Research and demonstration project
on the use of renewable kerosene at
Leipzig / Halle airport
(DEMO-SPK)

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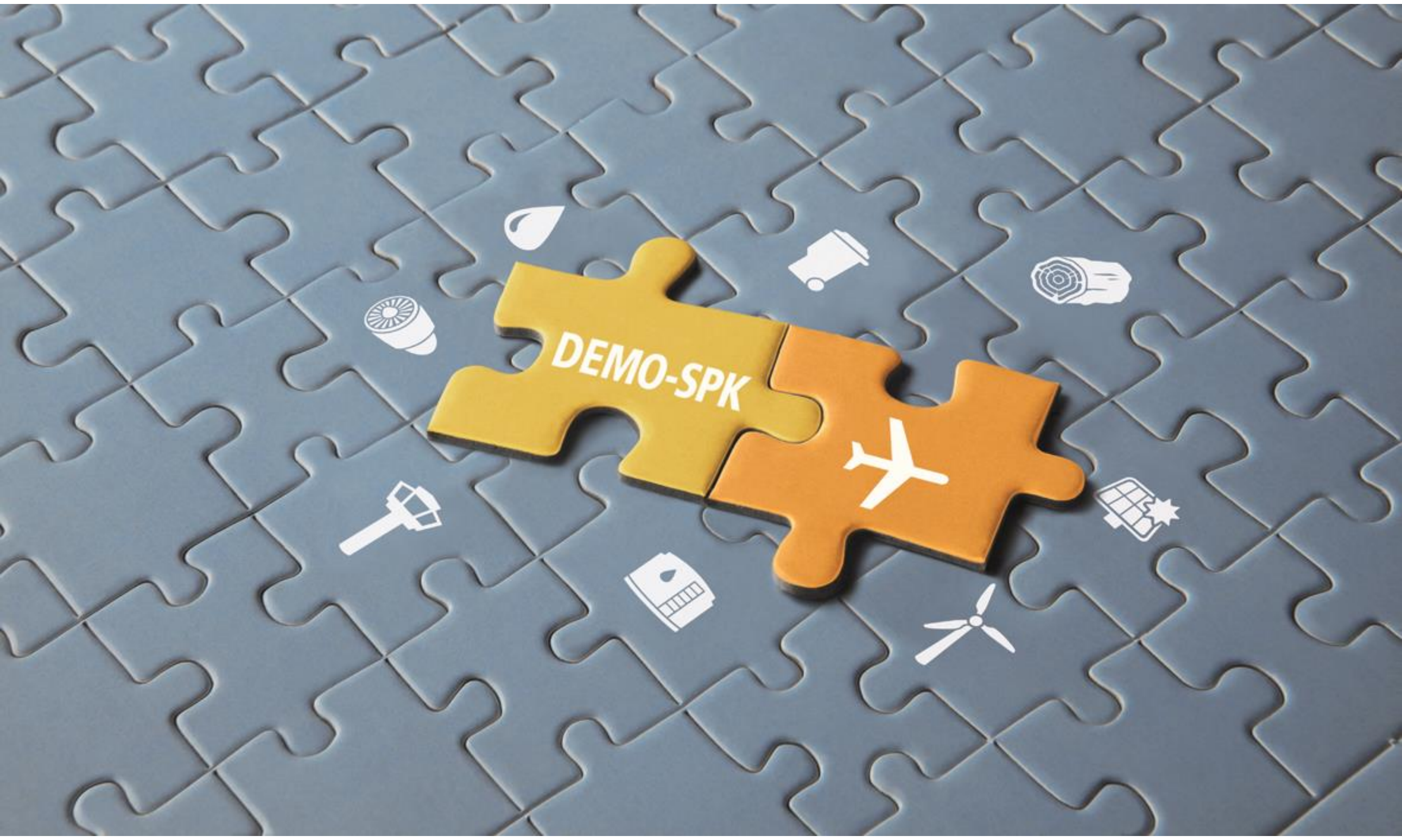

Use of multiblend JET A-1 in practice

Summary of the results from the model project of the Mobility and Fuel Strategy

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Completing a research and demonstration project of this scope has only been possible thanks to the great interest and exceptional commitment of the international partners from science and industry who have been involved in DEMO-SPK. We would therefore like to take this opportunity to thank, not only the Federal Ministry of Transport and Digital Infrastructure (BMVI) for sponsoring the MKS model project, but also aireg e.V. for being the initiator behind the project idea and all the partners in the DEMO-SPK core team: Adeptus Green Management, aireg, DLR, ifok, MCS, TUHH and WIWeB with coordination by DBFZ.

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BP Europa SE deserves special thanks for providing JET A-1 from the Lingen refinery (low sulfur) in different quantities for the pre-investigations at WIWeB, for producing the multiblend JET A-1, delivering the same JET A-1 to LEJ and for advice and support regarding the related logistical challenges.

We also would like to thank VTG AG and Dettmer Rail GmbH for equally excellent collaboration and focus on finding solutions. Examples include reserving the coated unit train, procuring HEFA from the USA directly from the manufacturer and the challenges in terms of interim storage and transport to the tank depot in Speyer. We would like to thank Knoell Germany GmbH for their support on all questions concerning REACH and PPORD for HEFA-SPK and ATJ-SPK.

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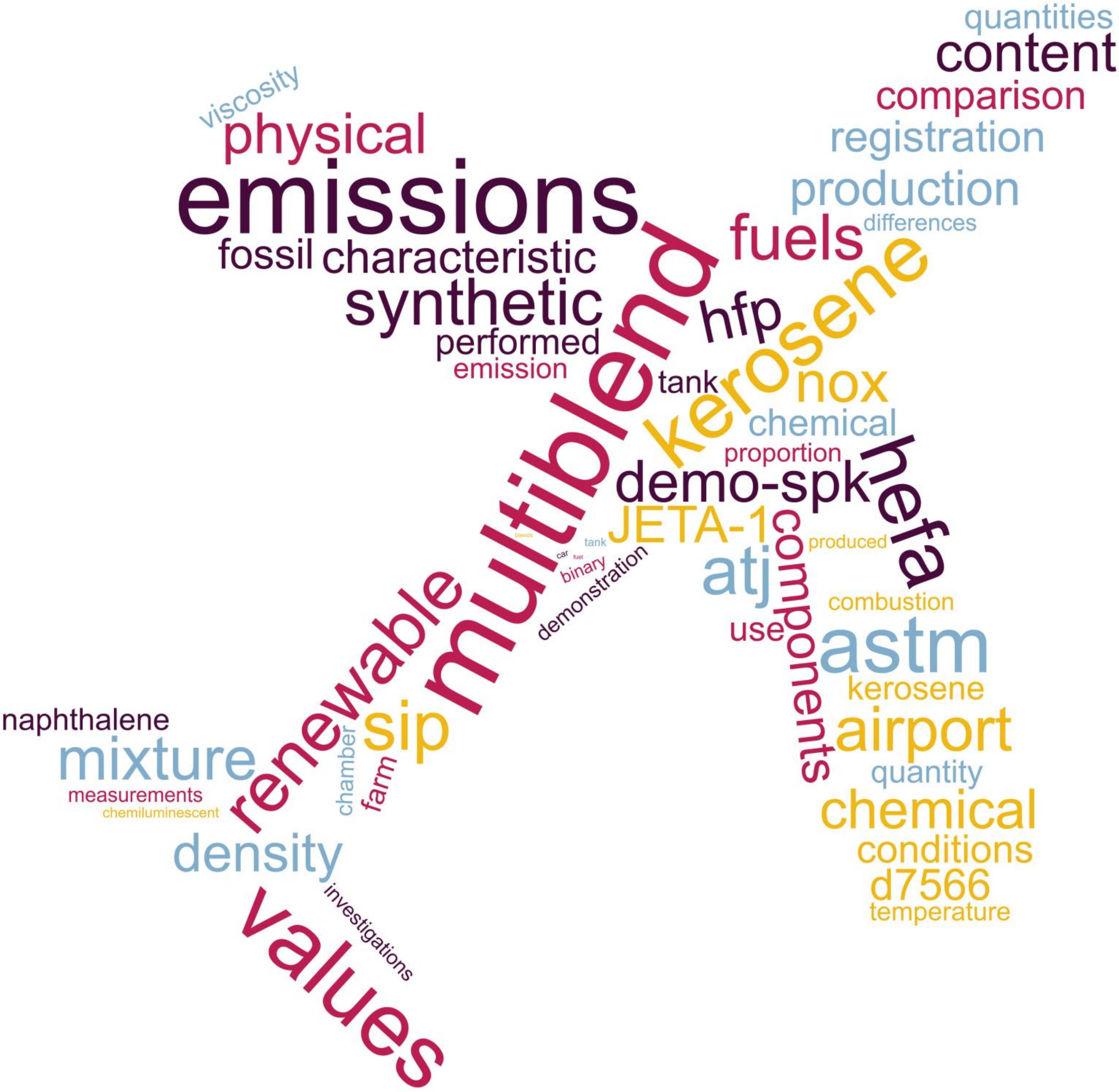
ALOP	Agricultural land occupation potential
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-JET
BfR	Federal Institute for Risk Assessment
BMVI	German Federal Ministry of Transport and Digital Infrastructure
BTL	Biomass-to-Liquid
CFD	Computational Fluid Dynamics
ChemG	German Chemicals Act
CHP	Combined heat and power plant
CLP	Classification, Labelling and Packaging
CN	Combined Nomenclature
CoA	Certificate of Analysis
CoO	Certificate of Origin
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DBFZ	DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH
DIN	Deutsches Institut für Normung e. V.
DLR	Deutsches Zentrum für Luft- und Raumfahrt e. V.
DSHC	Direct Sugar to Hydrocarbons
DStan	UK Defence Standardisation
EBV	German National Petroleum Stockpiling Agency
ECHA	European Chemicals Agency
EEA	European Economic Area
EMCS	Excise Movement and Control System
EnergieStG	German Energy Duty Act
EPA	Environmental Protection Agency
ErdölBevG	Germany Petroleum Stockholding Act
ETS	Emissions Trading System
FAME	Fatty Acid Methyl Ester
FDP	Fossil depletion potential
FEP	Freshwater eutrophication
FIFO	First In First Out
FT	Fischer-Tropsch
FTIR	Fourier Transform Infrared Spectrometer
FTJ	Fermetation-to-JET
GHG	Greenhouse gas
GoO	Guarantee of Origin
GWP	Global warming potential
HEFA	Hydroprocessed esters and fatty acids
HFP	High-Freeze-Point
HiPOT	High Pressure Optical Test rig
HS	Harmonized System
HTPinf	Human toxicity
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCFS	Low Carbon Fuel Standard
LDAS	Laser Diode Absorption Spectroscopy
LEJ	IATA code for Leipzig/Halle Airport
LTO cycle	Landing and Take Off Cycle
MBMS	Molecular Beam Mass Spectrometry
MCT	Maximum continuous thrust
MET	Marine ecotoxicity potential
METI	Ministry of Economy, Trade and Industry
MFS	Mobility and Fuel Strategy
MVO	Monitoring Regulation
NDIR	Non-Dispersive Infrared Absorption
OTC	Over-the-counter
PM	particle mass
PMFp	Particulate matter formation potential
PN	particle number
PoS	Proof of Sustainability
PPORD	Product and process orientated research and development
PTG	Power-to-Gas
PTL	Power-to-Liquid
PV	Photovoltaic
RCQ	Refinery Certificate of Quality
RE	Renewable energy/energies
REACH	Regulation Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals
RED	Renewable Energy Directive
RFS2	Renewable Fuel Standard 2
RSB	Renewable Sustainable Biomaterials
RSPO	Round table on Sustainable Palm Oil
RT	Recertification Test Certificate
RTRS	Round table on Responsible Soy
SAF	Sustainable Aviation Fuels, Sustainable Aviation Fuels
SIP	Synthetic kerosene from hydroprocessed fermented sugars
SMD	Spray droplet size distribution
SPK	Synthetic paraffinic kerosenes
TAP	Terrestrial acidification
TUBAF	TU Bergakademie Freiberg
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WDP	Water depletion potential
WIWeB	Wehrwissenschaftliches Institut für Werk- und Betriebsstoffe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Executive summary

DEMO-SPK is a research and demonstration project that investigated the use of renewable jet fuel at Leipzig / Halle airport. As a model project of the Mobility and Fuels Strategy (MFS), it was financed by the Federal Ministry of Transport and Digital Infrastructure (BMVI). The following summary of the DEMO-SPK project is geared towards answering public-sector questions and thus presents the project's basic components, results and recommendations in a simple and straightforward way.

What was the motivation behind the DEMO-SPK model project?

The necessity to reduce and prevent emissions in the German aviation industry has been addressed in the Mobility and Fuels Strategy of the German Government. In addition to technical and operational measures to reduce emissions, it focuses on substituting conventional fossil-based jet fuel with sustainable aviation fuels (SAF). For this purpose, new manufacturing processes, as specified in an international ASTM standard, are used instead of conventional oil refining processes. As the synthetic paraffinic kerosene (SPK) composition may differ from that of conventional fossil kerosene depending on the process used, market introduction is subject to certain restrictions. For example, synthetic kerosenes may not yet be placed on the market in their pure form. Instead, they have to be mixed ("blended") with fossil-based JET A-1.

Today, various SPK manufacturing processes have already been approved in accordance with the ASTM standard (e.g. HEFA-SPK, ATJ-SPK, FT-SPK, SIP). Other processes (e.g. HFP-HEFA) are currently in the process of standardization. In the medium term, airports in Germany are expected to be supplied with jet fuel containing varying proportions of different types of SPK. Since individual batches of jet fuel from different sources are usually transported and stored together within an airport's supply infrastructure, there is no physical separation of the delivered batches. This inevitably results in intermingling and mixing. As only specification-compliant JET A-1 may be used, this is formally permissible. However, the mixing behavior and compatibility of JET A-1 blends containing varying proportions of different types of SPK ("multiblending") had yet to be studied in Germany and internationally.

What were the objectives of the DEMO-SPK project?

The primary objective was to investigate and verify the behavior of mixtures of several renewable jet fuels under realistic conditions within the supply infrastructure of a major airport. The aim was to successfully demonstrate the deployment of the multiblend JET A-1 in the general fuel supply infrastructure, from procurement to aircraft refueling. In addition to analyzing the properties of the jet fuel, the project measured emissions, conducted life cycle analyses, analyzed the sustainability documentation and studied verification and credit allowances for the renewable fuels as part of European emissions trading. Furthermore, legal questions were clarified and organizational framework conditions were created.

What are the specific highlights of DEMO-SPK?

Thanks to the participation of more than 20 international partners from industry and academia, the MFS model project has been the first of its kind to succeed in:

- supplying nearly 600 tons of multiblend JET A-1 and utilizing this in flight operations at the Leipzig / Halle airport
- reducing (i) particle emissions in ground runs by approx. 30 to 60 % and (ii) CO_2 equivalent emissions by approx. 35 % through the use of multiblend JET A-1 in aircraft instead of pure fossil-based JET A-1 fuel

- preparing SPK using PTL (power-to-liquid) so that key requirements of the ASTM specifications can be met.

What is multiblend JET A-1 and how is it produced?

Multiblend JET A-1 is a blend of conventional fossil JET A-1 that is ASTM D1655 compliant, and at least two other (“multi”) renewable jet fuels that are in line with ASTM D7566.

Two important criteria were taken into account in the DEMO-SPK project when selecting the renewable jet fuels and their suppliers: (i) the current version of the ASTM approval process and (ii) their availability on the international market at the time of the preliminary investigations and the scheduled demonstration at Leipzig / Halle airport. The renewable jet fuels HEFA-SPK and ATJ-SPK, which were only available in the US, were used in the demonstration. The fossil-based JET A-1 was purchased from a refinery in Lingen. These components were used to produce approximately 600 tons of multiblend JET A-1 for DEMO SPK.

Current specifications do not explicitly cover multiblending, however successive mixing is implicitly permitted. In order to comply fully with the applicable regulations, the renewable jet fuels were added successively to the fossil-based JET A-1 to produce the multiblend JET A-1, and a fuel sample was taken after each mixing process. It was accepted that there would be additional work involved, as compliance with the ASTM specification had to be formally ensured in every case. The multiblend JET A-1 used at Leipzig / Halle airport was produced at a tank farm in Speyer. As jet fuel tanks normally do not have a mixing device, the tank farm’s infrastructure was adapted to the mixing task through the installation of a mixing device in a spherical tank that had previously been flushed several times.

How was the use of multiblend JET A-1 in the infrastructure of a major airport verified?

In preparation for demonstrating the provision and use of multiblend JET A-1, preliminary investigations were carried out on various multiblend formulations. It was shown that multiblends can be produced in line with specifications and that the chemical and physical variables can be precisely calculated as long as the pure fuels are known. No separation occurred, nor did the properties change when stored for a period of six months. Likewise, there was no decline in the quality of the fuel. Results obtained for lab-scale mixtures can be transferred.

Based on these findings, production began in Speyer on the multiblend JET A-1. The renewable jet fuels and the JET A-1 were supplied through combined logistics. The multiblend JET A-1 was delivered by railroad tank wagons in accordance with the specific requirements and conditions at the Leipzig / Halle airport. The fuel was stored there in an above-ground tank. In order to demonstrate the compatibility of a multiblend JET A-1 with the actual supply infrastructure of an airport, it was subsequently handled in the same manner as fossil-based JET A-1 for the purpose of aircraft refueling. This was the first time it could be verified anywhere in the world that multiblend JET A-1 can be used operationally in the same way as fossil-based JET A-1 without restrictions.

DEMO-SPK also planned to conduct comparative emission measurements on an aircraft turbine in a ground run. The quantities of multiblend JET A-1 and JET A-1 required to do this were transferred to field tank trucks, which are regularly used in aircraft refueling.

Does the use of multiblend JET A-1 contribute to a reduction in emissions and pollutants?

The DEMO-SPK project was able to demonstrate a reduction in emissions and pollutants in two ways. Both ways show which notable reduction potentials are possible in the short to medium term.

Measuring pollutant emissions. Comparative emission measurements were carried out on an aircraft turbine in an engine testing facility at Leipzig / Halle airport. Two ground runs were conducted based on a fixed measurement protocol that included a fossil JET A-1 reference measurement and a measurement with the multiblend JET A-1. The use of the multiblend JET A-1 reduced soot in relation to particulate mass by approx. 30 to 60 % for different operating points. The soot reduction was not associated with a "trade-off" in any other emission parameter. This was verified by comparative investigations in the technical laboratory.

Life cycle analyses for the renewable jet fuels and the multiblend JET A-1. In accordance with the methodology guidelines of the Renewable Energy Directive (RED), the specific greenhouse gas reduction emissions (as CO_2 equivalents) of the renewable jet fuels were balanced and their reduction was determined in the multiblend JET A-1. The findings showed that the use of multiblend JET A-1 on its own can reduce greenhouse gas emissions by 35 % compared to fossil JET A-1.

How were sustainability aspects taken into account by DEMO-SPK?

There is a consensus that only sustainable renewable jet fuels will be used in aviation. In the European Union, the sustainability criteria that have to be respected in practice are firmly anchored in the Renewable Energy Directive (RED). It specifies which raw materials can be used and stipulates the methods and minimum requirements of greenhouse gas reduction potentials over the fossil reference. Based on these standards, so-called life cycle analyses were also conducted for the renewable jet fuels used in DEMO-SPK. Their specific greenhouse gas reductions ranged from 57 to 96 %. The multiblend JET A-1, which contained fossil jet fuel, still achieved reductions of 35 %.

Furthermore, it was determined that the sustainability documentation criteria required by the certification process, which already apply to biofuels used in road traffic, can be transferred to the use of renewable jet fuel in multiblend JET A-1. DEMO-SPK also found that sustainability requirements and standards differ significantly from one another around the world. In a growing global market for renewable jet fuels, this can lead to additional administrative requirements for market participants. A solution to this problem lies in the mutual acknowledgment of existing systems and the development of so-called meta standards.

In addition, life cycle analyses of various sample supply chains were conducted with respect to cost sustainability. It was found that renewable jet fuels are likely to be much more costly than fossil jet fuels in the foreseeable future and will therefore not be competitive without specific incentives. An optimized logistics supply chain demonstrates a possible reduction in logistics costs of 85 % over the supply chain demonstrated in DEMO-SPK. However, a cost ratio of 1.3 was determined in the case of multiblend JET A-1 to fossil jet fuels, assuming the year-round supply and using Leipzig / Halle airport as an example. This would favor an industrial-scale introduction in the future. However, as long as there are cost reservations with respect to renewable jet fuels, further measures are needed to introduce the use of multiblend JET A-1 on a larger scale due to the fierce international competition in air transport.

How can the aviation industry offset its obligations in emissions trading?

Another important aspect for the market implementation of sustainable aviation fuels (SAF) is the intersection between the mass balance system for sustainability certification and documentation, on the one hand, and the inclusion of renewable jet fuels in the European Emissions Trading Scheme, on the other. Certification and credits based on the current legal approach are associated with high administrative and operational costs, which leads to limited use of credit allowances for renewable jet fuels and thus further reduces incentives for the use of SAF. Against this backdrop, DEMO-SPK has therefore developed various approaches for improving credit allowances in European emissions trading (so-called "track and trace" or mass balancing, and "book and claim" or the certificate solution) and has confirmed their basic functionality. In a further step, the developed procedures and approaches will be verified in practice beyond the experience gained in DEMO-SPK, thus identifying further measures for their future operationalization.

What other recommendations for action have emerged from DEMO-SPK?

The pilot project has identified not only numerous suggestions for operational project management, but also the concrete need for clarification, which is important for a successful implementation on the broader market. These include (i) the expansion of ASTM D7566 to include simultaneous production of multiblend JET A-1, (ii) a simplified REACH registration for renewable jet fuels and (iii) the amendment of the Energy Tax Act using the so-called similarity principle as per Article 2 (4) of the Energy Tax Act.

In addition, specific recommendations were derived for the international institutions (ASTM, JIG, ETS etc.) and addressed to them for consideration when further developing the respective specifications and guidelines. DEMO-SPK thus goes beyond the actual project and makes recommendations to internationally facilitate the operational coverage of renewable jets fuels as part of multiblend jet fuel and thus to enable market implementation.

Notwithstanding the successful investigations conducted as part of the DEMO-SPK MFS model project, the fact remains that, in addition to the above-mentioned recommendations for broad market implementation of renewable jet fuels, a massive expansion of production capacities and infrastructures (e.g. for the production of multiblend JET A-1) are required. Only then will it be possible to achieve the positive effects identified and verified by DEMO-SPK in relation to reducing potential pollutant emissions and greenhouse gases.

1 Background, objective and structure of the project

The Federal Government's Mobility and Fuel Strategy (MFS) [MKS13] addresses the need to reduce and prevent emissions in the German aviation industry. In addition to technical and operational measures to reduce emissions, it focuses on substituting conventional aviation fuel with sustainable kerosenes or Sustainable Aviation Fuels (SAF).

To produce alternative aviation fuels (synthetic paraffinic kerosene (SPK)), new manufacturing processes, as specified by the international ASTM D7566 standard, are used instead of conventional oil refining processes. As the SPK composition may differ from that of conventional fossil kerosene, depending on the process used, market introduction is subject to certain restrictions. For example, it has to be mixed (‘‘blended’’) with fossil-based kerosene. The blend can then be approved according to ASTM D7566 [AST19] and is then JET A-1 according to ASTM D1655 [AST19], which requires no further declaration.

Various different SPK production processes have already been approved (e.g. HEFA-SPK, ATJ, FT-SPK / BTL, FT-SPK / PTL , and SIP); others (e.g. HEFA-Diesel) are going through the approval process. In the medium term, it is expected that airports in Germany will be supplied with JET A-1 containing different types of SPK in variable ratios.

Within the supply infrastructure of an airport, the individual fuel batches of different origin are usually transported and stored together. There is no physical separation of the delivered batches, which inevitably leads to mixing. As only specification-compliant JET A-1 may be used, this is formally allowed. However, the blending behaviour and the compatibility of different JET A-1 blends with different types of SPK in variable ratios (multiblends) have not previously been investigated. There are also no known international projects in this regard.

With the primary objective of investigating and verifying the behaviour of multiblend kerosene under realistic conditions in the fuel supply infrastructure of a major airport, the Federal Ministry of Transport and Digital Infrastructure (BMVI) commissioned a comprehensive research and demonstration project on the use of renewable kerosene at Leipzig/Halle Airport (DEMO-SPK), which is unique in the international arena to date, as part of the MFS.

An overview of the specific tasks associated with DEMO-SPK is provided in the project structure below (Fig. 1).

The focus was the investigation of the blending behaviour of conventional JET A-1 with several renewable kerosenes. This included analyses of fuel properties, storage behaviour in the tank, blending behaviour under real conditions, compatibility with the fuel supply infrastructure and, for the multiblend JET A-1, use in an aircraft. The project also investigated local emissions at the airport. A laboratory analysis alone does not suffice to comprehensively answer these questions, since the realistic conditions in a tank depot and in the fuel supply infrastructure can lead to effects that cannot be simulated in a laboratory environment.

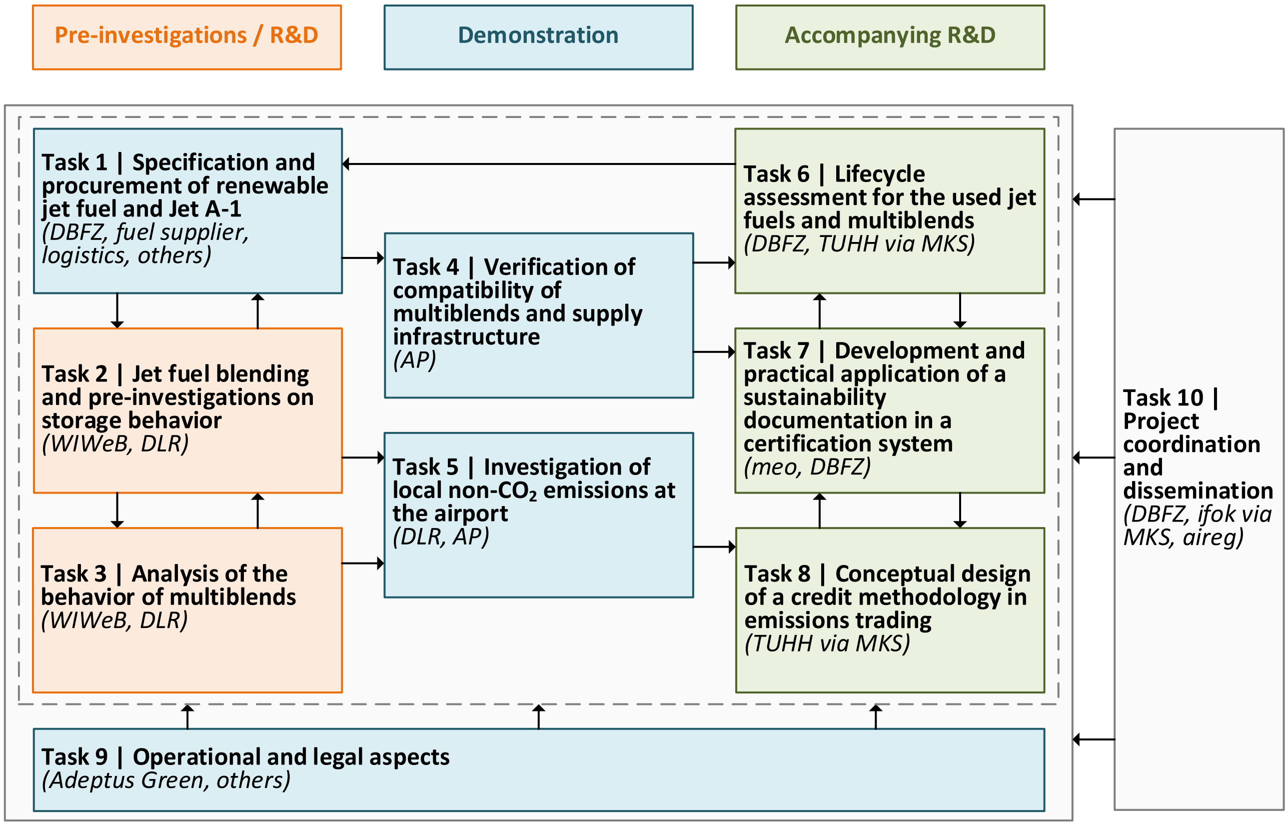

Fig. 1 Structure of the DEMO-SPK research and demonstration project

The project also provided the opportunity to tackle further outstanding questions directly linked to the widespread introduction of alternative aviation fuels. These include the development of viable sustainability documentation and the question of a standardised crediting procedure for emissions trading. In this context, the actual life cycle emissions of the renewable kerosenes and JET A-1 that were used have also been compared.

Furthermore, legal issues were clarified in the course of the project and organisational framework conditions were created that are intended to serve as a guideline for the future use of renewable kerosene in Germany.

A project of this kind, internationally unique as a vital contribution on the path to more sustainable and climate-friendly air transport, could only be successfully completed thanks to a large number of committed international partners from industry and science (Fig. 2).

The results and conclusions from the separate parts of the project are presented below, with the aim of providing a summary overview of the project. See section 9 for a discussion of renewable kerosene produced using the PTL approach. Finally, conclusions are drawn and recommendations are outlined.

Fig. 2 Overview of the international partners involved in DEMO-SPK (others include Amyris, Gerlach, and Panalpina)


Bio-Jet A-1

2 Renewable kerosenes investigated

In order to be used as aviation fuel, both fossil and renewable kerosenes require the relevant technical approval. ASTM International (formerly the American Society for Testing and Materials, ASTM), based in Pennsylvania/USA, is an international authority in this field. It plays a comparable role to the German Institute for Standardisation (DIN), developing technical standards for the use of objects and products, for specific procedures and services, and for testing and analysis methods [AST19f]. Compliance with and use of these standards is (almost) always voluntary. In most cases, however, certain sectors of industry, professional groups or companies themselves commit to complying with the relevant standards in order to agree on common values and qualities on the market.

A more common aviation fuel quality assurance standard in Europe has been developed by an organisation that is part of the UK Ministry of Defence (UK Defence Standardisation, DStan^{TM}). According to the agreements between ASTM and DStan, the field of "synthetic kerosenes" are handled by ASTM, whose decisions are then adopted by DStan and transferred to the regulations relevant for Europe.

Petroleum-based kerosene, for example, is standardised via the ASTM D1655 or DEF STAN 91-091 standards, while renewable kerosenes have to be approved under ASTM D7566. This involves testing their fuel and blend properties and defining blending limits as a result. At the start of the project, version D7566-16b was valid, which was supplemented several times by more up-to-date versions in the course of the project. The currently valid version is ASTM D7566-19.

ASTM D7566 allows a total of four different types of renewable kerosenes: FT-SPK (Fischer-Tropsch synthetic paraffinic kerosene), HEFA-SPK (hydroprocessed esters and fatty acids synthetic paraffinic kerosene), SIP (synthetic isoparaffins produced from hydroprocessed fermented sugars) and ATJ-SPK (alcohol-to-jet synthetic paraffinic kerosene). A fifth kerosene listed in ASTM D7566 is SPK/A (synthetic kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources), which is obtained from coal and was therefore disregarded entirely in DEMO-SPK.

Two main criteria were considered for the choice of the renewable kerosenes and suppliers:

a. ASTM approval under the currently valid version (ASTM D7566); and
b. Availability on the international market at the time of the pre-investigations and the planned demonstration at LEJ Airport.

The kerosene options used in DEMO-SPK are characterised briefly below. Comprehensive technical fact sheets for the individual options were prepared, e.g. as part of the MFS project "Biokerosin und EE-Kerosin für die Luftfahrt der Zukunft – von der Theorie zu Pilotvorhaben" [Zec 16].

2.1 HEFA-SPK

HEFA-SPK is currently the most important of the ASTM-approved renewable kerosenes on the international market in terms of volume. Synthetic paraffinic kerosenes from hydroprocessed esters and fatty acids (HEFA-SPK) can be produced by converting vegetable or animal oils or fats using hydrogen (hydrotreatment). The process, which is largely designed for diesel production, can be optimised by adjusting the operating conditions towards the kerosene fraction. The first step of this catalytic process saturates the double bonds and removes heteroatoms. To adapt the product properties, the second step involves isomerisation and mild cracking. Extensive investigations have been undertaken, such as in the MFS project "Machbarkeitsanalyse für eine PTG-HEFA-Hybridraffinerie in Deutschland" [Die17].

In addition to the market availability of the HEFA kerosene fraction, only kerosene that is verifiably not produced from palm oil or palm oil derivatives may be stored and used to comply with DHL's sustainability strategy. World Energy Paramount (formerly AltAir Paramounts LLC, California/USA) held relevant production capacity at the time. The raw material was exclusively beef tallow and the fuel has sustainability certification from the Roundtable on Sustainable Biomaterials (RSB). On 9 August 2016, the European Commission again confirmed that RSB complies with the sustainability criteria according to 98/70/EC and 2009/28/EC for a period of 5 years.

2.2 HFP-HEFA

HFP-HEFA (high-freezing-point HEFA) is being developed with the aim of simplifying the HEFA production process. As isomerisation is the most complex process step to obtain HEFA-SPK, it is kept as simple and short as possible. This is only possible at the expense of a shifted composition of HFP-HEFA, which in turn results in a higher freezing point. This results in a significantly lower blend rate compared to HEFA-SPK. This process is not yet approved and it therefore could not be included in the multiblend investigations themselves [Sta16]. In connection with the approval, however, some questions arose that are of interest from a safety point of view, but had not been investigated before. The climate chamber tests taking place as part of DEMO-SPK were therefore expanded to consider HFP-HEFA as well. The HFP-HEFA used for this purpose was provided by the provided by Neste Oyj in Finland.

2.3 ATJ-SPK

Alcohol-to-jet synthetic paraffinic kerosenes (ATJ-SPK) are produced from sugar-containing or saccharifiable feedstock via the primary production of an alcohol (ethanol or butanol) and secondary chain extension via dehydration and oligomerisation. Subsequent fractionation is carried out to recover the product. Until the beginning of 2018, ATJ-SPK from iso-butanol was the only approved ATJ-SPK. The only supplier was Gevo, Inc., which produces ATJ-SPK in a small refinery in Texas. The expansion plans assume a larger facility at the Luverne site in Minnesota. With ASTM D7566-18, ATJ from ethanol was also approved during the period of the DEMO-SPK project. As the approval was too late for the project and the market situation in terms of availability was unclear, this option was not considered.

2.4 SIP

SIP (synthesized iso-paraffins from hydroprocessed fermented sugars) is produced via a process called FTJ (Fermentation to Jet) or DSHC (Direct Sugar to Hydrocarbons). This involves the use of genetically modified yeasts that are able to produce long-chain hydrocarbons from sugar. These are separated and hydrogenated (saturation of double bonds) using hydrogen to form farnesane, prior to blending with conventional kerosene. Amyris, Inc., which was majority-owned by Total S.A. at the time, was the only available source of SIP.

SIP was obtained exclusively for laboratory and pilot plant scale investigations because of the limited availability. It was not possible to include it in the multiblend JET A-1 provided at the airport because, contrary to expectations, the quantities required for this purpose were no longer available. Amyris is now focusing less on SIP as a fuel and more on high-priced bio-based products [Leu18], so there is a question mark over the extent to which SIP will be relevant as a renewable blend component for kerosene in the future.

2.5 FT-SPK via PTL

The Fischer-Tropsch (FT) process for the production of synthetic kerosene was approved by ASTM in 2009. However, the ASTM approval of the FT process is for the second step and does not contain any specifications for generation of the synthesis gas, which is then converted into hydrocarbons (e.g. kerosene). The existing approval therefore also applies to FT kerosene obtained by means of other than natural gas or coal. The process itself was already in use by the South African company, Sasol, for the production of kerosene from coal under company-specific approval before it was approved by ASTM and is now used on a large scale in Qatar for the production of kerosene from natural gas. [Zsc17]

In terms of the use of renewable feedstock for FT-SPK, there are currently several projects to produce FT hydrocarbons from biomass or household waste on improved technology. However, none of these projects has reached a status capable of delivering FT biokerosene in quantities relevant for the purposes of DEMO-SPK, and in fact not even enough for the pre-investigations.

The FT process was instead included in DEMO-SPK by separately investigating a smaller quantity of an FT intermediate obtained from the Sunfire GmbH as a power-to-liquid (PTL) product. The special feature of the PTL process is that the synthesis gas is produced from carbon dioxide and hydrogen, whereby the hydrogen is produced electrolytically using renewable power. There are several processes available for subsequent processing of the synthesis gas into kerosene (e.g. methanol synthesis), but it is only the FT process that has already been approved. Sunfire therefore uses the FT process as a downstream stage, but initially only obtained an intermediate product from the process. The conditions for processing this intermediate into kerosene were investigated in more detail in DEMO-SPK.

3 Pre-investigations of the properties of renewable kerosene and multiblend JET A-1

Pre-investigations involved determining the physiochemical parameters of the neat blend components, calculating the blend ratios for specification-compliant binary blends with maximum synthetic proportions, and producing the blends. The multicomponent blends (hereafter referred to as multiblends) were designed based on the binary blends. After the multiblends had been produced on a laboratory scale and checked for conformity with the specification, they were produced on a pilot plant scale and placed in storage. At the beginning and end of the six-month storage period, the physiochemical parameters of the fuels were determined in order to make statements regarding potential changes in fuel quality. To exclude the implausible occurrence of separation, samples taken periodically from different fuel levels of the fuel blends were examined. The accuracy of calculation of the physiochemical properties of multiblends was checked by comparing the measured values obtained experimentally with the calculated values.

The aim of the pre-investigations was to demonstrate that semi-synthetic fuel blends that are compliant with the specification can also be produced from multiple synthetic fuels and stored without deterioriation of the fuel quality.

A multiblend and a binary blend containing HFP-HEFA and JET A-1 were also exposed to cyclically changing temperatures in a climate chamber to investigate the influence of changing climatic conditions.

3.1 Kerosene blending and storage

Fossil jet fuels must meet the requirements of the ASTM D1655 specification; synthetic fuels and their blends must meet the requirements of ASTM D7566. The latter is based on ASTM D1655 and imposes additional requirements for semi-synthetic fuel blends in terms of minimum aromatics content, low-temperature properties and the gradient of distillation. Pure synthetic fuels must also meet higher thermal stability requirements. According to ASTM D7566, the following 16 physiochemical parameter values must be complied with, which were determined at WIWeB in accordance with the relevant standards: Acid number (ASTM D3242 [AST17]), aromatics content (ASTM D1319 [AST18]), distillation curve (ASTM D86 [AST18])[1], flash point (IP 170 [IP 13]), density (ASTM D4052 [AST18]), freezing point (ASTM D7153 [AST15]), lubricity (ASTM D5001 AST14), viscosity at −20 °C and −40 °C (ASTM D445 [AST19]), existent gum (ASTM D381 [AST17]), net heat of combustion (ASTM D3338 [AST14]), thermal stability (ASTM D3241 [AST19]), smoke point (ASTM D1322 [AST18]), copper corrosion (ASTM D130 [AST19]), sulfur content (DIN EN ISO 14596 [DIN07]) and naphthalene content (ASTM D1840 [AST17]).

For DEMO-SPK, JET A-1 (produced at the Lingen refinery by BP) was available as conventional fossil jet fuel and HEFA (produced by World Energy), ATJ (produced by Gevo) and SIP (produced by Amyris) were available as synthetic kerosenes. In accordance with ASTM D7566, these synthetic fuels may be blended with conventional kerosene as long as the binary blend meets the requirements of this specification. To design the binary blends, the physiochemical properties of the single neat fuels were determined first (Tab. 1).

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[1] The distillation curve for pure SIP was determined according to ASTM D7345.

Tab. 1 Physiochemical properties of the neat fuels

Property	Fossil JET A-1	HEFA	ATJ	SIP	Requirement for blends according to ASTM D1655 or D7566	
	Value	Value	Value	Value	Value	Unit
Acid number	0.003	0.001	0.001	0.005	max. 0.10	mg KOH / g
Aromatics content	16.0	0	0	0	8–25	%v/v
Distillation curve						
Initial boiling point	160.9	149.3	171.6	239.8	Report	°C
10 %v/v	179.7	164.8	179.7	243.8	max. 205	°C
50 %v/v	200.5	199.5	184.8	244.1	Report	°C
T50–T10	20.8	34.7	5.1	0.3	min. 15	°C
90 %v/v	225.7	242.8	205.5	244.3	Report	°C
T90–T10	46.0	78.0	25.8	0.5	min. 40	°C
Final boiling point	250.4	251.3	257.9	245.6	max. 300	°C
Distillation residue	1.1	1.2	1.3	1.1	max. 1.5	%v/v
Distillation loss	0.9	1.0	0.6	0.3	max. 1.5	%v/v
Flash point	48.0	42.5	47.5	107.5	min. 38	°C
Density at 15 °C	811.7	751.5	758.0	772.0	775–840	kg/m^3
Freezing point	-81.9	-42.0	< -100	< -100	max. -47	°C
Lubricity (WSD)	0.629	0.709	0.827	0.523	max. 0.85	mm
Viscosity [−20 °C]	4.250	3.891	4.779	13.64	max. 8	mm^2/s
Viscosity [−40 °C]	8.497	7.697	9.037	42.41	max. 12	mm^2/s
Existent gum	< 1	2.9	2.2	< 1	max. 7	mg / 100 ml
Thermal stability						
VTR color code	< 1	< 1	< 1	1	< 3	Rating
Pressure drop	0	0	0	0	max. 25	mm Hg
Net heat of combustion	43.172	44.174	44.039	44.061	min. 42.8	MJ / kg
Copper corrosion	1b	1a	1b	1b	max. 1	Rating
Smoke point	22.9	> 43	34.5	—	Min. 25.0[a]	mm
Naphthalene content	0.243	0	0	0	max. 3.0	%v/v
Total sulfur	0.0023	0.0006	0	0	max. 0.30	%m/m

[a] Min. 25 mm or min. 18 mm for naphthalene content < 3 %v/v. The smoke point could not be determined for SIP because of its high viscosity.

