Franziska Müller-Langer[1,*]
Niels Dögnitz[1]
Christian Marquardt[2]
Alexander Zschocke[3]
Tobias Schripp[4]
Katja Oehmichen[1]
Stefan Majer[1]
Nils Bullerdiek[5]
Ann-Marlen Halling[6]
Dietmar Posselt[7]
Thomas Kuchling[8]
Joachim Buse[9]

Multiblend JET A-1 in Practice: Results of an R&D Project on Synthetic Paraffinic Kerosenes

The research and demonstration project, DEMO-SPK, a model project under the German Mobility and Fuel Strategy (MFS), investigated the use of renewable kerosene at the Leipzig/Halle airport. Its primary goal was to examine and verify the behavior of blends consisting of several types of renewable kerosene and fossil JET A-1, under the realistic supply conditions of a major airport. The project demonstrated that the supply chain for multiblend JET A-1 was technically feasible and that the fuel could be used without requiring any changes in the normal operating procedures. The project also confirmed that the use of multiblend JET A-1 resulted in a 30–60% reduction in particulate emissions for ground operations and a reduction in CO_2 equivalents, compared with pure fossil JET A-1.

Keywords: Airport demonstration, Emissions trading, Fuel properties, Sustainability, Sustainable aviation fuel

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1 Introduction

The aviation sector is facing particular challenges surrounding climate protection targets in light of the Paris Climate Agreement. At the same time, the industry is experiencing rapid growth. Against this backdrop, sustainable aviation fuels (SAF) as substitutes for fossil-based aviation fuel play a key role in the aviation sector.

Current climate protection strategies, i.e. targets of the International Air Transport Association (IATA), the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) of the International Civil Aviation Organization (ICAO), and proposals on blending mandates in some countries, increase the demand for such renewable SAF in the short to medium term. Fig. 1 shows the jet fuel demand of all departing flights in Germany, the amount of CO_2 emissions to be reduced, the share of renewable jet fuels required to fulfill targets like those of the Aviation Initiative for Renewable Energy in Germany e.V. (aireg), the IATA and Germany's Climate Action Plan 2050, as well as the required energy-related amounts of renewable SAF and their specific greenhouse gas (GHG) mitigation potentials. According to this, there is a massive demand for SAF with a high GHG mitigation potential compared to fossil jet fuel [1].

In the medium term, German airports are expected to be supplied with JET A-1 containing different proportions of various types of renewable SAF.

The need to reduce and prevent emissions in the German aviation industry has been addressed by the German government's Mobility and Fuels Strategy (MFS). In addition to technical and operational measures to reduce emissions, it focuses on substituting conventional fossil-based jet fuel with SAF. For

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[1] Dr. Franziska Müller-Langer, Niels Dögnitz, Katja Oehmichen, Stefan Majer
franziska.mueller-langer@dbfz.de
DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Strasse 116, 04347 Leipzig, Germany.

[2] Christian Marquardt
Bundeswehr Research Institute for Materials, Fuels and Lubricants, Institutsweg 1, 85435 Erding, Germany.

[3] Dr. Alexander Zschocke
Centre of Competence, Climate, Environment and Noise Protection in Aviation, Bessie-Coleman-Strasse 7, 60549 Frankfurt, Germany.

[4] Tobias Schripp
German Aerospace Center (DLR), Institute of Combustion Technology, Pfaffenwaldring 38–40, 70569 Stuttgart, Germany.

