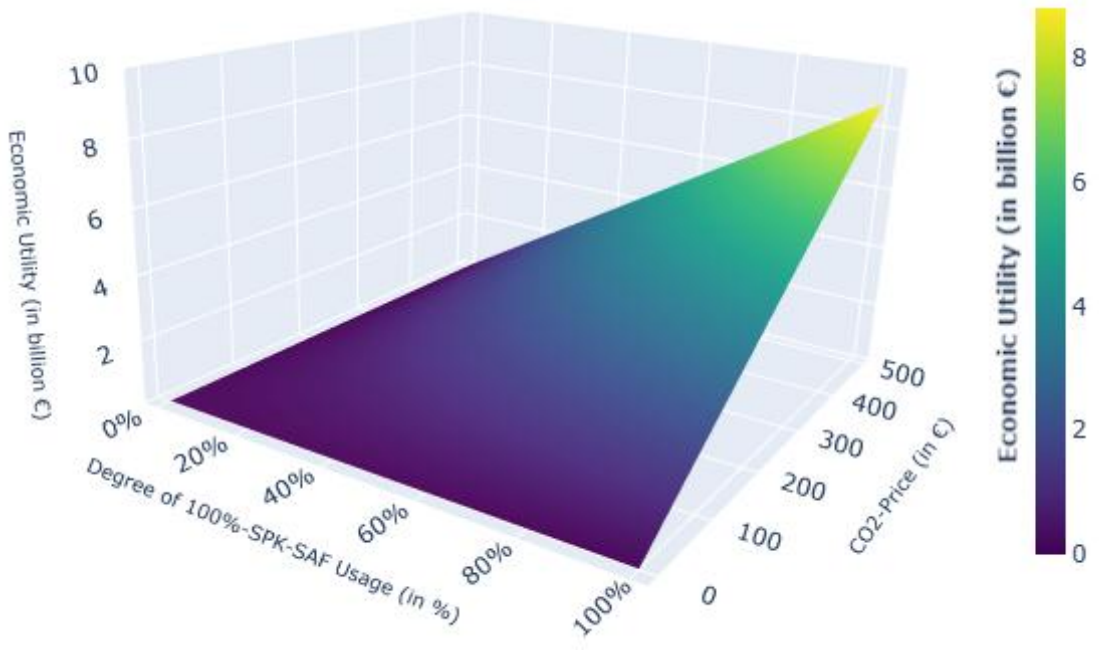


Figure 13: Estimation of economic utility of reducing non-CO_2 effects versus the degree of utilisation of 100% SPK-SAF and the CO_2-price (source: own graphic)

Assuming that flights with particularly high non-CO_2 effects are not prioritised for the use of 100% SPK-SAF (see discussion in section 6.4), the economic utility of avoiding non-CO_2 effects, such as when using 100% SPK-SAF on 50% of flights departing from German airports, would be approximately €880 million, based on an assumed CO_2-price of €100 per year, compared with the use of fossil fuel. However, the actual climate benefit may be

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smaller, e.g. if contrails can be avoided through operational measures, such as by adopting different routes or altitudes. In a more intensive evaluation of measures, the interaction between different strategies for avoiding non-CO_2 effects must therefore be examined.

This study does not separately consider the reduction of CO_2 life cycle emissions of 100% SPK-SAF in comparison with fossil fuel, as it is assumed that the quotas stipulated in the ReFuelEU Aviation regulation are met by 100% SPK-SAF. This means that, in the current regulatory framework, the reduction in CO_2 due to the use of SAF as a drop-in fuel is almost identical to that of general blending or the use of 100% SPK-SAF.

6.2.3 Benefit dimension "local air quality"

Another significant part of the benefit of using 100% SPK-SAF is the reduction of airborne pollutants in the vicinity of airports. In particular, particulate matter and sulphur oxides are considered harmful to health and the environment. Studies by NASA have found that the mass of fine particles emitted can be reduced by 86% relative to JP-8 fuel by using purely synthetic Fischer–Tropsch fuels[4] (Beyersdorf et al. 2014). The study's authors state that these findings are applicable to all practically sulphur- and aromatic-free fuels regardless of the feedstock used (Beyersdorf et al. 2014). In another study, particle reductions of 70% in comparison with fossil fuels were demonstrated for an aromatic-free ATJ fuel. This fuel did not meet the ASTM specifications and was tested in an engine on the test stand (Schripp et al. 2019). Rohkamp et al. (2025) showed that the reduction of the mass of particulate matter due to the combustion of aromatic- and sulphur-free fuels is largely caused by a reduction in particle size. As a result of the production processes, SPK-SAF is considered practically sulphur-free, meaning that the problem of the emission of sulphur oxides does not occur.

There are two key aspects that influence the analysis of benefits in terms of the improvement of local air quality when using 100% SPK-SAF. On the one hand, the question is whether, in relative terms, the concentrated use of 100% SPK-SAF has a bigger or smaller effect than general blending. Experimental analyses have shown that both the mass and number of particles exhibit a relatively linear correlation with the fuel's aromatic and hydrogen content (Brem et al. 2015). In global terms, therefore, it is assumed that it is

[4] JP-8 is used as a military fuel and is comparable with Jet A-1 but contains additional additives.

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irrelevant to the reduction of particles whether SAF is used in the form of 100% SPK-SAF or as a blend with significantly lower SBC content. On the other hand, the maximum benefit would be achieved if the particle reduction were implemented at airports in urban areas so that a greater number of residents could benefit from a reduction in emissions.

In general, airports rarely publish information on the emitted mass of particulate matter, as it is in fact the concentration levels in the vicinity of the airport that are of greater interest from the perspective of statutory requirements and residents. Table 3 below shows the mass of emitted particulate matter, PM_{10}, of a small selection of German commercial airports.

Airport	Mass of PM_{10}	Year	Source	Comments
Berlin Brandenburg	6 t	2023	Winkler et al. 2026	
Düsseldorf	9.41 t	2024	Flughafen Düsseldorf 2025b	Sum of PM_{10}, $PM_{2,5}$ and NVPM, LTO cycle + APU
Frankfurt Main	23.62 t	2024	Fraport 2025b	

Table 3: Particulate matter emissions at selected German airports

The total quantity of particulate matter emitted in the LTO cycle by aviation is set out in the German Informative Inventory Report from the Federal Environment Ministry (Umweltbundesamt 2025). According to this report, 68.6 t of particulate matter (PM) and 32.8 t of black carbon (fine particles of carbon) were emitted in the LTO cycle by domestic and international aviation in Germany in 2023. Given the relatively high sulphur content in fossil Jet A-1, these emissions are in addition to 577.8 t of sulphur oxides (SO_x).

The economic assessment of the damage cost of particulate matter and sulphur oxides is highly complex and typically follows a functional chain that involves the modelling of emissions, expansion and concentration and the health effects on the affected population. The damage cost is then estimated by means of a monetary evaluation of morbidity and mortality.