Various binary blends of fossil and synthetic fuels were investigated as part of the HBBA study[2]. Based on the findings gained in the study, the physiochemical parameter values of density, aromatics content, acid number, net heat of combustion, naphthalene content, total sulfur, existent gum and viscosity[3] can be calculated really precisely for binary blends. For the distillation curve and the gradients of the distillation curve, a calculation provides only inaccurate values.

Based on this knowledge and knowledge of the physiochemical parameter values of the neat components, binary blends were designed by calculation that contain a maximum ratio of synthetic components while meeting the requirements of the ASTM D7566 specification. According to the specification, binary blends may

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[2] A systematic investigation of binary, semi-synthetic blends of different synthetic and fossil fuels was carried out in the HBBA study [Zsc17] on behalf of the European Commission. The focus of this study was to investigate how the properties of synthetic fuels affect the properties of binary blends with fossil fuels. This involved blending various synthetic kerosenes in high and varying ratios with different fossil kerosenes and investigating the properties of the blends.

[3] While the density, aromatics content, acid number, net heat of combustion, naphthalene content, total sulfur and existent gum show a linear relationship, viscosity has a logarithmic correlation (Grunberg-Nissan equation).

contain a maximum of 50 %v/v HEFA or a maximum of 30 %v/v ATJ or a maximum of 10 %v/v SIP. For SIP, it was possible to achieve the maximum blend ratio of 10 %v/v (Tab. 2, column BB 2). For HEFA, a blend ratio of 45 %v/v was selected (Tab. 2, column BB 1) to maintain a safe margin to the lower specification limit of the aromatics content. For ATJ, a blend ratio of 25 %v/v was specified (Tab. 2, column BB 3), as otherwise the gradients of the distillation curve would only just meet the minimum specification limit.

The physiochemical parameter values of the binary fuel blends BB 1-BB 3 are set out in Tab. 2. Selected parameter values classified as potentially critical or non-calculable were determined experimentally, while those that can be calculated effectively were calculated in some cases (highlighted in grey). Some parameter values, which the neat blend components already achieved, were not determined again at this point (e.g. thermal stability, marked with X in the tables); in these cases, it is not expected that the parameter values will be worse for the blends.

Tab. 2 Properties of the binary blends (BB)

Property	BB 1 45 %v/v HEFA 55 %v/v JET A-1	BB 2 10 %v/v SIP 90 %v/v JET A-1	BB 3 25 %v/v ATJ 75 %v/v JET A-1	Requirement according to ASTM D 7566	
	Value	Value	Value	Value	Unit
Acid number	0.002	0.003	0.003	max. 0.10	mg KOH / g
Aromatics content	8.8	14.4	12	8–25	%v/v
Distillation curve					
Initial boiling point	154.0	163.7	164.6	Report	°C
10 %v/v	172.6	182.5	178.7	max. 205	°C
50 %v/v	200.8	205.6	195.3	Report	°C
T50–T10	28.2	23.1	16.6	min. 15	°C
90 %v/v	234.5	233.3	226.6	Report	°C
T90–T10	61.9	50.8	47.9	min. 40	°C
Final boiling point	251.1	248.8	253.0	max. 300	°C
Distillation residue	1.2	1.2	1.1	max. 1.5	%v/v
Distillation loss	0.9	1.0	1.0	max. 1.5	%v/v
Flash point	45.0	50.0	X	min. 38	°C
Density at 15 °C	784.6	807.7	798.5	775–840	kg / m^3
Freezing point	-52.5	-83.6	X	Max. −47	°C
Lubricity (WSD)	0.657	0.588	X	max. 0.85	mm
Viscosity [−20 °C]	4.082	4.660	4.375	max. 8	mm^2 / s
Viscosity [−40 °C]	8.121	9.633	8.646	max. 12	mm^2 / s
Existent gum	1.8	< 1	1.2	max. 7	mg / 100 ml
Thermal stability					
VTR color code	X	X	X	< 3	Rating
Pressure drop	X	X	X	max. 25	mm Hg
Net heat of combustion	43.623	43.261	43.389	min. 42.8	MJ / kg
Copper corrosion	X	X	X	max. 1	Rating
Smoke point	31.8	24.5	X	Min. 25.0[a]	mm
Naphthalene content	0.134	0.219	0.182	max. 3.0	%v/v
Total sulfur	0.0015	0.0021	0.0017	max. 0.30	%m/m

Calculated values are highlighted in grey. Values indicated by X were not determined. [a] Min. 25 mm or min. 18 mm for naphthalene content < 3.0 %v/v.

Based on the binary blends, one multiblend (No. 1) containing all three binary blends and therefore all the available synthetic fuels, and three multiblends (Nos. 2–4), each containing two binary fuel blends, were designed and produced. The assumption, which is confirmed in practice, is that specification-compliant fuels or fuel blends can be mixed with each other in any ratio, producing specification-compliant bends. The corresponding ratios of the binary blends in the multiblends are set out in Tab. 3.

Tab. 3 Blend ratios/ratios of fuels in the multiblends

Multiblend	**Binary blend ratio**		
	BB 1	BB 2	BB 3
No.	[%v/v]	[%v/v]	[%v/v]
1	36.9	49.8	13.3
2	42.6	57.4	0.0
3	0.0	41.7	58.3
4	66.5	0.0	33.5

After producing these multiblends, initially on a laboratory scale of 4 L per multiblend, the relevant physiochemical parameter values were determined to confirm that fuels compliant with the ASTM D7566 specification have been obtained. Tab. 5 to Tab. 8 show that all the multiblends meet all the requirements; specification-compliant semi-synthetic fuel blends can also be produced from several different synthetic fuels.

Multiblends were produced on a pilot plant scale for No 1 and No 2 (900 L each) and No 3 and No 4 (400 L each). For this purpose, type TA 950-A2 tank depots of the German Armed Forces were used. The fuels were transferred to the tank depots by a drum pump (EX50, made by Piusi S.p.A.). The quantity of fuel was measured with a digital flow meter (K24 ATEX, made by Piusi S.p.A.). The fuel blends were homogenized by circulation; this involved pumping the fuel in from the bottom via pipes and returning it to the tanks via the filler neck. Tab. 4 shows the blend ratios achieved.

Tab. 4 Absolute quantities and ratios of the individual components in the multiblends on a pilot plant scale

Multiblend	Composition of the blends							
	JET A-1		HEFA		SIP		ATJ	
No.	[L]	[%]	[L]	[%]	[L]	[%]	[L]	[%]
1	676	75.0	150	16.6	45	5.0	30	3.3
2	676	75.1	172	19.1	52	5.8	0.0	0.0
3	325	81.3	0.0	0.0	17	4.2	58	14.5
4	247	61.6	120	29.9	0.0	0.0	34	8.5

A comparison of the physiochemical parameter values of the blends produced on a laboratory scale and the blends produced on a pilot plant scale shows good agreement (Tab. 5 to Tab. 8). Slight fluctuations in the values can be explained by the higher dosing accuracy in the laboratory and the repeatability of the procedures. Furthermore, a comparison with the calculated parameter values (Tab. 5 to Tab. 8) shows that, as for binary blends, the parameter values of density, acid number, net heat of combustion, total sulfur, existent gum and viscosity can also be calculated with good accuracy for multiblends consisting of one fossil and several synthetic components.

At the start and end of the six-month storage period, samples were taken from each fuel blend and the relevant parameter values were sampled to detect any changes in fuel quality. In addition, samples at different fuel levels were periodically examined during the storage period to rule out the unlikely occurrence of deblending.

When comparing the physiochemical parameter values of the fuel blends (Tab. 5 to Tab. 8) determined before and after storage, no changes in terms of the repeatability of the measurement methods were identified. No change in fuel quality was observed.

Tab. 5 Physiochemical properties of multiblend No 1
The aromatics and naphthalene content of the blend was only calculated and entered once (highlighted in grey).

Property	Calculated	Laboratory	Pilot plant before storage	Pilot plant after storage	Requirement according to ASTM D 7566	
	Value	Value	Value	Value	Value	Unit
Acid number	0.003	X	0.002	0.002	max. 0.10	mg KOH / g
Aromatics content	12.0				8–25	%v/v
Distillation curve						
Initial boiling point	163.3	159.7	161.3	160.5	Report	°C
10 %v/v	180.4	177.9	178.1	177.8	max. 205	°C
50 %v/v	202.0	202.6	202.3	202.6	Report	°C
T50–T10	21.6	24.7	24.2	24.8	min. 15	°C
90 %v/v	228.8	233.7	233.0	233.4	Report	°C
T90–T10	48.4	55.8	54.9	55.6	min. 40	°C
Final boiling point	250.6	254.4	248.6	252.7	max. 300	°C
Distillation residue	1.1	1.2	1.2	1.2	max. 1.5	%v/v
Distillation loss	0.9	0.9	1.1	1.0	max. 1.5	%v/v
Flash point	X	48.5	48.0	47.0	min. 38	°C
Density at 15 °C	797.9	798.0	797.9	798.0	775–840	kg / m³
Freezing point	X	-63.8	-63.4	-63.4	max. -47	°C
Lubricity (WSD)	X	0.671	0.618	0.616	max. 0.85	mm
Viscosity [−20 °C]	4.455	4.385	4.365	4.355	max. 8	mm² / s
Viscosity [−40 °C]	9.071	8.817	8.753	8.862	max. 12	mm² / s
Existent gum	1.2	< 1	< 1	< 1	max. 7	mg / 100 ml
Thermal stability						
VTR color code	X	1	1	1	< 3	Rating
Pressure drop	X	0	0	0	max. 25	mmHg
Net heat of combustion	43.412	43.400	43.400	43.400	min. 42.8	MJ / kg
Copper corrosion	X	1a	1a	1a	max. 1	Rating
Smoke point	X	X	26.8	27.5	Min. 25.0[a]	mm
Naphthalene content	0.182				max. 3.0	%v/v
Total sulfur	0.0018	X	0.0018	0.0019	max. 0.30	%m/m

[a] Min. 25.0 mm or min. 18.0 mm for naphthalene content < 3.0 %v/v.

Tab. 6 Physiochemical properties of multiblend No 2
The aromatics and naphthalene content of the blend was only calculated and entered once (highlighted in grey).

Property	Calculated	Laboratory	Pilot plant before storage	Pilot plant after storage	Requirement according to ASTM D 7566	
	Value	Value	Value	Value	Value	Unit
Acid number	0.003	X	0.002	0.002	max. 0.10	mg KOH / g
Aromatics content	12.0				8–25	%v/v
Distillation curve						
Initial boiling point	163.2	159.4	160.3	159.8	Report	°C
10 %v/v	180.5	177.8	177.3	177.5	max. 205	°C
50 %v/v	202.8	203.9	203.7	203.7	Report	°C
T50–T10	22.3	26.1	26.4	26.2	min. 15	°C
90 %v/v	230.1	234.3	234.3	234.2	Report	°C
T90–T10	49.5	56.5	57.0	56.7	min. 40	°C
Final boiling point	250.3	251.4	251.1	252.6	max. 300	°C
Distillation residue	1.1	1.2	1.2	1.2	max. 1.5	%v/v
Distillation loss	0.9	0.9	1.1	1.0	max. 1.5	%v/v
Flash point	X	48.0	47.5	47.0	min. 38	°C
Density at 15 °C	797.8	798.1	797.9	797.9	775–840	kg / m^3
Freezing point	X	-62.4	-61.9	-62.0	max. -47	°C
Lubricity (WSD)	X	0.667	0.616	0.607	max. 0.85	mm
Viscosity [−20 °C]	4.468	4.394	4.402	4.369	max. 8	mm^2 / s
Viscosity [−40 °C]	9.143	8.842	8.884	8.871	max. 12	mm^2 / s
Existent gum	1.2	< 1	< 1	< 1	max. 7	mg / 100 ml
Thermal stability						
VTR color code	X	1	1	1	< 3	Rating
Pressure drop	X	0	0	0	max. 25	mmHg
Net heat of combustion	43.416	43.402	43.401	43.402	min. 42.8	MJ / kg
Copper corrosion	X	1a	1a	1a	max. 1	Rating
Smoke point	X	X	26.3	27.8	Min. 25.0[a]	mm
Naphthalene content	0.182				max. 3.0	%v/v
Total sulfur	0.0018	X	0.0019	0.0019	max. 0.30	%m/m

[a] Min. 25.0 mm or min. 18.0 mm for naphthalene content < 3.0 %v/v.

Tab. 7: Physiochemical properties of multiblend No 3
The aromatics and naphthalene content of the blend was only calculated and entered once (highlighted in grey).

Property	**Calculated**	**Laboratory**	**Pilot plant before storage**	**Pilot plant after storage**	**Requirement according to ASTM D 7566**	
	Value	**Value**	**Value**	**Value**	**Value**	**Unit**
Acid number	0.003	X	0.003	0.002	max. 0.10	mg KOH / g
Aromatics content	13.0				8–25	%v/v
Distillation curve						
Initial boiling point	165.8	163.2	165.1	163.9	Report	°C
10 %v/v	182.4	179.6	180.3	179.7	max. 205	°C
50 %v/v	200.0	199.5	199.4	199.3	Report	°C
T50–T10	17.6	19.9	19.1	19.6	min. 15	°C
90 %v/v	223.5	230.1	230.6	229.7	Report	°C
T90–T10	41.1	50.5	50.3	50.0	min. 40	°C
Final boiling point	251.3	253.8	253.5	252.2	max. 300	°C
Distillation residue	1.1	1.2	1.2	1.2	max. 1.5	%v/v
Distillation loss	0.8	0.9	0.9	1.0	max. 1.5	%v/v
Flash point	X	48.5	49.0	48.5	min. 38	°C
Density at 15 °C	802.1	802.4	802.2	802.2	775–840	kg / m³
Freezing point	X	-84.2	-84.2	-84.3	max. -47	°C
Lubricity (WSD)	X	0.673	0.611	0.602	max. 0.85	mm
Viscosity [−20 °C]	4.542	4.448	4.452	4.442	max. 8	mm² / s
Viscosity [−40 °C]	9.176	8.914	8.940	8.885	max. 12	mm² / s
Existent gum	1.1	< 1	< 1	< 1	max. 7	mg / 100 ml
Thermal stability						
VTR color code	X	1	1	1	< 3	Rating
Pressure drop	X	0	0	0	max. 25	mmHg
Net heat of combustion	43.337	43.330	43.331	43.328	min. 42.8	MJ / kg
Copper corrosion	X	1a	1a	1a	max. 1	Rating
Smoke point	X	X	24.4	24.5	Min. 25.0[a]	mm
Naphthalene content	0.197				max. 3.0	%v/v
Total sulfur	0.0019	X	0.0019	0.0018	max. 0.30	%m/m

[a] Min. 25.0 mm or min. 18.0 mm for naphthalene content < 3.0 %v/v.

Tab. 8: Physiochemical properties of multiblend No 4
The aromatics and naphthalene content of the blend was only calculated and entered once (highlighted in grey).

Property	**Calculated**	**Laboratory**	**Pilot plant before storage**	**Pilot plant after storage**	**Requirement according to ASTM D 7566**	
	Value	**Value**	**Value**		**Value**	**Unit**
Acid number	0.002	X	0.002	0.002	max. 0.10	mg KOH / g
Aromatics content	9.9				8–25	%v/v
Distillation curve						
Initial boiling point	158.3	158.7	159.0	159.1	Report	°C
10 %v/v	175.2	174.7	174.2	174.7	max. 205	°C
50 %v/v	198.9	198.8	198.8	199.0	Report	°C
T50–T10	23.6	24.1	24.6	24.3	min. 15	°C
90 %v/v	229.1	232.4	232.2	232.6	Report	°C
T90–T10	53.9	57.7	58.0	57.9	min. 40	°C
Final boiling point	251.3	252.6	251.2	253.0	max. 300	°C
Distillation residue	1.1	1.2	1.2	1.2	max. 1.5	%v/v
Distillation loss	0.9	1.0	1.0	1.0	max. 1.5	%v/v
Flash point	X	46.0	45.5	45.5	min. 38	°C
Density at 15 °C	789.1	789.5	789.0	789.0	775–840	kg/m^3
Freezing point	X	-57.2	-57.0	-57.0	max. -47	°C
Lubricity (WSD)	X	0.698	0.655	0.665	max. 0.85	mm
Viscosity [–20 °C]	4.178	4.123	4.198	4.112	max. 8	mm^2/s
Viscosity [–40 °C]	8.287	8.139	8.142	8.149	max. 12	mm^2/s
Existent gum	1.4	< 1	1.2	< 1	max. 7	mg / 100 ml
Thermal stability						
VTR color code	X	< 1	1	1	< 3	Rating
Pressure drop	X	0	0	0	max. 25	mmHg
Net heat of combustion	43.545	43.521	43.525	43.527	min. 42.8	MJ / kg
Copper corrosion	X	1a	1a	1a	max. 1	Rating
Smoke point	X	X	28.7	28.3	Min. 25.0[a]	mm
Naphthalene content	0.150				max. 3.0	%v/v
Total sulfur	0.0016	X	0.0016	0.0016	max. 0.30	%m/m

[a] Min. 25.0 mm or min. 18.0 mm for naphthalene content < 3.0 %v/v.

In the samples taken periodically at different fuel levels, the densities of the fuel blends are also unchanged (Tab. 9). There are also no relevant differences in the determined distillation curves. As expected, separation of the multiblends can therefore be ruled out.

Tab. 9 Densities of samples of multiblend Nos. 1–4 (in kg/m^3)
Taken at different fuel levels over the course of the storage period.

Month/year of sampling	**04 / 18**	**05 / 18**	**06 / 18**	**06 / 18**	**06 / 18**	**07 / 18**	**08 / 18**	**09 / 18**	**10 / 18**	**10 / 18**	**10 / 18**
Sampling level	Middle	Middle	Top	Middle	Bottom	Middle	Middle	Middle	Top	Middle	Bottom
No. 1	797.9	798.0	798.0	798.0	798.0	798.0	798.0	798.0	798.0	798.0	798.0
No. 2	797.9	797.9	797.9	797.9	797.9	797.9	797.9	797.9	797.9	797.9	797.9
No. 3	802.2	802.2	802.2	—*	802.2	802.2	802.3	802.3	802.2	—*	802.2
No. 4	789.0	789.0	789.0	—*	789.0	788.9	789.0	789.0	789.0	—*	789.1

* Not determined.

3.2 Climate chamber investigations

The aim of the climate chamber investigations was to demonstrate that changing climatic conditions have no influence on the properties and therefore no influence on the fuel quality of semi-synthetic fuel blends. Another type of HEFA, the High-Freezing-Point (HFP)-HEFA (see section 2.2) was included in the investigation at this stage. The quaternary multiblend No. 1 and a binary blend consisting of JET A-1 with the highest possible ratio of HFP-HEFA were stored in a climate chamber for this purpose. HFP-HEFA undergoes a milder hydroisomerisation step than HEFA during refining, so that HFP-HEFA has higher-boiling paraffins compared to HEFA or kerosene. HFP-HEFA is more similar to diesel fuel than kerosene and exhibits poorer low-temperature properties, e.g. due to the formation of precipitates at low temperatures.

For the climate chamber investigations, the maximum possible blend ratio for the HFP-HEFA/JET A-1 binary blend first had to be determined, which in particular complies with the requirements of ASTM D7566 for the freezing point and the viscosities at −20 °C and −40 °C. As can be seen in Fig. 3, blends with up to 20 %v/v HFP-HEFA meet these requirements. The values of the viscosities and freezing point are below the upper specification limit (Fig. 3; limit values are shown as red lines). The density requirement is met for all blend ratios (Fig. 3; the minimum and maximum limit values are shown as red lines). All the determined physiochemical parameter values of the 20 %v/v blend are set out in Tab. 10.

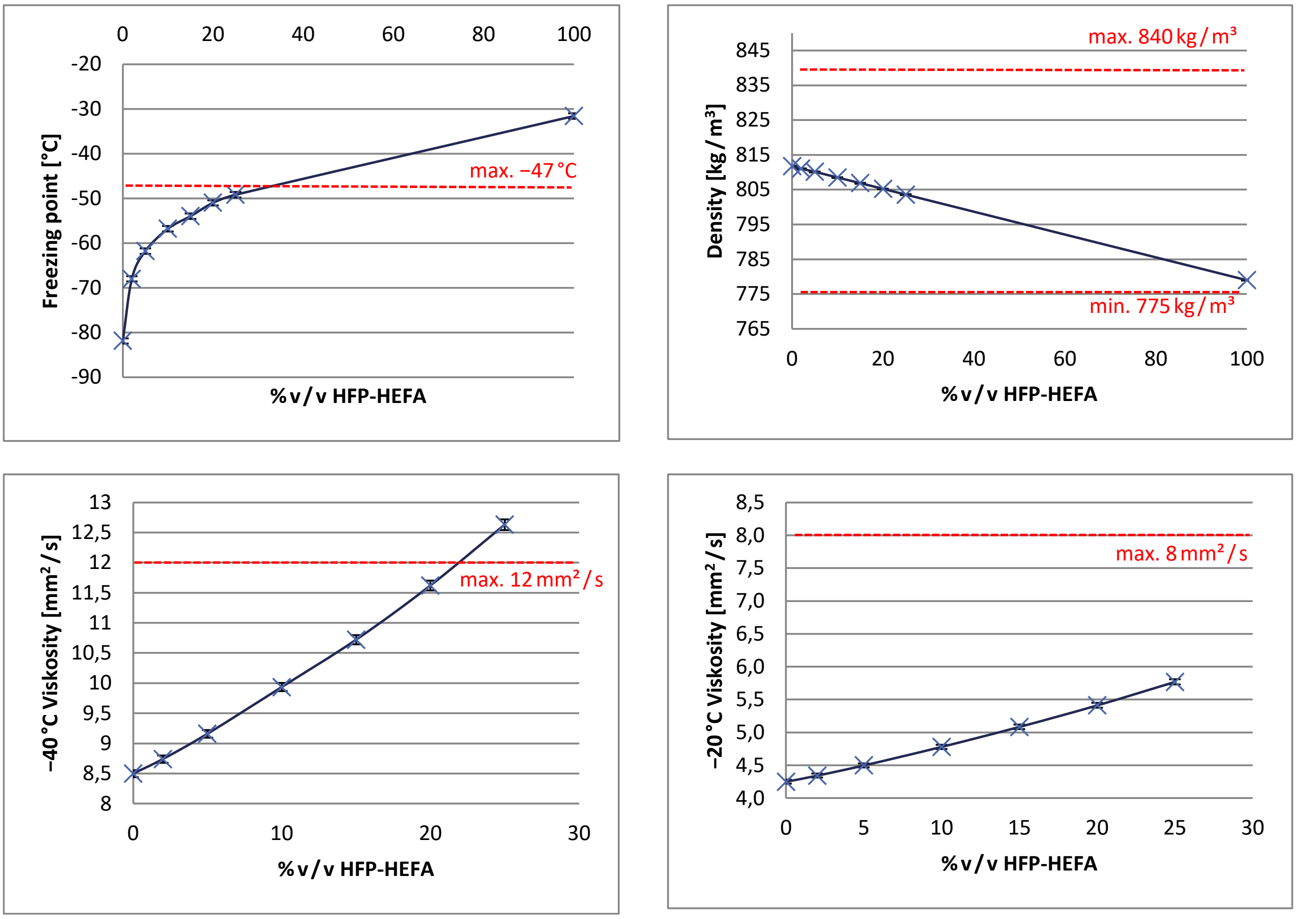

Fig. 3 Freezing points, densities and viscosities of binary HFP-HEFA/JET A-1 blends

In the climate chamber, the quaternary multiblend (No. 1) and a blend consisting of 20 %v/v HFP-HEFA and 80 %v/v JET A-1 were each subjected to ten cycles of 12 hours at −47 °C and then 12 hours at 47 °C alternately. The physiochemical parameter values were then determined and compared with the parameter values before storage to investigate the influence of the changing climatic conditions on the fuel quality. The densities were also determined at different fuel levels after the end of storage to rule out deblending.

A comparison of the physiochemical parameter values of the fuel blends before and after the climate chamber investigations (Tab. 10) shows that there are no changes to the values within the accuracy of measurement. Consequently, changing climatic conditions have no influence on the fuel properties; the fuel quality is not negatively affected. The determination of the density at different fuel levels also shows no changes; crystallisation of long-chain paraffins or separation due to changing temperatures was not observed.

Tab. 10 Physiochemical properties of multiblend No. 1 and a 20 %v/v HFP-HEFA blend before and after the climate chamber tests
The aromatics and naphthalene content was only calculated and entered once in each case (highlighted in grey).

Property	Multiblend No. 1 before climate chamber	Multiblend No. 1 after climate chamber	20 %v/v HFP-HEFA/ 80 %v/v JET A-1 before climate chamber	20 %v/v HFP-HEFA/ 80 %v/v JET A-1 after climate chamber	Requirement according to ASTM D 7566	
	Value	Value	Value	Value	Value	Unit
Acid number	0.002	0.003	0.002	0.003	max. 0.10	mg KOH / g
Aromatics content	12.0		12.8		8–25	%v/v
Distillation curve						
Initial boiling point	161.3	159.7	159.7	161.9	Report	°C
10 %v/v	178.1	177.3	183.7	183.6	max. 205	°C
50 %v/v	202.3	202.5	211.1	211.1	Report	°C
T50–T10	24.2	25.2	27.4	27.5	min. 15	°C
90 %v/v	233.0	233.4	274.0	273.4	Report	°C
T90–T10	54.9	56.1	90.3	89.8	min. 40	°C
Final boiling point	248.6	252.0	289.4	289.3	max. 300	°C
Distillation residue	1.2	1.2	1.3	1.3	max. 1.5	%
Distillation loss	1.1	1.0	1.2	1.1	max. 1.5	%
Flash point	48.0	48.0	49.5	50.5	min. 38	°C
Density at 15 °C	797.9	798.0	805.2	805.2	775–840	kg / m^3
Freezing point	-63.4	-63.4	-50.9	-50.8	max. -47	°C
Lubricity (WSD)	0.618	0.653	0.634	0.660	max. 0.85	mm
Viscosity [−20 °C]	4.365	4.352	5.436	5.428	max. 8	mm^2 / s
Viscosity [−40 °C]	8.753	8.806	11.68	11.67	max. 12	mm^2 / s
Existent gum	< 1	1.2	2.8	3.7	max. 7	mg / 100 ml
Thermal stability						
VTR color code	1	1	1	1	< 3	Rating
Pressure drop	0	0	0	0	max. 25	mmHg
Net heat of combustion	43.400	43.399	43.566	43.386	min. 42.8	MJ / kg
Copper corrosion	1a	1a	1a	1a	max. 1	Rating
Smoke point	26.8	26.3	25.7	25.8	Min. 25.0[a]	mm
Naphthalene content	0.182		0.194		max. 3.0	%v/v
Total sulfur	0.0018	0.0018	0.0017	0.0018	max. 0.30	%m/m

[a] Min. 25.0 mm or min. 18.0 mm for naphthalene content < 3.0 %v/v.

3.3 Summary

In the course of the pre-investigations, it was shown that semi-synthetic specification-compliant jet fuels in accordance with ASTM D7566 can be produced from several different synthetic fuels. A number of physiochemical parameter values of multicomponent blends can be calculated with good precision, provided that the parameter values of the neat blend components and the blend ratio are known. The physiochemical parameter values determined in the laboratory match the calculated values. Over a storage period of 6 months, there is no separation or change in properties; the quality of the semi-synthetic fuel blends was not reduced by six months of storage.

It was also demonstrated that HFP-HEFA can be used to produce a specification-compliant blend with up to 20 %v/v HFP-HEFA. Investigations of the quaternary multiblend No. 1 and a binary blend consisting of 20 %v/v HFP-HEFA and JET A-1 showed that changing climatic conditions had no effect on the fuel properties.

4 Demonstration of production, supply and use of multiblend JET A-1 at an airport.

DEMO-SPK included producing a multiblend JET A-1 and demonstrating its use in a real airport infrastructure. Due to existing regulations, the multiblend could not be produced directly at the airport. In addition, agreement had to be reached on the multiblend composition and on a procedure for blending and transport to the destination that complied with the regulations. The supply of all the blending components, the production of the multiblend JET A-1 (section 4.1) and the logistics for use of the multiblend JET A-1 at Leipzig/Halle Airport (LEJ) (section 4.2) are discussed below. A summary of all the necessary regulatory approvals and legally required transport documents (section 4.3) is also provided, as well as a conclusion regarding demonstration of the production, supply and use of multiblend JET A-1 at an airport (section 4.4).

4.1 Supply of the components and production of the multiblend JET A-1

Fig. 4 illustrates the supply chain schematically. Different transport methods and routes were chosen for the different kerosenes. This is due to the fact that the kerosenes were produced at different locations (section 4.1.1). The fossil kerosene was transported to the blending site by tank car via rail (section 4.1.5). The renewable kerosenes were delivered in ISO tank containers (section 4.1.2) by sea to the Port of Hamburg and onwards (partly via a container terminal) to the blending site (section 4.1.3). See section 4.1.4 for the blending procedure. After blending, the multiblend JET A-1 was loaded back into tank car and transported by rail to LEJ Airport.

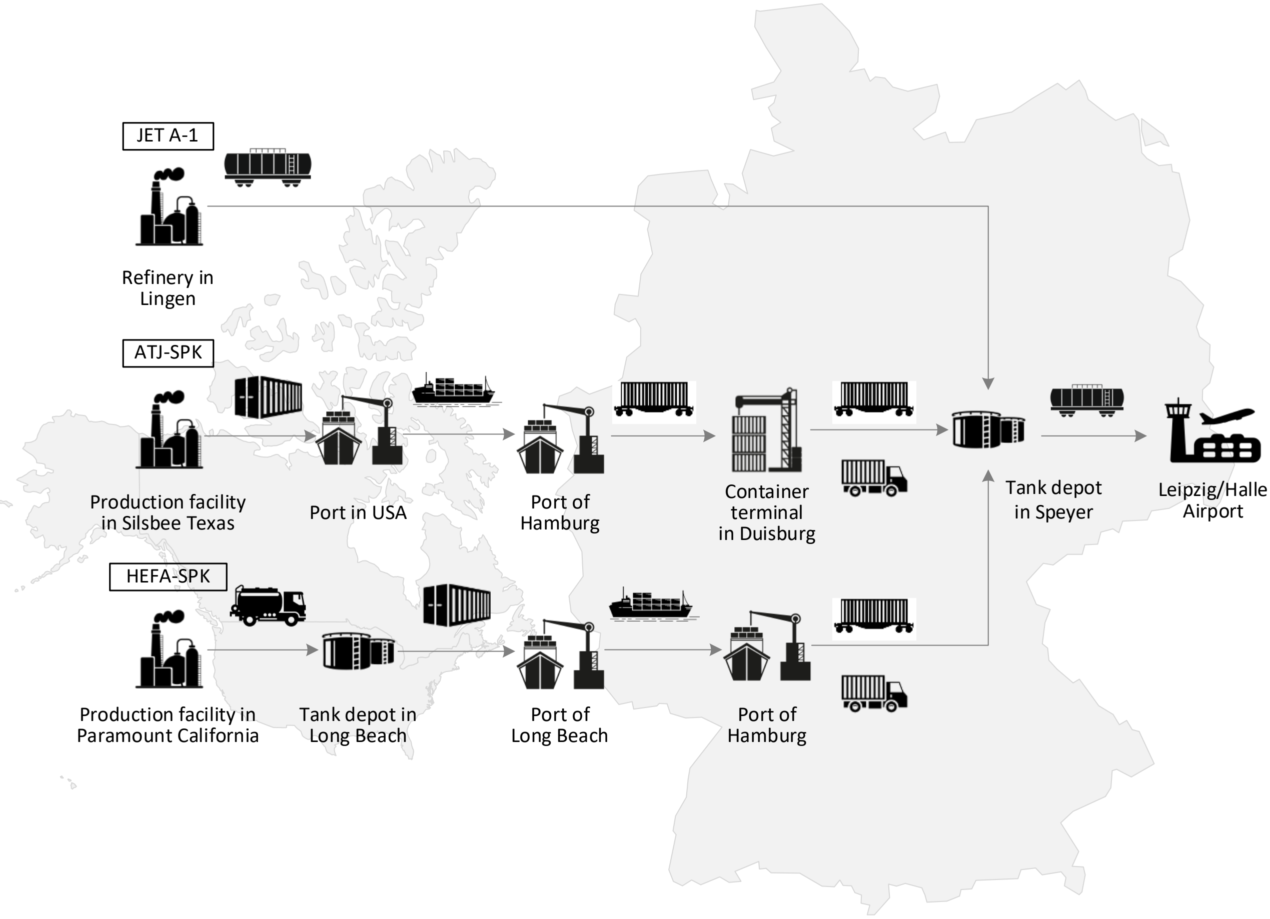

Fig. 4 Simplified schematic of the supply chain implemented to supply the multiblend JET A-1 to LEJ Airport

4.1.1 *Fuel production*

The HEFA-SPK and ATJ-SPK renewable kerosenes used for the demonstration are described in sections 2.1 and 2.3. Once it was decided to demonstrate the multiblend JET A-1 at LEJ Airport at DHL/EAT and to measure comparative emissions with and without renewable kerosene fractions, it was necessary to use the same fossil JET A-1 for blending as is used by DHL at LEJ Airport. This ultimately had to be used for the reference measurements, otherwise the comparison of the emissions would have been distorted by the differences in the fossil kerosenes.

DHL's supplier during the DEMO-SPK project was BP Europa SE. The decision to obtain the conventional kerosene for the pre-investigations and the demonstration from one refinery (in this case, the Lingen refinery) meant that it was possible to ensure almost constant and comparable fuel quality. See section 4.2.2 for the other logistics conditions that have been met.

4.1.2 *Container logistics*

Relative to the total quantity of multiblend JET A-1 produced, the synthetic components took up a comparatively small ratio. Tank containers were a useful means of supplying these quantities at the blending site. It was expected that they would be more flexible to handle as compared to tank cars and ship tanks. To make rail and road transport easier, particular attention was paid to the compatibility of the tank containers with European standards (dimensions, couplings, and loading parameters).

The purchased ATJ-SPK was shipped directly to the Port of Hamburg in two ISO tank containers. The fuel arrived in Germany at the beginning of July 2018 and was temporarily stored in a customs warehouse. When the blending process started, the containers were released for free circulation and brought to the tank depot under suspension of energy duty (section 4.3.4).

The HEFA-SPK could not be supplied directly from the refinery into tank containers because of a lack of infrastructure. The ordered quantity was therefore first transferred into tank trucks. The trucks were driven to a tank depot close to the refinery for transfer into tank containers. A total of 11 tank containers were taken to the Port of Long Beach and loaded onto a container ship bound for the port of Hamburg. The tank containers were released directly for free circulation at the port and taken to the tank depot.

4.1.3 *Blending site*

The requirements for the blending site were defined by external constraints.

a. Producing the kerosene blends at a refinery site is the simplest and most reliable procedure, especially if the refinery produces both fossil and renewable kerosene. In the specific case, however, it was necessary to take account of the fact that, as emissions were being measured as part of DEMO-SPK, the fossil kerosene from the Lingen refinery had to be used (section 4.2).

b. The kerosene supply to LEJ Airport is exclusively conducted by rail, which is why the multiblend JET A-1 had to be loaded to rail.

c. To avoid contamination with other fuels, dedicated JET A-1 pipes and experience in handling JET A-1 at the blending site had to be demonstrated.

d. Since ASTM D7566 only allows blending of the individual synthetic kerosenes one after the other, it had to be possible to store the material in a tank between the blending processes. There also had to be a mixing device in the tank to ensure sufficient blending.

Kerosene tanks do not normally have a blending device and, for the purposes of DEMO-SPK, the use of diesel blending tanks was out of the question because of the risk of contamination with FAME. Both, building a new blending tank and using an inland waterway vessel, were considered as options in the market survey and ultimately rejected because of the time required and particularly the considerable financial cost. Finally, a suitable tank depot was sought where storage of containers, storage and removal of rail tank cars and storage and blending of a multiblend JET A-1 were possible. These criteria were met by the TanQuid GmbH & Co KG tank depot in Speyer. The infrastructure of the tank depot was adapted to the blending task and a blending device was installed in a spherical tank that had been flushed several times.

4.1.4 *Blending procedure*

A major challenge was that the current specifications for blends with synthetic kerosene are designed for the production of binary blends. Producing multiblends consisting of several synthetic kerosenes with fossil kerosene is not explicitly regulated. The regulations only take into account the fact that, after producing a binary mixture, a second mixing may then be done. This case is explicitly allowed.[4] In this case, however, blending with the various alternative kerosenes is done with one kerosene after the other; simultaneous blending with several alternative kerosenes is not regulated.

In order to remain securely within the applicable regulations, the synthetic kerosenes were blended with the fossil kerosene one after the other during production of the multiblend JET A-1 for LEJ Airport and a sample was taken after each blending process. The higher cost associated with this approach was accepted to ensure formal compliance with the specification.

As part of the pre-investigations, binary blends were first produced for each synthetic kerosene and the maximum acceptable ratio of renewable kerosene for the binary blend was determined. The ratios of these binary blends for the multiblends with two and three synthetic components were then defined (section 3.1). This then also produced the target ratio for the multiblend JET A-1, on the basis of which the quantities of the individual synthetic kerosenes for the main investigation were determined and ordered. Positive interactions between the individual synthetic kerosenes were not taken into account. This resulted in a lower renewable kerosene ratio in the multiblend JET A-1 than would have been theoretically possible.

The quantities originally ordered for the main investigation were as follows: (i) 11 containers of HEFA-SPK, (ii) 3 containers of SIP and (iii) 2 containers of ATJ-SPK.

These synthetic fuels were originally to be blended with 1,130 m^3 of fossil kerosene, which would have resulted in a total quantity of multiblend JET A-1 of about 1,500 m^3.

As SIP was unavailable, the amount of synthetic fuel was reduced to 11 containers of HEFA-SPK and 2 containers of ATJ-SPK. This quantity was not changed and could not have been changed at this point, as the logistical preparations had already been completed and, in the case of ATJ-SPK, the product was already on its way to Germany. The quantity of fossil kerosene that was required was reduced to about half. This reduction was so large because SIP may be mixed with kerosene at a maximum ratio of 1:9 (i.e. a maximum ratio of 10 vol.-%), and the lack of 75 m^3 of SIP therefore meant that 675 m^3 of fossil kerosene was no longer needed.

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[4] ASTM D7566, Section 1.2.1; DEF STAN 91-091 Issue No. 10 dated September 2018, Annex B, Section B.1.3.

The containers used by World Energy and Gevo each had a volume of approx. 23 m³. In total, the following approximate blended volumes for the demonstration can be stated: (i) 247 m³ of HEFA-SPK, (ii) 46 m³ of ATJ-SPK and (iii) 472.5 m³ of fossil kerosene from the Lingen refinery[5].

4.1.5 *Rail logistics*

Fuels for flight operations can only be transferred to the DHL Hub Leipzig tank depot via tank cars (rail vehicles). The tank cars used to transport kerosene are typically special vehicles with an interior coating to prevent contamination of the transported product. Some refineries also require at least one JET A-1 pre-load. Normally, tank cars of this kind are not provided on a short-term basis, but are leased long-term.

For the DEMO-SPK project, a set of 22 tank cars was leased for a few months. They were for the planned transport of a total of 1,500 m³ of multiblend JET A-1, the retention of about 160 m³ of flushing kerosene (for the tank depot's pipes) plus a reserve tank car. The later adjustment of the multiblend composition (section 4.1.4) led to a reduction in the required number of tank cars to 16.

4.2 Logistics for using the multiblend JET A-1 at LEJ Airport

The investigations at LEJ Airport had the following objectives:

a. Demonstration of the compatibility of a multiblend JET A-1 with the real supply infrastructure of an airport.
b. Comparative emission measurements on an aircraft turbine as a ground run to investigate the influence of renewable kerosene on local emissions (section 5).

These two objectives of the project required very different logistical approaches to supply the multiblend JET A-1. While the first objective required the multiblend JET A-1 to be treated in the same way as fossil kerosene and therefore necessarily allowed it to mix with other kerosene batches in the tank depot, the second objective required the fuels to be separated by type.

4.2.1 *Local conditions*

A main line leads from the unloading facility at the airport fuel depot to the high tanks, which is connected to the refuelling facility of the DHL Hub. The tanks are used to fill the airport tank trucks used at the airport; direct transfer of the product from the (rail) tank car to the airport tank trucks is not possible. The aircraft are supplied on the tarmac by the airport tank trucks.

It is possible to completely empty the single high tanks of the tank depot so that there is no blending with a previous product in the tank itself. The pipes leading to the high tanks and the refuelling system cannot be emptied with reasonable effort, but are always filled with the product of the previous delivery.

4.2.2 *Procedure*

To ensure that the pipe content between the unloading station and the tank was filled with Lingen product, fossil kerosene from the Lingen refinery was preloaded in each case before the multiblend JET A-1 and the reference kerosene from Lingen were stored. This avoided blending the fuel with other previous supplies with unpredictable properties. The effect of residual fuel in the pipes was thereby limited to an unavoidable but minimal reduction in the renewable kerosene content of the multiblend JET A-1. The flushing kerosene was stored in a high tank not relevant to the project.

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[5] This is the amount of fossil kerosene that actually went into the mixture. This does not include kerosene purchased as flushing kerosene or as backup in reserve.

The multiblend JET A-1 and the fossil reference fuel from Lingen were transferred at different times into high tanks that had previously been emptied and assigned exclusively to these products. From each of these tanks, a previously emptied and rinsed airport tank truck was filled and assigned to the emission measurements. These fillings were scheduled so that the residual content from the pipes between the tank depot and the airport tank truck refuelling station, estimated on the basis of the volume of the pipe and the pumping rate, had already been filled into other vehicles.

The comparative emission measurements were carried out with the content of the two airport tank trucks. This was how both of the above mentioned project objectives were achieved. The remaining quantities of multiblend JET A-1 and reference kerosene from Lingen were tanked and flown out on DHL aircraft as per routine procedures.

4.2.3 *Emission measurements*

EAT provided an aircraft (Airbus A300/600) and the engine test run facility for the emission measurements on the LEJ Airport site. The aircraft was defuelled on arrival and filled with Lingen product from the assigned airport tank truck. For safety reasons, refuelling could not be carried out in or in front of the engine test run facility, which is why sampling was only first possible from the aircraft tank. For this purpose, a small amount of fuel was taken from the wing tank into a metal canister, which was rinsed three times and then filled with a fuel sample of about 10 L. This sample, together with the sample taken from the high tank, showed the initial state for the emission measurements. After the emissions measurement for the Lingen product was complete, the aircraft was moved from the engine test run facility to a parking position, where it was defuelled by airport tank truck and refuelled using the multiblend airport tank truck. Back at the engine test run facility, the wing tank was sampled again and the emission measurements were carried out (section 5).

The aim of the logistical operations at Leipzig/Halle Airport was, firstly, to provide a reference kerosene that was as similar as possible to the fossil kerosene that was used for blending and, secondly, to supply the multiblend with as little change as possible and only allow limited dilution of the biokerosene content by a kerosene that was as similar as possible to the fossil kerosene used for blending. As Tab. 11 shows, this was successful.

Tab. 11 compares the reference kerosene to the kerosene used for blending. The properties of the two kerosenes are largely identical within the range of normal measurement inaccuracies, except for water content and MSEP rating, where the fact that the sample was taken from the aircraft tank probably had an effect. (Aircraft tanks have openings for pressure equalisation and are therefore not completely sealed off from the outside air. The presence of minute amounts of water in aircraft tanks is therefore normal).

Tab. 11 also compares the multiblend in the aircraft tank with the original multiblend, the fossil kerosene used to produce the multiblend and the reference kerosene. The properties of the multiblend taken from the aircraft tank very largely match those of the original multiblend and the deviations are predominantly in the direction of the properties of the fossil kerosenes. For the water content and MSEP rating, it is once more the case that the conditions inside the aircraft tank probably had an effect.

Tab. 11 Properties of the multiblend JET A-1 and reference kerosene JET A-1 from Lingen

Property	Unit	Multiblend JET A-1 from aircraft tank	Multiblend JET A-1 original	Reference kerosene JET A-1 from aircraft tank	Fossil JET A-1 contained in multiblend
Colour (Saybolt)		+30	+30	+30	+30
Acid count	mg KOH/g	0.003	0.003	0.003	0.003
Aromatics content	Vol.-%	9.9%	9.5%	15.5%	14.6%
Olefins	Vol.-%	<0.5	<0.5	<0.5	<0.5
Total sulfur	m-%	0.0099	0.0028	0.0027	0.0029
Sulfur, mercaptan	m-%	<0.0003	<0.0003	<0.0003	<0.0003
Initial boiling point	°C	152.3	150.3	152.1	150.2
10% recovered	°C	168.6	168.3	170.7	170.5
50% recovered	°C	192.2	191.9	193.7	193.2
90% recovered	°C	231.4	231.1	225.9	225.1
Final boiling point	°C	256	254.6	257.8	253.4
Distillation residue	% (v/v)	1.2	1.2	1.1	1.1
Distillation loss	% (v/v)	0.8	0.5	0.7	0.6
Flash point	°C	42	42.5	42	42.5
Density at 15 °C	kg/m³	787.2	788.2	808.8	808.6
Freezing point	°C	-58.2	-57.9	-72.6	-78.3
Viscosity [−20 °C]	cSt	3.753	3.712	3.872	3.779
Net heat of combustion	MJ/kg	43.527	43.521	43.187	43.202
Smoke point	mm	30	30	24	24
Naphthalene content	Vol.-%			0.28	0.3
Hydrogen content	m-%	14.3	14.29	13.72	13.75
Copper corrosion		1	1	1	1
Pressure drop	mmHg	1	1	1	1
Deposits		0	0	0	0
Existent gum	mg/100 ml	<1	<1	<1	2
Water content	mg/kg	50	25	50	5
Interface rating		1b	1b	1b	1b
Water separation (MSEP)		95	98	86	98
FAME control	mg/kg	<5	<5	<5	<5
Lubricity (BOCLE)	mm	0.68	0.66	0.68	0.67
Viscosity [−40 °C]	cSt	7.099	7.109	7.302	7.249

4.3 Official permits and transport documents

The relevant official permits and transport documents for supplying multiblend JET A-1 of different compositions are outlined below and how they were used in DEMO-SPK is explained with reference to the statutory provisions.

4.3.1 *REACH registration or PPORD*

According to the EU Chemicals Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), all chemicals placed on the market in the European Community must be registered if the quantity of the substance placed on the market within one year exceeds one tonne. The obligated party is the party placing the product on the market, i.e. typically the producer in case of the production within the EU or the importer for import of the good. The requirements for the documents to be provided for registration increase depending on the quantity placed on the market (up to 10 t, up to 100 t, up to 1,000 t, and greater than 1,000 t).

In principle, every producer must register its product itself. For chemically similar substances, however, so-called co-registration is possible, where several producers submit a joint registration and share the costs. This option is used for fossil kerosene, which has a single uniform registration with which all European refineries and kerosene importers comply. The costs of registration are thereby spread over the entire volume of kerosene distributed in Europe (around 50 million tonnes annually) and are just few euro cents when calculated per tonne of kerosene. The product definition underlying this co-registration explicitly limits the product to kerosene produced from fossil crude oil. Renewable or synthetic kerosene must therefore be registered separately. At present, this kind of registration has only been done for HEFA kerosene (by Neste) and for SIP (by Total).

For the DEMO-SPK project, PPORD notifications were submitted to the European Chemicals Agency (ECHA) for renewable kerosenes in accordance with Regulation (EC) No 1907/2006 [Eur06]. This is possible when substances are used for research or development purposes and are not placed on the general market. For the DEMO-SPK project, this condition was met because the individual substances were mixed under the control of the DBFZ and the resulting multiblend JET A-1 was delivered to a single project partner.

4.3.2 *Preparation of the safety data sheets*

Kerosene is classified as a hazardous substance because it is flammable and potentially environmentally hazardous. The classification is based on the CLP Regulation, Annex 1: Classification and labelling requirements for hazardous substances and mixtures [Eur08]. As for all hazardous substances, a safety data sheet has to be prepared for kerosene as well. This applies to both fossil kerosene and renewable kerosene. The requirements for safety data sheets are set out in Article 31 of the EU Chemicals Regulation (EC) No 1907/2006 (REACH Regulation) [Eur06]. For transport of the product to Germany, it is sufficient to carry the manufacturer's safety data sheet, even if the safety data sheet has not been prepared in German. For storage and further processing of a product in Germany, however, a safety data sheet in German is mandatory [Eur06]. As the renewable kerosenes were going to be temporarily stored in Germany and blended into a multiblend JET A-1, a safety data sheet therefore had to be prepared in German and in accordance with the German regulations. A separate safety data sheet also had to be prepared for the subsequent multiblend JET A-1.

The data for the mixture itself must be used as the basis for the safety assessment of the blend properties. If data for the mixture is not available or if reasons according to EC Regulation No 1272/2008 (CLP) point (22) of the recital apply, the data of the individual components must be used as a basis [Eur08].

4.3.3 *Notification of hazardous mixtures*

The competent national body must be notified of hazardous mixtures before they are placed on the market for the first time, in accordance with Article 45 of the CLP Regulation (EC) No 1272/2008. The CLP Regulation specifies properties of substances and mixtures that require them to be classified as "hazardous". The same properties are defined in Section 3(1) of the German Chemicals Act (ChemG). The German Federal Institute for Risk Assessment (BfR) must be informed about these mixtures and their relevant product information (composition, trade names, labelling and their use) in accordance with Section 16e(1) ChemG. The aim is to be able to provide instructions on appropriate measures in the event of an incident, emergency or accident. The information is forwarded to all national poison centres.

For DEMO-SPK, notification was done using a form provided by the BfR. The safety data sheet of the multiblend JET A-1 was also enclosed. In recent years, the system has been switched over and product/mixture notification can now be done electronically.[6]

4.3.4 *Customs registration*

Energy products are liable to energy duty within the fiscal territory (see Section 1 of the German Energy Tax Act (EnergieStG). The energy duty is an excise duty administered by customs. With revenues of around 40 billion euros, the energy duty is the most important source of excise duty revenue for the federal budget [Zol19].

The amount of duty depends on the nature and the use of the energy product. Kerosene falls within the scope of the German Energy Duty Act as a product under subheading 2710 (19 21) of the Combined Nomenclature (CN), which applies to JET A-1. For renewable kerosenes, the nomenclature is not yet unequivocal. The SPKs were ultimately classified under CN subheading 2901 10, as this is the closest to renewable kerosenes. For goods within heading 2901, no amount of tax is specified in Section 2 of the EnergieStG. In accordance with the principle of resemblance under Section 2(4) of the EnergieStG, the SPKs are subject to the same tax as the energy products which they most closely resemble in terms of their purpose and actual nature.

Jet fuel under CN subheading 2710 19 21 may be used in aircraft for aviation purposes, exempt of tax. However, only aviation companies may submit an application under the permit procedure based on Section 27(2) of the EnergieStG. As it was envisaged that there would be immediate transport between the place of import (for the renewable kerosenes, this was the Port of Hamburg) and a tax warehouse as well as between two tax warehouses, the transport could take place under duty suspension in accordance with Section 10(1) No. 1 of the EnergieStG.

In order to be allowed to transport under duty suspension, an application for a permit as a registered consignor for energy products must first be submitted to the competent main customs office (in this case, Dresden). The relevant energy product to be transported must also be stated. Excise Movement and Control System (EMCS) is used for formally processing the movement. EMCS is an electronic procedure that must be used for the movement of goods. For this purpose, the excise number allocated during the application for registered consignor must be recorded in the master data management of the “Directorate-General of Customs” (Generalzolldirektion). This is done via the application for “entry/change of tax number/tax identification number for the internet EMCS application (IEA)” (Antrag auf Erfassung/Änderung der Steuernummer/Steuer-Identifikationsnummer für die Internet-EMCS-Anwendung (IEA)). Participants who do not wish to install the software themselves can use an IT service provider. For this process, an “application for the use of an IT service provider within the framework of EMCS message exchange” (Antrag zur Nutzung eines IT-Dienstleisters im Rahmen des EMCS-Nachrichtenaustauschs) must be submitted to the Directorate-General of Customs.

Product released for free circulation may only be transported under duty suspension to a tax warehouse or to the beneficiary (Section 10(3) EnergieStG). Therefore, the EMCS procedure was initially used for transport of the HEFA-SPK, the fossil kerosene and the multiblend JET A-1. Since the ATJ containers had arrived in Germany well before the planned production of the multiblend JET A-1 and it was not possible to receive them in the Speyer tax warehouse for storage reasons, the ATJ-SPK was handled and imported via a customs warehouse in Duisburg. This is a warehouse where goods may be stored, duty unpaid and untaxed, for 90 days. The goods are registered by customs during a T1 transit procedure. This is a customs transit procedure that is used when goods are to be transported within the EU under suspension of customs clearance and taxation. A T1 declaration is an application for the customs ATLAS system procedure to be applied. After a while, the

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[6] For more information, got to http://www.bfr.bund.de/de/meldung_von_rezepturen-9375.html.

goods were released for free circulation at the Duisburg customs office and the import duties were paid. They were then transported to the blending site, once again using the EMCS procedure.

4.3.5 *Settlement of contributions to the German National Petroleum Stockpiling Agency*

The German National Petroleum Stockpiling Agency (Erdölbevorratungsverband, EBV) was formed in 1978 under the Petroleum Stockholding Act (Erdölbevorratungsgesetz/"ErdölBevG") The aim of this Agency is to secure the energy supply in Germany (Section 1 ErdölBevG) by holding stocks of gasoline, diesel fuel, extra-light heating oil and jet fuel. For this purpose, a specific stockpiling period and a stockpiling volume are defined with reference to the average national demand over 90 days (Section 3(1) ErdölBevG). Importers and producers of petroleum products, provided they are domiciled in the EU and import or produce at least 25 tonnes per calendar year as a commercial enterprise, are compulsory members of the EBV within the meaning of the Act (Section 13(1) ErdölBevG). The blending and processing of petroleum products also constitutes a production process within the meaning of the Act (Section 13(6) ErdölBevG). Members must pay EBV contributions according to the quantities processed or imported (Section 23(1) and (2) ErdölBevG). The contribution rates are announced annually in the Agency's Contribution Statute.

In general, only petroleum products are subject to mandatory stockpiling and contributions. However, biofuels are included in the EBV stockpile that is to be maintained, provided that they do not exceed a maximum ratio of 50 m-% in the blend with mineral products. They are taken into account in the actual stock level if they have been blended with petroleum products in accordance with specification or are intended for corresponding blending (Section 3(5) and Section 4(3)ErdölBevG). There is only a mandatory contribution for biofuels if they are present in blends with a max. 50 m-% ratio of mineral oil-based products. In this case, it is a production process that increases the quantity of the petroleum product (Section 23(4) ErdölBevG); the quantity added is therefore subject to contribution. If the ratio of biofuel in the blend is above 50 m-%, only the petroleum-based component is relevant for the contribution (section 23(4) ErdölBevG). The members must submit a monthly and an annual report on the imported and produced quantities to the EBV.

4.4 Summary

The experience gained in DEMO-SPK from demonstrating the use of a multiblend JET A-1 in practice provides the following conclusions on specific issues:

- *REACH registration of renewable kerosenes.* According to EC Regulation No 1907/2006, every importer or producer of chemical products has to register its products with the European Chemicals Agency via a REACH registration. The costs for registration are calculated depending on quantity imported or produced. Most producers of renewable kerosene are currently smaller companies that are only producing small quantities. The cost of registration would be disproportionately high and would increase the price of fuel prohibitively. In addition, a considerable amount of time is required for registration. The product is therefore transferred at the place of production, which makes the buyer the importer of the product. And the buyer must carry out registration and bear the costs. The time and financial expense for the buyer can only be a barrier to the general supply of renewable kerosenes. The aim should therefore be to implement either a shorter and lower-cost registration or a generic registration for all synthetic aviation fuels based on their ultimate use.
- *Multiblend production in ASTM D7566.* The blending of multiblends is not explicitly regulated in ASTM D7566. It is only possible to determine from the standard that multiblends are allowed. However, this only applies where the individual synthetic components are blended one after the other.

Blending the individual renewable kerosenes one after the other means considerable additional effort in the production of the multiblends in practice, as it involves steps such as: (i) production of a binary blend A, which, according to ASTM D7566-16b section 1.2.1, becomes JET A-1 according to ASTM D1655; (ii) blending of blend A with another renewable component to form blend B; (iii) blending of blend B with another renewable component to form blend C; etc. The settling times and sampling for certification must also be taken into account. In real use, this would mean that no multiblend JET A-1 of different blend compositions is produced. The aim should therefore be to include provisions in ASTM D7566 that allow the production of differently composed multiblends via simultaneous blending of several synthetic kerosenes.

- *Energy duty for synthetic kerosenes.* For synthetic kerosenes according to ASTM D7566, there is no clear provision in the German Energy Duty Act (EnergieStG) on the nomenclature to be applied and therefore on the amount of to be applied. For relevant importers, extensive research and enquiries are necessary before the energy product may be imported. This can be remedied by applying the resemblance principle under section 2(4) EnergieStG. According to the provision, the renewable kerosenes are subject to the same tax as the energy products which they most closely resemble in terms of their purpose and actual nature (in this case, JET A-1). It would be expedient and coherent to include renewable kerosenes certified according to ASTM D7566 in the German Energy Duty Act and, in the international context, to strive for harmonisation of the international HS code (Harmonized System) and the German customs tariff number according to the CN.

5 Local emissions from use of multiblend JET A-1 in aircraft

In addition to reducing carbon dioxide emissions, using alternative kerosenes in aviation can also contribute to reduced release of soot into the environment. This is highly relevant as reduced soot emission can reduce contrail formation and contribute to improved local air quality at airports. As part of DEMO-SPK, an emissions test was therefore carried out on a real aircraft to demonstrate the positive effects for multiblend JET A-1 as well. The aim was also to demonstrate in practice that the reduction of soot emissions is not achieved by releasing other pollutants (e.g. nitrogen oxides).

5.1 Emission measurement on engines

The ground measurements were carried out on 30 September 2018 at Leipzig/Halle Airport at an engine test run facility. An A300-600 (cargo version, Fig. 5) with two Pratt & Whitney PW4158 engines was used. Two consecutive ground runs were carried out using a pre-defined measurement protocol. First, a reference measurement was carried out with a regular JET A-1. The multiblend produced in DEMO-SPK was then measured. A total of seven steady-state engine operating conditions were approached per kerosene option and kept stable for several minutes. The target points for engine power were set using the speed of the first fan (% N1). 100 % N1 would be the maximum engine power. For safety reasons, it was decided that the maximum power during the ground run should be 85 % N1 ("maximum continuous thrust", MCT). In addition to two operating points at 23 % N1 at the beginning of the measurement and after the MCT run, the sequence of operating points was 40 % N1 (8 min), 60 % N1 (5 min), 50 % N1 (8 min), 30 % N1 (8 min), 85 % N1 (approx. 1 min), 75 % N1 (5 min) and 23 % N1 (8 min).

Samples were taken using a sampling probe built for the project at a height of approximately 2.5 m (center of the PW4158 engines). The distance between the probe and the engine was 20 m. Based on the specifications in the engine manual, it was determined that the maximum air speed at this distance would be approx. 545 km / h. A probe was designed and then built on this basis. The probe was then fixed directly in front of the engine test run facility (Fig. 6) using ground anchors.

Fig. 5 The A300-600 for ground measurement in the engine test run facility

Fig. 6 Sampling probe in position in the engine test run facility

The exhaust gas was transported via a heated sampling line (45 m, 120 °C) and then measured. The devices used are described in Tab. 12. The sampling flow was generated by a DI-1000 diluter (Dekati) and a piston pump. For particulate emissions, the fraction of both vaporisable and non-vaporisable particles was determined. The latter fraction represents the pure soot emissions of the engine.

Tab. 12 Overview of the measuring devices used for the ground run emission measurements

Device (manufacturer)	Abbreviation	Parameter
Engine Exhaust Particle Sizer (TSI)	EEPS	Only non-volatile particles; particle number concentration and -size distribution: 5.6 to 560 nm in 32 channels
Condensation Particle Counter (TSI)	CPC	Total particle count: 7 nm to 3 µm
Scanning Mobility Particle Sizer (TSI)	SMPS	Volatile and non-volatile particles; particle number concentration and -size distribution: 8 to 279 nm in 64 channels
Aethalometer (AethLabs)	MA-200	Soot as black carbon
Optical Particle Sizer (TSI)	OPS	Volatile and non-volatile particles; particle number concentration and -size distribution: 0.3 to 10 µm in 12 channels
Nitrogen oxide monitor (ecophysics)	CLD64	NO, NO_x (diluted)
Nitrogen oxide monitor (ecophysics)	CLD700	NO, NO_x (undiluted)
Enclosed Path CO_2 / H_2O Analyzer (LI-COR)	LI-COR 7000	CO_2, H_2O
Multigas 2030 (MKS)	FT-IR	CO_2, NO_x, organic compounds

Particle emissions are stated as an emission index, i.e. the released particle number is normalised to the quantity of kerosene burnt. This is done on the basis of the measured carbon dioxide concentration and the known kerosene composition. The procedure follows the SAE recommendations in AIR6241 [E-313]. The emission index has the advantage that dilution effects generated by the ambient air have no influence and the values are directly comparable. For the development of the particle number emission with increasing engine power, the result is a profile with a minimum at approx. 30 % N1 (Fig. 7). The emission index of regular kerosene is higher at the lowest operating point than at the highest. This is probably due to the fact that the engine is not running in an optimal operating condition in this range. A reduction is achieved at all operating points by using the multiblend. The reduction is highest at the lowest operating point (approx. −60 %) and decreases with increasing engine power to approx. –23 % for MCT. This reduction is not achieved by a shift in particle distribution (Fig. 8). The non-volatile particle number emissions of the engine mainly occur in the range of ultrafine particles (< 100 nm). A shift in the particles from smaller diameters to larger diameters can be observed across the different measured power levels. This is probably triggered by the distance between the sampling probe and the engine, as the particles have time to agglomerate. However, this effect is representative of an aged aerosol and the data can therefore be used directly to estimate local effects on air quality.

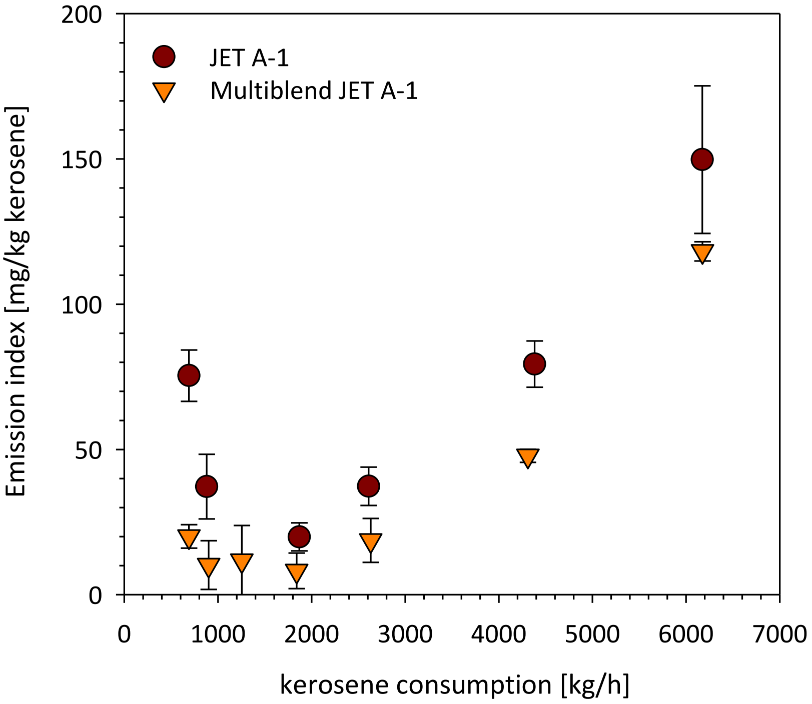


Fig. 7 Development of the non-volatile particle number emission against kerosene consumption

Volatile particles in engine exhaust gas are often indicators of the sulfur content of the kerosene or of less than ideal combustion conditions. They can significantly influence the particle number, as they usually occur with very small diameters (< 20 nm). The multiblend had no effect on the release of volatile particles. In total, approx. 30 % volatile particles were found in the exhaust gas stream. Given the small diameter, the volatile particles had no influence on the measured particle mass. For the released particle mass, an estimate is possible, based on the devices selecting according to particle size. However, assumptions have to be made regarding the particle shape and the effective particle density. Previous experiments have shown that the latter parameter in particular can vary across operating points and can even be influenced by the fuel. Given the above uncertainties, the calculation of the particulate mass emission index is based on the data from the aethalometer.

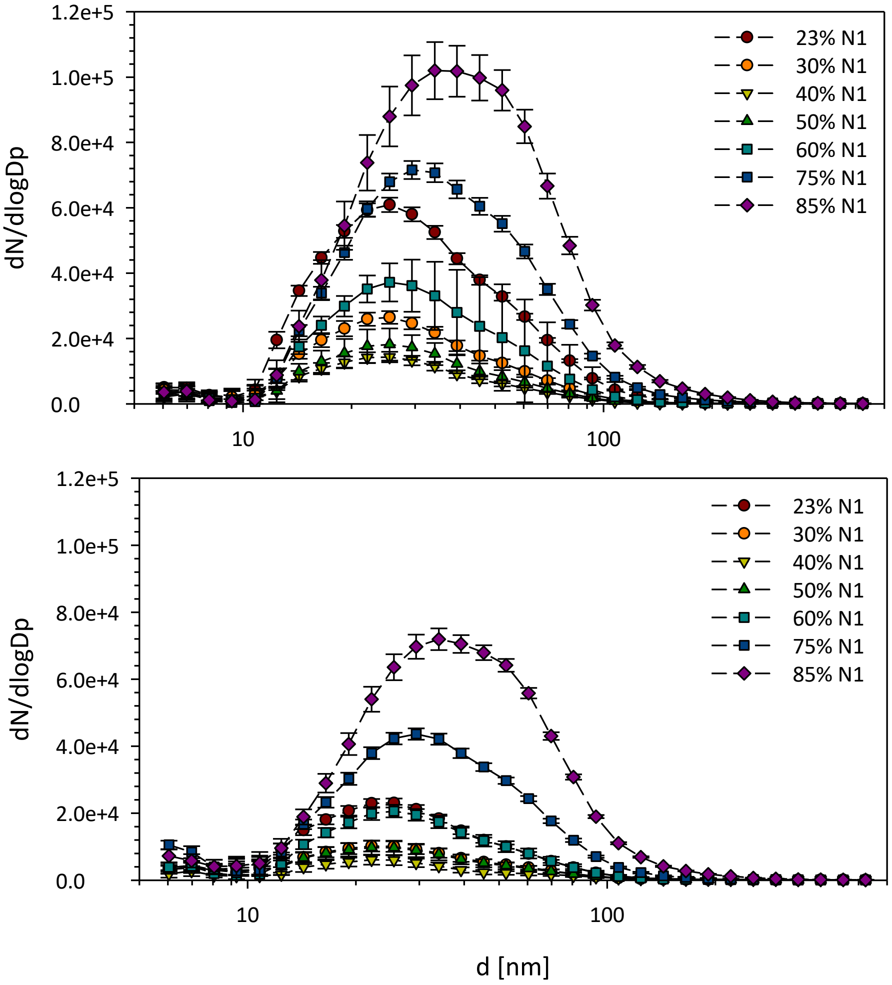


Fig. 8 Particle number distributions for the different operating points using the reference kerosene (top) and the multiblend (bottom)

In order to demonstrate the effects of the multiblend in an application-related context, the measured emission indices were interpolated and transferred to a standardised scenario. The landing and take-off (LTO) cycle defined by the ICAO is used for this purpose, which covers four different operating modes and the time in each mode. The measured data is interpolated on the basis of the fuel consumption (Fig. 9), as this allows for better transfer to the LTO operating modes than the fan speed N1. It was not possible to determine the highest LTO state ("take off" = 100 % thrust) for safety reasons. This value therefore had to be extrapolated from the existing data (Tab. 13). Given this value is highly relevant for estimating the total emission, a further estimate was done using the ICAO SCOPE11 model [Aga19]. This model is based on the smoke number of the relevant engine type stored in the ICAO database. Given the low emissions, only the smoke number for the highest operating point is listed for the PW4158 (8.1). The SCOPE11 model therefore gives 235 ± 35 mg / kg for the "take off" operating mode. This value is in very good agreement with the estimates from the extrapolation. When looking at the total emissions derived from the LTO cycle, use of the multiblend led to a 37% reduction in the released particle number and a 29% reduction in released particle mass. The significance of this reduction is underlined by the absolute figures set out in Tab. 13. The total particle mass emitted in the LTO cycle of approx. 95 g (approx. 0.01 m % of the fuel used) is reduced by approx. 28 g for just one aircraft engine. For comparison, that is equal to the soot mass emitted by a diesel car emitting soot in the range of the Euro 6d limit over a distance of 6,200 km.

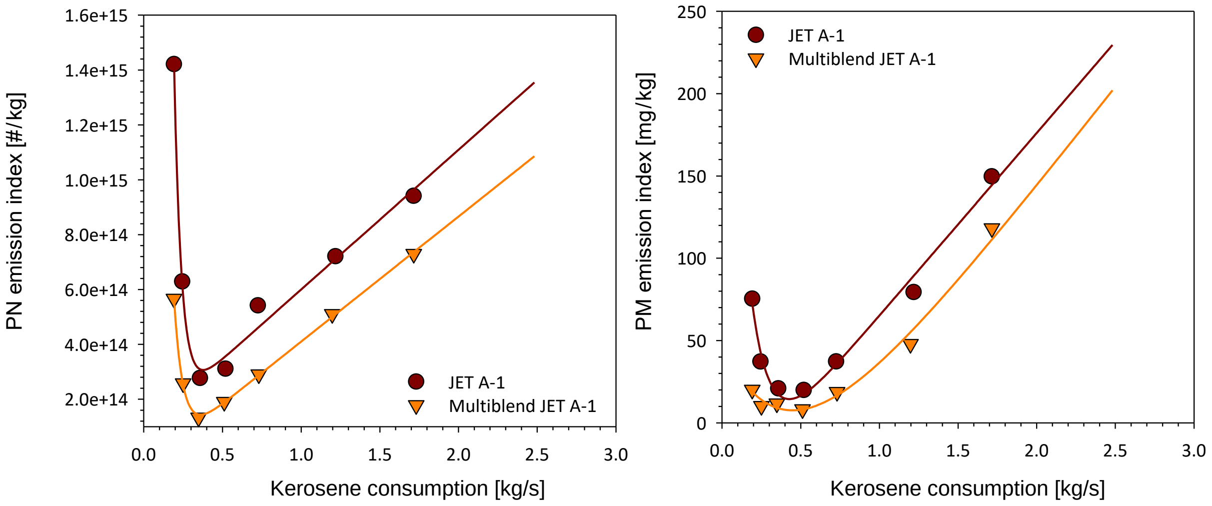


Fig. 9 Emitted particle number (PN, left) and particle mass (PM, right) against kerosene consumption

Tab. 13 Estimation of particle number (PN) and particle mass (PM) emissions for the LTO cycle with reference kerosene and multiblend

				PN[a] $[10^{15}\ \#/\text{kg}]$		PM[a] [mg/kg]	
LTO point	**Thrust [%]**	**t [min]**	**Fuel consumption [kg/s]**	**JET A-1**	**Multiblend JET A-1**	**JET A-1**	**Multiblend JET A-1**
T/O	100	0.7	2.481	1.35	1.09	230	202
Climb	85	2.2	2.004	1.11	0.87	176	145
Approach	30	4	0.682	0.44	0.27	31	14
Taxi	7	26	0.211	1.00	0.42	59	17
Total	-	-	-	836.24	523.01	95234	67227

[a] Interpolated.

When assessing the observed soot reduction, the question of adverse developments in other pollutants in the exhaust gas is important. Nitrogen oxides are of particular relevance in this case ("soot-NO_x tradeoff"). However, a direct comparison of the two ground runs is not possible for nitrogen oxides, as the ambient conditions differ significantly. While the outside temperature during the first run (reference kerosene JET A-1) was 6-10 °C, the temperature during the second run (multiblend JET A-1) was about 16 °C. The formation of nitrogen oxides is mainly due to the temperature in the combustion chamber and is therefore influenced by the temperature of the incoming air. The release of nitrogen oxides is therefore higher for the second run than for the first run, regardless of the kerosene selected. To identify the influence of the kerosene, the correlation between the combustion chamber inlet temperature and the nitrogen oxide emission index is therefore required. This shows the higher combustion chamber inlet temperatures for the second run, which is caused by the higher outside temperature. The correlation shows no significant differences in the emission of nitrogen oxides from using the multiblend. This result is also in line with expectations from previous studies [Sch18] and is confirmed in the test rig measurements set out below (section 5.3) as well. For the reference kerosene JET A-1, slightly higher nitrogen oxide values are observed at the very low operating points. These differences cannot be explained on the basis of the available data. For the release of carbon monoxide (CO), there are also no discernible differences between the two fuels. The values also show very good agreement with the ICAO reference values for CO emissions documented for the engine. This point is also confirmed by the test rig measurements (section 5.3).

The demonstration that was carried out shows the expected soot reduction from using the multiblend JET A-1. Soot reduction is not associated with the deterioration ("trade-off") of other emissions parameters. In order to ensure that the determined results are not specific to the tested engine, additional measurements were carried out in the pilot plant. These investigations are designed to demonstrate that the fundamental processes during combustion in the engine are not influenced by the various multiblend components, and are described below.

5.2 Reaction chemistry and soot formation potential

In addition to the emission measurements on the engine, the task was also to describe the chemical influences of the kerosenes on the reaction process during combustion, in particular the expected emission behaviour of the multiblend created for DEMO-SPK. DLR-VT operates a high-temperature flow reactor for this purpose, where the chemical reactions that take place can be observed under precisely defined constraints, decoupled from flow, evaporation and mixing effects. The use of Molecular Beam Mass Spectrometry (MBMS) provides a comprehensive, quantitative insight into the combustion chemistry of fuels. As the combustion temperature and the reaction process are the main determining factors for pollutants such as nitrogen oxides and carbon monoxide, the focus of these investigations is on soot formation. This is also where the expected impact of the chemical fuel composition is greatest. For a detailed description of the DLR flow reactor with coupled MBMS, please see the relevant technical literature [Oßw15].

The two kerosenes (JET A-1 and multiblend JET A-1) from the demonstration at the airport (sampling after test) and a SIP-containing sample (SIP) were investigated after the investigations at the pilot plant scale (section 3.1). Tests were carried out at both lean ($\Phi = 0.8$) and rich ($\Phi = 1.2$) combustion conditions. The reaction conditions are based on previous investigations of aviation fuels and are summarised in Tab. 14. The temperature range considered extends from full oxidation (thermal equilibrium) to unreacted kerosene and is a continuous temperature ramp. This produces a temperature interval of 2.5 K per data point (TOF) for the measurement.

To ensure comparability of the results with previous measurements, combustion conditions were selected under the assumption of a constant carbon flow and the oxidiser was adjusted according to the stoichiometry. The carrier gas flow was also kept constant throughout all the tests. This results in a total volume flow of approx. 10 slm (standard litres per minute). Tab. 15 specific flow rates of the individual tests for each of the fuels and the oxidiser. The argon carrier gas flow was divided uniformly between the evaporator (6.00 g / min) and the flow reactor (11.64 g / min) for all measurements. This results in a total argon flow of 17.64 g / min.

Tab. 14 Reactor conditions for the combustion conditions investigated

Combustion condition	Equivalence ratio ϕ	Start temperature	End temperature	Temperature ramp
Lean	0.8	1,123 K (850 °C)	773 K (500 °C)	−200 K / h
Rich	1.2	1,223 K (950 °C)	773 K (500 °C)	−200 K / h

Tab. 15 Flow rates in mg/min for the investigated combustion conditions of the fuel measurement series at constant argon flow (17.64 g / min)

Kerosene	**Kerosene [mg / min]** Φ = 0.8 | Φ = 1.2	**Oxidator O_2 [mg / min]** Φ = 0.8	**Oxidator O_2 [mg / min]** Φ = 1.2
Reference kerosene JET A-1 (Ref)	31.08	131.7	87.8
Multiblend JET A-1 (MB)	31.27	133.6	89.1
Multiblend with SIP (MB+SIP)	31.20	133.0	88.7

The main species (stable products and oxygen) are set out against oven temperature in Fig. 10. At comparatively cold oven temperatures, there is no reaction in the reactor and the reactants (kerosene and oxygen) pass through the reaction section unchanged. Owing to the complex composition of technical kerosenes, the individual fuel species are not shown separately. The reaction rate of the oxidation reactions is continuously increased via the applied temperature. The temperature axis can therefore be interpreted in the broadest sense as the reaction progress. From a temperature of about 800 K, the kerosene components can be degraded within the residence time in the reactor; this is accompanied by moderate oxygen consumption and the formation of the first hydrocarbon intermediates. As the temperature continues to rise, carbon monoxide and elemental hydrogen are then formed. Above a certain temperature, increased chain branching reactions cause an exponential increase in the available radical pool and thereby a rapid increase in the reaction rate. There is then significant oxygen consumption. This is accompanied by the oxidation of carbon monoxide to carbon dioxide. This clear jump can be interpreted as "ignition", even if no self-sustaining reaction takes place within the reactor. Only the reaction products can then be detected at the reactor outlet.

For the lean condition (Φ = 0.8), the products are only CO_2 and water and a corresponding residue of excess oxygen. The rich condition (Φ = 1.2) additionally has carbon monoxide and hydrogen products. As the temperature continues to rise, there is a slight shift in the equilibrium concentrations. As expected, the main species profiles of the three kerosenes that were investigated demonstrate identical behaviour in both stoichiometries. This also applies in comparison with other certified kerosenes. The addition of the alternative kerosenes in blend therefore does not lead to a significant change in the global reaction behaviour under the conditions investigated here. This also underlines the fuel-independence of nitrogen oxide emissions, as determined in sections 5.1 and 5.3, as the combustion temperature (controlled by heat release) in the combustion chamber is primarily relevant in this regard.

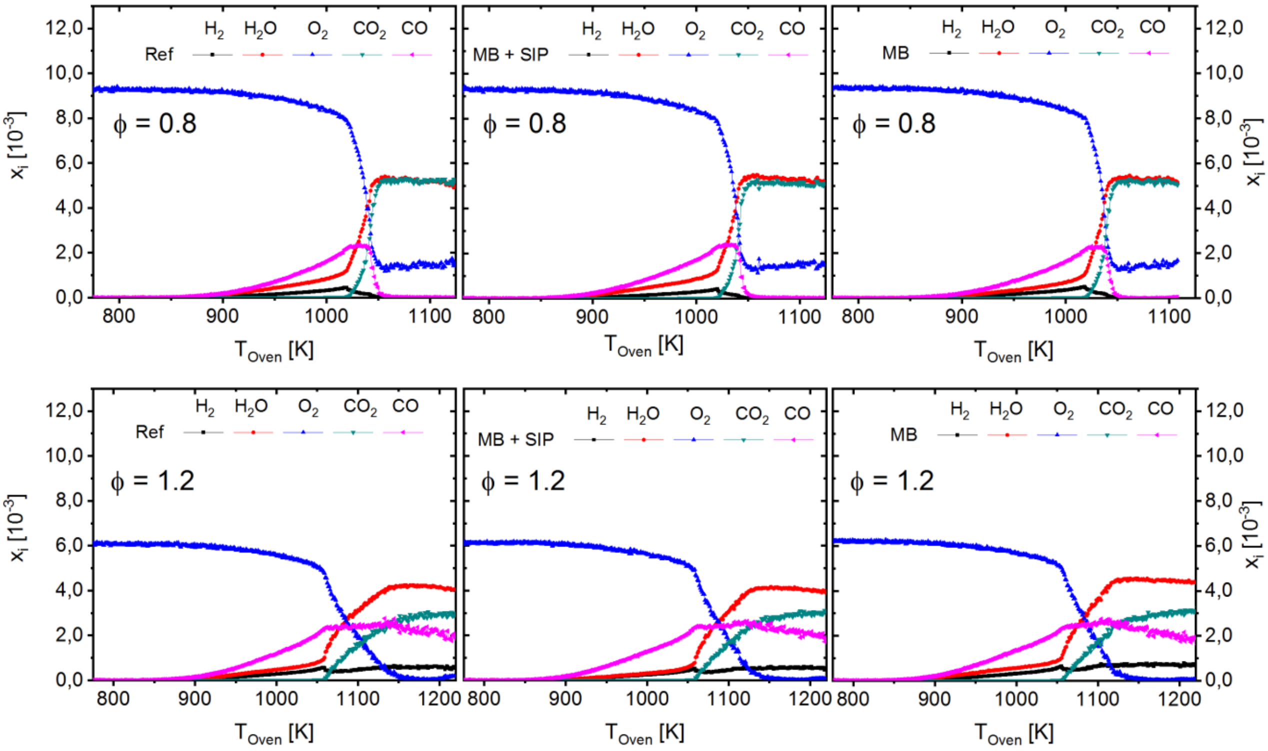


Fig. 10 Mole fraction profiles of the main species as a function of oven temperature

While the main species show virtually no differences between the kerosenes investigated, this does not necessarily apply to the combustion intermediates that are formed (and degraded again) during the combustion reaction. Consideration of these intermediates therefore makes it possible to estimate or explain pollutant emission patterns, especially soot formation, on technical combustion systems. It should however be noted that the data collected here only allow a statement to be made about the chemical pollutant formation potentials and that, in technical combustion chambers, it is the reaction process in particular that determines the pollutant emissions.

Fig. 11 shows a selection of typical combustion intermediates. This selection includes the comparatively small intermediates methane (CH_4) and ethylene (C_2H_4) as well as the oxygenates formaldehyde and acetaldehyde (C_2H_4O) or its tautomeric enol. These species are usually at the end of the reaction chain and occur in the combustion of almost all hydrocarbons. This also explains the only slight dependence of the concentrations that occur on the kerosene composition. To illustrate the fuel dependency, the maximum concentrations in each case as a function of the hydrogen content of the kerosene are also provided inset in addition to the concentration profiles. The hydrogen content has proven to be a useful sum parameter for the characterisation of complex blends, as it provides a good representation of the contained chemical components [Sch18]. Particle emissions in particular are sensitive to this parameter. For the kerosenes under investigation, a hydrogen content of 13.79 m-% was determined in the reference kerosene JET A-1 (Ref), 14.14 m-% in the multiblend with SIP (MB + SIP) and 14.32 m-% in the multiblend JET A-1 (MB). The hydrogen content increases with the proportion of alternative fuel components, as the alternatives mainly contain aliphatic hydrocarbons.