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Type of emission	Damage cost (in €$_{2021}$ per t), Environmental Prices Handbook	Damage cost, FTIP (in €$_{2012}$ per t)
Particulate matter (PM_{10})	44,300	122,800 to 364,100
Particulate matter ($PM_{2.5}$)	81,200	
Nitrogen oxides (NO_x)	19,300	15,400
Volatile organic compounds (NMVOC)	2,160	1,700 (HC)
Sulphur dioxide (SO_2)	26,600	13,200
Carbon monoxide (CO)	16.50	62

Table 4: Damage cost for different airborne pollutants (source: own graphic based on CE Delft 2024 and PTV Planung Transport Verkehr AG et al. 2016)

Table 4 shows the average damage cost of airborne pollutants. These values are taken from the European Environmental Prices Handbook (CE Delft 2024) and the Methodology Manual for the Federal Transport Infrastructure Plan 2030 (PTV Planung Transport Verkehr AG et al. 2016). The damage costs are made up of, among other things, the impact of pollutants on human health, the environment (such as changes in biodiversity), or materials and buildings (CE Delft 2024). In some cases, the ranges of the damage costs are relatively large, such as in the case of PM_{10}/$PM_{2.5}$, which in CE Delft lie between 44,300 €/t (PM_{10}) and 81,200 €/t ($PM_{2.5}$) and in the Methodology Manual for the FTIP 2030 between 122,800 €/t (outside built-up areas) and 364,100 €/t (in built-up areas). In CE Delft, sulphur dioxide is in turn assessed as being significantly higher, at 26,600 €/t, than in the Methodology Manual for the FTIP 2030 (13,200 €/t).

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Given PM emissions in the LTO cycle by aviation in the order of some 100 t per year, the environmental costs are approximately €4.4 million to €12.3 million. The damage costs of sulphur dioxide emissions are in the order of between €7.6 million and €15.4 million.

The use of 100% SPK-SAF can significantly reduce the damage costs. However, the following points must be taken into account:

- The shares of SAF due to general blending of SAF in accordance with the ReFuelEU Aviation regulation already lead to an improvement in air quality, i.e. the quantified increase in benefit results purely from the comparison between general blending of SAF and the scenarios considered here.
- The local pollutant emissions indicated here include both take-offs and landings in Germany. The benefit for local air quality due to the use of 100% SPK-SAF could then be at its maximum if the aircraft compatible with 100% SPK-SAF can be refuelled with 100% SPK-SAF not only in Germany but also abroad.
- Depending on the exposed population, the effective environmental costs could be higher or lower than the average values set out by CE Delft or the Methodology Manual for the FTIP.
- Ultimately, the share that 100% SPK-SAF makes up of total fuel consumption ultimately determines the benefit for local air quality.

6.2.4 Further benefit dimensions

Another category of benefit could consist of reduced maintenance costs for engines. Given the cleaner combustion, there is a tendency for less deposits to form in the engine, so that maintenance intervals can potentially be extended and maintenance costs reduced (Boehm et al. 2024). In the literature and in the stakeholder survey, however, experts were not yet able to quantify the reductions, partly because there is still a lack of long-term experience with SAF with a high proportion of SBC.

Lastly, a higher energy density (energy per volume) and a higher specific energy content (energy per mass) of 100% SPK-SAF could be assessed as another benefit category. Boehm et al. (2024) point out that the energy density, or the specific energy content, can be specifically increased in the design of a new fuel standard. In the context of 100% SPK-SAF, an improvement in fuel efficiency by approx. 0.3% appears to be possible, although the efficiency increase depends on the aircraft type and the distance covered (Boehm et al.

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2024). A higher specific energy content can reduce take-off weight or allow a proportionally larger payload to be carried for the same take-off weight.

6.3 Economic implications of the use of 100% SPK-SAF

6.3.1 Description of status quo of SAF use

The use of 100% SPK-SAF is not envisaged in the current regulatory framework of the ReFuelEU Aviation regulation. The aim of the EU SAF mandate is to meet the SAF blending quotas, which rise over time, at all major airports. One key aspect of the current regulatory framework is that it is the fuel suppliers and not the airlines that must meet the requirements of the blending quota. On a transitional basis, the suppliers can offset SAF used throughout the EU (mass balancing), i.e. the quota need not initially be met at each individual airport. Airlines report that fuel suppliers apply uniform surcharges in order to cushion the additional costs for the SAF used. However, the airlines have no guarantee that they will also physically receive the quantity of SAF for which they have paid a surcharge.

During the transition to 100% SPK-SAF, the question is therefore how the current regulatory framework could be adapted in order to maximise the benefit dimensions (in particular the reduction of non-CO_2 effects) while also making implementation as competitively neutral as possible so as not to unilaterally impose high costs on airlines that want to use 100% SPK-SAF.

6.3.2 Physical duplication of infrastructure

In the case of the **physical duplication of infrastructure** at all relevant airports, the airlines would have the option to refuel their compatible aircraft with 100% SPK-SAF.

For large airlines with a mixed fleet of aircraft compatible with 100% SPK-SAF and those that are not yet compatible, the SAF quota could be met by using 100% SPK-SAF on those flights that are compatible with 100% SPK-SAF and have particularly high non-CO_2 effects.

However, there are several problems with this approach: first, it would be necessary to switch the obliged entities from the suppliers to the airlines so that the quota could be met at the airline level. Second, it would be difficult to meet the quota exactly, particularly if there is a limited number of aircraft that are compatible with 100% SPK-SAF. In that case, it would be necessary to use additional SAF as a drop-in fuel for the conventional fleet in order to meet the quota. However, airlines that already had lots of aircraft that are compatible with

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100% SPK-SAF would have no interest in refuelling with SAF as a drop-in fuel beyond meeting the SAF quota, which is achieved with 100% SPK-SAF. Consequently, in order to achieve optimum fuel use, it would be necessary to offer not only two types of fuel (100% SPK-SAF and fossil kerosene) but also drop-in fuel with a proportion of SAF. Third, in the absence of further mechanisms, an airline that only had aircraft compatible with 100% SPK-SAF would have no direct incentive to use more 100% SPK-SAF than is stipulated by the quota. Fourth, this approach alone would not provide direct incentives to use aircraft compatible with 100% SPK-SAF on routes with particularly high non-CO_2 effects and then also to operate these aircraft with 100% SPK-SAF. There would therefore be a need for additional, accompanying measures or instruments. Last but not least, when creating duplicate physical infrastructure for the simultaneous supply of conventional and non-drop-in fuel, it is important to bear in mind that refuelling infrastructure is user-financed. Purely user-based financing of the required investments in adapting the infrastructure, as outlined above, would impose huge additional costs on the German aviation industry.