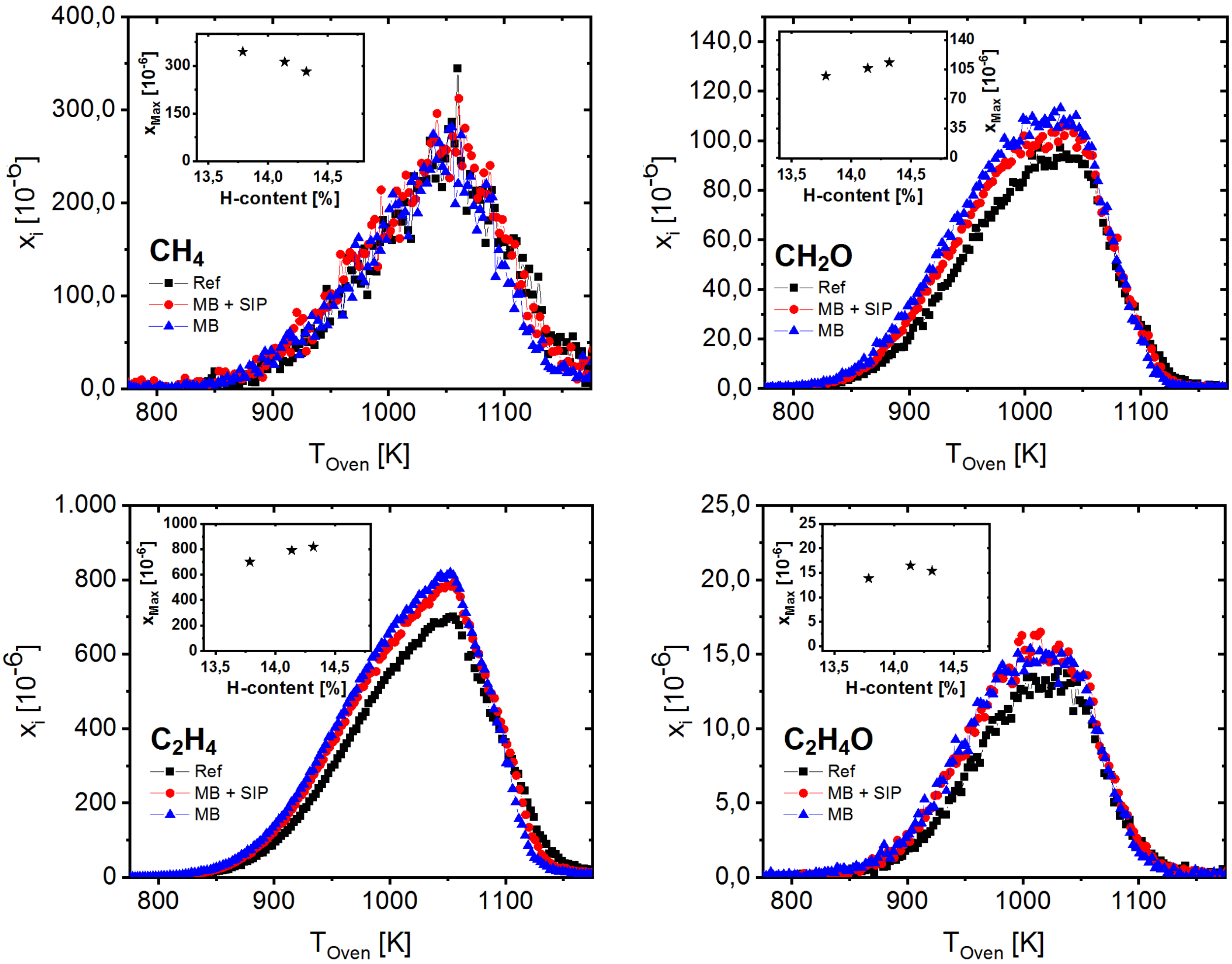


Fig. 11 Selected typical small combustion intermediates of the fuel-rich series (Φ = 1.2)
The maximum mole fractions in each case are shown inset as a function of the hydrogen content of the kerosenes

For methane, no fuel dependency can be determined because of the experimental noise. Ethylene shows a slight increase from the addition of alternative components. This can be attributed to the increased occurrence of methyl branches of the open-chain aliphatics in HEFA and SIP, as this tends to favour the splitting of C3 fragments. A slight but detectable increase can also be observed for the oxygenated intermediates. This can lead to a correspondingly slightly increased emission of aldehydes. However, significant concentrations of formaldehyde and acetaldehyde could not be detected for any of the kerosenes investigated during the test facility measurements on the A300.

The decomposition of the fuel components is examined in more detail below. Fig. 12 illustrates this using C_{12} molecules as example. The sum formula $C_{12}H_{26}$ combines the linear and branched isomers of the dodecane in this case. These species are present in both the fossil kerosene and the alternative components (HEFA and ATJ). The isomer composition, on the other hand, differs significantly. $C_{12}H_{22}$ contains aliphatic ring structures within, specifically bicylododecane isomers. Direct comparison shows that the open-chain structures ($C_{12}H_{26}$) are degraded somewhat earlier, i.e. at lower temperatures. The isomers of $C_{12}H_{16}$ form alkylated tetralins; this group of cycloaclyaromatics (naphthenoaromatics) is almost exclusively part of the fossil kerosene component. Here, too, decomposition can be observed at somewhat higher temperatures.

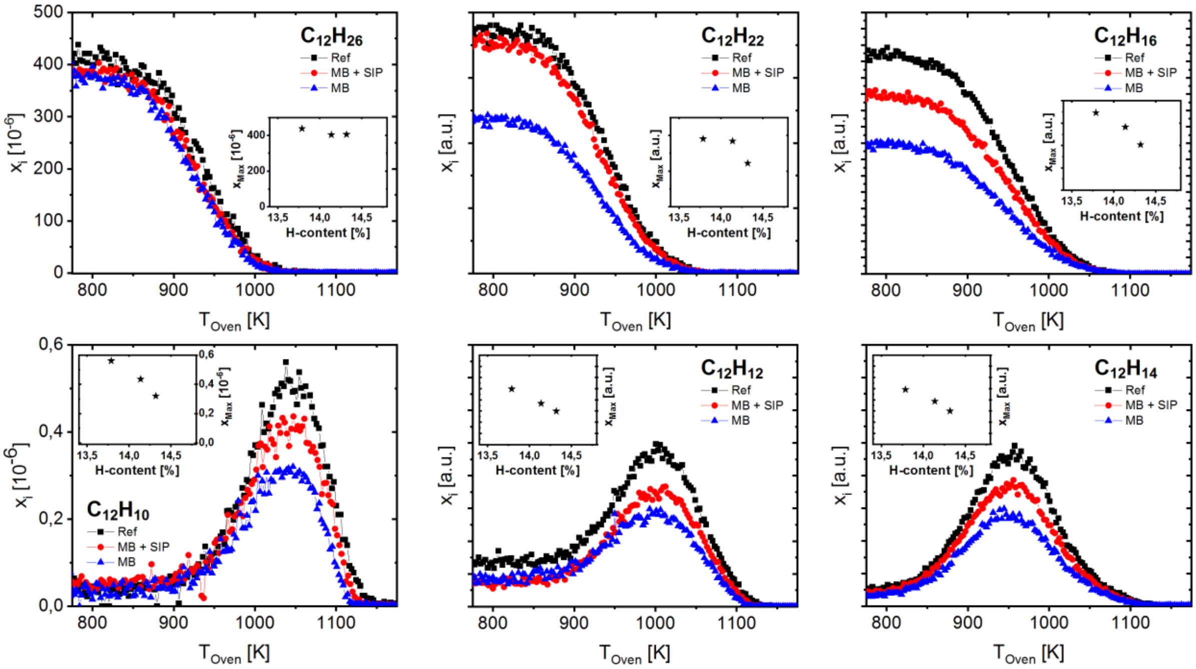


Fig. 12 Selected C_{12} species as an example of alkanes ($C_{12}H_{26}$), naphthenes and cycloalkanes ($C_{12}H_{22}$). In this case, with double ring structure and naphthenoaromatics ($C_{12}H_{16}$) in the upper row and aromatic kerosene components, which occur primarily as soot precursors, in the lower row $C_{12}H_{10}$: acenaphthene (1,2-dihydroacenaphthylene); $C_{12}H_{12}$: alkylated naphthalenes and $C_{12}H_{14}$: alkylated indenes. The maximum mole fractions in each case are shown inset as a function of the hydrogen content of the kerosenes.

The bottom row in Fig. 12 shows examples of the aromatic C_{12} fuel components. These are the polynuclear aromatics: acenaphthene ($C_{12}H_{10}$), alkylated naphthalene ($C_{12}H_{12}$) and alkylated indene ($C_{12}H_{14}$). However, these species are not only a component of fossil kerosene, they are also involved in soot formation. These species are therefore not degraded at first, but in fact increase significantly in concentration. They then continue through a maximum and demonstrate a typical intermediate profile. A clear correlation to the hydrogen content of the kerosene can be observed in the sequence of maximum mole fractions. This trend is observed for almost all soot precursor species. Fig. 13 illustrates the trend using significant soot precursor species measured in the fuel-rich series ($\Phi = 1.2$): Benzene (C_6H_6), styrene (C_8H_8), indene (C_9H_8), naphthalene ($C_{10}H_8$), acenaphthylene ($C_{12}H_8$) and anthracene ($C_{14}H_{10}$). In addition to the dependence on fuel composition, a decrease in the occurring concentrations as the soot precursor molecules increase in size is also observed.

A significant reduction in the concentration of soot precursor species during the oxidation of the multiblend compared to the fossil JET A-1 can therefore be observed. The reduction for benzene, for example, is 33 %. A similar reduction (32 %) is also observed in the lean series, although in this the concentrations of all soot precursors are correspondingly lower. This is roughly in line with the reduction in particle concentration observed in the test facility in the exhaust gas of the PW4158 engine. However, the agreement between the numerical values for the reduction of the soot precursor species and the observed reduction in the LTO cycle is incidental and cannot be generalised. On the other hand, the trends in both parts of the experiment are clear. The trend can also be confirmed by the soot luminescence in the test rig measurements (section 5.3). The observed effect of soot reduction from use of the alternative kerosenes used can therefore be directly attributed to the chemical reactions taking place during combustion. A beneficial effect of the alternative fuel constituents on particle emissions can therefore be expected over a wide range of different reaction conditions.

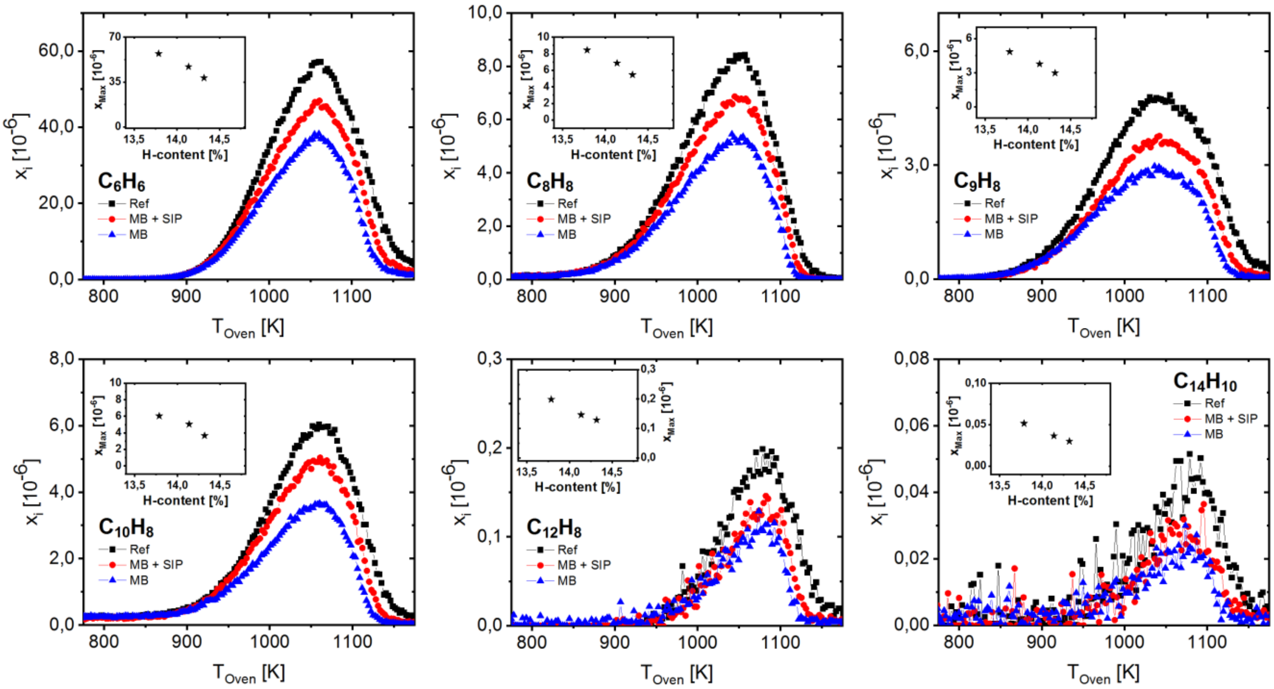


Fig. 13 Typical soot precursor species: benzene (C6H6), styrene (C8H8), indene (C9H8), naphthalene (C10H8), acenaphthylene (C12H8) and antracene (C14H10) and corresponding isomers structures
The maximum mole fractions in each case are shown inset as a function of the hydrogen content of the fuels.

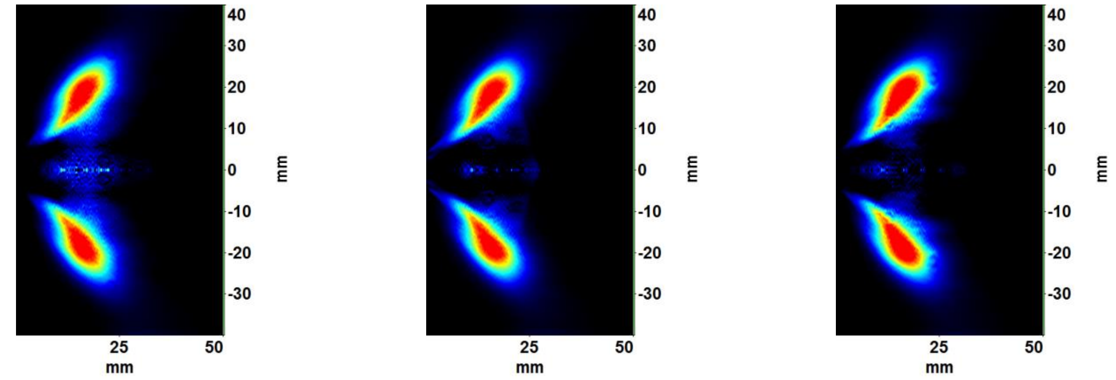
5.3 Reaction chemistry and emission measurements at the pilot plant

The effect of the chemical composition and the physical properties of the kerosenes on their combustion characteristics and on the emission behaviour (CO; NO_x) were also investigated experimentally. The kerosenes defined and supplied by WIWeb for the pre-investigations (section 3.1). The fuel parameters important for determining the combustion stoichiometry and other standard properties were determined partly by WIWeB and partly by DLR-VT.

An aviation, swirl-stabilised spray burner was installed on a high-pressure combustion test rig (HiPOT) as experimental platform. The test rig and the experimental platform are described in publications [Gro16, Box15, Gou16]. In the spray burner, an engine-relevant, film-laying airblast atomiser is used to process the liquid fuel into a fine spray. This spray or the vaporous part of the fuel is ignited. The starting flame is then adjusted to the desired flame stoichiometry and to the desired pressure and temperature conditions. The combustion chamber of the HiPOT is optically accessible from four sides so that, firstly, the flame and the thermal soot radiation emissions can be observed and, secondly, modern optical and laser-based measurement techniques can be used to record important combustion parameters in-situ. In contrast to the real engine, this means that e.g. validation data sets for CFD simulations can also be provided from the combustion chamber and not just ex-situ data based on exhaust gas measurements.

The following investigations were carried out on the HiPOT: The combustion zone (heat release regions) of the different flames were recorded with OH* chemiluminescence measurements in the ultraviolet range. The temporal change of the thermal natural soot luminosity in the near-infrared region was recorded with a high-speed camera. A spectrometer was also used to measure the chemiluminescence spectrum of various intermediate species, i.e. molecules that occur as an intermediate product during combustion, and the proportion of the thermal radiation background (the soot heat radiation) along the combustion chamber. Conventional emission measurements on the burner exhaust gas were also carried out simultaneously with a multi-component exhaust gas analysis system, equipped with electrochemical sensors for O_2, CO, NO, NO_2 and SO_2 and with a Non-Dispersive Infrared Absorption (NDIR) sensor for $_2$. The CO emissions were also recorded using the laser diode absorption spectroscopy (LDAS) technique. The measurement techniques are described in the following publications [Mos10, Mos14, Mos15, Mos12].

The following JET A-1 kerosenes according to ASTM D7566 were available for the high-pressure combustion tests: a conventional JET A-1 kerosene (Lingen refinery) and two blends with synthetic fuels (blend 1: 61.7 Vol.-% JET A-1 + 29.9 Vol.-% HEFA + 8.4 Vol.-% ATJ from WIWeB Tank 1, Blend 2: 75.1 Vol.-% JET A-1 + 16.6 Vol.-% HEFA + 3.3 Vol.-% ATJ + 5 Vol.-% SIP from WIWeB Tank 3). These kerosenes were tested under the following burner operating conditions: Combustion chamber pressures of 5 bar and 6 bar, global combustion stoichiometry of φ = 0,7 to φ = 1, fuel temperature of 20 °C and air inlet of temperature 50 °C.



DEMO-SPK 1

JET A-1 (Lingen refinery)

DEMO-SPK 2

JET A-1 + HEFA + ATJ

DEMO-SPK 3

JET A-1 + HEFA + ATJ + SIP

Fig. 14 Example comparison of the planar OH* chemiluminescence distribution of the examined kerosenes at 6 bar combustion chamber pressure and stoichiometric fuel-air ratio

The flames of all three kerosenes show a very similar flame shape and flame position under the same combustion chamber operating conditions, according to the recorded spatial OH* chemiluminescence distribution. Fig. 14 shows the OH* chemiluminescence distribution in the axial plane of the combustion chamber for all three fuels as an example. This is the Abel-transformed planar representation of the measured, line-of-sight-integrated, axially symmetric OH* chemiluminescence distribution.

The intensity profiles along the combustion chamber were considered for further analysis. The position of maximum heat release is between 15 and 20 mm downstream in relation to the burner face plate, depending on the equivalence ratio. The heat release region shifts upstream with increasing global equivalence ratio for both combustion chamber pressures. At 5 bar, the maximum heat release does not go below a minimum distance to the burner face plate of 17 mm. The expansion of the heat release region in the combustion chamber increases with increasing global equivalence ratio. Significant kerosene differences in these parameters were not observed.

The OH* chemiluminescence of the kerosenes integrated over the combustion chamber volume exhibits the expected functional dependence on the equivalence ratio. The chemiluminescence curve of the kerosenes at 6 bar combustion chamber pressure is identical. At 5 bar combustion chamber pressure, the OH* chemiluminescence intensity of the reference JET A-1 is on average 5 % lower for all global equivalence ratios.

The chemiluminescence spectrum of the flame was measured with a spectrometer in addition to the imaging OH* chemiluminescence measurement technique. The integral chemiluminescence (i.e. integrated over all spectral regions of the chemiluminescence bands of the kerosenes' intermediate species OH*, CH*, C_2* and CO_2*) increases as expected linearly with increasing power, i.e. with increasing equivalence ratio and with increasing pressure at constant equivalence ratio and constant air mass flow per bar. At both combustion chamber pressures, the integral chemiluminescence of the JET A-1 reference kerosene is 20 % to 30 % lower compared to the multiblends, which exhibit no significant differences in their integral chemiluminescence.

At an air preheat temperature above the final boiling temperature of the kerosenes of e.g. $T_{Air} = 300$ °C, the flames show only a very slight sooting tendency. The sooting tendency increases significantly with decreasing air preheat temperature. Air preheat temperatures around the starting boiling temperature of the kerosenes lead to unstable flame behaviour. At an air preheat temperature of $T_{Air} = 50$ °C and a pressure of 6 bar, the flames of the kerosenes soot noticeably and the flames burn stably. In general, the sooting tendency of all kerosenes increases with the pressure and the equivalence ratio, as expected. The analysis of the recorded natural soot luminosity shows that the location and size of the sooting flame regions of the kerosenes are very similar. The maximum soot luminescence is found 30 mm downstream of the burner face plate, i.e. about 10 mm downstream of the maximum heat release. For these fuel-rich flames, optical measurements were only possible to a limited extent, because the inner combustion chamber panes were covered extensively by soot. To be able to compare the kerosenes in terms of their soot luminescence, a smaller region in the combustion chamber downstream was therefore analysed. The volume-integrated soot luminescence in this region increases exponentially for all kerosenes from an equivalence ratio of $\varphi = 0,9$ (Fig. 15). The intensity of the soot luminescence of the fuels is about one order of magnitude higher at 6 bar combustion chamber pressure than at 5 bar combustion chamber pressure.

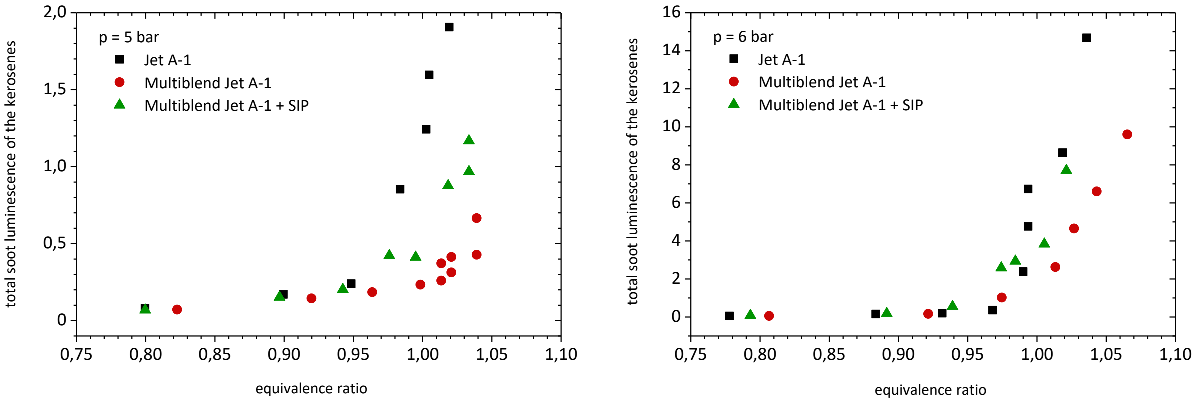


Fig. 15 Measured total soot luminescence of the kerosenes as a function of the equivalence ratio at a combustion chamber pressure of 5 bar (left) and 6 bar (right)

The CO emissions were measured with three different measuring devices/measuring techniques (chemical sensor, LDAS, and FTIR). The NO_x emissions were also determined using three different techniques (chemical sensor, FTIR, and chemiluminescence detector). All the measuring devices provide matching CO and NO_x exhaust emission values in the relevant measuring ranges and measuring accuracies. In particular, for the combustion chamber operating conditions investigated, i.e. for all selected equivalence ratios and pressures, no significant difference was found between the kerosenes. Fig. 16 shows the FTIR measurements (CO, CO_2, CO_x, NO_x) and the measurement results of the NO_x chemiluminescence detector as an example (see the open symbols).

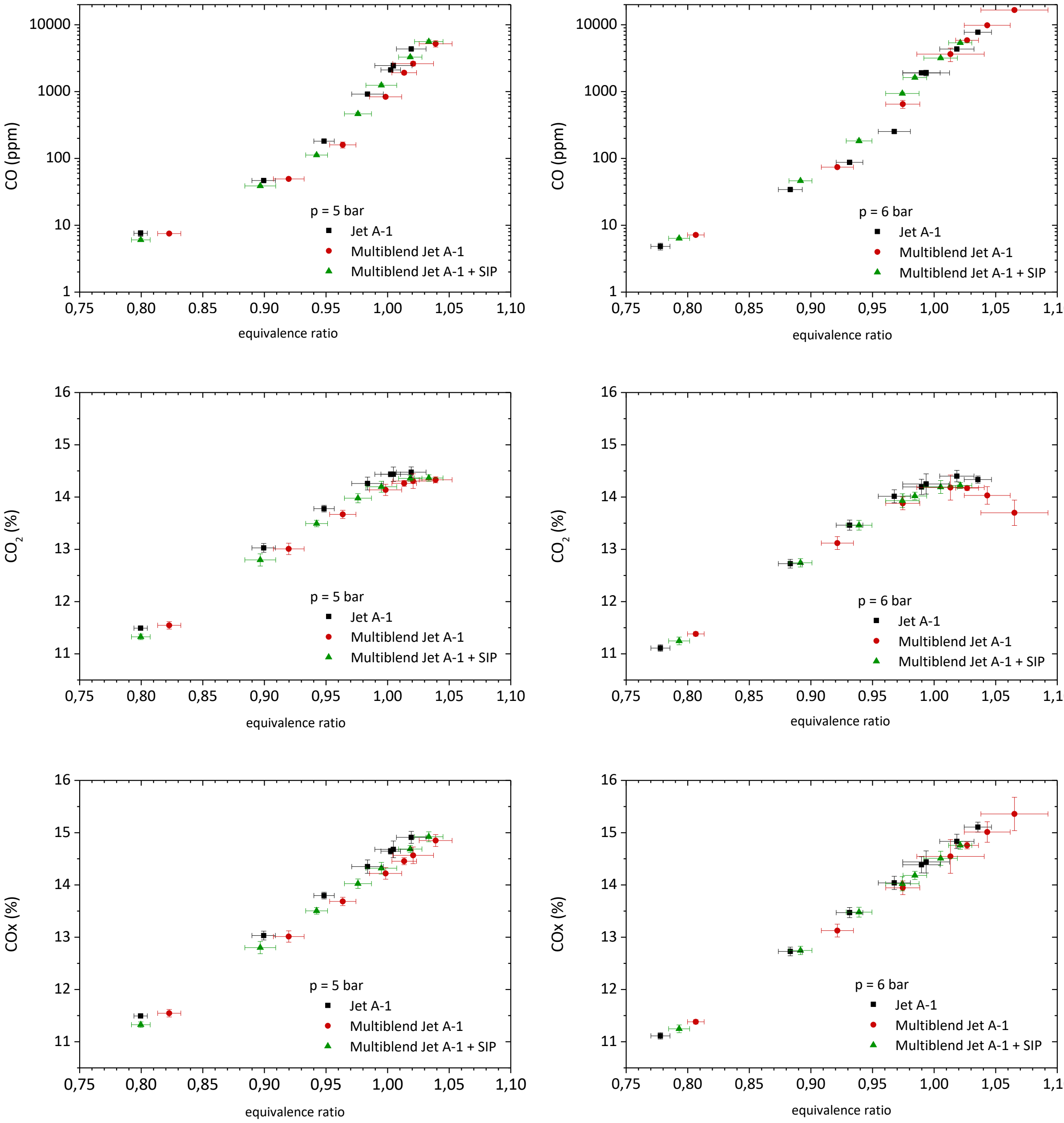


Fig. 16 Measured exhaust emissions of CO, CO_2, CO_x and NO_x of the kerosenes as a function of the equivalence ratio at a combustion chamber pressure of 5 bar (left column) and 6 bar (right column) – continued on next page

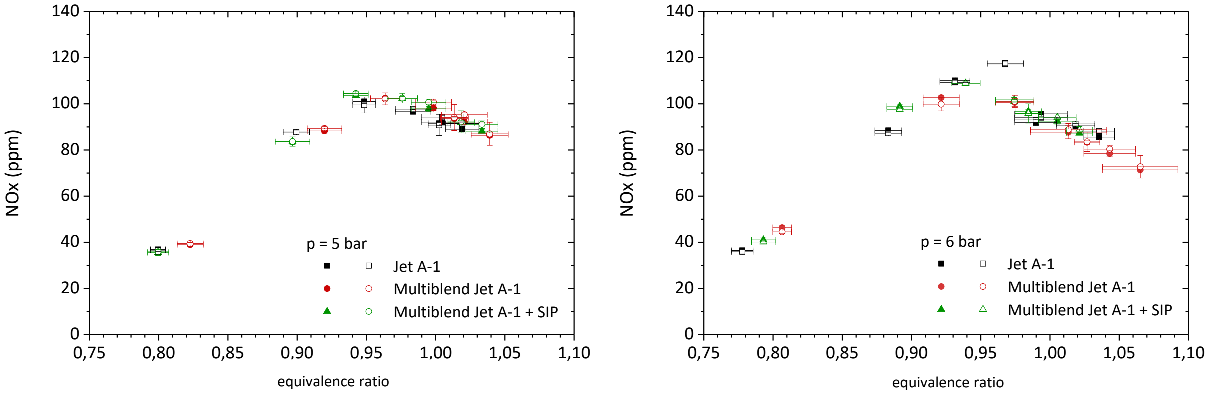


Fig. 16 Measured exhaust emissions of CO, CO_2, CO_x and NO_x of the kerosenes as a function of the equivalence ratio at a combustion chamber pressure of 5 bar (left column) and 6 bar (right column)

The measurements that were carried out showed that differences between the kerosenes, e.g. in terms of sooting tendency, become more evident with fuel-rich, almost stoichiometric flames under increased pressure and at low air preheat temperature and that the soot formation in the combustion chamber reacts sensitively to these experimental conditions. Furthermore, the measurement results from the high-pressure combustion test rig show that, although no differences were found in the exhaust emissions (e.g. CO and NO_x) between the investigated kerosenes, the optical measurement techniques can nevertheless show slight differences between the kerosenes.

It is known that NO_x emissions correlate with the liquid fuel load in the combustion chamber, more specifically, with the local fuel-to-air ratio, i.e. with the local stoichiometry. The fuel load arises from the physical fuel properties that underlie the atomisation and evaporation of the liquid fuel. Larger regions of fuel-rich, almost stoichiometric fuel-air blends, despite globally lean combustion conditions, lead locally to significantly higher combustion temperatures and therefore to increased NO_x formation. Thermally formed NO_x is the largest contributor to NO_x emissions from burners relevant to gas turbines. The formed NO_x concentration is determined by the maximum temperature, the residence time in the areas of elevated temperature and the local concentrations of nitrogen and oxygen. The NO_x formation rate increases with the square root of the combustion chamber pressure and exponentially with the temperature. Significant quantities are produced as soon as a temperature of about 1,700 K is exceeded. NO_x formation is also greatest under globally near-stoichiometric conditions. Richer combustion conditions suppress O_2 dissociation in the formation mechanism and leaner conditions slow down the formation rate due to the lower flame temperature. The identical NO_x emissions of the investigated kerosenes can be interpreted as an indication of very similar fuel preparation in the combustion chamber.

The combustion of hydrocarbons at a given stoichiometry (fuel-air ratio or flame temperature) is based on a complex chemical conversion of the initial kerosene into CO and its oxidation to CO_2. The detail of the CO oxidation mechanism depends on the concentrations of H_2O, H_2 and HO_2. If H_2O dominates, CO is essentially oxidised by OH to CO_2. The concentration of OH is non-linearly related to the O_2 concentration. The decrease in oxygen content as the equivalence ratio increases leads to a disproportionate decrease in CO oxidation and accordingly to the measured exponential increase in CO. The kerosenes do not exhibit any significant differences in CO. This indicates that the essential chemical reactions and in particular the final oxidation reactions are running to the same extent. This result confirms in particular the exhaust gas values determined during the ground runs (section 5.1).

It is well known that the exhaust emissions of a kerosene depend not only on the set combustion conditions and the selected combustion system, but also on its chemical and physical properties. Kerosenes with almost identical chemical combustion properties (such as ignition delay time and flame speed) can differ in their physical properties to such an extent that the heterogeneous combustion of the kerosenes in technically relevant combustion systems is demonstrably different.

Tab. 16 Chemical kerosene parameters

Fuel	Kerosene/ multiblend [Vol.-%]	Aromatics content [Vol.-%]	Hydrogen content [m-%]	H / C
1	100 % JET A-1 (Lingen)	16	13.920	1.927
2	61.7% JET A-1 + 29.9% HEFA + 8.4% ATJ	9.9	14.314	1.991
3	75.1% JET A-1 + 16.6% HEFA + 3.3% ATJ + 5.0% SIP	12	14.085	1.954

Tab. 16 provides an overview of some parameters that arise from the chemical composition of the kerosenes. Emissions correlate with the aromatics content and with the H content or the H/C ratio. It is known that the aromatics content in particular has a major influence on the soot emissions. Cycloalkanes have an additional, smaller influence. Sorting the kerosenes by decreasing mass fractions of aromatics and cycloalkanes produces a ranking of the expected sooting tendency. The ranking of the measured soot luminescence intensity of the kerosenes follows their aromatics content or the H/C ratio. Provided that the gas temperatures in the sooting regions do not vary greatly, the local soot luminescence intensity can be treated as a measure of the local soot volume fraction. It should be noted, however, that camera recordings always provide line-of-sight-integrated information. Therefore, they are always average soot luminescence intensities or soot volume fractions.

Tab. 17 Selected physical kerosene properties

Fuel	Density (15 °C) [kg/m³]	Calorific value [MJ/kg]	kin. viscosity (−20 °C) [µm² / s]	Surface tension (20 °C) [N/m]	Initial boiling point [°C]	Final boiling point [°C]
1	807.0 811.7	43.210 43.172	4.957 4.250	25.3	160.9	250.4
2	789.0	43.525	4.195 4.198	24.3	159.0	251.2
3	797.9	43.400	4.421 4.365	25.0	161.3	248.6

Tab. 17 compares some selected physical kerosene properties. The kinematic viscosity exhibits the greatest variability. For the ability to compare the combustion properties of different fuels, it is important to keep the combustion chamber operating conditions constant, but this is in principle only possible to a limited extent because of the generally different physical properties. The air mass flow per bar was therefore kept constant for all measurements in order to keep the flow field in the combustion chamber as similar as possible. This set the desired global equivalence ratio using the fuel mass flow, which depends on the kerosene due to the different stoichiometric fuel to air mass flows. As a direct result, the thermal output of the different kerosene flames usually varies. The different viscosity, surface tension and density also influence the spray loading of the combustion chamber. There are kerosene parameters that characterise the evaporation of the spray droplets as well. Higher combustion chamber pressures and/or higher air mass flow rates usually make it easier to assess the influence of chemical kerosene properties on combustion behaviour, as the atomisation and vaporisation become less sensitive to the physical fuel properties.

Tab. 18 Operating parameters, physical kerosene properties and calculated Sauter diameter of the fuel spray at φ = 1, p = 6 bar

Fuel	Fuel consumption [g/s]	Thermal energy [kW]	Dynamic viscosity (20 °C) [µPa s]	Kin. viscosity (20 °C) [µm²/s]	Density (20 °C) [kg/m³]	Surface tension (20 °C) [N/m]	SMD [µm]
1	1.839	79.5	1,588.4	1.976	804.0	25.4	12.7
2	1.828	79.5	1,398.6	1.779	786.1	24.4	12.2
3	1.834	79.6	1,464.5	1.842	794.9	25.1	12.4

Tab. 19 Operating parameters, physical kerosene properties and calculated Sauter diameter of the fuel spray at φ = 1, p = 5 bar

Fuel	Fuel consumption [g/s]	Thermal energy [kW]	Dynamic viscosity (20 °C) [µPa s]	Kin. viscosity (20 °C) [µm²/s]	Density (20 °C) [kg/m³]	Surface tension (20 °C) [N/m]	SMD [µm]
1	1.532	66.2	1,588.4	1.976	804.0	25.4	13.6
2	1.523	66.3	1,398.6	1.779	786.1	24.4	13.0
3	1.528	66.3	1,464.5	1.842	794.9	25.1	13.3

Tab. 18 and Tab. 19 show some physical properties for the following combustion chamber operating conditions : $Q_{Air} = 4.5$ g/s/bar, $T_{Fuel} = 20$ °C, $T_{Air} = 50$ °C. Data is entered for combustion chamber pressures of 6 bar and 5 bar. Under the stated combustion conditions, the MB + SIP generally shows the maximum differences in the presented parameters in comparison to the reference kerosene JET A-1. The viscosities, the surface tensions and the calculated Sauter diameter of the fuel spray show the largest deviations. The Sauter diameter is the mean diameter of a spray droplet size distribution, abbreviated as SMD (or d_{32} or d_S), and is defined by the volume-to-surface ratio of all spray droplets. A standard correlation by Lefebvre and El-Shanawany was used to calculate the Sauter diameter (equation 6.31 in [Lef10]). The viscosity and surface tension of the kerosenes were measured for different temperatures. This data was used to determine the parameters in the equations for surface tension $\sigma(T) = \sigma_0 \left[\frac{1-T/T_c}{1-T_0/T_c}\right]^{11/9}$ and kinematic viscosity $\eta(T) = A\ exp\left(\frac{B}{T-C}\right)$. The dependence on temperature of the density was taken into account, as presented in DLR communication 98-01 by Rachner [Rac98]. The viscosity, surface tension, density and mass flows of air and kerosene are the key parameters for calculating the Sauter diameter of a spray droplet size distribution. The Sauter diameter decreases exponentially with increasing air mass flow and with increasing combustion chamber pressure at constant air mass flow per bar and therefore becomes increasingly insensitive to pressure and air mass flow fluctuations. The better atomisation results in better evaporation of the spray and a more homogeneous blend of fuel and air. The influence of the kinematic viscosity on the Sauter diameter increases with increasing air mass flow, but then the Sauter diameter is usually already so small that a significant influence can only be observed for kerosenes with extremely different viscosities. The difference in the viscosities of the investigated kerosenes is not great enough for the combustion behaviour of the fuels to be affected.

In summary, all DEMO-SPK fuels showed very similar combustion behaviour in the HiPOT. The measured CO and NO_x emissions exhibit no fuel dependency. The general flame structure, the flame position and the chemical reaction regions of the different fuels exhibit no sensitivity to the fuel. The location and size of the combustion chamber regions that exhibit thermal soot radiation emissions are also insensitive to the fuels investigated. The intensities of the soot radiation emissions of the fuels are different. The blends exhibit a lower sooting tendency compared to the reference kerosene. The multiblend JET A-1 without SIP exhibits the lowest sooting tendency. The ranking of the soot luminescence intensity of the investigated kerosenes follows their aromatics content or the H/C ratio. The intensity of the soot luminescence of the fuels is about one order of magnitude higher at 6 bar combustion chamber pressure than at 5 bar combustion chamber pressure.

5.4 Summary

The pilot plant tests and test facility measurements accompanying the demonstration provide information on the basic combustion characteristics of the multiblend in technical systems and pollutant reduction. The test facility measurements show the expected reduction in soot emissions from using an alternative kerosene with a higher hydrogen content. No change in other emission parameters was observed in this context. It was possible to validate this finding via tests on the high-pressure test rig. The multiblend again exhibited no change in the gaseous emissions. Additional measurements on the plug flow reactor demonstrate a reduction of the soot precursor species on conversion of the multiblend. By this selection of investigations, it was therefore possible to demonstrate that the change in emissions is not due to specific engine effects in the aircraft turbine that is used, but to fundamental aspects of the multiblend.

6 Life cycle analyses for multiblend JET A-1

Alternative fuels are a promising, short-term tool for reducing greenhouse gas emissions in the aviation sector. Alternative fuels with high greenhouse gas emissions abatement can therefore play a key role in achieving the sector's ambitious targets. However, one of the essential conditions for achieving the targets is the supply of sustainable fuels with clear environmental assessments. One possible approach is to use sustainability certification methods from the context of the Renewable Energy Directive 2009/28/EC (EU RED). Although crediting alternative aviation fuels to national quotas has not played a role in most EU member states to date, the general sustainability targets of the EU RED, including binding greenhouse gas emissions reductions, may be the basis for possible crediting of alternative fuels in other schemes such as the ETS or CORSIA.

The investigation of the concrete greenhouse gas emissions and greenhouse gas reduction effects for the SPK and multiblend JET A-1 on the basis of actual values was an essential part of the DEMO-SPK project. The results of these investigations are the subject of this section.

In order to be able to assess the SPKs and multiblends used in the DEMO-SPK project more comprehensively in terms of their sustainability, life cycle analyses were carried out for all the fuels discussed to record their ecological (Life Cycle Assessment; LCA) and economic (Life Cycle Costing; LCC) effects. The investigated supply chains re the basis for this, which are initially presented generally for all analyses.

6.1 Supply chains

For the life cycle analyses of the supply of multiblend JET A-1, three different supply chains are considered, which are referred to below as case A, case B and case C. The following constraints apply to all these cases:

a. The renewable kerosenes investigated in DEMO-SPK are included

b. The renewable kerosenes are supplied from the manufacturers' existing sites or sites under construction

c. SPK is always delivered to Leipzig/Halle Airport with DHL/EAT as the customer, whose tank depot is supplied exclusively via tank car

d. JET A-1 is included as the fossil component of the multiblend

In addition to these constraints, case-specific assumptions are also taken into account, which are explained below for each of the cases.

6.1.1 *Case A | Demonstrated supply chain in DEMO-SPK*

Case A is the supply chain demonstrated under real conditions in the DEMO-SPK project (section 4.1). The analyses are therefore intended to demonstrate a DEMO-SPK-compliant supply chain, which is why project-related shipping and logistics documents are the main data. For A, large-scale production of the synthetic components was only assumed for calculation of the kerosene production costs.

6.1.2 *Case B | Planned supply chain in DEMO-SPK*

Case B is the supply chain originally planned for demonstration in DEMO-SPK with a multiblend JET A-1 consisting of four components (including SIP). The supply chains for the HEFA-SPK, the ATJ-SPK and the manufactured multiblend JET A-1 are therefore the same as case A. In case B, there is just a fourth component (SIP) added to the other components for multiblend production. The SIP is filled into tank containers at the refinery site in Brazil and transported to Hamburg. As for the ATJ-SPK, it is transported onwards to Speyer via Hamburg as the port of import, using on-road container transport.

6.1.3 *Case C | Example of year-round supply to LEJ Airport*

Case C looks at the theoretical, large-scale production of the synthetic components, taking into account the volumetric composition of the multiblend JET A-1 actually tested in the DEMO-SPK project (Case A, section 4.1.4). This is based on the assumption that the customer, DHL/EAT, agrees to year-round supply to Leipzig/Halle Airport for fuelling its own and its contract customers. The supply chain is optimised based on the variant tested in case A, so that real, large-scale conditions can also be taken into account. In order to achieve the greatest possible comparability with cases A and B in case C, the sites in the USA are still taken into account as the production sites of the synthetic components. Depending on the project planning by the plant operators, the only change is an increase in plant capacities.

The multiblend JET A-1 (the blending process) is produced in the USA at the port of Long Beach, i.e. close to the site of the HEFA-SPK producer (Paramount, Long Beach), in order to keep the transport of the synthetic components to a minimum (the HEFA-SPK makes up the largest proportion of the synthetic components in the multiblend, Fig. 17). The proximity to the port also lends itself to the delivery of the required quantities of JET A-1. A tank depot at the port of Long Beach is used for the blending process. The subsequent sea transport of the multiblend JET A-1 to Europe is by product tanker. Delivery was to the port of Rotterdam, where tank depots are approved for handling JET A-1 and where tank car loading and subsequent tank car transport are possible. Case C assumes a monthly delivery of multiblend JET A-1 from the USA to the tank depot at the port of Rotterdam. The multiblend JET A-1 is delivered to the EAT/DHL tank depot at LEJ Airport via tank car. In addition, case C also takes into account crediting of the multiblend that is used within the EU emissions trading system.

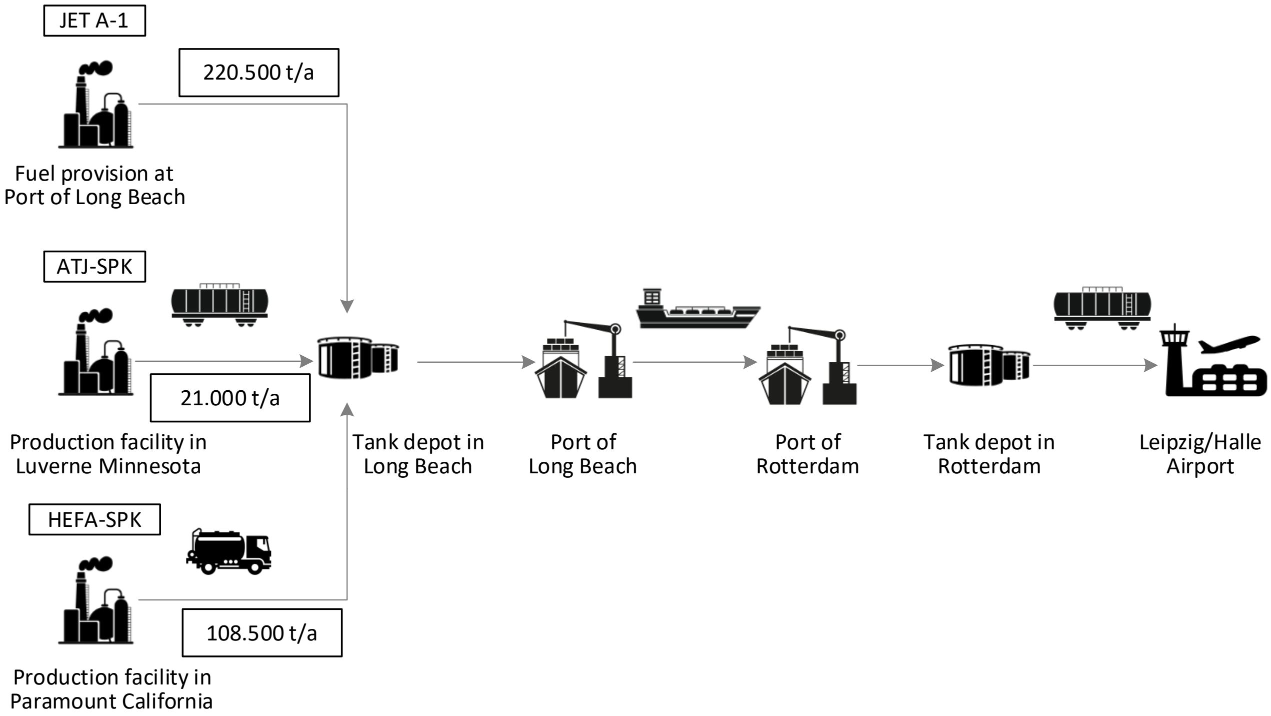


Fig. 17 Schematic of the supply chain for case C

6.2 Life Cycle Assessment

The environmental life cycle analyses were initially prepared separately for the renewable kerosenes under consideration. On that basis, the entire supply chain for the multiblend was analysed, including the fossil JET A-1 and finally the engine combustion of the fuels. These life cycle analyses considered various areas of environmental impact (e.g. GHG emissions, acidification, and eutrophication) and applied various methodological approaches. The methods used are based firstly on the sustainability assessment at the scientific level (methodology of ISO 14040) and secondly on the current and future political framework for bio-based fuels (methodology of the EU RED) [DIN14][Eur09].

The Life Cycle Assessment (LCA) tool is used to assess the environmental impact of the supply concepts for the renewable kerosene and the multiblend JET A-1 under consideration. This involves analysing the life cycle of the investigated product from the cultivation and provision of feedstock and production to use and disposal in order to capture the potential environmental effects associated with this product as fully as possible. All the auxiliary and operating materials used along the life cycle are also considered. The costs and emissions associated with the production and use of these auxiliary materials and supplies and use of other products and services are also taken into account. The Life Cycle Assessment method is defined in DIN ISO standards 14040 and 14044 [DIN14, 18]. The following constraints were defined for application of the DIN ISO 14040/14044 method:

- System boundaries for the assessment of renewable kerosenes. The analysis of the renewable kerosenes covers the entire supply chain, from biomass production and conversion processes to transport of the kerosenes to the tank depot where the multiblend is produced. The biomass production process includes the applicable cultivation and supply processes for the use of cultivated biomass. If residual and waste materials are used for the purpose of biofuel production, the assessment only begins with transport of the feedstock to the conversion plant. Upstream emissions are not taken into account.
- System boundaries for assessment of the multiblend JET A-1. For the multiblends under consideration, the life cycle assessment framework includes the supply chains of the renewable kerosenes, the supply chain of the JET A-1 to the tank depot, the transport of the multiblend to the airport and the engine use in the aircraft turbine.
- The functional unit was defined as 1 MJ kerosene. The functional unit is the reference value for the presentation of results. Results of the greenhouse effect environmental impact category are therefore expressed in g CO_2equivalent per MJ fuel.
- The ReCiPe (H) v.1.13 [Hui] method was used for the impact assessment. This method allows the determined emissions to be summarised according to defined factors and expressed within more easily understandable categories (e.g. greenhouse effect).
- Co-products were taken into account by allocation according to the lower heating value.[7] Surplus electricity was accounted for by credit.[8] These methods make it possible to allocate the environmental impacts to the different produced products, thereby allowing for a product-related assessment, even for multi-product systems. For allocation, the determined environmental impacts are divided between the produced products according to a defined parameter (e.g. the lower heating value, the product prices or the mass). The credit method assumes that the produced co-product can replace other products and therefore the other products no longer need to be produced. The emissions thereby avoided are credited to the product system.

The results are described and discussed below.

6.2.1 *Life Cycle Assessment of renewable kerosenes according to DIN ISO 14040/14044*

The results of the life cycle assessment of renewable kerosenes are presented in Fig. 18 on page 58. This results show the effect of the process steps of biomass supply, transport and conversion (of the raw material to kerosene) proportionally to the total effect of the relevant impact categories. The environmental impact categories presented in Tab. 20 were considered for the assessment.

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[7] This allocation procedure was chosen as the co-products under consideration here are exclusively products for energy use.

[8] An emission factor is used for the same type of electricity generation based on fossil fuels, e.g. it is assumed that electricity from a biogas CHP replaces the same amount of electricity from a natural gas CHP, accordingly an emission factor for electricity from a natural gas CHP is used for the credit.

Tab. 20 Impact categories considered

Impact category	Description
GWP **(Global warming potential)**	Greenhouse effect: potential to change global temperatures through greenhouse gas emissions. Unit: kg CO_2-eq.
ALOP **(Agricultural land occupation potential)**	Agricultural land use: refers to the continuous use of agricultural land. Unit: m²
FDP **(Fossil depletion potential)**	Consumption of fossil resources: expresses the decrease in the availability of fossil resources. Unit: kg oil-eq.
FEP **(Freshwater eutrophication)**	Freshwater eutrophication: ammonia, nitrate, nitrogen oxide and phosphorus emissions affect eutrophication (the build-up of a concentration of chemical nutrients in an ecosystem). Unit: kg PO_4^{3}-eq.
HTPinf **(Human toxicity)**	Human toxicity: index that expresses the toxic effect on humans of a chemical unit released into the environment. Unit: kg 1,4 DB-eq.
MET **(Marine ecotoxicity potential)**	Ecotoxicity: Impact of e.g. heavy metals on the ecosystem. Unit: kg 1,4 DB-eq.
PMFp **(Particulate matter formation potential)**	Particle emission potential: expresses the potential for emissions of extremely small particles from anthropogenic processes, such as combustion, raw material extraction, etc. Unit: kg PM
TAP **(Terrestrial acidification)**	Acidification: Acidification potential of water and soils due to SO_2 and NO_x emissions. Unit: Kg SO_2-eq.
WDP **(Water depletion potential)**	Water consumption. Unit: m³ water

As expected, the contributions vary considerably, starting from the global warming potential (GWP100) across the other impact categories, such as water demand (WDP), eutrophication and acidification potential (FEP; TAP100), across the entire supply chain.

In the case of ATJ-SPK, for example, the impact categories for agricultural land use (ALOP) and water consumption (WDP) are dominated by the biomass supply process. In this case, this is essentially due to the use of arable land for maize cultivation and the water demand associated with cultivation. The terrestrial acidification potential (TAP) for ATJ-SPK is also primarily driven by the process of biomass supply, which is caused by the airborne ammonium and nitrogen oxide emissions of the cultivation processes. Although the emissions/costs of biomass supply also contribute significantly to the overall impact of the other categories under consideration, which are dominated by the emissions/costs of the conversion processes. This is the result of the use of fossil fuels to supply process energy. The use of precisely these fuels and the resulting heavy metal and climate-relevant emissions are responsible for the high contribution to fossil resource consumption (FDP), human toxicity (HTPinf) and global warming potential (GWP). The high contribution of the conversion processes to marine ecotoxicity (METPinf) is also due to heavy metal emissions from the combustion of fossil resources. The phosphate and phosphorus emissions that cause freshwater eutrophication (FEP) originate from both the conversion and biomass supply processes, and are caused not only by fertiliser application in the cultivation processes, but also by combustion emissions from fossil fuels. On the other hand, climate-relevant nitrous oxide emissions associated with fertiliser application, together with GHG emissions from fertiliser production, have a significant impact on the total GHG potential (GWP) of ATJ-SPK.

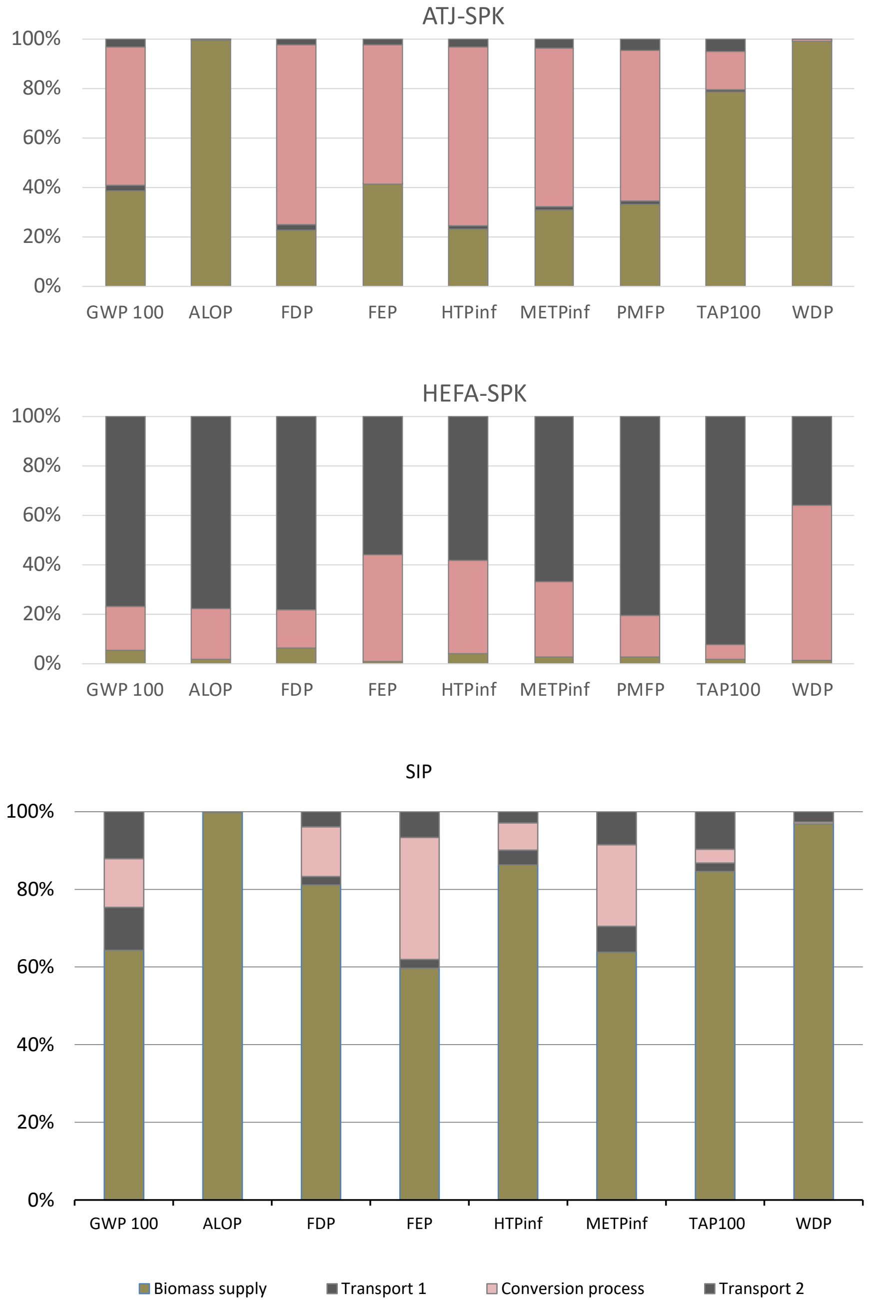

Fig. 18 LCA of the renewable kerosenes under consideration
The following impact categories were considered, according to ReCiPe (H) v.1.13: Global Warming Potential (GWP100), Agricultural Land Occupation Potential (ALOP), Fossil Depletion Potential (FDP), Freshwater Eutrophication Potential (FEP), Human Toxicity Potential (HTPinf), Marine Ecotoxicity Potential (METPinf), Particulate Matter Formation Potential (PMFP), Terrestrial Acidification Potential (TAP100), and Water Depletion Potential (WDP)

The method of presentation in Fig. 18 was chosen, firstly, to show the shift in the main drivers within the life cycle assessment of a process chain and, secondly, to show the disparity between the renewable kerosenes under consideration. This is discussed below using the GHG balances as an example.

GHG balance. A similarly disparate picture as for the impact distribution of the individual process steps is evident in the level and distribution of the total GHG emissions of the renewable kerosenes. These range from 3.1 (HEFA-SPK) to 35.8 g CO_2-eq. / MJ (ATJ-SPK).

These relatively large differences are due to a number of factors which will be explained in more detail using Fig. 19 below. Significant differences in the assessment of emissions from biomass supply are due, firstly, to the raw materials used and, secondly, to the system boundaries selected in this context. While ATJ-SPK and SIP are based on the processing of cultivated biomass, HEFA-SPK uses beef tallow, a raw material declared as waste. This means that the assessment of the supply chain starts with the transport of the beef tallow to the conversion plant; the upstream processes for supplying of the beef tallow (e.g. making it available in a rendering plant) are outside the selected system boundaries because it is declared as waste. Therefore, the specific emissions for the supply of beef tallow are significantly lower than the emissions for the supply of cultivated biomass, which are mainly due to the emissions from fertiliser production, the direct emissions from N-fertiliser application and the emissions from the use of fossil fuels in agricultural machinery.

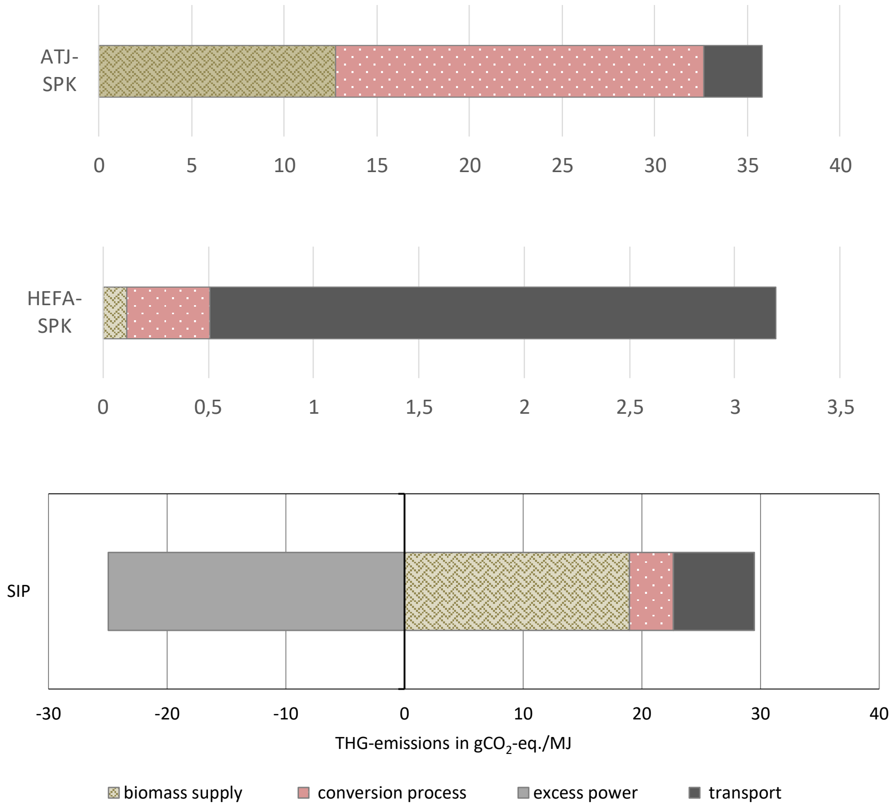

Fig. 19 Specific GHG emissions of the renewable kerosenes under consideration
For the sake of clarity, the x-axis to display the GHG emissions of the HEFA-SPK has been enlarged by a factor of 10.

The emissions associated with the conversion processes also differ greatly. Again in this case, the lowest emissions are caused for HEFA-SPK. The reason for this is the use of co-products supplied within the process to generate the process energy. In this case, it is the use of naphtha, firstly for steam reforming of the production of the required hydrogen and, secondly, to supply process steam. The same applies to conversion-related GHG emissions for SIP. The bagasse produced during the processing of the sugar cane is used with other agricultural residues as the substrate for biogas production. The downstream use of the biogas in a CHP therefore supply the required process energy, which, as is the case for HEFA-SPK, results in a low emission load for the conversion process. Surplus electricity can be used externally and is taken into account by credit. The emission factor of a natural gas-fired CHP was assumed for the credit. This leads to a significant reduction in total GHG emissions for SIP-SPK.

Since the means of transport used, the fuel consumption, fuels and kilometres travelled are subject to approximately the same constraints across all three concepts (cf. description of the logistics chains), there are no significant differences in the level of GHG emissions associated with the transport processes. The high contribution of transport emissions to the total GHG emissions of HEFA-SPK, as already described, is due to the very low GHG emissions of the biomass supply and conversion processes.

The relatively high GHG emissions caused by the conversion processes for ATJ-SPK result primarily from the use of fossil fuels to provide the process energy demand. An increased share of renewable energy in the process energy mix could lead to a significant reduction in total GHG emissions in the future, as the following sensitivity assessment shows. If, as shown in Fig. 20, both fossil heat and electricity are provided by renewable energy, the GHG emissions associated with ATJ-SPK can be reduced by up to 43 % compared to the base case. In this case, it was assumed that heat would be provided by a woodchip burner and electricity by a photovoltaic plant (RE).

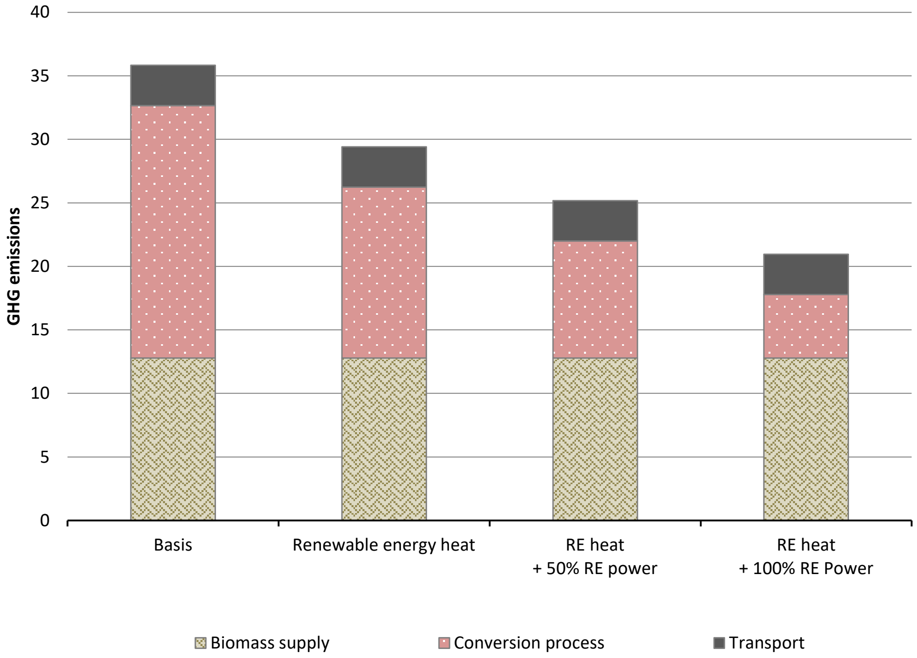

Fig. 20 Sensitivity analysis of GHG balance using ATJ-SPK as an example

6.2.2 *Life cycle assessment of multiblend JET A-1 according to DIN ISO 14040/14044*

Based on the assessment of the individual renewable kerosenes described in section 6.2.1 and the assessment for the supply of the fossil JET A-1[9], life cycle assessments were prepared in the subsequent step for the produced multiblends, including their transport from the tank depot to LEJ Airport and their use in the aircraft.

The GHG reduction of the multiblends for the different supply chains (section 6.1) is described and discussed below.

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[9] The life cycle assessment according to DIN ISO 14040/14044 produced a value of 90 g CO_2-eq. / MJ for the GHG emissions of the investigated conventional JET A-1.

Fig. 21 shows a significant GHG reduction of up to 35 % for the multiblends compared to the fossil JET A-1. The largest contribution to total GHG emissions is caused by engine combustion in the aircraft. The GHG effect of emissions at high altitudes was not considered here; for simplicity, it can be assumed that this effect would be the same for all SPK and multiblends under consideration. As the biogenic CO_2 emissions are not taken into account in the GHG balance[10], the contribution of the fossil JET A-1 is decisive for the balance. This is shown by the higher GHG emissions of case B in contrast to cases A and C. The reason for this is the low blend rate of the SIP and the correspondingly higher ratio of fossil JET A-1 in the mix (section 6.1.3). The GHG emissions associated with the supply of the renewable kerosenes do not have a significant impact on the overall emissions in this composition.

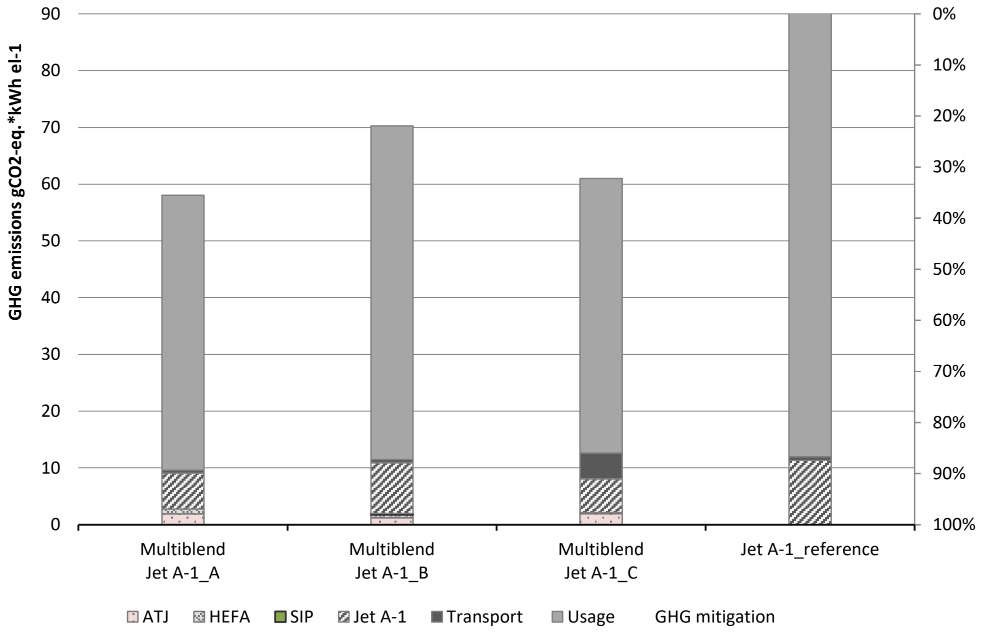

Fig. 21 Specific total GHG emissions and GHG reduction potential of the multiblends JET A-1 compared to conventional JET A-1

6.2.3 *GHG reduction of renewable kerosenes according to EU RED 2009/28/EC*

Biofuels must meet the sustainability criteria of EU RED (and, from 2021, those of RED II) if they are counted towards the applicable national quota (cf. also section 7.2.1.1). In addition to matters of nature conservation and land protection, the core of these criteria is the demonstration of a GHG reduction compared to a defined fossil reference value. For this reason, for the renewable kerosenes used in the DEMO-SPK project, in addition to the life cycle assessment in accordance with the DIN ISO 14040 and 14044 standards (section 6.2.1), the GHG emissions and corresponding reduction potentials were also determined in accordance with the requirements of the EU RED. The method in Annex V of the EU RED is essentially based on the life cycle assessment method already described in detail in section 6.2.1. The specifications and assumptions to be made within the phases of the life cycle assessment allow for dedicated life cycle assessment in accordance with the defined goal. From a scientific point of view, these degrees of freedom are one of the strengths of the life cycle assessment, but the results are difficult to compare because of the often different assumptions and constraints, which is somewhat unsuitable for application in a regulatory framework. A robust and consistent approach is required here. For this reason, the EU RED includes the description of a simplified approach (e.g. the specification of a fossil reference value for determining the GHG reduction) for the calculation of the GHG reduction

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[10] According to the IPCC, biogenic CO_2 emissions are not considered climate-relevant, as it is assumed that the CO_2 emitted during combustion was absorbed when the plant grew; this also implicitly applies to biogenic residual/waste materials.

potential, which must be at least 50% for the biofuel (60% for new plants) in order to count towards the national quota. The following requirements listed in Tab. 21 apply to determining the GHG reduction potential according to the requirements of the EU RED.

Tab. 21 Requirements for determining the GHG reduction potential according to EU RED

EU RED 2009/28/EC or RED II Directive (from 2021)	
System boundaries[11]	Well-to wheel
Characterisation factors	IPCC 2001
Consideration of co-products[12]	Allocation by lower heating value
Fossil reference for determining GHG reduction	83.8 g CO_2-eq. / MJ (RED) and 94 g CO_2-eq. / MJ (RED II)

As can be seen in Fig. 22, the renewable kerosenes under consideration achieve the required GHG reduction of 50 % compared to the defined fossil reference. While a good 57 % of the GHG emissions can be avoided by using ATJ-SPK, for HEFA-SPK there is in fact a 96 % GHG reduction compared to the fossil reference due to the exclusive use of beef tallow declared as waste, as well as the use of co-products generated within the process to cover the process-specific energy demand. For the GHG emissions of the multiblend based on the assumptions of multiblend JET A-1 case A, using the GHG emissions of the renewable kerosenes determined according to the RED and the fossil reference value for the blend defined in the RED would result in a GHG reduction potential of 35 %.

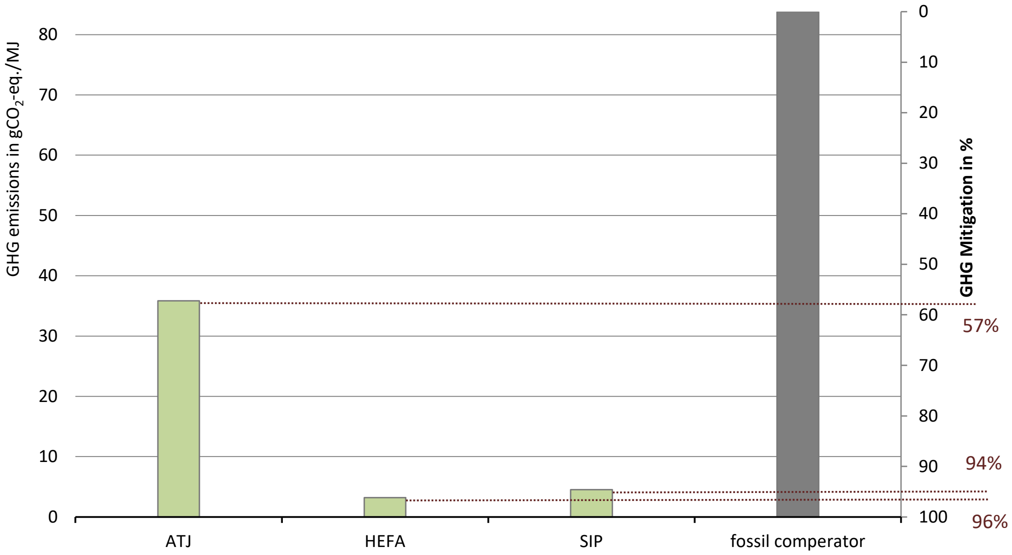

Fig. 22 Specific total GHG emissions and GHG reduction potential of the renewable kerosenes under consideration compared to the fossil reference according to EU RED

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[11] According to RED, no upstream chain emissions are assumed for the use of residual and waste materials. This matches the procedure as described in section 6.2.1.

[12] According to the RED, surplus electricity is taken into account by credit. For this purpose, an emission factor is used for the same type of electricity generation based on fossil fuels, e.g. it is assumed that electricity from a biogas CHP replaces the same amount of electricity from a natural gas CHP, hence an emission factor for electricity from a natural gas CHP is used for the credit.

6.3 Cost consideration

A life cycle cost analysis was performed as a supplement to the ecological assessment for further assessment of the utilised SPK and the multiblend. Here, the goal is to analyse the costs and also the key cost parameters of the multiblend for the supply chains and to classify them in comparison with a fossil alternative. Life cycle costs denote the cumulated costs of a product over its entire life cycle. The Life Cycle Costing (LCC), according to [Deu04], represents the economic analysis process for estimating the acquisition, ownership and disposal costs of a product. Here, the life cycle phases should be selected so that they are adapted to the special requirements of the specific analysis [Deu04]. Under the marginal conditions in DEMO-SPK, the production, transport and distribution, storage and also offsetting in the EU ETS are taken into consideration as life cycle phases of the multiblend.

Calculation of the production costs is essentially based on VDI Guideline 6025. Ecological assessment of the multiblend preparation is undertaken for cases A, B and C. A sensitivity analysis is performed to determine the influence of the individual input parameters on the specific supply costs. In doing so, the effects of the important parameters are analysed. In each case, only one input variable is changed and the effect of this variation on the overall supply costs is analysed [Tur18].

Project-related shipping, logistic and tank depot costs serve as the essential data foundation for balancing the multiblend supply chain for cases A and B. Freight rates, market data and company information are primarily used for balancing case C. The reference year of the analysis is 2018. In the same way, the minimum, maximum and average price for JET A-1 in 2018 will be used as a data foundation for the comparison with a fossil alternative.

6.3.1 *Production costs for renewable kerosenes*

The calculated production costs for renewable kerosenes are compared for the individual production processes in Fig. 23. 806 EUR/t were determined for HEFA-SPK, slightly above this are the production costs for ATJ-SPK with 989 EUR/t and above this is SIP with 1,493 EUR/t. All three kerosene production costs are in the lower third of the literature values according to the compilation by [Zec 16]. The values are 1.3 to 2.5 times higher than the fossil cost price.

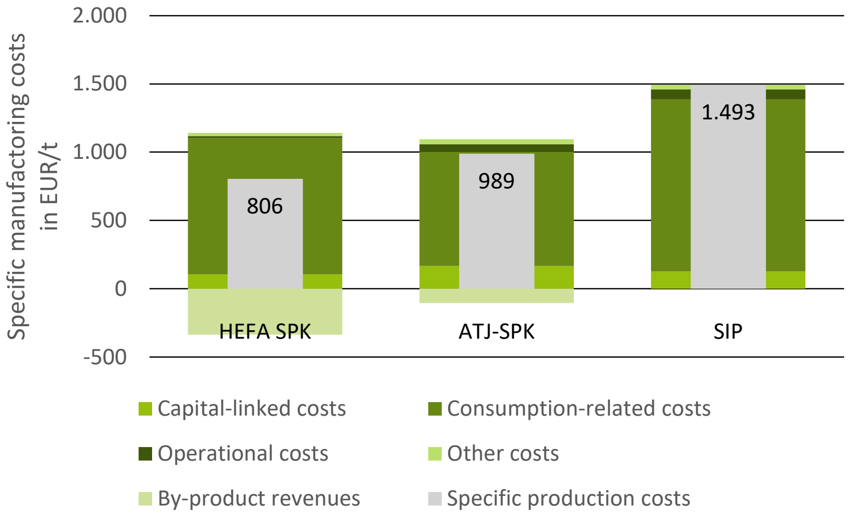


Fig. 23 Production costs for renewable kerosenes

The dependence of the production costs on the consumption-dependent costs is apparent. In each case, these make up more than 80 % of the overall production costs. All other costs amount to just 15 to 30 % of the overall production costs. By-products are another influential factor that can considerably reduce the production costs, especially in the case of HEFA-SPK and SIP.

In the case of HEFA-SPK, the consumption-dependent costs are approx. 87 % of the overall costs, these include the costs for the raw material beef tallow at around 98 %, since the hydrogen required for the process is extracted from the naphtha and fuel gas fraction within the processes and the other external adjuvant is simply drinking / process water. Capital-linked costs amount to a proportion of about 9 %. Operational and miscellaneous costs have very little influence with 1 to 2 %. The costs are reduced in part by profits from by-products, for HEFA-SPK these amount to about 30 % of the incurred costs. The sale of excess naphtha, fuel gas and diesel from production is included.

For ATJ-SPK production most of the costs result from procurement of the raw materials. These costs amount to about 78 % of the consumption-dependent costs, which in turn amounts to about 77 % of the overall costs. Other consumption-dependent costs are incurred for hydrogen as an adjuvant and the provision of power in the form of electricity as well as natural gas and cooling water. Capital-linked costs comprise the second largest component. These amount to about 15 % of the overall costs. The profits from the by-products maize germ oil and distillers' grains add up to about 10 % of the overall costs and correspondingly reduce these.

In the case of SIP production, the largest proportion of expenditure is also used for the supply of raw materials. About 96 % of the consumption-dependent costs are incurred by the raw material. Again, these amount to 84 % of the overall costs. Other proportions of the cost are the capital-linked costs, which amount to about 9 % of the overall costs.

6.3.2 *Supply costs for multiblend JET A-1*

Fig. 24 presents the pure supply costs of the renewable kerosenes or multiblend JET A-1 for the cases A, B and C which, unlike the aforementioned production costs for the renewable kerosenes, include the costs for downstream supply of the multiblend. In the case of A, the determined supply costs of the multiblend are approx. 650 EUR / t. At about 56%, the provision and rent of a suitable tank depot infrastructure for mixing the individual components or storage of the multiblend makes up a majority of the supply costs determined for case A. In particular, this is due to the comparatively smaller moved fuel quantities and the utilised tank depot infrastructure. In the case of an optimised logistics chain in which larger quantities of fuel are (continuously) supplied, especially this proportion can be substantially reduced (see case C).

In case B, on the one hand the multiblend is differently composed with respect to case A, on the other hand about double the quantity of multiblend is obtained. The reduction of supply costs compared to case A (approx. 44 %) results from the downstream supply chain. In case B, in spite of the approximately 2-times overall quantity of multiblend, the same provided tanker and tank wagon infrastructure could be used for storage and blending as well as tank wagon transport from Speyer to Leipzig / Halle airport. With the same prices for provision and leasing of this infrastructure and simultaneously larger overall quantity of multiblend, the specific costs and hence the overall supply costs are reduced. A comparison of case A and B shows that the logistics and infrastructure on which case A is based is excessively scaled for the transported quantities of multiblend JET A-1 due to the originally planned procedure being different (chapter 4.1.4) and that appropriate adjustment offers substantial potential for reduction of the multiblend supply costs.

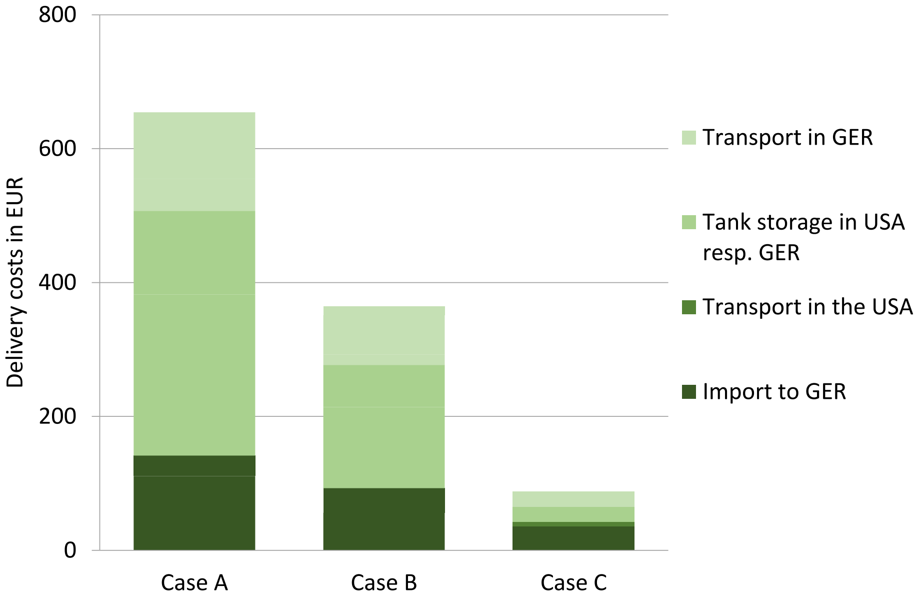


Fig. 24 Supply costs for case A, case B, case C

The optimised supply chain in case C, which was designed for larger fuel quantities, leads to much lower supply costs compared to case A. Compared to case A and B, these are about 87 % or 76 % lower at approx. 87 EUR / t.

In addition to the lower proportion of costs for the use of tank wagon infrastructure, a substantial difference in import costs can be discerned. Whilst these are about 140 EUR / t and 90 EUR / t in case A and B, in case C they are merely about 35 EUR / t. This difference is due to the fact that in case C, the import of multiblend JET A-1 is assumed via product tanker and for larger fuel quantities, which substantially reduces the specific transport costs. By contrast, in DEMO-SPK smaller SPK quantities were transported in special tank containers. Based on the comparative consideration of cases A, B and C, it is apparent that cost reduction potential can be primarily achieved by the provision of larger fuel quantities in conjunction with a coordinated supply chain.

6.3.3 *Life cycle costs of multiblend JET A-1*

The procured quantities of renewable kerosenes are comparatively low in cases A and B – these are merely fuel quantities at the level of a demonstration project, but not representative fuel quantities for actual flight operation of an airline. Hence the life cycle costs are only considered for case C, for which future, industrial-scale manufacture of renewable kerosenes as well as the associated adapted supply chain was assumed. In this way, an appropriate comparability to the fossil reference is portrayed. Life cycle costs of approx. 760 EUR/t for multiblend JET A-1 result from the combination of determined production costs and associated supply costs for case C. Here, costs for the procurement of EU ETS emissions permits for the fossil proportion of the multiblend are less than 1 % and are thus negligibly small. The proportion of logistics and supply of the multiblend components and the multiblend in case C are about 12 % of the overall life cycle costs (Fig. 25).