For successful, comprehensive and competitively neutral introduction of 100% SPK-SAF that achieved maximum climate benefit, it would therefore be necessary to create a cross-airline incentive model, which could take the form of a **levy** or **book-and-claim** system.

6.3.3 Levy system

A comprehensive **levy system** would need to be different from the current practice whereby airlines generally pay a SAF surcharge on the fuel price, which fuel suppliers charge to cover the additional costs of SAF. The stakeholder interviews revealed that this current practice is criticised by the airlines because there is no guarantee that the SAF is actually physically supplied to the respective airline. This is problematic because only then can the respective airlines claim credit for the SAF use in the EU ETS. In a system featuring targeted use of 100% SPK-SAF, the fuel must physically reach the respective users, while the costs should be shared as much as possible.

One option would be a levy system in which the additional costs of SAF use are shared between all airlines or passengers and, where applicable, the senders of air freight, thereby cushioning the costs for individual airlines that deliberately use 100% SPK-SAF. Airline interest groups have already proposed such a system for the current regulatory framework of ReFuelEU Aviation (Steer 2025). Levy systems are also used outside Europe to fund the

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introduction of SAF. In future, a system of this kind is to be implemented in Singapore (Civil Aviation Authority of Singapore 2025).

A levy system would potentially also be suitable for the targeted use of SAF within the framework of the present analysis. The targeted use of 100% SPK-SAF on particularly climate-sensitive flights would place a particularly heavy burden on the airlines that operate these flights, thereby adversely impacting acceptance and the likelihood of implementation. Acceptance could be improved by spreading the costs evenly across all airlines or passengers. A system of this kind would have to cover as large a geographical area as possible (e.g. the entire EU) in order to achieve a fair distribution of costs and benefits. The additional costs of using 100% SPK-SAF would therefore be borne equally by all passengers and, where applicable, by the senders of air freight. Thanks to the levy, airlines using 100% SPK-SAF could purchase the fuel at a price corresponding to the level of fossil kerosene or a drop-in SAF blend.

One unresolved issue in the context of the levy system would be how the emissions reduction due to the use of 100% SPK-SAF is credited in the EU ETS or CORSIA. In the existing system, only airlines that have actually physically refuelled with the SAF can claim the emissions reduction from SAF use in the EU ETS. This would also apply to the use of 100% SPK-SAF – under the current legislation, the airline would then receive a complete exemption from the requirement to surrender emission rights in the EU ETS, or could in future reduce the obligation to cancel offsets if 100% SPK-SAF were to be credited in CORSIA (CORSIA Eligible Fuels, see ICAO 2025). However, this would be unfair in the sense that the use of 100% SPK-SAF would be paid by other airlines, or rather their passengers, due to the levy system. Accordingly, the benefit from using 100% SPK-SAF should be returned to the stakeholders who financed the fuel.

For the levy system to work, it would ultimately be irrelevant at which or at how many airports 100% SPK-SAF was available if all departing airlines, or rather their passengers/senders of air freight, paid into the system and the users of 100% SPK-SAF benefited from it. Accordingly, there would be no need for complete, duplicate physical infrastructure for supplying 100% SPK-SAF.

6.3.4 Book and claim

As an alternative to a comprehensive, obligatory levy system, 100% SPK-SAF could be implemented in a **book-and-claim** system for a voluntary group of participants. In book and

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claim, there is a separation between physical fuel use and the underlying financial flows. From an economic perspective, the advantage of such an approach is that it would not be necessary to provide 100% SPK-SAF at all airports, but that all airlines (including those without a fleet of aircraft compatible with 100% SPK-SAF) could potentially profit from the resulting benefit. However, this would require the quantification and certification of the generated benefits so that stakeholders that pay for the use of 100% SPK-SAF could also claim these benefits for themselves. Funding the use of 100% SPK-SAF at other airlines could therefore be credited towards their own fulfilment of the SAF quota. In this approach, it would probably also be necessary to shift the level of the obliged entities from the suppliers of the fuel to the users (aircraft operators). The benefits could also be credited as part of market-based measures such as the EU ETS or CORSIA through a reduction of the obligation to surrender emission allowances or offsets, or the generation of carbon credits. This would be one option, particularly in light of the benefit delivered by a reduction in non-CO_2 effects.

Such an approach could simplify the fuel logistics significantly, as it would now only be necessary to offer 100% SPK-SAF at a small number of airports. If a sufficient number of compatible aircraft were refuelled at those airports, the infrastructure investments could be kept within limits. However, the cost of using 100% SPK-SAF could be spread across a larger number of stakeholders that had an interest in the reduction of non-CO_2 effects.

6.4 Prioritisation of individual flights

Particularly in the first years following the introduction of 100% SPK-SAF at airports, the amount of usable SPK-SAF will be limited by the availability of compatible commercial aircraft. As the results have shown, however, it can be assumed that fleet growth and the renewal of the existing fleet will mean that aircraft compatible with 100% SPK-SAF will already be able to cover the available amount of this fuel within several years. If the fuel demand for aircraft compatible with 100% SPK-SAF exceeds the amount defined by ReFuelEU Aviation, the question is which flights are refuelled with 100% SPK-SAF. One possibility is to prioritise individual flights based on their climate impact. As the climate costs are the biggest factor in the evaluation of aviation's cost to society, the efficient use of 100% SPK-SAF could lead to a significant reduction in climate costs.

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To identify the most climate-intensive departing flights, the DLR tool FlightClim v1.0 is used to estimate the CO_2 equivalents of each simulated departing flight from German airports. The underlying data consists of the departing flights from the year 2024 from the German aviation statistics, which were extrapolated using the growth rates from DEPA2070. For the year 2040, this results in greater potential quantity requirements of SPK-SAF for the ReCert Fleet and NextGen 2035 scenarios – due to the greater number of aircraft compatible with 100% SPK-SAF – than are actually stipulated by the ReFuelEU Aviation regulation. In particular, when it comes to prioritising the most climate-intensive flights, it is clear that the quantity requirements are dominated by the larger airports in Germany. Accordingly, between 59% (NextGen 2035) and 69% (ReCert Fleet) of the total available quantity of SPK-SAF would be used in refuelling at the two major hubs Frankfurt Main and Munich in 2040, as can be seen in Figure 14. This is primarily because these airports serve a large number of long-haul flights, which generally have a greater non-CO_2 climate impact per unit of fuel consumed than short- and medium-haul flights. Leipzig/Halle and Köln Bonn airports also account for a significant share of the total demand for 100% SPK-SAF, principally due to long-haul flights operated by the high volume of cargo planes at these airports. As the Late Adoption scenario still lacks a sufficient number of aircraft in 2040 that could be refuelled with the quantity of 100% SPK-SAF available at that time, the question of prioritisation does not arise here.