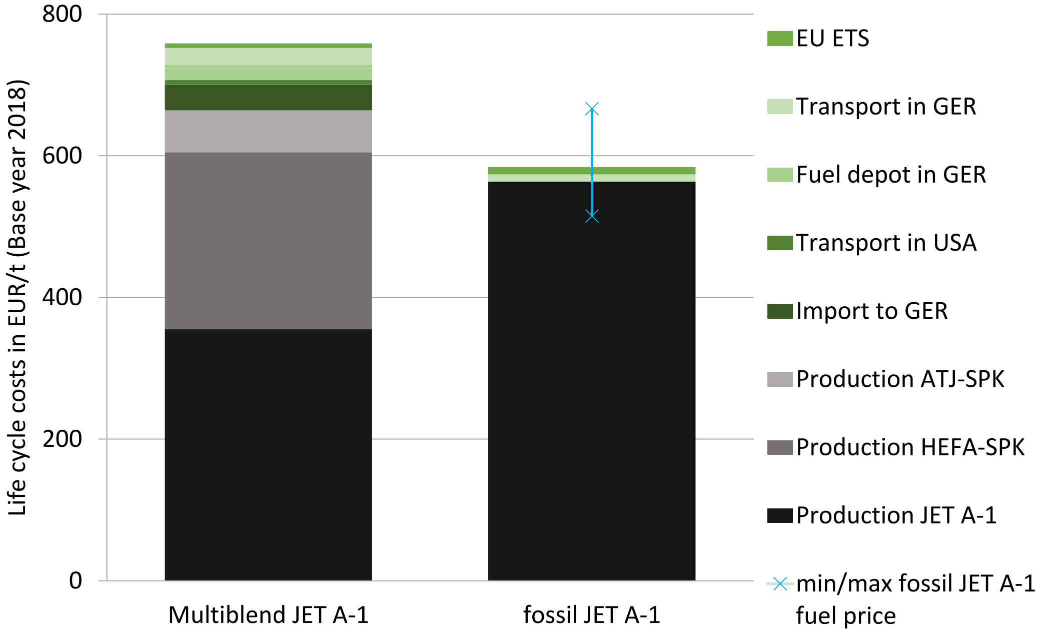


Fig. 25 Life cycle costs for multiblend JET A-1 in case C compared to the fossil reference JET A-1

In 2018, the average price for fossil JET A-1 (ex refinery) was about 560 EUR/t [EIA19]. In consideration of supply to LEJ Airport as assumed here, and consideration of fossil fuel in the EU ETS, life cycle costs of approx. 580 EUR/t result. This remains about 23 % below the determined life cycle costs of the multiblend JET A-1 in case C. Specific GHG abatement costs of approx. 128 EUR/t of saved CO_2 result from the achieved emissions savings due to use of the multiblend JET A-1 and the determined life cycle costs of the multiblend and the fossil reference.

6.3.4 *Sensitivity analysis*

A sensitivity study of the life cycle costs for case C is presented in Fig. 26. The figure shows the variation in the key input variables from -50 % to +50 % and the relevant percentile effect on the life cycle costs of the multiblend for case C.

The results of the sensitivity analysis in Fig. 26 show that a change in the production costs of fossil JET A-1 as well as the raw materials for HEFA-SPK have the greatest influence on the life cycle costs of the multiblend. An increase and reduction of conventional JET A-1 production costs and raw material costs for HEFA production by +50 %/-50 % leads to about 23 % (fossil JET A-1) and 20 % (HEFA) higher or lower life cycle costs. ATJ-SPK has the lowest proportion within the fuel components, due to the actual proportions of the various fuel components in the multiblend. The further parameters for production of the fuel components that were examined in the sensitivity analysis have a much lower influence on production costs and hence on the supply costs of the multiblend. The profits from by-products, particularly in the case of HEFA-SPK (naphtha, diesel, fuel gas) and the investment costs have a higher influence.

Apart from production, the influence of the remaining parameters is much lower. Corresponding variation of the tank wagon freight rates for transporting the fuel from the port of Rotterdam to LEJ Airport leads to about 2 % higher or lower life cycle costs. Variation of the remaining input variables such as tank depot fees, product tanker freight rates or prices for EU ETS emissions permits only lead to a marginal increase or reduction in the life cycle costs of the multiblend (in each case approx. 1 to 2 % higher and lower).

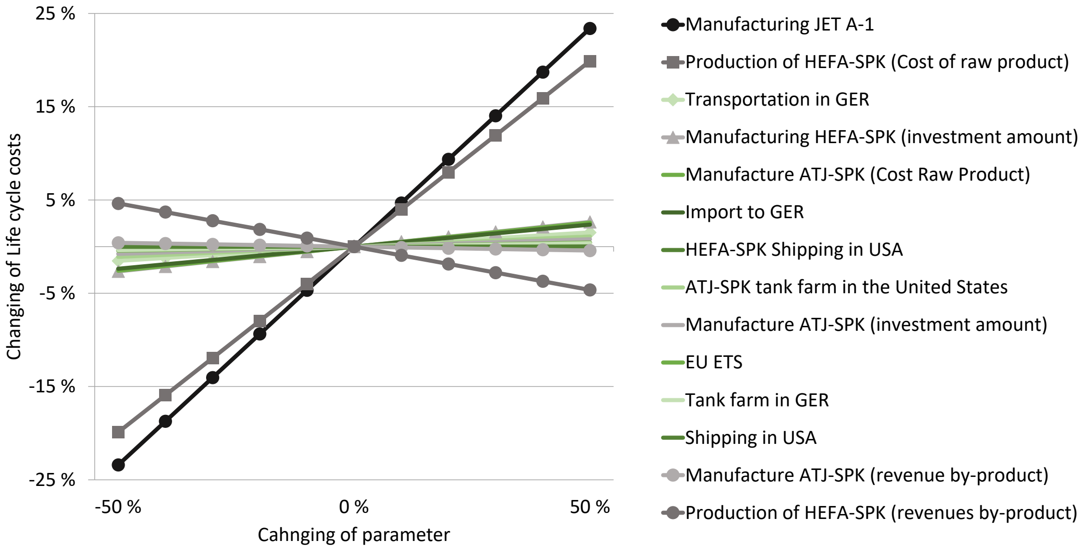


Fig. 26 Sensitivity analysis of the life cycle costs, case C

Ultimately, it is apparent that the production costs of fossil JET A-1 have the key influence on life cycle costs of the multiblend. Raw material costs represent the key cost variables within the production costs both for fossil aviation fuel and also the biogenic HEFA and ATJ aviation fuels. These have a strong dependency on market developments and thus form dynamic cost variables with corresponding fluctuations. Within the framework of future utilisation and discussion of the results presented here, the high dependency of production costs on raw material costs should always be emphasised. Apart from the raw material and production costs of the fossil and biogenic multiblend components, the remaining input variables represent a negligibly low influence on the life cycle costs.

6.4 Summary

The ecological assessment and – especially here – assessment of the overall GHG emissions showed clear benefits on the part of the multiblends. With the mixtures considered here, up to 35 % of GHG emissions can be prevented compared with conventional fossil JET A-1 kerosene. Since the majority of the GHG emissions are caused by combustion of fossil kerosene, the fossil proportion in the multiblend JET A-1 can be identified as the main driver with respect to overall GHG emissions. Thus, with the highest proportion of renewable kerosenes, multiblend JET A-1 case A has the lowest GHG emissions and with 35 % the highest GHG saving compared with fossil JET A-1. A determined look at GHG emissions of the renewable kerosenes shows on the one hand considerable benefits associated with the use of residual and waste materials compared to the use of cultivated biomass, and on the other hand benefits associated with the use of renewable energy to cover the process-specific energy requirements. Correspondingly, the HEFA-SPK concept appears to be particularly beneficial, on the one hand because beef tallow is used here – a raw material that has been declared as waste – which means that upstream processes are not taken into consideration, and on the other hand the naphtha that is provided as part of the process is used for both steam reforming production of the required hydrogen and also for the provision of process steam. The relatively high GHG emissions that are caused by the conversion processes for ATJ-SPK primarily result from the use of fossil energy sources to cover the energy requirements of the process. In perspective, an increased proportion of regenerative energy in the process energy mix could lead to considerable reduction of the overall GHG emissions. This would also be beneficial with regard to corresponding certification in accordance with the Renewable Energies Directive and associated verification of compliance with defined GHG reduction targets. Calculation of the GHG reduction of the considered renewable kerosenes in accordance with the method contained in the RED resulted in up to 97 % reduction for the HEFA-SPK concept.

The cost considerations confirm that even the future industrial-scale manufacture of sustainable aviation fuels alone will not be sufficient to attain costs comparable to those of conventional aviation fuels. Hence higher production costs for multiblends will result. From the cost considerations, the production of fuel components arises as a key influencing factor on life cycle costs of the multiblend JET A-1. It thus also represents a component that largely co-determines the competitiveness and benefits of the use of multiblends or sustainable aviation fuels. In this connection of improving the competitiveness of sustainable aviation fuels, one option is to develop the other by-products from the manufacturing processes. These profits from these by-products represent a possibility of reducing production costs.

The high supply costs of the multiblend in DEMO-SPK are particularly due to the low fuel quantities and the short-term nature of the fuel procurement. The cost considerations show that there is great potential for reducing supply costs here by optimisation of the supply chain and in general should absolutely be implemented for further provision of a multiblend JET A-1 or sustainable aviation fuel. Otherwise, their use is not economically justifiable from the perspective of an end consumer. To do this, the procurement of sufficiently large quantities of fuel is necessary, as is a contractual basis that agrees long-term ties between the contractual parties. However, even with an improved supply chain for the multiblend JET A-1, the supply costs amount to a comparatively low proportion measured against the overall life cycle costs (only approx. 12 % in this analysis). A further cost reduction within provision of a multiblend JET A-1 is insufficient or incapable of substantially influencing the competitiveness of a multiblend JET A-1 compared to conventional aviation fuels.

Even the obligation of an aircraft operator to cover the generated CO_2 emissions for EU ETS-relevant flights with emissions permits is not enough to significantly influence the life cycle costs and hence the competitiveness of multiblend JET A-1 compared to the fossil reference.

As long as the cost reservation relating to renewable kerosenes remains in place, no widespread use is to be expected due to the stiff international competition in aviation. In any case, securing the required future fuel volume – for example, in the case of a future supply to Leipzig / Halle Airport – requires significant expansion of the manufacturing capacities for SPKs at all considered production sites. In turn, the associated investments require secure long-term sales opportunities for the fuel manufacturers for their products.

7 Sustainability documentation and certification

Another important issue for broad market implementation of DEMO-SPK is the development and operationalisation of sustainability documentation and the certification of sustainable aviation fuels under the current relevant regulations for biofuels and aviation in the EU. The task includes the feasibility of verification for multiblend JET A-1 and essentially requires an answer to two questions. Is verification and certification possible for the value chains considered in the project for HEFA-SPK, ATJ-SPK and FT-SPK via PTL? And if yes, what options for such verification exist within the framework of the regulations?

In light of the global relevance of aviation, some selected regulations in third countries as well as currently existing certification systems and extended requirements for aviation fuels are also highlighted. Handouts will still be provided to support the future implementation process.

7.1 Requirements

7.1.1 *Framework conditions of sustainability documentation for renewable kerosene*

Specific framework conditions must exist to develop and secure sustainability documentation and certification along the entire value chain. These conditions form a basis on which the various requirements of sustainability documentation or certification can be orientated and defined:

a. Social and ecological sustainability criteria (e.g. for the cultivation of raw materials),

b. Specifications for the calculation (methodology) and saving of greenhouse gases (GHG),

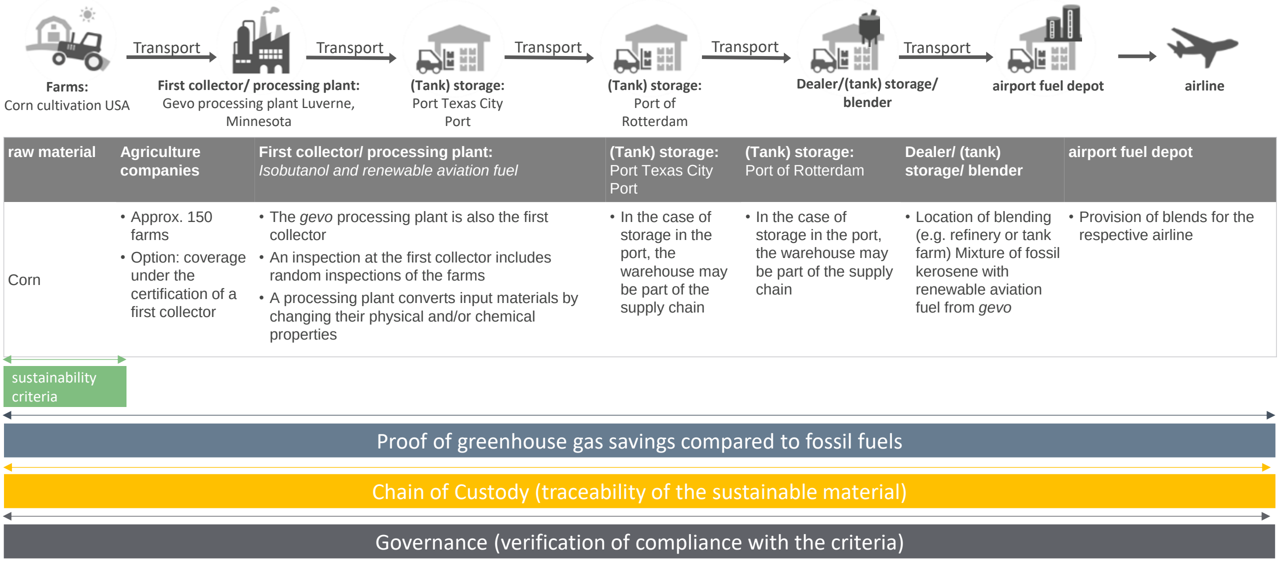
c. Requirements for traceability and verification (chain of custody),

d. Regulations for checking compliance with criteria (governance).

For traceability documentation, the options of segregation, mass balance and book & claim are fundamentally available. Depending on the selected chain of custody model, the traceability requirements and the associated expenditure along the supply chain are different.

7.1.2 *Requirements for sustainability documentation for defined value chains (ATJ-SPK, HEFA-SPK, FT-SPK via PTL)*

The framework conditions defined in chapter 7.1.1 can be applied to the process and supply chains examined in the DEMO-SPK project (chapter 2). The supply chain presented in Fig. 27 shows the production of sustainable aviation fuel of ATJ-SPK, as defined together with the practice partner Gevo Inc. [Gev18]. The first part of the supply chain is comprised by the agricultural enterprises that produce the raw material. For theoretical demonstration of the sustainability documentation, the question of the existence of environmental and social sustainability criteria is already relevant to this part of the supply chain. In the same way, requirements for GHG savings compared to fossil fuels and traceability and governance criteria must be defined along all elements of the value chain. In this case, the primary distributor of the sustainable raw material is the Gevo processing plant in Luverne, Minnesota. Within the framework of sustainability documentation or certification, verification of compliance with the sustainability requirements is effected with the primary distributor. To this end, the supplying agricultural enterprises are randomly checked. Among other things, the magnitude of such a random check is based on a risk assessment and the total number of supplying enterprises. In the processing plant at Luverne, firstly renewable isobutanol is extracted from the raw material via the ATJ process and this is then converted into sustainable aviation fuel, among other things [Gev18]. The finished ATJ-SPK is then transported to the port in Texas and via sea to Europe (port of Rotterdam). Sustainable ATJ-SPK is mixed with fossil JET A-1 or with other sustainable fuels in a tank depot (blending). The multiblend JET A-1 is then delivered to the respective airport tank depot for refuelling the aircraft.



raw material	Agriculture companies	First collector/ processing plant: *Isobutanol and renewable aviation fuel*	(Tank) storage: Port Texas City Port	(Tank) storage: Port of Rotterdam	Dealer/ (tank) storage/ blender	airport fuel depot
Corn	• Approx. 150 farms • Option: coverage under the certification of a first collector	• The *gevo* processing plant is also the first collector • An inspection at the first collector includes random inspections of the farms • A processing plant converts input materials by changing their physical and/or chemical properties	• In the case of storage in the port, the warehouse may be part of the supply chain	• In the case of storage in the port, the warehouse may be part of the supply chain	• Location of blending (e.g. refinery or tank farm) Mixture of fossil kerosene with renewable aviation fuel from *gevo*	• Provision of blends for the respective airline

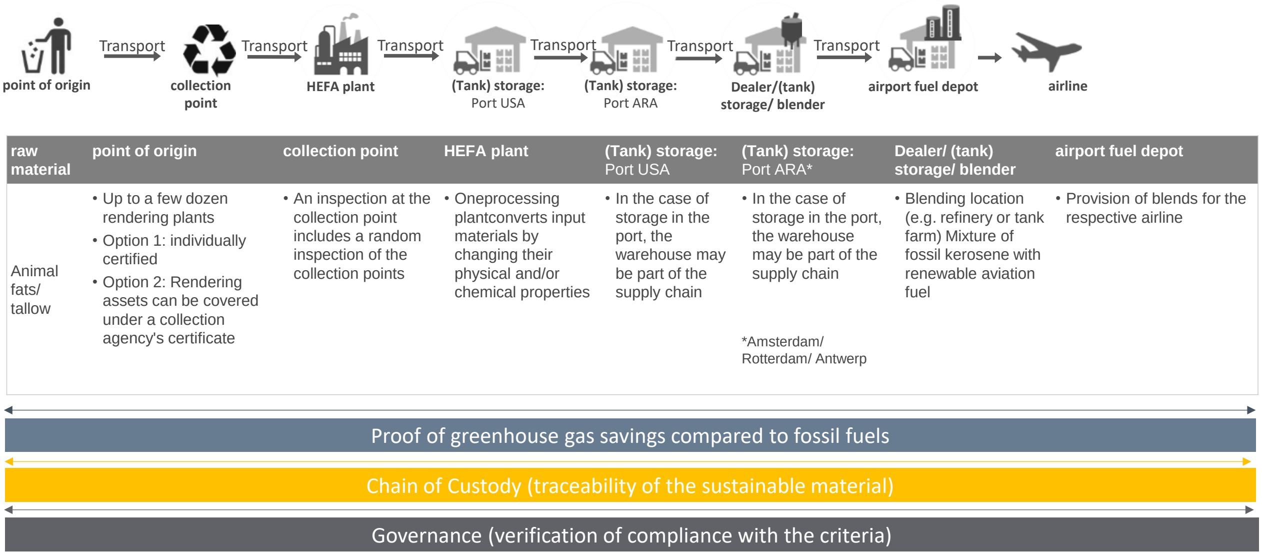
Proof of greenhouse gas savings compared to fossil fuels

Chain of Custody (traceability of the sustainable material)

Governance (verification of compliance with the criteria)

Fig. 27 Requirements for sustainability documentation of a value chain for ATJ-SPK using the example of Gevo (Own representation based on [Gev18].)

Fig. 28 represents the production of HEFA-SPK based on beef tallow, produced by World Energy LCC. The provisions already defined for Fig. 27 apply here, but with the exception that no sustainability criteria have to be met for the cultivation of raw materials as only waste and residual materials are used as raw materials. Nevertheless, it must be ensured that these fulfil the requirements for use as a sustainable raw material.



raw material	point of origin	collection point	HEFA plant	(Tank) storage: Port USA	(Tank) storage: Port ARA*	Dealer/ (tank) storage/ blender	airport fuel depot
Animal fats/ tallow	• Up to a few dozen rendering plants • Option 1: individually certified • Option 2: Rendering assets can be covered under a collection agency's certificate	• An inspection at the collection point includes a random inspection of the collection points	• Oneprocessing plantconverts input materials by changing their physical and/or chemical properties	• In the case of storage in the port, the warehouse may be part of the supply chain	• In the case of storage in the port, the warehouse may be part of the supply chain *Amsterdam/ Rotterdam/ Antwerp	• Blending location (e.g. refinery or tank farm) Mixture of fossil kerosene with renewable aviation fuel	• Provision of blends for the respective airline

Proof of greenhouse gas savings compared to fossil fuels

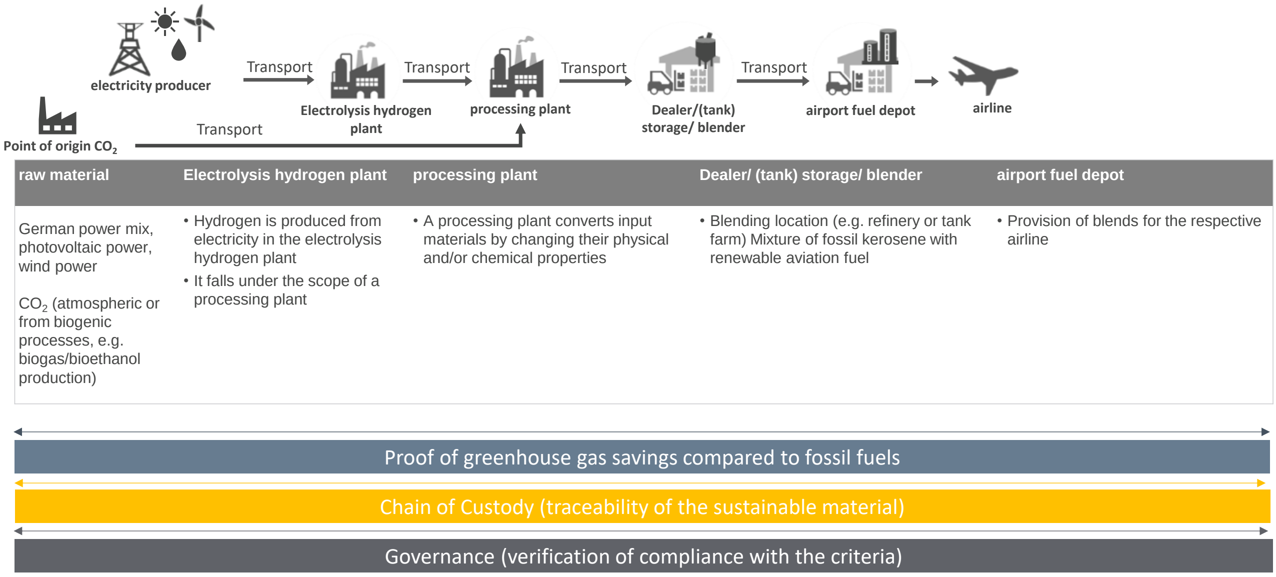
Chain of Custody (traceability of the sustainable material)

Governance (verification of compliance with the criteria)

Fig. 28 Requirements for sustainability documentation of a value chain for HEFA-SPK from waste and residual materials (Own presentation)

With respect to the production process for FT-SPK via PTL (Fig. 29), there are also no land-related sustainability requirements. However, there are provisions regarding the use of renewable energies for the production of PTL fuels.

In order to be able to carry out an audit and subsequent certification along the respective value chain, economic operators must provide extensive information which is verified annually in an on-site audit.



raw material	Electrolysis hydrogen plant	processing plant	Dealer/ (tank) storage/ blender	airport fuel depot
German power mix, photovoltaic power, wind power CO_2 (atmospheric or from biogenic processes, e.g. biogas/bioethanol production)	• Hydrogen is produced from electricity in the electrolysis hydrogen plant • It falls under the scope of a processing plant	• A processing plant converts input materials by changing their physical and/or chemical properties	• Blending location (e.g. refinery or tank farm) Mixture of fossil kerosene with renewable aviation fuel	• Provision of blends for the respective airline

Proof of greenhouse gas savings compared to fossil fuels

Chain of Custody (traceability of the sustainable material)

Governance (verification of compliance with the criteria)

Fig. 29 Requirements for sustainability documentation of a value chain for FT-SPK via power-to-liquid (PTL) (Own presentation)

7.1.3 *Interim conclusion*

Within the framework of EU RED, certification of all value chains considered in the project for the production of renewable paraffin is fundamentally possible. The certification systems recognised by the EU Commission are applicable to all types of biomass as well as other renewable raw materials. Furthermore, the process technologies used for the value chains also correspond to the technical applications that are already certified. Individual auditing and certification of the individual elements of a value chain means that it is possible to map any composition of a supply chain; the documentation requirements for each of the elements guarantees uninterrupted traceability of sustainability information. Ultimately, the methodology specified by the EU RED for calculating GHG emissions offers flexibility that makes it possible to map and include new production paths at any time.

7.2 **Documentation**

The following chapter contains a brief description of the regulations at EU level and the options based on these regulations for verification of sustainable aviation fuels and (multi-)blends discussed in this project. Due to the global nature of the topic, an outlook is also given on some selected non-European regulations and currently relevant certification systems that can serve as the basis for sustainability documentation for sustainable aviation fuels.

7.2.1 *Regulatory framework conditions for verification at EU level*

The regulatory conditions at EU level include the EU Renewable Energies Directive (EU RED) and the EU Emissions Trading Scheme (EU ETS).

7.2.1.1 Certification of biomass and waste / residual materials according to EU RED

The EU Renewable Energy Directive (2009/28/EC) is part of the European Climate and Energy Package and sets out the legal framework for the integration of renewable energy in the EU member states. The Directive is linked to the requirements of the Fuel Quality Directive (DIR 2009/30/EC) for the mineral oil industry and service station operators with the aim of a 6% reduction in greenhouse gas emissions by 2020 [Eur19]. The EU RED II (DIR 2018/2001) was adopted in December 2018 to regulate renewable energies after 2020. Here, a multiplier of 1.2 of the actual energy content is provided for aviation to count towards the 14 % target in the transport sector [Eur18]. For sustainable fuels to be considered sustainable and count towards the transport sector target, it must be demonstrated that they fulfil the sustainability requirements set out by the EU Commission [Eur09]. In addition to minimum savings in GHG emissions, this also includes land-based sustainability criteria for the cultivation of raw materials [Eur09]. Biogenic raw materials that are used for the production of biofuels must not be obtained from land with high biodiversity or high carbon content. Among others, this includes primary and rain forests as well as peatlands. In particular, primary forests have been subject to a ban on land use change since January 2008. Exception: If the respective raw material is a residual or waste material, the area-related sustainability criteria do not apply [Eur09]. To ensure transparent traceability along the entire production and supply chain, the EU RED provides for segregation or mass balancing as chain of custody options. A book & claim process is not permitted [ISC16].

Examination of the above sustainability criteria is covered by voluntary or national certification systems, compliance with which is determined by independent inspection bodies along the supply chain. All voluntary certification systems must be acknowledged by the EU Commission in a 5-year cycle. [Eur19]

7.2.1.2 Verification within the framework of the EU Emissions Trading System (ETS)

The European Emissions trading System (EU ETS) came into force in 2005. It restricts the GHG emissions of around 11,000 energy-intensive installations in the power generation and manufacturing industries in the order of ≥ 20 megawatts as well as in aviation [ICA19]. In aviation, emissions trading has been mandatory since 2012 for all aircraft operators that take off or land flights in the European Economic Area (EEA: territory of the EU member states, Iceland, Norway and Liechtenstein). CO_2 certificates must be obtained for all emissions that are above the permissible exempt amount [Eur16].

The number of GHG emissions a participant in the EU ETS is allowed to emit is continuously reduced. A certificate must be submitted for every tonne of CO_2. The quantity of available certificates is reduced annually. CO_2 certificates can be traded. If a company has more certificates than its emissions require, it can sell them to other participants in the EU ETS. Regulations on monitoring, reporting and verification of the respective greenhouse gas emissions are laid down in the Monitoring Regulation (Regulation 601/2012/EU; shortened: MVO) (see also chapter 8.1 for details of the EU ETS).

EU ETS is linked to the EU RED with respect to the use of biomass. For example, in order to create an incentive for aircraft operators to also directly make increased use of biomass in installations or also in air transport, the EU ETS stipulates that no emissions certificates have to be obtained for emissions from EU RED-certified biomass. [Eur17]

Outside of the EU, other countries have introduced ETS systems including Switzerland, Norway, New Zealand, China, Canada and South Korea [Int19, Dah, ICA19, Int19, Int18, Int19]. Although all ETS have a similar function, there are differences between the individual systems including the consideration of different greenhouse gases, emissions ceilings, time periods for reduction, etc. This makes it difficult to compare the individual systems. Most ETS primarily focus on energy-intensive industry branches, but an increasing number of systems also take civil aviation into account.

7.2.2 *Verification options*

Various verification options for the use and offsetting of sustainable aviation fuels will be discussed and demonstrated within the framework of the DEMO-SPK project. On the one hand, this involves the traceability of the individual SPK value chains defined in the project. On the other hand, transfer of the sustainability information of the utilised sustainable aviation fuels after blending with fossil jet A-1 into a multiblend should also be guaranteed; right up to the airport fuel depot and subsequent fuelling of the aircraft or offsetting under EU ETS. The three options for such verification will be described in the following text:

1. Option 1: Certification of the entire value chain of the sustainable aviation fuel under the EU RED
2. Option 2: Transition from EU RED certification to a book & claim system
3. Option 3: Transition from EU RED certification to a track & trace system

7.2.2.1 Option 1 | Sustainability certification under the EU RED

In option 1 the entire supply chain is certified from the source of the raw material to the last tank depot before the airport tank depot. According to the EU RED, all economic operators in a value chain must be certified (Fig. 30). Sustainability information must be passed on with the physical material from one element in the supply chain to the next. [Eur09]

Analogous to the transfer of sustainability information within the supply chain, the manufacturer of the SPK issues verification of sustainability upon delivery (Proof of Sustainability, shortened: PoS), that must contain additional information about the fuel (see Fig. 30). Irrespective of precisely where the blending of pure sustainable aviation fuel with fossil JET A-1 takes place, all relevant sustainability information remains traceable via the respective mass balance system of the certified supply chain elements.

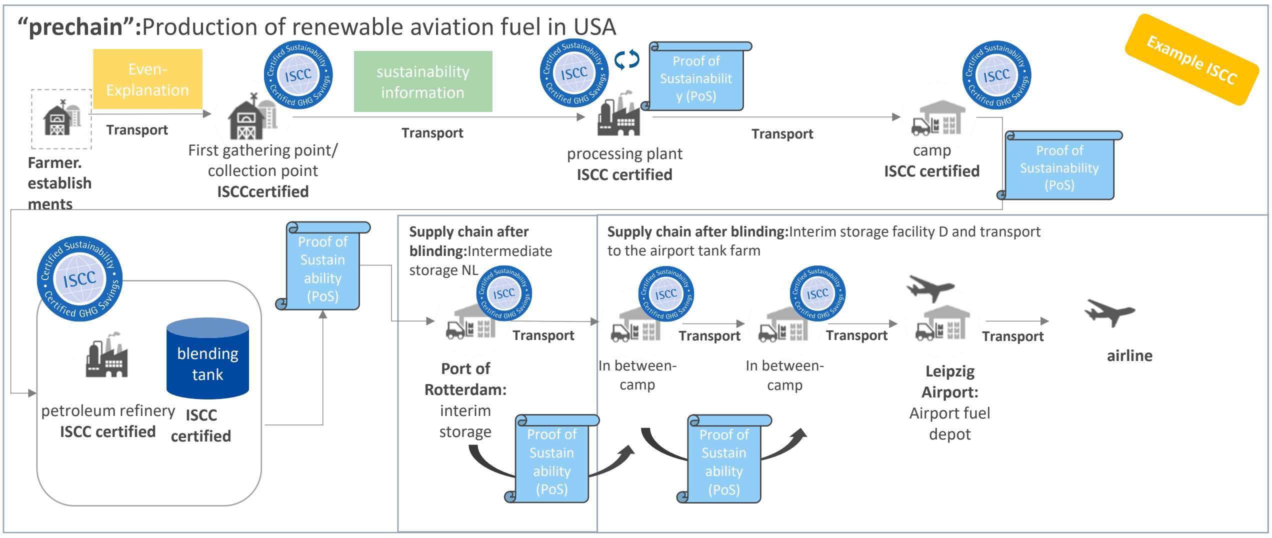


Fig. 30 Option 1: EU-RED certification of the entire supply chain up to a delivery stage before the airport tank depot (Example ISCC. Own presentation.)

The advantage of option 1 that it uses the EU-RED system, which is already globally established and is used in more than a hundred countries [ISC19]. It can be assumed that due to this established structure, transfer of both the pure sustainable aviation fuel and the (multi-)blend across all country borders is possible without any restrictions (e.g. due to different customs regulations). Offsetting of the sustainable quantities in the EU ETS can then be effected at the respective airport depot.

In principle, since the transition from EU RED to EU ETS verification can take place at any point in the supply chain, two combinations are presented below. These are the book & claim and track & trace options developed in DEMO-SPK (cf. chapter 8.2). The system user that is the first in the EU to create or receive a multiblend was chosen as the interface for the transition from EU RED to EU ETS.

7.2.2.2 Option 2 | Sustainability certification interfaces based on the EU RED and book & claim

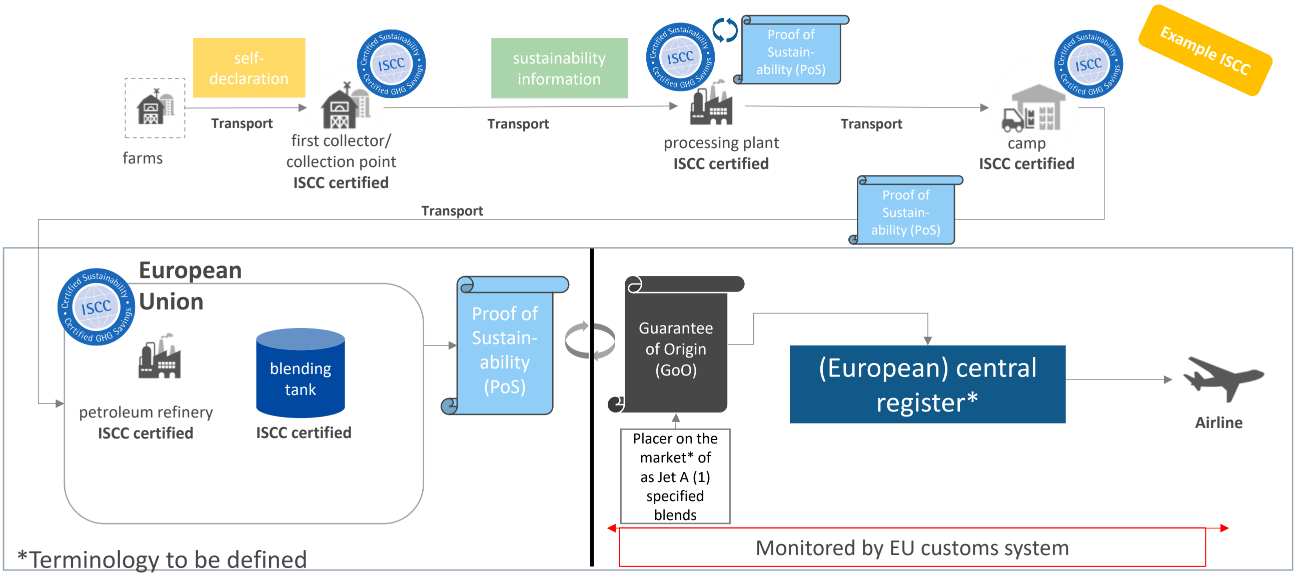


Fig. 31 Option 2: Blending in the EU
If blending occurs in the EU, then the GoO is issued by the blender (example ISCC. Own presentation.)

The option of a book & claim procedure developed in DEMO-SPK represents a solution approach for simplified offsetting of sustainable aviation fuels in emissions trading systems such as the EU ETS (chapter 8.2.2). The approach envisages the use of a system wherein airlines can offset verification of purchased batches of sustainable aviation fuel in the form of a certificate of origin (Guarantee of Origin, shortened: GoO) without necessarily having refuelled the physical material.

In order to avoid double counting the actually produced sustainable aviation fuels and the issued GoOs, and to guarantee barrier-free transition of the sustainability information from one system (EU RED) to the other (Book & Claim), the sustainability information of the respective batch of sustainable aviation fuel must be transferred from the PoS to the GoS and the PoS must be invalidated. Here, there are essentially two conceivable variants:

1. If the sustainable fuel is blended within the EU, resulting in a (multi-)blend specified as JET A-1 when blended, the interface of the two systems is at the place of blending. As shown in Fig. 31, the blending process can take place in a mineral oil refinery or independently of this in a separate tank depot.
2. If the final fuel is blended outside the EU, the sustainability information in the form of the PoS, based on the EU-RED compliant mass balance, is transferred with the physical (multi)-blend until the blend specified as JET A-1 arrives in the EU. This requires EU-RED certification of all intermediate supply chain elements, up to and including the first tank depot in the EU (Fig. 32).

In all cases, the issuer of the GoO is the party defined in the context of this project as the "distributor" (i.e. first accepting owner within the EU) of the blend specified as JET A-1. Various options were discussed for verifying proper issuing of the GoO and the associated transfer of relevant sustainability information from the

PoS. In consultation with the project partners, on-site examination by an independent EU-RED auditor is currently the most plausible solution, since an EU-RED auditor carries out annual on-site inspections anyway and hence no further costs are incurred for additional external examination.

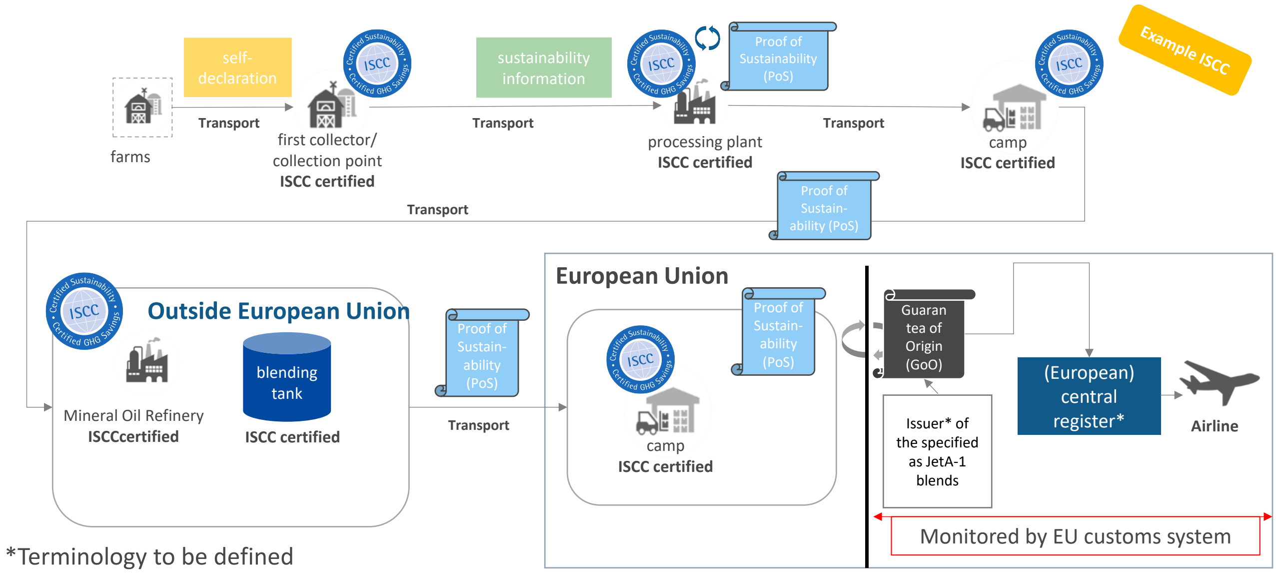


Fig. 32 Option 2: Blending outside the EU
If blending occurs outside the EU, then the GoO is issued by the first recipient of the blend in the EU (example ISCC. Own presentation.)

The issued and acquired GoOs are finally entered into a "central register" to ensure that they can be offset in the EU ETS (cf. chapter 8.1). Examination of the entered quantities in the registry and the corresponding offset quantities in the EU ETS must also be carried out by an independent party.

Another item in this project was the discussion about which sustainability information must be transferred from a PoS to a GoS in order to guarantee complete traceability. In this respect, the following information is defined in order to pass on all data relevant in both systems without omissions: Unique identification number (this is transferred from the PoS to the GoO when the PoS is converted), date and country of issue, energy source (raw materials from which the sustainable aviation fuel was produced and product classification), manufacturing plant of the sustainable aviation fuel (name, location, type) and date of commissioning of the manufacturing plant.

If the conditions described here are fulfilled, a book & claim solution after the EU-RED compliant supply chain is a reasonable way to offset the consumed quantities of sustainable fuel in an ETS system.

7.2.2.3 Option 3 | Sustainability certification interfaces based on the EU RED and track & trace

According to the proposal from project partner Adeptus Green Management, the third option for verification is the track & trace methodology for offsetting sustainable aviation fuels in emissions trading (chapter 8.2.1).

An interface between mass balance-based traceability in an EU-RED certification system and a track & trace system is to be considered analogous to an interface between the EU-RED system and book & claim approach. At this point, the sustainability information of the PoS transitions into a verification of origin (Certificate of Origin, to differentiate from the GoO term in the book & claim concept; shortened: CoO), which is then transferred as verification with the physical blend. Fig. 33 shows the transition between

EU-RED certification and a track & trace option using the example of a blend process outside the EU. Analogous to option 2, the interface can also be within the EU if the aviation fuel is first blended there.

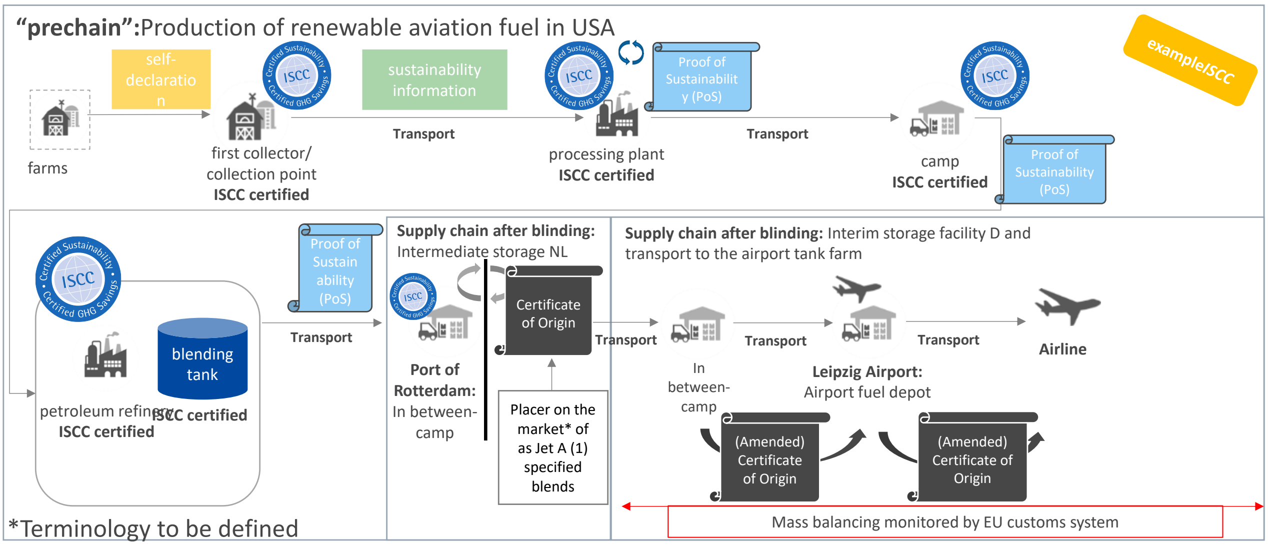


Fig. 33 Option 3: Mass balancing under track & trace
Example of the supply chain before and after blending (non-EU) (example ISCC. Own presentation.)

Analogous to the book & claim option (option 2), the sustainability information defined above would have to be transferred from a PoS to a CoO.

In order to achieve a reduction of information on a GoO or CoO, use of a database in which the relevant sustainability information is stored with a unique identification number is to be discussed for option 2 and 3.

7.2.2.4 Interim conclusion

Fundamentally, all three proposed options achieve the desired objective. Therefore, it is apparent that their excellence should be assessed on the basis of the additional administrative burden.

The additional burden of using an established EU RED certification scheme lies within the certification of manufacturers and warehouses that have not previously conducted transactions under EU RED and the preparation of a mass balance for the EU ETS system.

The additional burden of the book & claim option consists of a Europe-wide register (e.g. "European Central Register") for the examination of GoOs. It is to be assumed that this will be handled by an already-existing institution if possible. The additional burden lies in the creation of the central register (database) and its support.

The additional burden of the track & trace option consists in the establishment of a European Inventory Management and Reporting System (where applicable, extension of the previous functions of the customs system) along the supply chain (database) and the assumption of additional support and control tasks by the main customs offices of the member states.

7.2.3 *Regulatory framework conditions for verification at international level*

Within the framework of the DEMO-SPK project, the EU RED and the EU ETS are used as the regulatory framework for what is considered to be the realistic supply chain of the multiblend. In view of the increasing emissions in international air traffic and the current efforts of, among others, the International Civil Aviation Organisation (ICAO), to develop a uniform mechanism for emissions reduction, relevant regulations for the verification of sustainable biofuels in third countries as well as the global offsetting system CORSIA adopted by the ICAO are outlined below.

7.2.3.1 CORSIA

The CORSIA mechanism (Carbon Offsetting and Reduction Scheme for International Aviation) serves as a climate protection instrument in international aviation and is the first market-based agreement of an entire industrial sector for the reduction of greenhouse gas emissions [Bun17]. It concentrates on international flights. More precisely: Flights that take off in one ICAO member state and land in another ICAO member state. It will be discussed as to whether to continue covering flights within the EEA under the EU ETS whilst flights between the EEA and third countries will fall under CORSIA. Double reporting will apply to international flights within the EEA [DEH19]. The implementation of CORSIA is divided into several phases: Monitoring phase (since 2019), pilot phase (2021–2023), first phase (2024–2026) and second phase (from 2027) [Int18].

7.2.3.2 Selected regulations in third countries

National and regional systems are used as examples of regulations in third countries (outside of Europe):

- National systems such as e.g. (i) USA: Renewable Fuel Standard 2 (RFS2), (ii) Canada: Renewable Fuels Regulation, (iii) Japan: Act on the Promotion of Use of Non-fossil Energy Sources and the Effective Use of Fossil Energy Materials by Energy Suppliers of the METI (Ministry of Economy, Trade and Industry) & 5th Strategic Energy Plan of the METI
- Regional systems such as e.g. (i) California / USA: Low Carbon Fuel Standard (LCFS), (ii) Queensland / Australia: Liquid Fuel Supply Regulation

Since all systems have different requirements in terms of sustainability criteria, GHG calculation and GHG savings, governance and chain of custody, the differences are briefly outlined below:

Sustainability criteria. In some biofuel directives there are prescribed land-based sustainability criteria, e.g. in RED (EU) [Eur09], RFS2 (USA) [Far19], Liquid Fuel Supply Regulation (AUS) [Sta17]. In part, compliance with these criteria is verified via independent international standards (e.g. in Australia by ISCC, RSB and Bonsucro).

GHG calculation. In the EU RED emissions from agricultural production, industrial processing and transport are calculated using default values, actual values or disaggregated default values. [Eur09] In RFS2 (USA), emissions are calculated using so-called renewable fuel pathways, based on the components: starting material, production process and fuel type. A life cycle analysis (LCA) is conducted and approved by the Environmental Protection Agency (EPA)[Uni]. In Australia, calculation of the GHG emissions is required via the application of ISO standards [Sta17]. In Japan, default values are provided for the import of bio-ethanol with respect to ethanol from Brazil and USA by the Ministry of Economy, Trade and Industry (METI) [ISC18].

GHG savings. The individual regulations specify how high the GHG savings of the fuels must be compared to fossil energy sources. While under the EU RED, fuel savings are specified depending on their production period (e.g. 50 % for production before 2015, 60 % from 2015) [Eur15], the RFS2 makes provisions for different saving targets per fuel type [Uni]. Fundamentally, most of the analysed systems have specifications for GHG saving but refer to different reference values.

Chain of custody. Under the EU RED, the requirements for the chain of custody are either mass balance or segregation. Under the RFS2, a mass and energy balance of all main, intermediary and by-products is required to define the individual "pathways" [Uni]. Under the RFS2, so-called RINs (Renewable Identification Numbers) can be generated after the final biofuel has been produced. These can be separated from the fuel after blending and traded independently [Uni]. Since the LCFS and the Liquid Fuel Supply Regulation (AUS) work with "pathways" or LCA methods to determine the respective GHG emissions along the entire supply chain, concrete determination of the chain-of-custody methods for these systems is difficult [Cal19]. In Japan, a mass balance for traceability is foreseen within the framework of sustainability certification [ISC18].

Governance. In most regulations, examination by independent parties is now mandatory (e.g. EU RED, Liquid Fuel Supply Regulation (AUS), LCFS (California) [Eur09, Sta17, Sta19]. In Japan, at least for bio-ethanol, verification by third parties is envisaged within the framework of sustainability certification [ISC18]. Under the RFS2, approval of the biofuel "pathways" is taken over by the EPA [Far19].

7.2.3.3 Standards in third countries

Sustainability criteria are being increasingly taken into account in international regulations for sustainable fuels. In addition, some of the standards recognised by the EU Commission as voluntary certification schemes are also applied internationally, as these not only cover the EU requirements but also provide a basis for the fulfilment of certain sustainability criteria. In addition, an internationally recognised sustainability standard offers the possibility of covering supply chains that extend across different locations and countries. In this way, for example, the systems ISCC EU and ISCC PLUS, RSB Global, RSPO or Bonsucro are being utilised by system users for the verification of sustainability requirements in Japan, Australia and the USA [ISC18, Sta17, ISC19, Air].

7.2.4 *Existing certification standards and other sustainability requirements*

The following chapter provides an overview of the minimum requirements of the certification systems that are used under EU RED and recognised by the EU Commission. Some of the currently recognised systems are examined in more detail and relevant similarities and differences are described. Additional requirements for sustainability certification and documentation that may be relevant for the development of a meta standard are presented.

7.2.4.1 EU RED standards

In order to be allowed to import biofuels, and hence also sustainable aviation fuels, into the EU or to produce them there, these must be certified in accordance with the EU RED requirements. The European Commission has recognised a number of certification schemes for this purpose. The recognition of individual schemes is reviewed at regular intervals and can be viewed on the homepage of the EU Commission. As of February 2019, 14 certification systems are recognised [Eur19]. Seven of the 14 recognised systems cover the entire value chain (ISCC EU, Bonsucro EU, RSB EU RED, RTRS EU RED, 2BSvs, REDcert, Better Biomass) [Eur19]. These are fundamentally also suitable for the certification of sustainable aviation fuels, but in some cases they differ significantly in their requirements level with respect to sustainability, chain of custody and governance.

7.2.4.2 Other sustainability requirements

One of the important future tasks will be to define the "sustainability level" that sustainable aviation fuels should fulfil – e.g. via a meta standard. The requirements to be discussed include changes to the legal basis at EU level that will result when EU RED II comes into force in 2021, such as the exclusion of certain fuels (e.g. those with a high risk of indirect land use change) [Eur19]. Other topics include the use of a database and innovative remote sensing tools that can significantly reduce the certification burden, and support for small farmers.

7.3 Summary

Sustainability certification of sustainable aviation fuels is fundamentally possible. It can be effected for all value chains defined in the project (ATJ, HEFA, SIP and PTL). There are fundamentally three viable options for demonstrating sustainability for the transition from the EU RED to the EU ETS regime. Option 1 includes EU-RED certification along the entire supply chain up to the supplier for the airport depot. In option 2 and 3 sustainability certification is limited to the supply chain up to the point of blending and/or arrival of the blend in the EU. At this point, the transition from a Proof of Sustainability to a Guarantee of Origin for the book & claim option or Certificate of Origin for the track & trace option takes place.

Assistance for the implementation of next steps. In order to ensure smooth implementation of any of the above options, it is necessary to agree the level of sustainability requirements in a stakeholder-based process. To this end, hand-outs were developed that support future organisation and process steps, and a tool was provided that can be used to create a meta standard against which already-established certification systems can be benchmarked.

Implications of implementation within the European and international context. With regard to the development of a meta standard, it should be noted that differentiation must be made between a European and an international approach since a European solution necessarily contains the specifications of the EU RED. For this process, differentiation is made between two cases. Case A is the development of a meta standard based on the EU-RED requirements. Accordingly, this exclusively requires consideration of the criteria specified by the EU RED. Case B represents an extended meta standard, although the legal basis of this continues to be the EU RED. This contains requirements in the areas of sustainability, chain of custody and governance that go beyond the EU criteria. The development of such additional criteria should take place in a multi-stakeholder process. Existing meta standards such as the aireg meta standard and the available tool can be a helpful basis for this [Avi13]. Case C considers the development of an international meta standard. Such a standard can be orientated on the relevant legal requirements in the EU as well as in third countries (e.g. RFS2 in the USA, LCFS in California, etc.) and CORSIA as an international mechanism. The aim of such an approach is to combine those elements from the different systems that show similarities in the areas of sustainability, chain of custody and/or governance. However, due to the in part very different approaches of the regulations, this cannot be implemented in the short term and is rather part of a medium-term adjustment that is to be discussed.

8 Conceptualisation of a crediting methodology for emissions trading

Sustainable aviation fuels (SAF) can be used without restriction as drop-in fuel both in the existing supply infrastructure and in existing aircraft fleets. Although this has been demonstrated many times, their use in commercial aviation has thus far been limited. In addition to high production costs compared to conventional aviation fuels, the hitherto insufficiently operationalised approach to obtaining emission reduction certificates, for example in the European Emissions Trading Scheme (EU ETS), represents another barrier to market entry.

For flights that are subject to a greenhouse gas regulation mechanism such as the EU ETS, airlines offset their CO2 emissions by purchasing emission certificates (e.g. EU ETS emissions permits). Alternatively, an airline can reduce its emissions by purchasing and using SAF – due to their advantageous emissions balance – and thus reduce or potentially avoid the purchase of emissions permits. In order for an airline to be able to prove and offset the use of SAF to an authority in the case of an area-wide use of SAF, practicable procedures are required with which e.g. consumed SAF quantities and sustainability proofs can be documented, checked and passed on and tracked along the provision chain with little administrative effort. These requirements are not met by the existing procedures, which are neither coordinated with each other nor do they follow a holistic, practical approach – which is clearly illustrated by the example of the EU ETS. Hence in the context of reducing barriers to market entry and paving the way for the seamless and widespread use of SAF, practical procedures for the verification and crediting thereof are also absolutely necessary.

8.1 Status of existing offsetting systems in the EU ETS

Aviation was integrated into the EU ETS in 2010. Since 2012, aircraft operators have had to cover their emissions for flights within the European Economic Area with emissions permits [Eur08]. In contrast to conventional aviation fuels, an emission factor of zero is currently used for SAF in the EU ETS, provided they meet the sustainability criteria of the EU RED. Hence they are deemed to be emissions-free [Eur18, Eur12].

In the EU ETS, only the physical consumer of SAF was originally eligible for offsetting. The most realistic possible allocation of the fuels used to the respective flights was required (per flight approach). Using the existing fuel supply infrastructure or especially at large commercial airports that rely on pipeline systems and/or jointly operated tank depots[13], it is only possible to a limited extent, if at all, to provide proof of consumption of the actual physical composition of consumed fuels since –at the latest – fuels of different origins are continuously mixed at the airport tank depot and SAF and fossil fuel molecules stored in the tank depot can no longer be tracked separately. Dedicated and individual aircraft refuelling with fuel mixtures of a desired, individual composition cannot be implemented here, since each future draw-off from the airport fuel depot contains an SAF component. The system is designed to accommodate aviation fuels of a single fuel type, without separation of different fuel batches and/or properties [Eur18].

In light of this problem, the offsetting of SAF for airlines was made more flexible by means of a mathematical / financial offsetting approach. In actual and large-scale use, SAF are introduced into the common fuel infrastructure at the airport (airport fuel depot, tanker trucks, open field refuelling systems) at the latest and are hence also physically refuelled and consumed by all aircraft operators operating at the location. However,

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[13] Aviation fuels are a standardised product that allows unified operational handling and avoids separate logistics for different fuel batches. With respect to the supply of fuel and refuelling of aircraft, different fuel suppliers / distributors therefore usually use a common infrastructure (e.g. tank depots and pipelines) where mixing of individual fuel batches is unavoidable. This collective use of infrastructure is expedient from a technical perspective and is advantageous from an ecological and economic perspective since the logistics complexity and infrastructure requirements as well as transport-related emissions and costs are reduced.

offsetting is only desired for the aircraft operator that has purchased the sustainable fuel and has thus paid for the sustainable properties of the fuel. Here, a corresponding allocation for offsetting the purchased and remunerated SAF is only possible in the balance sheet.

As a further development of the "per flight approach", a financial approach can therefore be used in which the SAF quantities used are accounted for on the basis of invoicing documents from fuel suppliers. The SAF proportion results from the quantities of sustainable fuel delivered to the respective airport fuel depot on behalf of an aircraft operator over a certain delivery period, and the total quantity of fuel refuelled for EU ETS relevant flights of the aircraft operator at the respective airport within the same period of time. In this offsetting procedure, the respective airport or the respective airport fuel depot represents the balance limit [Eur18, Pel19].

Although this approach eliminates the strict allocation of EU ETS relevant flights and the physically consumed fuels, this procedure has neither been operationalised in a practical way nor harmonised across the EU ETS to date. On the software side, systems for the storage of aviation fuels are also not designed (across the board) for the financial offsetting procedure, as they only measure physical deposits and withdrawals in order to determine the inventory and, with regard to the use of the consumption quantity, rely on feedback from fuelling services on their performed aircraft fuelling operations. The complexity of this approach is further increased when an aircraft operator at an airport operates EU ETS relevant and non-EU ETS relevant flights as well as flights under different climate instruments (e.g. EU ETS and CORSIA). Here, differentiated verification and offsetting of fuels as well as the testing and verification of use of SAF via recognised verifiers and competent authorities for emissions trading is neither manageable nor cost-efficient with today's procedures, especially in the case of the widespread use of SAF.

In addition, the aircraft operator must provide RED-compliant sustainability proofs to offset the SAF quantities in each case, without which the renewable aviation fuels are considered conventional and the aircraft operator must subsequently acquire a sufficient quantity of EU ETS emission permits [Eur18, Eur12, Eur09, EEA19]. The required sustainability certificate as well as relevant information about the sustainability characteristics of an SAF must therefore accompany the physical fuel along the supply chain to the airport fuel depot. However, the current logistics, existing procedures for verification and relevant documentation foundations in the transport chain are not designed for this, which may require separate fuel logistics up to the airport fuel depot. The upstream existing infrastructure of the fuel supply system and thus also the drop-in potential of the fuels remain unused under these conditions, which is technically unnecessary and ecologically and economically disadvantageous.

Overall, a holistic verification and offsetting procedure for SAF has been lacking in the EU ETS (as well as globally) to date. Widespread use of SAF requires extension of the EU ETS system / balance limit to the entire fuel supply system and developing suitable procedures for verification (chain of custody[14]) and offsetting.

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[14] A chain of custody designates the chronological physical or electronic verification and/or documentation of the purchase, transport, control and transfer of a product or certain product properties (e.g. sustainability properties) or the method of linking properties of raw materials / intermediate products (e.g. sustainability properties of a raw material) with end products [IPI10, Eur13]. Chain of custody concepts are usually differentiated into the three options "physical separation", "mass balance" and "book & claim" [Deh07, Sta15].

8.2 Conceptualisation of possible offsetting procedures

If an aircraft operator decides to reduce its emissions through the use of SAF, the accounting options track & trace and book & claim fundamentally facilitate effective offsetting of these fuels in a greenhouse gas regulatory system such as the EU ETS with respect to financing. The basic principles and binding requirements of both approaches are described below using the example of the EU ETS.

8.2.1 *Track & trace*

Within the framework of the track & trace approach, the identity of the manufactured fuel quantity must match the corresponding certificate quantity. This is ensured by complete tracking of the supply chain of SAF, i.e. from its origin to its storage, blending and transport to the airport fuel depot, by implementing transport-accompanying provision of the required documents that accompany the physical flow of goods every time it is moved and placed in storage. This can be affected by means of electronic data transmission and does not necessarily require a paper document accompanying the transport.

However, the precise tracking of quantities in the track & trace procedure comes to an early end at the airport fuel depot, because the storage and retrieval of quantities does not have to follow any mandatory sequence and, moreover, due to the joint storage of different production quantities with simultaneous joint retrieval to all aircraft awaiting refuelling, the identity of product and product property (i.e. emissions benefit) is lost through operation of the airport fuel depot. Since the airport fuel depot is also subject to customs monitoring for the proof of use of tax-exempt aviation turbine fuel and all fuel recipients report their quantity data back to the airport fuel depot via the apron fuel services, the calculated verification of use can be documented and tracked without omissions in the airport fuel depot. Since the identity of the product is inevitably lost in a communal tank, the special feature of the track & trace procedure is that the tank depot operator can precisely evaluate SAF stocks with quite different emissions reduction factors using a conventional consumption tracking procedure and, based on the total consumption of aviation fuels, mathematically allocate them to the respective owners of the product quantities and thus verify the consumption. With regard to the currently discussed reform of the EU RED by amending the offsetting methodology to raw material-specific offsetting values, the track & trace procedure can also emissions-congruently map multiblends and hence enable the respective owner or seller to issue an adequate certificate.

Simply put, within the framework of the track & trace approach the manufacturers and subsequently the owner of a fuel mixture are obliged to carry the calculated quantity shares of the sustainable aviation fuels in a mixture in the (transport) documentation all the way to the airport fuel depot, although physical separation in the mixture is no longer possible. In the airport fuel depot, the quantity accounting for the stocks of individual shareholders or third parties is expanded accordingly.

The airlines and the product vendors are required by regulation, via their concession contracts, to disclose the volume-related contract components for SAF to the tank depot operator and to Customs as the regulatory authority. In this way, financial verification of consumption can be presented in the quantity accounting of the airport tank depot and reported back to the seller of the SAF for the issue of corresponding certificates. Since the quantity accounting of an airport tank depot is subject to customs supervision due to the tax exemption in commercial air transport, the end-user verifications of use of SAF can also be included in customs supervision in the sense of the EU ETS.

Workshop findings

Together with representatives from Customs as the competent authority for tax warehouses, representatives of a service provider in the field of aircraft fuelling and also providers of special software for the storage of aviation fuels, a workshop was held on issues relating to the presentation of mixture proportions in quantity accounting of a warehouse operator within the framework of a track & trace approach.

The software products of both providers are recognised by German Customs as a data provision foundation. Hence there is approved software for checking the tax exemption for aviation turbine fuel. To date, the scope of the Customs audit has covered the tracking of quantities and consumption of aviation turbine fuel by entitled persons[15]. According to information provided, checking the consumption of SAF for the purpose of issuing certificates in emissions trading is not currently a task performed by Customs. However, it is thematically obvious to place the monitoring obligations for SAF in analogy to the monitoring of duty suspension also with the customs authorities, since these act on behalf of the Federal Ministry of Finance and in order to involve a national authority in the monitoring of SAF. However, the proof periods for the tax exemption and for the emissions offsetting must be harmonised in this solution.

In the framework of quantity tracking based on mass balance, it should first be noted that inventory management in the stock quantity management of both providers is affected in a volumetric manner. The expansion behaviour of the aviation turbine fuel during longer storage time in a storage tank with an increase in quantity and simultaneous decrease in density is recorded in both software products by means of calculated correction factors and the additional stock is accredited to the respective stockholders (owners) for accounting purposes without any tax implications. This accreditation procedure is recognised by customs. Dead stock in the pump sump of a tank as well as dead stock in pipes and hydrant systems may also be initially stored under tax exemption as long as the final use has not yet been determined. In quantity accounting of active stocks, these dead stocks are attributed to the tank depot but not to the stock level of individual stockholders. For recording the sustainable fuel proportions in the inventory management of an airport tank depot, the dead stock quantity in the tank depot is therefore not relevant with respect to consideration of the sustainable fuel proportions.

Stocks are generally managed in the quantity accounting of a tank depot operator according to the first-in-first-out (FIFO) method of inventory change. Accordingly, the stored product quantities physically leave the warehouse in the sequence in which they were put into storage. If this is the case, a stored mixture or blend of sustainable and conventional JET A-1 shall also be transferred to offloading in the FIFO sequence and the physical stock of the blend of sustainable aviation fuel and JET A-1 shall be delivered to all aircraft receiving aviation turbine fuel from the offloading tank by way of common storage of all stocks. Since the mixture of sustainable fuel and JET A-1 meets the certification requirements of ASTM D1655 and the JET A-1 specification, separate declaration of the mixture with respect to the receiving airline is not required.

With respect to the physical storage and retrieval of a mixture, in this respect the physical storage location and removal from stores can be roughly tracked right up to the complete emptying of a tank. However, the transfer of ownership to the aircraft of an airline (in the sense of the end user certificate) cannot be traced from this. Therefore, in the inventory management of the airport fuel depot, it must be taken into account in future that removal of SAF in accounting can be completed independently of physical removal of the storage quantity in which the mixture is located.

The decisive factors for removal in accounting are the supply contracts between airlines and stockholders in the tank depot, which contractually provide a mixed supply of sustainable aviation fuel and conventional JET A-1. Here, the wording of these supply contracts is a bilateral matter between the seller and the buyer, and the result of the negotiations must be accounted for by the warehouse operator of the airport tank depot. For example, an airline may demand that all of the airline's aircraft at an airport be fuelled with a specified

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[15] This must be distinguished from consumption subject to normal taxation, such as ferry flights without passengers and/or cargo, test flights, engine test runs or flushing quantities after tank cleaning.

percentage of sustainable fuel. Alternatively, the airline could also specify that a defined quantity of SAF be delivered to it in the form of a blend over the course of a month. These contractual specifications can be mapped in accounting inventory management by means of the daily refuelling quantity feedback from the tank services to the tank depot operator for all aircraft refuellings, if management of the SAF quantities in blended form is tracked in a so-called "second accounting level" in addition to the purely quantity-based inflow and outflow movements.

This implies that in order for the verification of use to be recognised, sellers and end users will be required to disclose to the tank depot operator the volume and chosen type of aircraft refuelling from a supply contract, so that the tank depot operator can transfer the "accounting consumption" from the tank quantity information of the tank services to the "second level of accounting". This applies both to binary blends of renewable aviation fuel and conventional JET A-1 and also to multiblends of several sustainable components in a mixture with JET A-1 outside of physical blending due to joint storage with the JET A-1 of other stockholders in an airport tank depot.

The accounting representation of consumption of an SAF based on contract specifications does not necessarily correspond to the physical consumption due to removal of a tank from storage for the purpose of aircraft fuelling. Thus, in accounting terms, there may still be a stock of SAF at the "second accounting level" for a stockholder even though the physical stock has already been completely consumed by withdrawal of a tank from stock with a mixture of sustainable fuel and conventional JET A-1 because all recipients have been supplied from this tank.

For quantity tracking by mass balance by way of the track & trace procedure, the customs tax warehouse keeper will therefore split the mixture quantities they store into renewable components and JET A-1 for accounting purposes, in order to be able to manage a virtual sustainable aviation fuel inventory. This also applies in the same way to the administration of multiblends. For this purpose, the composition of the multiblend must be known in order to be able to record and track the individual sustainable components in terms of quantity. However, the different sustainability rating of individual components is not a criterion to be documented for the warehouse keeper, who only documents the quantity accounting in the "second accounting level" quantitatively for a quantity management that differs from physical stock removal. The assignment of offsetting values for individual sustainable aviation fuel types is the responsibility of the seller, who must take this circumstance into account when issuing certificates. This applies in particular to the amendment of the EU RED currently in progress, with possible limitation of CO_2 credit to the actual CO_2 saving or a raw material-specific "default value", which will then be applied. It is therefore possible that in future SAF will no longer be counted as "emissions free" in a generalised way, but that their respective CO_2 savings will be reflected in the EU ETS according to EU RED. In any case – that is, in the case of a sustainable aviation fuel with only one alternative fuel type as well as with presence of a multiblend – the warehouse keeper reports his stocks back to his stockholders daily in the "second accounting level". In accordance with the supply contracts available, for each aircraft refuelling of a contracting party wishing to be refuelled with SAF, the warehouse keeper also books the specified quantity of SAF outflow from each refuelling as consumption in the "second accounting level" and thus reduces the SAF stock of a stockholder to the extent of the contract rules that are to be observed. The consumption quantity of SAF of a stockholder to be determined in this way authorises the stockholder to issue a corresponding consumption certificate to the seller of the sustainable fuels (previous owner) as well as to Customs as the supervisory body of the tax exemption, which in turn is converted into a certificate by the seller.

Since all consumptions of a tank depot are subject to fiscal control, confirmation of SAF consumptions to aircraft in terms of the end user certificate can also be provided in an auditable manner. Confirmation of the tank depot operator is affected to the owner, who in turn can issue (or is issued) certificates for this quantity. The congruence of certificate quantities with the consumption quantities of an airport tank depot can therefore be documented and proven quite easily, provided that the airport tank depot has a "second accounting level" in its quantity accounting and the contractual specifications from the supply contracts are disclosed to the depot operator in order to be able to implement these regulations in the inventory management of a stockholder.

8.2.2 *Book & claim*

The book & claim approach is an alternative, flexible approach for offsetting sustainable aviation fuels. This approach is established in practice, e.g. for the marketing of electricity from renewable energy sources, heating / cooling and biomethane in the German and European energy sector [UBA17, UBA18, den10]. Book & claim is already listed as a concept for the crediting of renewable aviation fuels in the guidelines of Regulation 601/2012/EC (Monitoring Regulation), but there are no formulations for a conceptual design [Eur18]. Against this background, the basic design of a book & claim concept and its essential functioning is required, taking into account the specific framework conditions of (European) air transport. Building on this, the detailed operationalisation of this approach is to be investigated and developed.

Compared to other chain of custody concepts such as physical separation or mass balance, a book & claim approach completely removes the separation of certified and non-certified products. To this end, the sustainability characteristics of an SAF batch are transferred to negotiable Guarantees of Origin (GoO) at a certain point in the supply chain. The previously certified product (here SAF) is now considered non-certified and can be blended with other non-certified products along the supply chain[16]. For a quantity of SAF fed into the fuel supply system, the manufacturer / distributor[17] receives a quantity of SAF Guarantees of Origin corresponding to the value, which can be transferred and traded independently of the original physical product. With redemption of a Guarantee of Origin by the end consumer (in this case an airline), the product property (in this case the sustainability properties or the emissions benefit of an SAF) is transferred to a product quantity of an equivalent value of another certified or non-certified product. This means that, based on a valid and binding sales contract, the manufacturer / distributor of SAF can first issue a quantity of SAF Guarantees of Origin corresponding to the value and then transfer them to the respective airlines as end users, which can use the SAF Guarantees of Origin as verification of SAF consumption and for offsetting in the EU ETS. The sustainable aviation fuel does not have to have been physically consumed by the end user itself; the Guarantees of Origin prove to the competent authority (e.g. the German Emissions Trading Authority) that an equivalent amount of RED-compliant SAF is or was fed into the fuel supply system and hence burned in an aircraft [Has09, Sta15, IPI10, ISE16].

The end consumer pays a higher market price for the SAF compared to fossil JET A-1 and receives Guarantees of Origin to compensate for the additional price – in proportion to the procured quantity of SAF. Alternatively, the SAF can be sold at the market price of fossil JET A-1 wherein the manufacturer / distributor covers their increased manufacturing costs from separate sale of the Guarantees of Origin.

Verification of compliance with RED sustainability criteria and verification of certain SAF product properties (e.g. GHG emissions properties) do not have to be mapped and tracked in the quantity accounting of the

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[16] Since an ASTM D7566 specification-compliant SAF blend receives an ordinary JET A-1 re-designation according to ASTM D1655 when it is placed on the market and can be correspondingly treated as conventional JET A-1 along the further supply chain, such a blend is not only compatible under the book & claim approach but is also technically and practically permissible.

[17] Not exclusively a refinery or refinery site is meant here. What is meant is the first tax warehouse in the EU (e.g. a refinery / production facility, a blending facility or a tank depot at an import port) where a specification-compliant SAF blend, declared as JET A-1, leaves the tax warehouse premises via an EMCS procedure.

airport tank depot, at least for offsetting in the EU ETS. Although it may also be necessary in a book & claim concept for liability / insurance reasons to show the sustainable / synthetic fuel components in the tank depot accounting, e.g. to fulfil the Indemnification Agreement[18], this does not require any sustainability documentation but rather documentation of "technical" fuel properties and qualities, which in this respect is not a concern with respect to verification and offsetting of SAF in the EU ETS. The assignment of fuels after aircraft refuelling in accordance with the contractual provisions between the seller and the buyer must still be tracked in the tank depot and mapped in the volume accounting, but does not require any adjustment for the offsetting of SAF by means of a book & claim concept.

The essential components of the described book & claim approach are shown schematically in the following Fig. 34. Its functions and links will be explained in the following section.

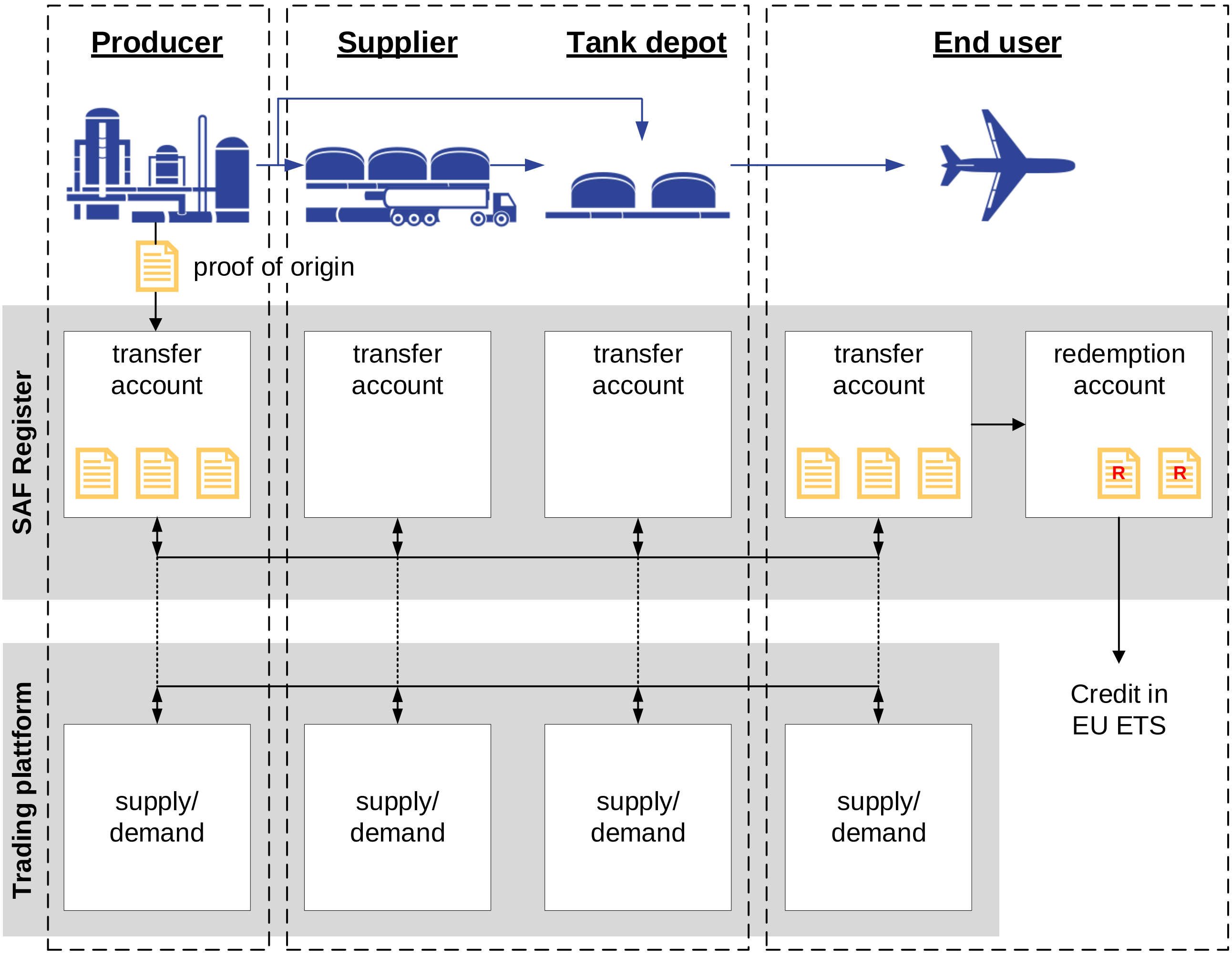

Fig. 34 Key elements and functionality of the book & claim approach

Fraud protection and fiscal control

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[18] In accordance with the Indemnification Agreement Consortium, the seller on whose behalf an aircraft was fueled, is liable in the first instance. This liability exists regardless of fault in order to be able to settle a case of damage (crash) very promptly. However, the liable seller is at liberty to subsequently seek legal redress against the actual perpetrator of the damage. Hence in the case of synthetic fuel blends, blend and specification conformity must be demonstrated during storage in the tank depot. This is an obligation of the tank depot operator if the tank depot is operated under the framework conditions of the international Indemnification Agreement Consortium.

For a book & claim concept for the offsetting of sustainable aviation fuels, it must be possible to exclude system-immanent possibilities for abuse, in particular double / multiple offsetting[19]. This means that a monitoring and control mechanism is necessary.

Fuels for commercial air transport are exempt from excise duty (energy tax) [Eur03]. In order to prevent potential misappropriation, i.e. untaxed use of aviation fuels in energy tax-relevant applications, the movement of excisable goods that are subject to tax exemption, including aviation fuels, is monitored by national customs authorities. The respective actors that come into contact with the tax-free aviation fuel (except during transport) must register as so-called "registered economic operators". Documentation of registered economic operators is regularly monitored via an annual inventory within the framework of fiscal control. For fuel transports, the involved actors use a DTP-supported transport and control system – the Excise Movement and Control System (EMCS) [Gen18]. The transport of synthetic fuels within DEMO-SPK also fell under the control of the EMCS, which served as an interface to the Federal Customs Administration.

In the framework of workshops on the verification of alternative aviation fuels, the EMCS procedure was discussed with representatives from Customs, among others, in connection with a book & claim approach. As a result, it should be noted from a conceptual perspective that the EMCS provides a functioning monitoring mechanism via which all transport of aviation fuel within the EU can be monitored and double / multiple offsetting of SAF due to an unnoticed withdrawal of fuel from the supply chain by the EMCS within the framework of fiscal control can be excluded. Here, there are special cases such as domestic / national transports wherein exceptions to the EMCS procedure are possible according to the current status of the specification. This requires regulations that obligate all contractual partners within the framework of the provision of SAF in the book & claim system limit to use the EMCS procedure and to deny exceptions in these cases – unlike today.

However, the scope of the EMCS is not sufficient to ensure seamless tracking across the EU ETS system; the system limits of the EU ETS and the EMCS are not identical, as EFTA states are not part of the EU customs territory[20]. For transport of energy products from EFTA states to the EU (and vice versa), no conveyance takes place with tax exemption and consequently the EMCS procedure does not apply. This is where import and export regulations first come into play [HZA18]. The EMCS regulation only has legal character and validity within the EU [Eur09]. Within the system limits of the EU ETS, the EMCS is thus initially not universally suitable for guaranteeing seamless tracking of SAF movements. Although the EMCS procedure does not apply in EFTA states, fiscal control is nevertheless exercised there. In this context, it is important to examine how the relevant fiscal control procedures can be used to avoid misappropriation or double-/multiple offsetting and whether the exchange on fuel movements at the interfaces between EU and EFTA states can ensure seamless tracking.

SAF Guarantee of Origin registry

For the monitoring and documentation of Guarantees of Origin, a platform is required within a book & claim approach that serves equally as a common interface for the actors involved. For the monitoring and documentation of the issuance, transfer and cancellation of Guarantees of Origin in the book & claim concept, an electronic register should be operated analogously to the European energy sector [UBA12, UBA18, Eur09, den10, den18]. Unlike in the European energy sector, this register should be implemented in the form of a

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[19] Within the framework of a book & claim approach, it must be possible to e.g. exclude double or multiple offsetting. This means multiple issuance of SAF Guarantees of Origin based on the same SAF fuel unit / quantity, e.g. due to unnoticed removal of SAF from the fuel supply system and reintegration into it. As a result, there would be a discrepancy between the Guarantees of Origin issued and the actual quantity of SAF used.

[20] The EU ETS takes into account flights within the European Economic Area, i.e. states of the European Union and also states of the European Free Trade Association (EFTA states). The latter are not part of the EU customs territory [DEH18, DEH18, Bar18].

single and common SAF Guarantee of Origin register at European level and should refrain from individual national registers, as airlines source fuel transnationally.

An account model is followed for the transfer of SAF Guarantees of Origin. This is an established solution and has been implemented e.g. in the European Union register, the Guarantee of Origin register for electricity from renewable energy sources, heating / cooling or the biogas register [DEH16, den10, UBA14]. The actors involved in the supply chain (manufacturers / distributors, supply and fuelling service providers or airlines subject to emissions trading as end users) have a transfer account containing the SAF Guarantees of Origin in their possession. Consumers, i.e. airlines, also have a redemption account which acts as an interface between the airline and the competent (national) authority for emissions trading and that serves to offset SAF in this sense.

For the supervision of the issuance, transfer and cancellation of SAF Guarantees of Origin in the SAF register of Guarantees of Origin, a registry administrator is to be designated, i.e. a legitimate body, institution or authority that shall perform registry management and relevant monitoring tasks. Since a national register solution should be rejected for the SAF register of Guarantees of Origin and a Europe-wide or EU ETS-wide register solution should be sought, the register should also be maintained by an institution or authority with EU-wide scope.

SAF Guarantees of Origin

Since SAF must fulfil the RED sustainability criteria in order to be offset in the EU ETS, Guarantees of Origin issued in accordance with RED for the European energy sector should serve as a (design) basis and thus also reduce the cost of possible implementation. They should include the following minimum information [Eur09]:

- Energy source: Information on raw materials from which the SAF was produced and the production process (i.e. Fischer-Tropsch, Hydro-processed Esters and Fatty Acids (HEFA), Synthesised Isoparaffins (SIP), Alcohol-to-JET (ATJ))
- Details related to the manufacturing plant of the SAF: Name, location, type
- Date of issue and issuing country
- Unique identification number of the underlying sustainability certificate/s (Proof of Sustainability, PoS)
- Unique identification number of the SAF Guarantee of Origin

To issue an SAF proof of origin, this information must be available at the issuing interface within the supply chain (e.g. a refinery or a blending plant). In order to carry the required sustainability characteristics as well as a required RED proof of sustainability up to the issuance of a SAF Guarantee of Origin to the respective manufacturer / distributor and to seamlessly connect the book & claim concept to an upstream chain of custody system, the upstream chain has to be certified according to a sustainability certification system approved by the EU RED.

Analogous to the book & claim concept in the European energy sector, SAF Guarantees of Origin are issued in each case for a defined quantity of fuel fed into the fuel supply system. Since calculation of emissions in the EU ETS is based on the activity data, i.e. the mass of fuel consumed in the reporting year, a mass reference with the unit of one tonne would be expedient. A Guarantee of Origin thus relates to one tonne of RED-compliant pure sustainable / synthetic aviation fuel. Issuance is carried out according to the value of the pure sustainable / synthetic fuel component of a binary blend or a multiblend. Here, transfer of a unique identification number of the proof of sustainability (PoS) to the SAF Guarantee of Origin that is to be issued is particularly important. This link prevents the multiple issue of SAF Guarantees of Origin based on a PoS without this being registered in the SAF Guarantee of Origin register. Furthermore, in order to ensure that a PoS which has already been used to issue SAF Guarantees of Origin within the book & claim system is not used in the book & claim system or in any other application for offsetting purposes, the PoS must be invalidated as soon as SAF Guarantees of Origin have been issued on its basis. The issued Guarantees of Origin are then posted in the SAF register of Guarantees of Origin to the transfer account of the manufacturer / distributor. For offsetting in the EU ETS, the SAF is deemed to have been expended when it is fed into the fuel supply system and the associated Guarantees of Origin are issued.