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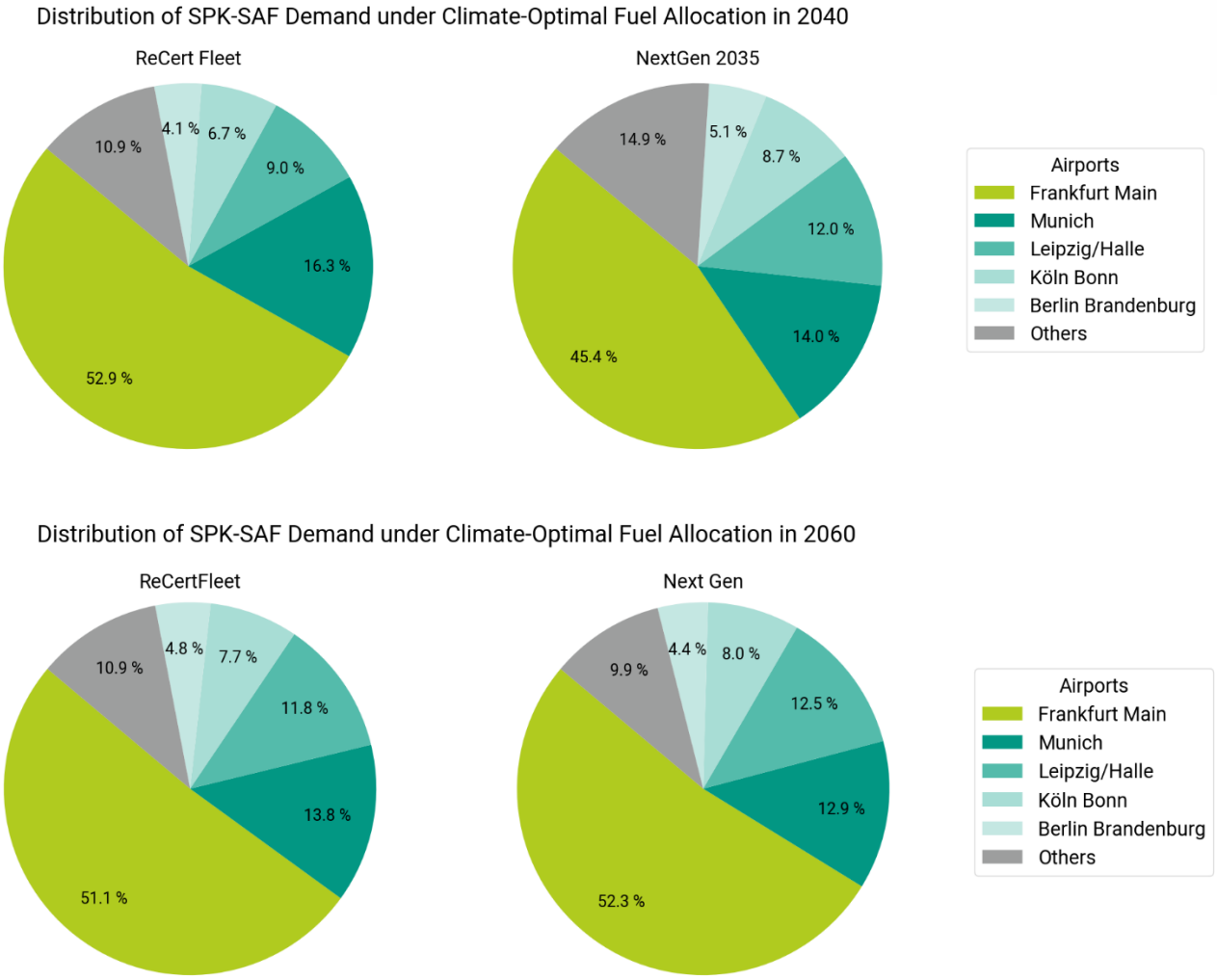


Figure 14: Relative use of 100% SPK-SAF by airport in the event of climate optimisation in the ReCert Fleet and NextGen 2035 scenarios in 2040/2060 (source: own graphic)

As demand for most of the available 100% SPK-SAF will come from Frankfurt Main and Munich airports, as seen in Figure 14, it is worth considering whether, given the significant costs, 100% SPK-SAF should only be offered at those two airports, at least initially. The declining infrastructure costs would be offset by a smaller benefit due to the less-efficient reduction of climate-relevant emissions. For the basic scenario of NextGen 2035, for example, Figure 15 compares the climate-optimal allocation of 100% SPK-SAF across Germany with the allocation of the fuel to all compatible aircraft types leaving Frankfurt Main and Munich with regard to demand for 100% SPK-SAF and the overall climate impact. The share of the requirement for 100% SPK-SAF and of the CO_2 equivalents of all compatible aircraft at Frankfurt Main and Munich remains relatively consistent over time,

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at between 55% and 75%, compared with the allocation of fuel to the most climate-intensive flights originating in Germany.

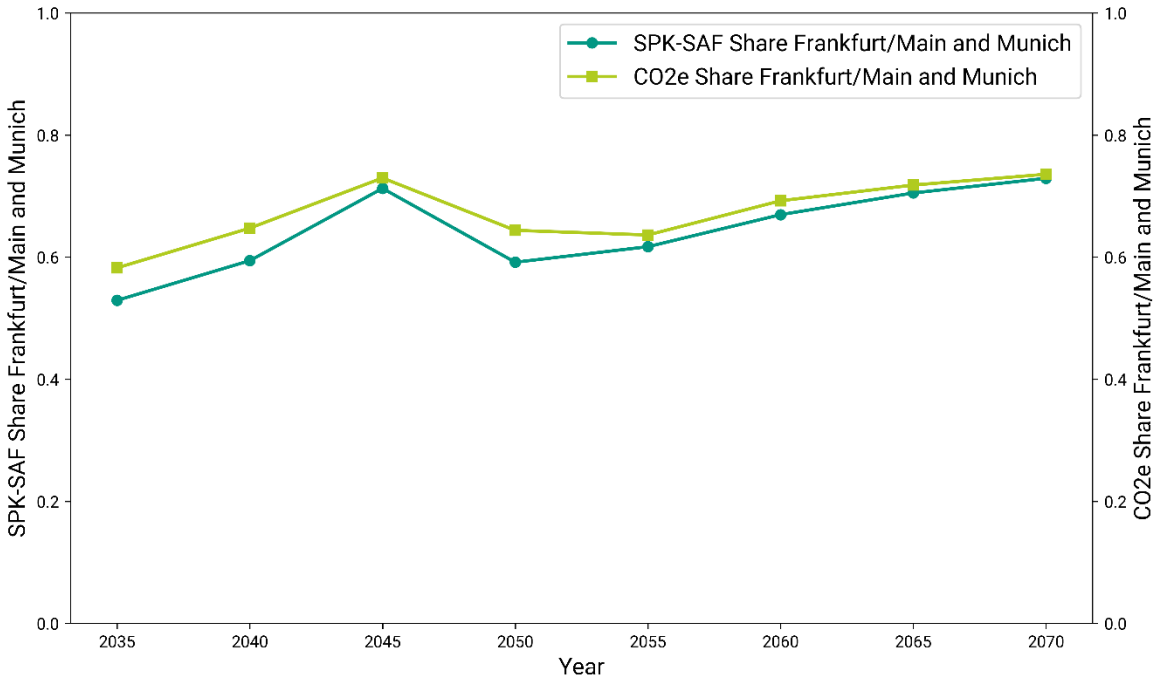


Figure 15: Share of Frankfurt Main and Munich airports of the CO_2 equivalents and of the use of 100% SPK-SAF compared with climate-optimised use of 100% SPK-SAF at all German airports between 2035 and 2070 in the NextGen 2035 scenario (source: own graphic)