A SAF Guarantee of Origin must be issued as long as the pure sustainable / synthetic content in a binary SAF blend or SAF multiblend is still known or can be determined from documents accompanying the transport[21]. The further SAF is transported along the supply chain, the more blending with other batches of fuel potentially occurs and the more difficult it becomes to determine the proportion on the basis of (transport-accompanying) fuel documents. As the scope of the book & claim crediting system is only reached upon issuance of a SAF Guarantee of Origin, each interface in the supply chain up to issuance of the SAF Guarantee of Origin must be certified and monitored with regard to sustainability documentation, e.g. according to an EU RED recognised sustainability certification scheme. This potential expenditure reaffirms that SAF certificates of origin should be issued as early as possible in the supply chain. Two conditions must be met for this:

1. The SAF is processed and blended with conventional aviation fuel to the extent that the JET A-1 fuel specification is met. This is necessary so that the fuel is registered as jet fuel for use in an aircraft within the framework of fiscal control and for subsequent shipments to be monitored by EMCS.
2. The SAF is located within (a tax warehouse of) the European Union. This is necessary because the JET A-1 specification could already be fulfilled outside the EU (for example in the case of a JET A-1 import), but fiscal control is only exercised within the European Customs Union by means of EMCS, and potential multiple offsetting is thus avoided.

With fulfilment of these two conditions, SAF Guarantees of Origin are issued as soon as the fuel leaves the first tax warehouse via an EMCS procedure and for use in an aircraft.

Various procedures are conceivable for issuing SAF Guarantees of Origin: Issuance of Guarantees of Origin by the respective manufacturer / distributor themselves or issuance by the register administrator. The first procedure requires a mechanism to check that the issued Guarantees of Origin have been issued in corresponding numbers and values only for the synthetic / sustainable fuel quantities and that each is accompanied by a recognised RED sustainability certificate. This can be affected e.g. by means of regular audits. Within the framework of the second procedure, the propriety of the issuance in corresponding numbers and values of SAF Guarantees of Origin would be carried out directly by the register administrator.

Redemption and offsetting

SAF Guarantees of Origin are continuously issuable and redeemable by an airline by booking the Guarantees of Origin to the offsetting account. To prevent multiple offsetting of Guarantees of Origin, these bookings must be irrevocable even if an airline ceases activities within the framework of the book & claim system. The redeemed SAF Guarantees of Origin in the offsetting account serve as verification for the competent emissions trading authorities as well as all other stakeholders that a certain amount of aviation fuel consumed, regardless of origin, has been declared as "sustainable" by the airline and is accounted for within the framework of the EU ETS reporting scheme.

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[21] The Refinery Certificate of Quality (RCQ) issued by the manufacturing plant shows the proportion of synthetic components in a fuel batch in accordance with EI / JIG 1530. In the following documents, such as a Certificate of Analysis (CoA) or a Recertification Test Certificate (RT), which are issued in the course of fuel distribution and further storage to verify that the fuel quality has not changed due to commingling and contamination, this information is no longer listed [EI13, IAT15]. Issuance should therefore take place as soon as possible after blending.

In order to include SAF Guarantees of Origin in the EU ETS emissions calculation, an aircraft operator must first determine the total annual fuel consumption or fuel mass consumed of the flights that are subject to emissions trading. In order to credit SAF in the EU ETS via book & claim, during a reporting year an aircraft operator books SAF Guarantees of Origin in the SAF Guarantee of Origin register from the transfer account to the redemption account. The quantity of SAF corresponding in value to the Guarantees of Origin is subtracted from the total fuel consumption of the aircraft operator in order to obtain the mass of fossil fuel and the GHG emissions to be calculated from it. A sufficient number of EU ETS emissions permits must be demonstrated for this quantity. Evidence that a sufficient number of SAF Guarantees of Origin are held in an end user's redemption account can be tracked by the competent authority for emissions trading in different ways, depending on the system design. The competent authority could directly verify the account by accessing aircraft operators' redemption accounts. Alternatively, a register extract from an end user's redemption account could be produced by the register administrator and made available to the competent authority. Depending on the system design, redemption of Guarantees of Origin in the emissions report is either explicitly effected for a pair of airfields or evenly distributed over the reporting year.

Trading platform

If a purchase agreement between the airline and the manufacturer does not stipulate that the airline also receives corresponding SAF Guarantees of Origin for its procured SAF quantities, the manufacturer / distributor can nevertheless issue SAF Guarantees of Origin insofar as the fuels meet the RED sustainability criteria. In this case, the manufacturer / distributor has the option of selling the SAF Guarantees of Origin to third parties or other airlines. For such cases, the potential offer of the manufacturer / distributor must be matched with a possible demand from a third party or another airline, which can be facilitated via an appropriate trading platform[22]. Organised platforms such as an over-the-counter (OTC) trading platform or a certificate exchange are conceivable as the trading platform.

8.3 Summary

The current offsetting procedure and also the current legal situation block the placement of SAF on the market in Europe, if the end user wants to offset them in the EU ETS. The current procedure for offsetting SAF follows a mass balance approach based on accounting records with the airport tank depot as the balance limit. Although this approach allows sustainable aviation fuel to be offset without it necessarily being physically consumed, only the respective airport tank depot exists as a balance limit. In individual cases, it must also be ensured that all verification and documentation required for offsetting, such as EU RED-compliant sustainability certificates, are available up to the point of storage in the airport tank depot and that they exist and are passed on accordingly along the upstream chain. Ensuring this is currently the sole responsibility of the end user (airline) and is associated with a high administrative burden as there is no operationalised and harmonised offsetting procedure to fall back on. Overall, a holistic verification and offsetting procedure for sustainable aviation fuels with the entire supply chain as system / balance limit is lacking so far. However, given the price level of today's SAF production, it can be assumed that SAF purchasers intend to reduce the additional price compared to the current JET A-1 price level by using emissions reduction certificates. As long as this is not practically possible under the conditions of the EU ETS, the current offsetting methodology and legal situation will have a prohibitive effect on the widespread use of SAF. Against this background, the track & trace (mass balancing) and the book & claim approach (certificate solution) represent two approaches for improved

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[22] An agreement of supply and demand is also possible bilaterally between two parties without a trading platform. However, the supply and demand of market participants can be placed transparently and a larger spectrum of potential buyers and sellers can be represented by means of a trading platform. The SAF Guarantee of Origin register is not a trading platform. The transfers of Guarantees of Origin there are based on individual purchase contracts already agreed before the SAF Guarantees of Origin are issued.

offsetting of renewable aviation fuels. Both approaches were discussed in various workshops within the framework of DEMO-SPK and their basic functionality was confirmed. As a logical consequence, the approaches formulated here require their practical validation in a further step, in which further measures for operationalisation can be identified and possible weaknesses highlighted.

The **track & trace** approach obliges manufacturers and subsequently the owners of a fuel blend to carry the calculated quantity shares of the sustainable aviation fuels in a blend in the (transport) documentation all the way to the airport tank depot, even though physical separation in the blend is no longer possible. In the airport fuel depot, the quantity accounting for the stocks of individual shareholders or third parties is expanded accordingly. In result, it can be stated that the track & trace procedure can be implemented (quite simply) on the basis of mass balances in order to map the verification of delivery to authorised persons required for the issuing of certificates in a manipulation-proof manner. From a legal perspective, the monitoring function of the inventory management of sustainable aviation fuel is to be assigned to Customs, and the documentation obligation of the supply contracts for sustainable aviation fuel quantity transferred in part is to be imposed on the tank depot operator. The latter can be achieved by supplementing the lease and permit contract between the airport operating company and the tank depot operator or by including it as a requirement in the airport regulations in order to create a legal framework for the issuance of certificates.

The **book & claim** approach provides for the separation of the sustainability properties of sustainable aviation fuels from the physical fuel at a certain point in the supply chain and transfers the properties of SAF to transferable and negotiable certificates (Guarantees of Origin). The Guarantees of Origin can then be transferred to airlines as purchasers and end users, and redeemed to offset an equivalent value of SAF in the EU ETS. Although a book and claim approach to offsetting SAF offers the highest possible flexibility, it is evident that even in combination with the EU-wide EMCS procedure alone, coherence of the fuel supply system within the EU ETS scope of application is not guaranteed and thus there is no seamless tracking of SAF movements. In this context, it must be examined as to what extent fiscal control exists outside the EU for monitoring SAF transports and whether corresponding interfaces to the EMCS exist that guarantee a seamless exchange of information. In this context, with regard to a book & claim concept, it must primarily be examined as to how a mechanism for the avoidance of double / multiple offsetting can be ensured even beyond the limits of the EMCS. Substitute solutions – such as the linking of sustainability certificates and SAF Guarantees of Origin – must both prevent double / multiple offsetting and ensure the use of SAF batches in aircraft or even be able to verify this in a legally compliant manner.

In addition to the track & trace and book & claim approaches described here, it should also be investigated as to what extent comprehensive verification and offsetting of SAF along the entire supply chain would also be possible and expedient through an EU RED-recognised mass balance system.

The concepts presented here were initially designed and examined for the scope of the EU ETS. The future widespread use of SAF also requires the investigation of refuelling with SAF outside this area of application. As with the EU ETS, CORSIA does not yet have a proven and operationalised concept for offsetting sustainable aviation fuels; this makes their future market entry and large-scale use more difficult. Up to now, regulatory requirements for the verification and offsetting of sustainable aviation fuels have differed from one country and/or region to the next. In contrast, fuel procurement by airlines can take place across their entire route network (i.e. globally). In this heterogeneous supply situation, it cannot be assumed that globally procured sustainable aviation fuels can always be offset in accordance with the respective offsetting procedure in the domestic market. In order to adequately take these framework conditions into account and to be able to seamlessly use sustainable aviation fuels in global commercial air transport, there is a need for the development, evaluation and implementation of suitable concepts at international level, analogous to the approaches presented here.

The work in DEMO-SPK has shown that the verification and offsetting of sustainable aviation fuels is a matter for various stakeholders, e.g. fuel manufacturers and distributors, supply and fuelling service providers, airlines, but also customs authorities, emissions trading authorities, emissions trading verifiers and sustainability certification organisations. Currently, there is no addressee whose scope of tasks and competences adequately embraces all relevant issues. For implementation of a suitable offsetting procedure, the topic of verification and offsetting of sustainable aviation fuels should therefore be placed with a political / regulatory decision-maker and dealt with holistically in conjunction with all involved actors. Without the future further development of the current offsetting approach and the current legal situation, limited potential for offsetting will further prevent the purchase of SAF quantities and inhibit the possibility of improving the climate balance of aviation across sectors through low-emission aviation fuels.

9 Excursus | FT-SPK via PTL

In addition to the examined sustainable kerosenes based on biogenic raw materials, kerosene based on renewable electricity and CO_2 (PTL, chapter 2.5) will also play a role in the future. Hence PTL was examined within the framework of DEMO-SPK from two perspectives which are explained in summary below in a side note. In the case examined in greater detail in DEMO-SPK, PTL represents intermediate products from the Sunfire GmbH demonstration plant that were produced based on Fischer-Tropsch synthesis (FT). Products from this synthesis process are organic multi-component mixtures with a very wide boiling point distribution.

9.1 Production and product analysis

In order to provide international verification of the production of specifications-compliant FT-SPK for the first time, investigations were carried out at the TU Bergakademie Freiberg and by ASG Analytik-Service Gesellschaft mbH on the processing of approx. 30 litres of a Fischer-Tropsch intermediate product (in this case the diesel cut) from Sunfire GmbH to FT-SPK under various process conditions including the corresponding product analysis (Fig. 35). At the same time, statements on the influence of important process parameters on the product properties and yields should be made possible.

The above-mentioned FT product was first subjected to hydro-isomerisation at different reaction temperatures. The process of hydro-isomerisation primarily serves to convert unbranched n-alkanes into branched iso-alkanes, which are characterised by comparatively low melting temperatures. The process is very sensitive with respect to the reaction temperature. A temperature change of only a few Kelvin can lead to significant differences in the product distribution or composition; therefore 230 °C ("mild" isomerisation) and 238 °C ("sharp" isomerisation) were chosen. In addition, the originally planned separation of the low-boiling petrol fraction before isomerisation was dispensed with, as co-processing of the petrol cut leads to an improvement in the petrol quality (anti-knock properties) and an influence on the reaction process for the kerosene and diesel fractions was not to be expected. As an alternative to isomerisation, part of the educt was subjected to mild hydrocracking.

The higher-boiling diesel and wax components remaining in the product after isomerisation were separated and subjected to hydrocracking in a second process step in order to increase the SPK yields. Hydrogen and so-called bifunctional catalysts were used in the continuously operating research facilities, analogous to industrial refinery processes.

The extensive results of the investigations are presented below in extracts and with the focus on the PTL-SPK produced.

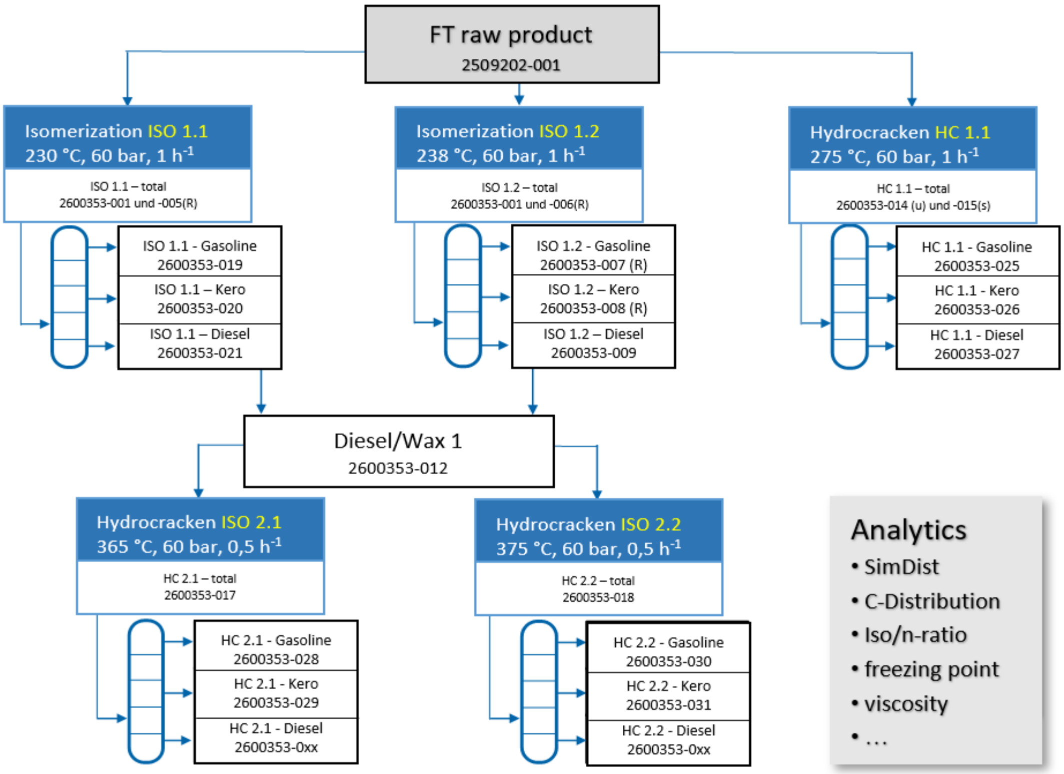

Fig. 35 Simplified preparation and analysis scheme for PTL-SPK
(© TUBAF)

Boiling curve after isomerisation

Increase of the isomerisation temperature by just 8 °C causes a significant fall of the crystallisation point from -31.9 °C (not conforming to specifications) to -43.4 °C (conforming to specifications for JET A and for FT kerosene). The viscosity at -40 °C is also above the specification maximum of 12 cST after isomerisation at 230 °C, but significantly below it after isomerisation at 238 °C (see Tab. 22 on page 97). The boiling behaviour of the FT crude product and the isomerisates shows that treatment under mild conditions only leads to a slight shift in the boiling point. In contrast, the proportion of diesel and waxes decreases significantly under more severe isomerisation conditions. At the same time, the proportion of naphtha in the product increases (Fig. 36).

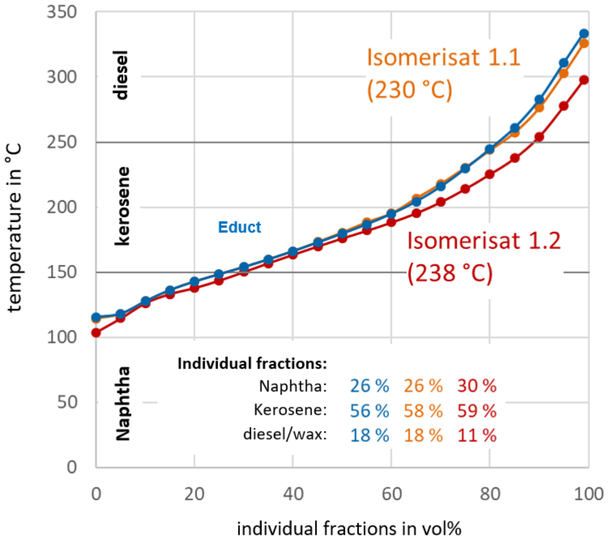

Fig. 36 Boiling behaviour after hydro-isomerisation (total product)

Boiling curve after hydrocracking

To characterise the individual fractions, the total samples HC 2.1 and HC 2.2 were fractionated. The boiling curves of the total products as well as the individual fractions is shown in Fig. 37.

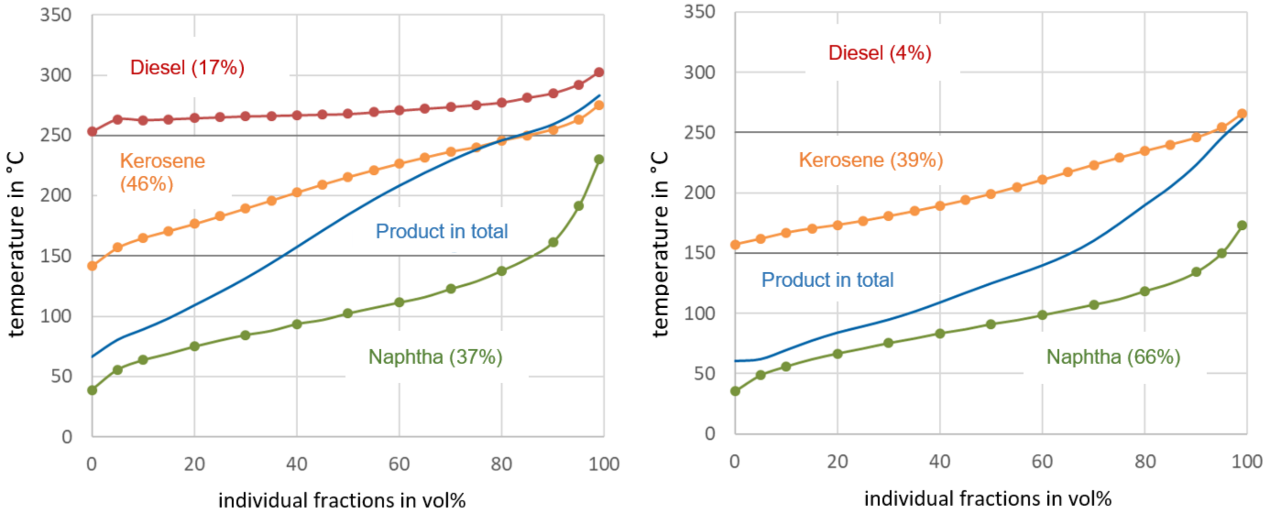

Fig. 37 Boiling curves for individual fractions after hydrocracking the high boilers

Quantity balance

The results of the quantity balancing for the individual process stages as well as the entire chain from the FT intermediate product to the PTL-SPK is shown in Fig. 38. It is clear that a considerable proportion of diesel could be converted into lighter products (kerosene, naphtha, gas). The kerosene yield can be increased to over 60 m-%. The quality of the additionally extracted kerosene proportions is excellent.

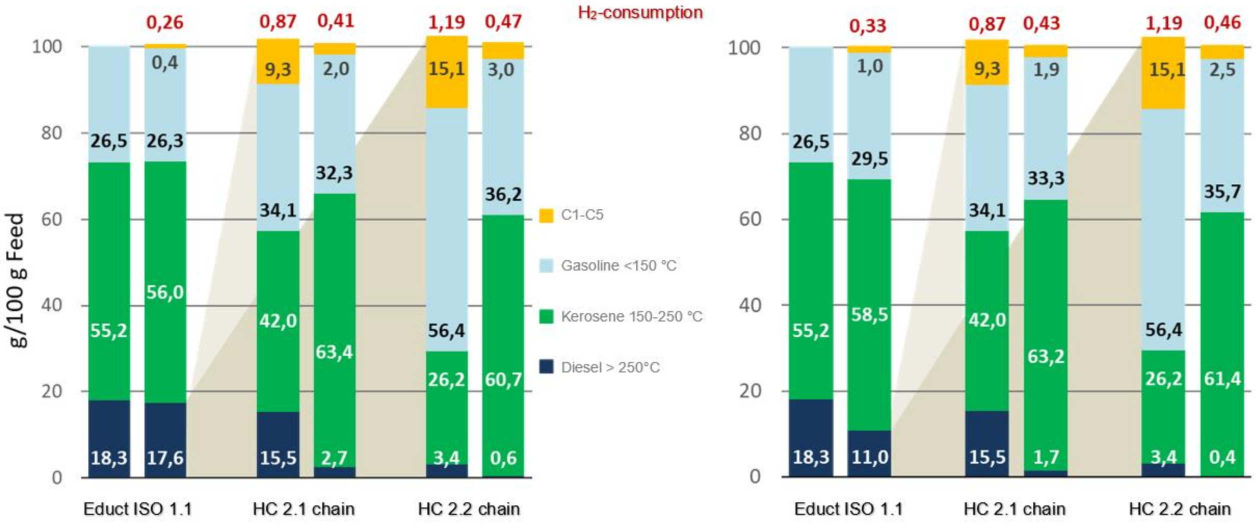

Fig. 38 Quantity balance from FT intermediate product to PTL-SPK
(Left: Isomerisation at 230 °C and hydrocracking; right for isomerisation at 238 °C and hydrocracking.)

It should be noted that the FT crude product already contained approx. 30 m-% of naphtha components that are not usable for kerosene production but can be marketed as a by-product. The hydrogen consumption in the case of a simple isomerisation is about 0.3 g / 100 g feed; for the entire process chain including hydrocracking of the high boilers, about 0.5 g / 100 g FT crude product are required.

Kerosene properties

The results of the application characterisation of the kerosene fractions produced under the different process conditions are summarised in Tab. 22 and compared with the requirements according to ASTM D7566-19 [AST19].

The crystallisation point as a criterion for the cold behaviour of the kerosene has turned out to be the critical parameter. In order to comply with the ASTM limit of -40 °C for paraffinic synthetic products, sufficiently sharp reaction conditions are required during hydro-isomerisation of the FT crude product. The other parameters (flash point, density, viscosity and probably also thermal stability and acid value) can be easily achieved by upgrading Fischer-Tropsch products.

The mixed product of isomerisation at 238 °C and at 230 °C also fulfils the requirements of ASTM in all respects, also with regard to the low-temperature properties.

The product additionally obtained from higher-boiling components in the second process stage has excellent refrigeration properties with crystallisation points of -44 °C and -52 °C respectively. In this way, isomerisation products with possibly insufficient crystallisation temperatures could be upgraded to standard-compliant products when blended with hydrocrack kerosene.

Tab. 22 Comparison of kerosene properties with the requirements according to ASTM D7566-13 for FT-SPK

Parameter		ASTM standard	Requirements ASTM D7566-13	ISO 1.1 230 °C	ISO 1.2 238 °C	ISO 1 Mix[1]	HC 1.1 Batch 1	HC 1.1 Batch 2	HC 2.1 365 °C	HC 2.2 375 °C
Crystallisation point	°C	D7153	max. -40	-31.9	-43.4	-42.9	-47.0	-39.8	-44.1	-51.7
Flash point	°C	D7094	min. 38	38.6	42.5	51.5	52.5	39.5	40.5	n. b.[2]
Density (15 °C)	kg/m^3	D4052	730–770	743.4	745.0	744.5	749.8	745.6	756.2	n. b.[2]
Acid count	mg KOH / g	D3242	max. 0.015	—	—	0.006	—	—	—	—
kin. viscosity (−40 °C)	mm^2/s	D7042	max. 8	13.260	6.379	6.447	7.047	6.395	9.356	8.234
kin. viscosity (−30 °C)	mm^2/s			4.517	4.572	4.668	4.970	4.587	6.319	5.652
kin. viscosity (−20 °C)	mm^2/s			3.467	3.48	3.776	3.733	3.495	4.588	4.157
kin. viscosity (−10 °C)	mm^2/s			2.759	2.756	2.9	2.926	2.768	3.053	3.205
kin. viscosity (0 °C)	mm^2/s			2.257	2.249	2.326	2.368	2.26	2.777	2.563
kin. viscosity (10 °C)	mm^2/s			1.889	1.879	1.925	1.965	1.899	2.266	2.106
kin. viscosity (20 °C)	mm^2/s			1.612	1.598	1.625	1.662	1.607	1.893	1.769
kin. viscosity (30 °C)	mm^2/s			1.390	1.381	1.404	1.429	1.389	1.61	1.512
kin. viscosity (40 °C)	mm^2/s			1.216	1.12	1.249	1.252	1.216	1.391	1.312
10 % temperature	°C	D2887	max. 205	153.4	157.4	172.6	173.3	157.9	165.0	167.0
50 % temperature	°C		to be specified	195.0	194.6	192.4	195.9	196.0	215.4	199.1
90 % temperature	°C		to be specified	244.3	242.8	218.7	230.0	243.1	255.1	245.8
Final boiling temperature	°C		max. 300	285.1	279.2	235.6	256.2	277.3	275.2	267.5
T90–T10	K		min. 22	90.9	85.4	46.1	56.7	85.2	90.1	78.8

[1] The kerosene fraction ISO 1-Mix was obtained by blending the total products ISO 1.1 and ISO 1.2 and fractionating the mixture. It is therefore not a blend of the individual kerosene fractions. Since the cut points differ somewhat between fractionings, the properties of the kerosene fractions do not correspond to the average values. In extreme cases, values can lie outside the limits specified by the individual fractions (flash point).

[2] Insufficient sample material was available to determine density and flash point.

9.2 Life cycle analyses

In addition to the life cycle analyses for the sustainable kerosene of biogenic origin (chapter 6), the same exemplary analyses were carried out for the processed PTL-SPK (based on Fischer-Tropsch synthesis). The specific GHG emissions were examined as the decisive impact category with regard to the reduction of CO_2 eq. emissions.

For calculation of the GHG emissions of the PTL-SPK, the methodological approach as well as the basic assumptions were used analogously to the biogenic kerosene (chapter 6.2). In contrast, for the PTL-SPK only the emissions from fuel production are considered without subsequent fuel logistics. The data required to draw up the life cycle inventory (primarily the mass and energy balance of the manufacturing process) was determined with the aid of a flow chart process simulation based on the Sunfire GmbH process. A production capacity of approx. 141 MW was assumed, based on the lower calorific value.

The results of the calculation of GHG emissions according to EU RED 2009/28/EC are described below. Six different concepts were considered, based on the use of two different CO_2 sources (extraction from biomethane plants, separation from ambient air) and three different electricity sources (German power mix, electricity from PV plants, electricity from wind turbines). The results of the GHG emissions as well as the resulting GHG reductions related to the fossil reference are shown in Fig. 39.

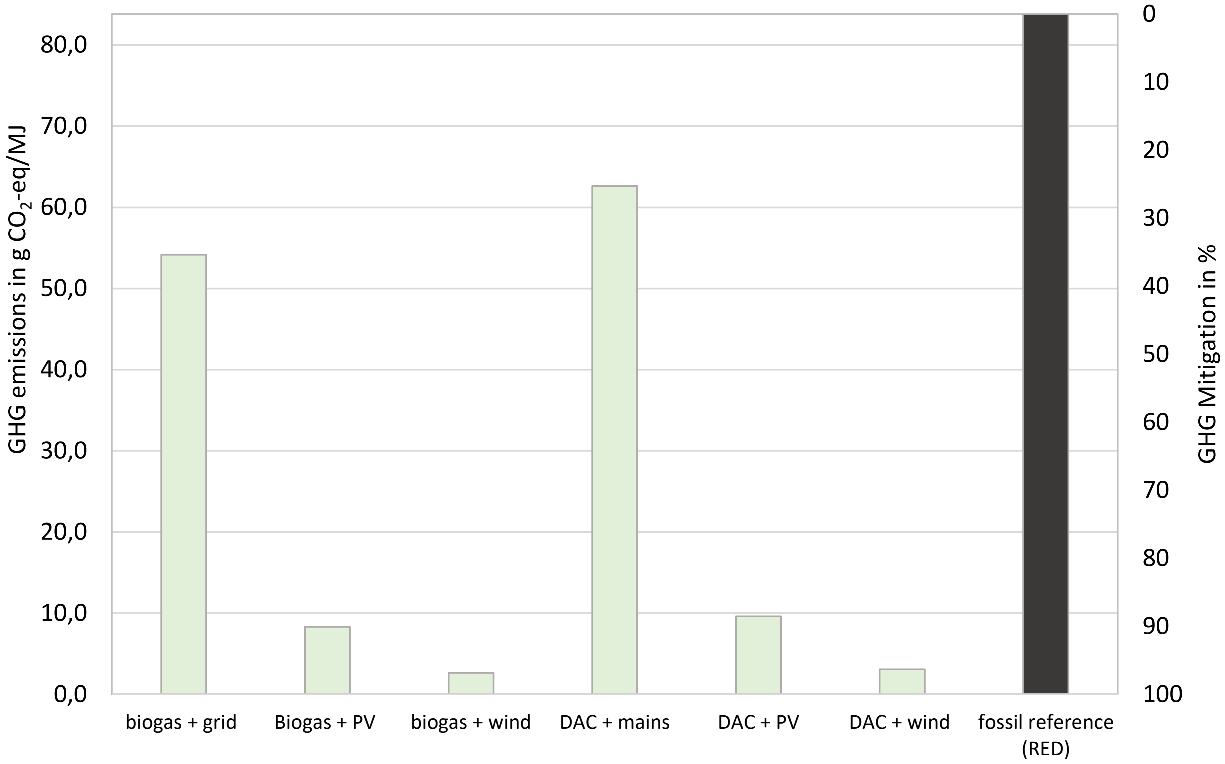

Fig. 39 Specific GHG emissions and GHG reduction potential of the considered FT-SPK concepts compared to the fossil reference of the EU RED

The results are not shown separately according to the proportions of power supply, CO_2 supply and conversion, since for all scenarios the GHG emissions of power supply dominate the total emissions with a share of more than 99.7%. The difference in total emissions is mainly due to the higher energy input for the separation of CO_2 from the ambient air. Since the heat released in the PTL process by the exothermic reactions of the

Fischer-Tropsch synthesis is not sufficient to supply both the high-temperature electrolysis and the air separation, additional thermal energy is required. To provide this additional energy, electricity was also used as a feedstock to ensure that the process can be fully powered by electricity from renewable energy and does not require additional energy sources.

Overall, it is clear that GHG reductions for both sources of CO_2 when using grid electricity and the associated emissions of the German power mix are not sufficient to be recognised as a sustainable fuel under the EU RED. This would require a GHG saving of at least 60% compared to the fossil reference[23]. On the other hand, concepts for the pure use of wind or photovoltaic electricity can achieve significantly higher emissions reductions. Here, PV concepts achieve an emissions reduction of approx. 90% and concepts for the use of wind energy achieve reductions of approx. 95%. Since the resulting FT kerosene may be blended with fossil kerosene at a maximum rate of 50%, this results in emissions reductions of up to 45% or 47.5% for the kerosene blend used in aviation.

It should be noted, however, that FT systems run in continuous operation. Switching off is not possible in times when wind or solar energy is not available. This means that fluctuations in solar or PV systems must be buffered, e.g. by means of hydrogen storage, to facilitate operation of a PTL system. The conversion losses associated with this are not taken into account in the above calculations. Alternatively, in the case of a grid connection, accounting solutions, e.g. through direct marketing contracts and corresponding certification mechanisms, would also fundamentally be conceivable, which could ensure continuous operation.

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[23] According to RED II, sustainable fuels of non-biogenic origin must demonstrate a GHG saving of at least 70% from 1st January 2021. However, this value also refers to a higher fossil reference value of 94 g CO_2 eq. / MJ in comparison with RED I.

10 Conclusions and recommendations for action

Within the framework of the DEMO-SPK MKS model project commissioned by the BMVI, the use of multiblend JET A-1 in the general fuel supply infrastructure was successfully demonstrated for the first time internationally, from procurement to refuelling in the aircraft. In addition to analyses of kerosene properties, emissions measurements, life cycle analyses, practicable sustainability documentation and offsetting procedures in emissions trading were also carried out. This project was made possible by more than 20 international partners from business and science.

With particular focus on the results achieved, this final report on the project summarises the extensive work carried out in the course of preliminary investigations, demonstration and the accompanying investigations (see Fig. 1 on page 6).

In the following section, conclusions and recommendations for action that are to be derived from the project will be explained with reference to the focal points examined:

Validation of the chemical-physical properties of semi-synthetic multiblends from several different synthetic fuels during preliminary tests.

It has been demonstrated that specification-compliant multiblends can be produced from several different synthetic fuels provided that only synthetic fuels approved in accordance with ASTM D7566 are used. Corresponding approval already includes detailed analytical tests for the individual components and variable blend compositions. It could be shown that the chemical-physical properties of the ternary and quaternary blends can be precisely calculated. After a storage period of six months, the chemical-physical characteristic values are unchanged from those before removal from storage; no change in fuel quality is discernible. Changing climatic conditions have no effect on the fuel properties. It should also be noted that a change in the multiblend composition within the framework of the individual components approved and tested by ASTM at this time does not require repetition or re-adjustment of the tests from DEMO-SPK; the results are transferable.

Internationally first successful demonstration of multi-blend JET A-1 production, deployment and use at an airport.

Thanks to the commitment of the project partners, the procurement of renewable kerosene, its blending with fossil JET A-1 to form multiblend JET A-1, and its supply and use in the fuel infrastructure of a major airport were successfully demonstrated. Nearly 600 tonnes of multiblend JET A-1 were supplied and flown. It could be shown that technical implementability fundamentally exists and is feasible; further infrastructural additions are necessary in the area of the blending devices for the production of multiblend JET A-1, depending on the location and local conditions, as blending tanks for kerosene are not regularly available. During preparation and implementation of the demonstration, extensive experience was gained that not only provided numerous pointers for operational project management, but also identified gaps or clarification requirements that need to be closed for successful broader market implementation. These include:

- *Extension of ASTM D7566 with the option of multiblend production.* Although it is possible to produce a multiblend JET A-1 in compliance with ASTM, the additional operational and time costs associated with successive blending are disproportionately high and thus counterproductive for broad market implementation. It is therefore suggested that regulations are included in ASTM D7566 that allow the production of differently composed multiblends in the context of simultaneous blending of several synthetic kerosenes.
- *Simplified REACH registration of renewable kerosenes.* With reference to the fact that producers of renewable kerosene are currently smaller companies that are initially producing comparatively small quantities, both the time required and the costs of registration are disproportionately high. *With respect to SPK, it would be desirable to aim for either shortened and cost-reduced registration, or for generic registration for all synthetic aviation fuels based on their use.*
- *Amendments to the Energy Tax Act.* In the absence of clear regulations in the Energy Tax Act on the applicable nomenclature and consequently on the amount of tax to be assessed for multiblend JET A-1, it is suggested that the situation is remedied by applying the so-called similarity principle according to § 2 para. 4 Energy Tax Act. For broader practical implementation, it is considered expedient to include the renewable kerosene certified according to ASTM D7566 in the national Energy Tax Act and, in the international context, to strive for harmonization of the international HS code and the German customs tariff number according to the combined nomenclature.

Significant reduction of local pollutant emissions (especially soot particles by 30 to 60 % depending on the operating point) possible at an airport.

The demonstration also included comparative measurements of pollutant emissions in an engine test installation with an A300-600 (cargo version). Two successive ground runs were carried out according to a defined measurement protocol, whereby firstly a reference measurement was carried out with a fossil JET A-1 and then a measurement with the multiblend JET A-1. The expected soot reduction through the use of the multiblend JET A-1 was proven; this was approx. 30 to 60% based on the particulate mass for different operating points. Soot reduction is not associated with the deterioration ("trade-off") of other emissions parameters. To prevent the determined results only being specific to the tested engine, supplementary measurements were carried out in the technical centre. A significant reduction in the concentration of soot precursor species was recorded during oxidation of the multiblend JET A-1 compared to the fossil JET A-1. Supplementary investigations into the reaction chemistry and the soot formation potential on at research facility scale also demonstrated that the knowledge gained there on improving local air quality at airports through alternative multiblends can be transferred to a real application scenario. In addition, it was shown that good predictability of the engine-related local emissions is possible via mathematical models.

Life cycle analyses for multiblend JET A-1 show a greenhouse gas reduction potential of at least 35% compared to the fossil reference.

Since the majority of the GHG emissions are caused by combustion of fossil kerosene, the fossil proportion in the multiblend JET A-1 can be identified as the main driver with respect to overall GHG emissions. Thus with the highest proportion of renewable kerosenes, multiblend JET A-1 has the lowest GHG emissions and with 35 % the highest GHG saving compared with fossil JET A-1. A determined look at GHG emissions of the renewable kerosenes shows considerable benefits associated with the use of residual and waste materials compared to the use of cultivated biomass on the one hand, and on the other benefits associated with the use of renewable energies to cover the process-specific energy requirements. The related methods LCA according to

DIN ISO 14040 and GHG balancing according to EU RED are established methods and do not pose an extraordinary challenge in their application for assessment and certification processes in the field of renewable kerosene and multiblend JET A-1.

Cost reduction potentials with wide-scale implementation of multiblend JET A-1.

Perspectively, dedicated cost considerations for renewable kerosene confirm that the large-scale production of renewable kerosene alone will not be sufficient to bring costs closer to conventional kerosene costs. The same applies to the life cycle costs of the multiblend JET A-1 examined in the different supply chains. Costs are significantly higher compared to fossil JET A-1, but there is potential for cost reductions with wider implementation (e.g. supplying a major airport with multi-blend JET A-1 all year round). As long as the cost reservation relating to renewable kerosenes remains in place, no widespread implementation beyond individual examples is to be expected due to the stiff international competition in aviation. In any case, securing the required future fuel volume – for example, in the case of a future supply to Leipzig / Halle Airport – requires significant expansion of the manufacturing capacities for SPKs at all considered production sites. In turn, the associated investments require secure long-term sales opportunities for the fuel manufacturers for their products.

The sustainability documentation in the certification system known to date for biofuels can be transferred to renewable kerosene and multiblend JET A-1.

Various sustainability frameworks and certification systems have been established for biofuels in recent years. These systems differ significantly in terms of the criteria they contain and their target markets. Within the framework of DEMO-SPK, it was possible to trace the sustainability documentation as the basis of comprehensive sustainability certification for all alternative aviation fuels examined. Sustainability certification from within existing systems and structures is thus also feasible for renewable kerosene and does not represent a fundamental hindrance to its market implementation. Work within DEMO-SPK also shows that sustainability requirements and -standards sometimes differ significantly globally. In a growing global market for renewable kerosene, this may lead to additional administrative requirements for market participants. One possible way of dealing with these challenges could be increasing mutual recognition of existing systems and the development of so-called meta standards. These approaches are to be correspondingly further developed. Another important point for the market implementation of renewable kerosene is the interface between sustainability certification and documentation with the mass balance system on the one hand and the offsetting of biogenic fuels in the ETS on the other hand. Within the framework of DEMO-SPK, a corresponding proposal was developed for the design of this interface.

Conceptual approaches to offsetting methodology for emissions trading require validation in practice.

Despite the repeatedly demonstrated technical feasibility of using renewable kerosene, the fact that no broad market implementation is taking place has to do not only with the high costs of kerosene but also with the to date insufficiently operationalised approach for obtaining emission reduction certificates, for example in European emissions trading (EU ETS). In DEMO-SPK, the various possible approaches for improved offsetting in emissions trading were conceptualised (so-called track & trace or mass balancing and book & claim or certificate solution) and their pros and cons were also discussed in various workshops and their basic functionality was confirmed. It must be stated that without the future further development of the current offsetting approach and the current legal situation, limited potential for offsetting will further prevent the purchase of renewable kerosenes and inhibit the possibility of improving the climate balance of aviation across sectors through low-emission aviation fuels. As a logical consequence, the approaches formulated here require their practical validation in a further step, in which further measures for operationalisation can be identified and possible weaknesses highlighted.

ASTM-compliant PTL kerosene (FT-SPK) prepared for the first time internationally.

PTL is seen as an important renewable kerosene for future aviation and is already approved in principle in ASTM via the Fischer-Tropsch synthesis route. The proof that intermediate products from the Fischer-Tropsch synthesis of CO_2 and electrolytically generated hydrogen from renewable electricity can be processed to FT-SPK at research facility scale was achieved for the first time in DEMO-SPK. Important process parameters for maximising the kerosene yield could be identified, which provides an indispensable basis for further steps in technology development. The kerosene prepared in this way meets the properties according to the ASTM specification. In addition, taking into account different approaches for CO_2 and electricity supply, GHG reductions were calculated which in the best case are in the order of 95% compared to the fossil reference and thus in a comparable order of magnitude as is also possible with HEFA-SPK from residual materials.

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