This finding has significant consequences for the strategies for introducing 100% SPK-SAF in Germany. Particularly in the early phase of the roll-out of 100% SPK-SAF, it is likely to be economically disadvantageous to supply the fuel to many German airports for two reasons:

(I) On the one hand, it is likely that, initially, relatively little 100% SPK-SAF will be available and use will be made of only a small number of aircraft that are compatible with 100% SPK-SAF. Broad distribution to multiple airports would lead to relatively high costs in terms of infrastructure construction and logistics (see section 6.2) without it being possible to use the fuel effectively.

(II) On the other hand, the results set out here show that most of the non-CO_2 effects stem from flights departing from Frankfurt Main and Munich.

Particularly high non-CO_2 effects are caused by long-haul flights that form contrails over bright surfaces at night (e.g. the polar region, snow-covered areas) (Teoh et al. 2022a). Stuber et al. (2006) showed that 60% to 80% of warming non-CO_2 effects stem from the 25% of traffic that takes place at night.

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It would therefore make sense to prioritise the use of 100% SPK-SAF on such flights. However, this usage scenario is associated with a number of challenges, as well as some simplifications:

- departure airports of long-haul flights and the respective fuel supply infrastructure
- number of refuelling processes with 100% SPK-SAF
- areas of operation and commissioning dates of aircraft that are compatible with 100% SPK-SAF
- availability of 100% SPK-SAF
- allocation of aircraft compatible with 100% SPK-SAF to particularly climate-sensitive routes.

At the **departure airports of most long-haul flights** from Germany (Frankfurt Main and Munich), fuel is supplied via hydrant fuelling systems. A dedicated supply of 100% SPK-SAF for certain flights would therefore mean the complete duplication of refuelling (into-plane services) with tankers. This would also entail the construction of new infrastructure for the tankers, an increase in traffic volume on the apron and potentially longer turnaround times, as it takes longer to refuel wide-body aircraft with tankers than with hydrants because of the lower flow rate and the limited total quantity of fuel carried per tanker.

At the same time, the targeted use of 100% SPK-SAF on long-haul flights reduces the **number of refuelling processes**, while the quantities of fuel needed per refuelling process are relatively large. While refuelling quantities are, on average, significantly less than 10 t for short-haul flights, e.g. intra-European traffic with flying distances of 500 to 2,000 km, wide-body aircraft are refuelled with 80–150 t of fuel per refuelling process for long-haul flights. This in turn reduces the complexity if only a small number of refuelling processes must be carried out in order to use the limited quantity of 100% SPK-SAF available, at least in the initial phase. However, from the perspective of the airlines, it is also important to bear in mind that the refuelling of long-haul flights with tankers is a more-complex operation, as the capacity of the tankers is limited and it may take two or more tankers to refuel a long-haul flight.

At present, it is unclear **which aircraft will be approved for the use of 100% SPK-SAF** and when these aircraft will be ready for use. In the two scenarios “NextGen 2035” and “Late Adoption”, only the next generation of aircraft will be approved for 100% SPK-SAF. At present, however, there are no projects for a new long-haul aircraft model that will reach the market in the foreseeable future. Only Airbus has so far declared that it wants to bring the

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successor to the Airbus A320 family for short- and medium-haul flights to the market after 2035, and that the successor will most likely be compatible with 100% SPK-SAF (Airbus 2025).

Another challenge is the **availability of 100% SPK-SAF**. If there were a limited quantity of 100% SPK-SAF, the airports of Frankfurt Main and Munich would already absorb most of it, such that barely any 100% SPK-SAF would be available for use at the other airports.

It follows from this that it is probably sensible to focus the supply of 100% SPK-SAF on a small number of airports. This leads to considerable cost-saving potential in terms of infrastructure expansion and operation across the country. At the same time, the creation of infrastructure for 100% SPK-SAF and the refuelling of aircraft is hardest to implement at Frankfurt Main and Munich airports due to the quantities required there, the operational complexity due to the large volume of traffic, and the limited space available.

Overall, over 85% of non-CO_2 effects stem from departures from just five airports (Frankfurt Main, Munich, Leipzig/Halle, Köln Bonn and Berlin Brandenburg), with 68% coming from the airports of Frankfurt Main and Munich alone. In other words, the climate benefit of 100% SPK-SAF at the other airports is relatively small, while the supply costs, at least at the larger airports, such as Düsseldorf, Hamburg or Stuttgart, are likely to be of a similar order of magnitude as at Berlin Brandenburg, Leipzig/Halle or Köln Bonn.

Lastly, another challenge is the **use of aircraft that are compatible with 100% SPK-SAF on the particularly climate-sensitive routes**. In order to maximise benefit as intended by using 100% SPK-SAF, it is necessary for the airlines to base the compatible aircraft precisely where 100% SPK-SAF is offered as part of their basing and rotation planning. Ideally, the aircraft would then also be used on routes that have a particularly high potential for the reduction of non-CO_2 effects. The provision of 100% SPK-SAF must therefore be tailored to the growth in the fleet of compatible aircraft, taking local circumstances into account.

Concentrating the supply at only a few departure airports, which has been discussed here as a scientifically sound course of action, may preclude the supply of a small number of particularly climate-sensitive flights with 100% SPK-SAF on departure from the other airports. At airports without a fixed supply of 100% SPK-SAF, it may be possible to allow the supply of this fuel to flights with particularly high non-CO_2 effects to a limited extent using a combination of road tankers and airport refuelling vehicles. This would necessitate spot checks to determine whether the further increased logistics costs due to the provision of

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relatively small quantities of 100% SPK-SAF are outweighed by the benefits of reducing non-CO_2 effects. If mobile supply were not possible, flights with lower non-CO_2 effects would alternatively receive 100% SPK-SAF at the airports with a supply of 100% SPK-SAF. In this case, the "lost" benefit depends on the difference between the non-CO_2 effects of flights departing from an airport that receives no 100% SPK-SAF and the departing flights with the next-highest non-CO_2 effects at an airport that does have a supply of this fuel. The size of the difference between the benefit analyses for the two flights should be examined on a case-by-case basis after the cost of supplying 100% SPK-SAF is taken into account. This would allow a decision to be made as to whether a mobile supply with a combination of road tankers and airport refuelling vehicles is a sensible option. There is no blanket answer to this question; rather, it is first necessary to assess the ranking of non-CO_2 effects at airports with and without a supply of 100% SPK-SAF and the logistics costs in the individual case.

If the supply of 100% SPK-SAF is focused on a few airports in the introductory phase, there would be three options in the very long term (e.g. after approximately 2050) as to how to proceed with the other airports:

- maintain the exclusive supply with Jet A-1 or SAF as a drop-in fuel
- duplicate the infrastructure for simultaneous supply with 100% SPK-SAF and Jet A-1
- switch from Jet A-1 to 100% SPK-SAF on a set date.

From a scientific perspective, the use of 100% SPK-SAF could also remain limited to a few airports, given the strong concentration of fuel demand. However, another conceivable option is to provide 100% SPK-SAF at a larger number of airports, as the large number of aircraft compatible with 100% SPK-SAF and the large overall quantity of supplied 100% SPK-SAF would mean there was no longer a need to strongly prioritise particularly climate-sensitive flights. In addition, there should then also be demand for larger quantities of 100% SPK-SAF at smaller airports, such that the capacity of duplicated fuel-supply infrastructure can be better utilised. In the scenarios set out in section 5, for example, it is assumed that there will be demand for an estimated 6 million t of 100% SPK-SAF in Germany in 2060. This would mean that, even at the smaller airports, which only account for 3% to 5% of fuel demand across Germany, there would be demand for 500 to 800 t of 100% SPK-SAF per day, assuming that the 70% SAF quota from the ReFuelEU Aviation regulation is maintained. To avoid the cost of duplicating the infrastructure, one option would be to switch over the supply from Jet A1 to 100% SPK-SAF completely at smaller airports on a set date far in the

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future. However, this would require the almost total adoption of aircraft compatible with 100% SPK-SAF. The advantage of this option lies in the savings in terms of the investment and operating costs involved in duplicating the infrastructure. At present, however, it is impossible to predict whether such a scenario can be regarded as realistic.

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7 Conclusion and outlook

This study has explored the challenges and potential strategies for the introduction of 100% SPK-SAF at German airports. The measures set out here should be regarded as possible courses of action based purely on a scientific analysis.

Table 5 summarises the key findings of the scenario analysis with regard to the alternatives – that is, establishing duplicate physical infrastructure, on the one hand, or a book-and-claim or levy system, on the other.

The three introduction scenarios (ReCert Fleet, Next Gen 2035 and Late Adoption) do not differ significantly when it comes to the creation of refuelling infrastructure at the airports. Creating duplicate physical infrastructure would require considerable investment at all airports, while a book-and-claim or levy system would allow the infrastructure investments to be targeted at a small number of airports.

In terms of the fleet of aircraft, the scenarios ReCert Fleet (1A and 2A) would produce the greatest complexity and potentially the highest costs if aircraft models of the existing fleet were recertified and the aircraft were individually retrofitted. This expenditure would not be necessary in the other scenarios. The modelling of the adoption of aircraft that are compatible with 100% SPK-SAF and the availability of this fuel showed, based on the assumptions made, that the recertification of the existing fleet is not strictly necessary in order to achieve broad adoption/use of 100% SPK-SAF.

In terms of the regulatory framework, adjustments will have to be made regardless of the scenarios in order to overcome some of the scepticism around the introduction of 100% SPK-SAF from representatives of the aviation industry, as identified in the stakeholder survey. The demonstrated economic benefits alone will not be sufficient to incentivise the use of 100% SPK-SAF. From an economic perspective, therefore, the approach should be to create regulatory incentives that harmonise the economic and operational objectives regardless of whether there is duplicate physical infrastructure or a book-and-claim system.

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Scenario		Infrastructure	Aircraft fleet	Regulatory framework	Benefit dimensions
Duplicate physical infrastructure	ReCert Fleet (1A)	High costs if 100% SPK-SAF is to be made available at all airports Potentially limited capacity utilisation of the infrastructure for 100% SPK-SAF at smaller airports if only a small number of compatible aircraft are operated there	High complexity and costs if aircraft are recertified and retrofitted	Adjustments needed to incentivise use of 100% SPK-SAF Create incentives so that additional costs of use can be borne in a competitively neutral manner	Targeted use on particularly climate-sensitive flights is possible if 100% SPK-SAF is available at almost all airports
	Next Gen 2035 (1B)		Only new aircraft are compatible with 100% SPK-SAF; there is no need for recertification or retrofitting costs		Even without retrofitting the existing fleet, it is possible to achieve a considerable reduction of non-CO_2 effects
	Late Adoption (1C)		Only new aircraft are compatible with 100% SPK-SAF; there is no need for recertification or retrofitting costs		The very late introduction (2040) shifts the realisation of the benefit far into the future
Book-and-claim/levy system	ReCert Fleet (2A)	Targeted infrastructure investments are possible at airports with potentially high demand for 100% SPK-SAF Next Gen/Late Adoption scenarios allow later infrastructure investments	High complexity and costs if aircraft are recertified and retrofitted		Some very climate-sensitive flights potentially cannot be supplied with 100% SPK-SAF; flights supplied with alternative fuels have potentially lower non-CO_2 effects, which are reduced
	Next Gen 2035 (2B)		Only new aircraft are compatible with 100% SPK-SAF; there is no need for recertification or retrofitting costs		
	Late Adoption (2C)		Only new aircraft are compatible with 100% SPK-SAF; there is no need for recertification or retrofitting costs		

Table 5: Summary of scenario analysis

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With regard to maximising the achieved benefit, the results of the analysis show that flights with the highest non-CO_2 effects are highly concentrated at a small number of departure airports. It would therefore be sensible from an economic perspective to focus the supply of SPK-SAF on a small number of airports insofar as these flights are operated with aircraft compatible with 100% SPK-SAF in the future. One potential consequence of this is that not all highly climate-sensitive flights could be supplied with 100% SPK-SAF, although the net benefit would potentially be higher after taking the infrastructure and logistics costs into account in the event that 100% SPK-SAF were only offered at a few airports.

Ultimately, the challenges for the introduction of 100% SPK-SAF at German airports necessitate systemic optimisation in six areas of action:

- production and provision of a sufficient quantity of 100% SPK-SAF
- definition of airports at which 100% SPK-SAF should be provided and adaptation of the fuel infrastructure and refuelling processes at those airports
- use of aircraft fleets that are compatible with 100% SPK-SAF and departure airports that provide 100% SPK-SAF
- allocation of aircraft compatible with 100% SPK-SAF to flight routes with the highest non-CO_2 effects
- refuelling of flights with the highest non-CO_2 effects with 100% SPK-SAF
- economic incentivisation of the use of 100% SPK-SAF.

The particular challenge here is that it requires optimum cooperation between different stakeholders. The optimisation problem is summarised again in Figure 16.

At the present time (as of April 2026), it is still impossible to predict what exactly the fuel standard will look like and which aircraft will be compatible with the fuel. However, the definition of the fuel standard is the key prerequisite in order to subsequently define the certification standards for aircraft/engines and to establish standards for handling, distribution and refuelling processes (e.g. through an adaptation of the JIG standards). At the same time, work is needed on the implementation of regulatory instruments in order to offer stakeholders an economic incentive. Subsequently, aircraft could be retrofitted and the fuel infrastructure at airports could be adapted. Given optimum conditions, this could be achieved by the start of the 2030s (Figure 17).

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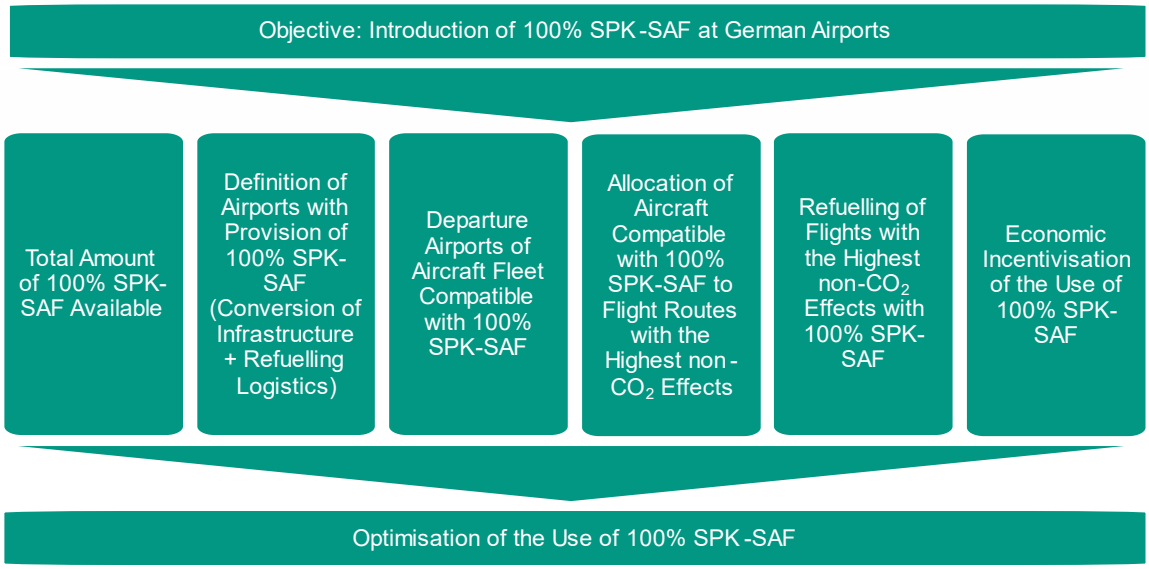


Figure 16: Challenges for optimising the use of 100% SPK-SAF (source: own graphic)

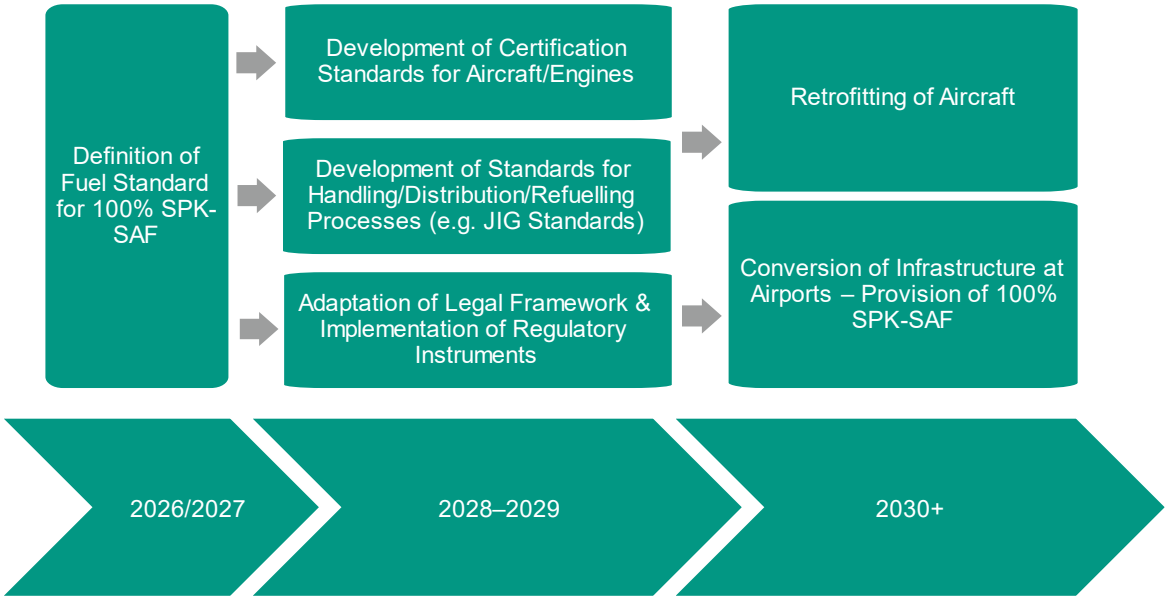


Figure 17: Timeline for the introduction of 100% SPK-SAF (source: own graphic)

This study has shown that, both in the scientific literature and in the practical experience of stakeholders, there are considerable uncertainties around the introduction of 100% SPK-SAF. These uncertainties span almost all areas, including the definition of the fuel standard, the level of infrastructure and logistics costs, the regulatory environment and also the quantification of the benefit, particularly with regard to reducing non-CO_2 effects.

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So far, the cost-benefit analyses are purely theoretical in nature, and there are few practical insights from the use of 100% SPK-SAF. One conceivable option would be to carry out a longer-term demonstration project in order to generate knowledge, dispel uncertainties and boost acceptance among stakeholders. For example, a closely delimited regional flight route could be operated on an ongoing basis as part of a public service obligation (PSO) with aircraft running on 100% SPK-SAF for this purpose. Insofar as long-haul aircraft that are compatible with 100% SPK-SAF are available for commercial operations, this fuel could also be used on the particularly climate-sensitive long-haul flights by way of a demonstration project. For example, one successful demonstration of the use of a new fuel is the BurnFAIR project, in which bio-kerosene was tested in commercial operations on the Hamburg–Frankfurt route in 2011 in conjunction with scientific monitoring (Zschocke 2014). With ongoing operation over a prolonged period of time, it would be possible to record the long-term effects for the aircraft and engine technology, to gather experience in relation to fuel logistics, and thereby to gain valuable insights with a view to widespread use.

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Acknowledgements

The authors would like to thank Franziska Bietke and Paula Wirth from the DLR Institute of Air Transport for their editorial assistance in preparing this report, as well as with the creation of graphics and thorough proofreading. They would also like to thank the project team at InnoFuels and the staff of the DLR Institute of Combustion Technology, the Centre of Competence for Climate, Environment and Noise Protection in Aviation of Hessen Trade & Invest GmbH (CENA Hessen), and Condor Flugdienst GmbH for their support with the project. Sincere thanks are due to the consulted stakeholders, who made a substantial contribution by providing a wealth of practical information. Lastly, a special thank you also goes to Ulrike Schulte and the team from Köln Bonn Airport and Andreas Grabe from AFS Aviation Fuel Services GmbH for holding the stakeholder workshop in November 2025.

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List of abbreviations

Abbreviation	Meaning
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
BER	IATA location identifier for Berlin Brandenburg Airport
FTIP	Federal Transport Infrastructure Plan
CAEP	Committee on Aviation Environmental Protection
CAGR	Compound annual growth rate
CEPS	Central European Pipeline System
CGN	IATA location identifier for Köln Bonn Airport
CHJ	Catalytic Hydrothermolysis Jet Fuel
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
Def Stan	Defence standard
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
DUS	IATA location identifier for Düsseldorf Airport

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EAGWP	Efficacy-weighted absolute global warming potential
ECLIF	Emissions and Climate Impacts of Alternative Fuels
EU	European Union
EU ETS	European Emissions Trading System
FRA	IATA location identifier for Frankfurt Main Airport
FT	Fischer–Tropsch
H_2	Hydrogen
HAJ	IATA location identifier for Hannover Airport
HAM	IATA location identifier for Hamburg Airport
HEFA	Hydroprocessed Esters and Fatty Acids
HHC	Hydroprocessed Hydrocarbons
HHN	IATA location identifier for Hahn Airport
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IKFT	Institute of Catalysis Research and Technology
JIG	Joint Inspection Group
LEJ	IATA location identifier for Leipzig/Halle Airport
LTO	Landing and take-off

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MRV	Monitoring, reporting and verification
MUC	IATA location identifier for Munich Airport
nvPM	Non-volatile particulate matter
PSO	Public service obligation
RED	Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
SAF	Sustainable aviation fuel
SBC	Synthetic blending component
SIP	Synthetic Iso-Paraffin
SKA	Synthetic Kerosene with Aromatics
SPK	Synthetic Paraffinic Kerosene
STR	IATA location identifier for Stuttgart Airport
t	(Metric) tonnes
TCDS	Type certificate data sheet
vPM	Volatile particulate matter
WACC	Weighted average cost of capital

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Appendix

List of questions for stakeholder survey

SAF production

- What challenges are faced in SPK-SAF production?
- What are the possible feedstocks for SPK-SAF production?
- How big is the benefit in terms of the life cycle emissions of SPK-SAF compared with fossil fuel and other SAFs?
- How does SPK-SAF impact local pollutant emissions (NO_x, soot, SO_x)?
- What is your assessment of the production costs, prices and long-term availability of SPK-SAF?
- Which distribution chains (e.g. pipeline, rail, boat, heavy goods vehicle) are currently used to transport Jet A-1 and SAF, and how suitable is this infrastructure for 100% SPK-SAF?
- Do existing distribution chains need to be modified or duplicated in order to deliver Jet A-1, SAF blends and 100% SPK-SAF in parallel?
- Does the handling of 100% SPK-SAF differ in terms of transport, storage or quality assurance from Jet A-1 or SAF blends, and what safety regulations apply?
- How do transport types, distance and geographical location impact the distribution costs, and how do the investment and operating costs for fuel distribution systems and vehicles behave in comparison?

Distribution, airport infrastructure and refuelling

- How are the delivery, storage and quality control of aviation fuel currently carried out at airports? (JIG2, RCQ/COQ…)
- How is the aircraft refuelling process currently carried out, and what process steps are safety- or time-critical?
- Which safety-relevant standards apply to fuel handling, and how would they need to be adapted for the introduction of 100% SPK-SAF?

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- What additional requirements or adaptations would be necessary in order to integrate 100% SPK-SAF into the existing refuelling process?
- What are the components of the existing airport infrastructure for fuel storage and distribution, and what additional systems would be necessary in order to integrate 100% SPK-SAF?
- What are the investment and operating costs and the service life of existing and additional systems and vehicles, and what incentive mechanisms could encourage airports to invest in SPK-SAF-compatible infrastructure?
- How do the refuelling processes differ depending on the distribution route (e.g. pipeline vs tanker), and what are the advantages and disadvantages of these systems in terms of efficiency, costs and safety? (fuel flow rate, capacity…)

Aircraft and engine manufacturers

- What is the current status of manufacturers' plans with regard to the compatibility of new aircraft/engine types with 100% SPK-SAF?
- Can existing aircraft/engine models be certified or retrofitted for 100% SPK-SAF – and what are the associated technical or financial costs?
- What costs would airlines incur for the retrofitting or replacement of incompatible aircraft/engines, and what impact would compatibility with 100% SPK-SAF have on manufacturers' prices for new aircraft/engines?
- What would be the operational impact on airports and airlines of using 100% SPK-SAF from the point of view of aircraft/engine manufacturers?
- Are there other impacts to take into account, such as changes in maintenance costs/reduced deposits of combustion residues?

Airlines

- Is the refuelling of wide-body aircraft with tankers an operational problem?
- How is fuel currently tested during ongoing operations?
- How do SAF logistics work?

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- What is your view on the situation whereby maximum blends of 50% SAF are currently approved but ReFuelEU Aviation stipulates 70% in 2050?
- Is 100% SPK-SAF cheaper to manufacture than SPK-A-SAF?
- What economic or regulatory incentives could persuade airlines to make greater use of SPK-SAF, and how can airlines protect themselves against rising fuel prices (e.g. hedging, supply contracts)?
- What other topics should be addressed in the study?

Market & regulatory

- Have you already dealt with non-drop-in fuels (100% SPK-SAF) and do you already have a position on them?
- How do you assess the long-term prospects for SPK-SAF in comparison with other synthetic or biogenic SAF?
- To what extent can non-CO_2 effects (e.g. contrails, NO_x) be integrated into future regulations or flexibility mechanisms?
- What offsetting or crediting mechanisms could be considered for the use of SPK-SAF in existing emissions systems (ETS, CORSIA, voluntary emissions reductions)?
- How can state or market-based mechanisms (e.g. funding programmes, carbon pricing, certificate trading) accelerate the ramp-up of SPK-SAF?
- What is your appraisal of flexibility mechanisms such as book and claim?

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