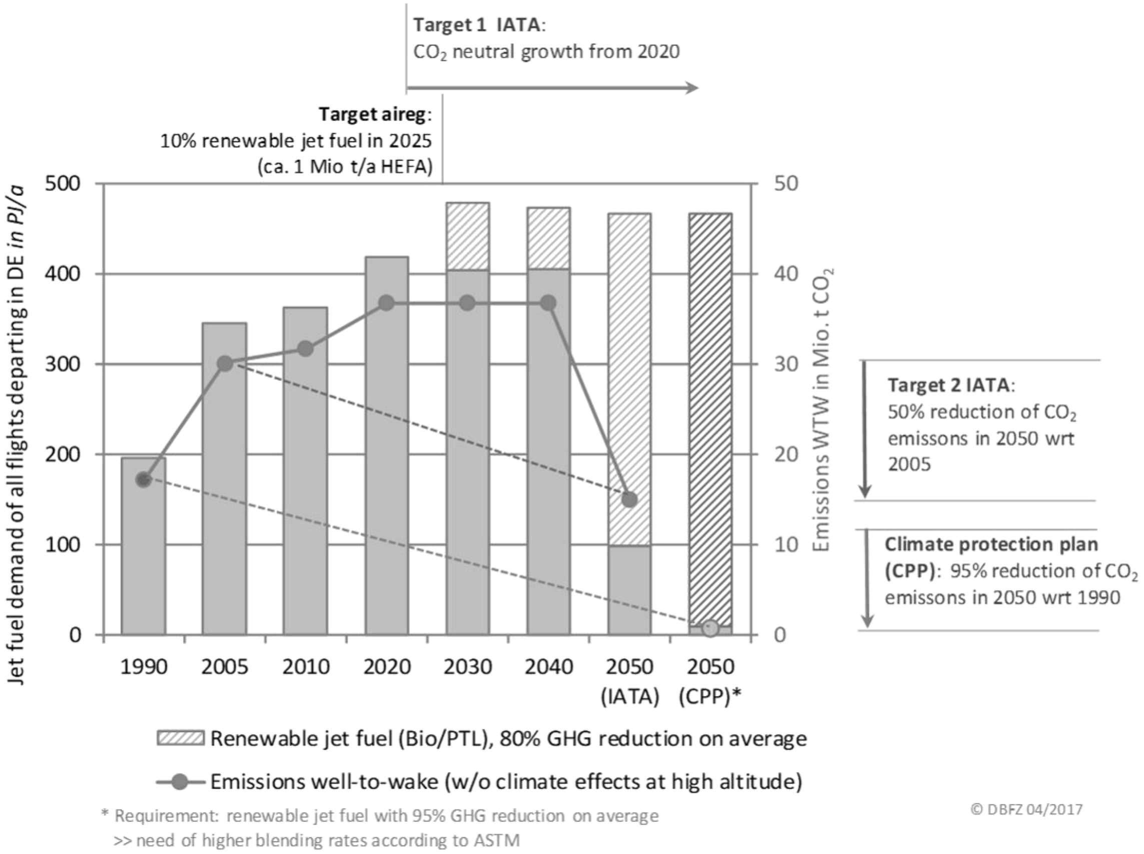
[5] Nils Bullerdiek
Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE), Eissendorfer Strasse 40, 21073 Hamburg, Germany.

[6] Ann-Marlen Halling
Meo Carbon Solutions GmbH, Hohenzollernring 72, 50672 Cologne, Germany.

[7] Dietmar Posselt
aireg – Aviation Initiative for Renewable Energy in Germany e.V., Bundesratufer 10, 10555 Berlin, Germany.

[8] Dr. Thomas Kuchling
TU Bergakademie Freiberg (TUBAF), Institute of Energy Process Engineering and Chemical Engineering, Fuchsmühlenweg 9, 09599 Freiberg, Germany.

[9] Joachim Buse
Adeptus Green Management GmbH, Lerchennest 24, 21244 Buchholz in der Nordheide, Germany.



* Requirement: renewable jet fuel with 95% GHG reduction on average
>> need of higher blending rates according to ASTM

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Figure 1. Jet fuel demand of all flights departing in Germany, emissions to be reduced and share of renewable jet fuels required to fulfil targets like those of aireg, IATA, and Germany's climate protection plan [1].

this purpose, new manufacturing processes, as specified by the international ASTM (American Society for Testing and Materials) 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 kerosene may not yet be placed on the market in its pure form. Instead, it has to be mixed ("blended") with fossil-based JET A-1.

The primary objective of the research and demonstration (R&D) project, DEMO-SPK, was to investigate and verify the behavior of several renewable jet fuel mixtures 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 (LCA) and analyzed the sustainability documentation as well as options to verify and account for the use of the renewable fuels in the European emissions trading system. Furthermore, legal questions were clarified and organizational framework conditions were created.

The objective of this article is to summarize the work done as part of the DEMO-SPK project by providing an overview of the general methodical approach and the key results.

2 Methods

The DEMO-SPK project was organized into three main pillars, which are briefly explained below. Addressing legal and operational aspects was fundamental to all three pillars.

2.1 Pre-Investigations and R&D

Here, the focus was on analyzing different multiblends of conventional JET A-1 with either two or three sustainable aviation fuels. This included many different analyses of fuel properties in accordance with standard ASTM methods, storage stability over a period of 6 months (chemical-physical parameters of the fuels specified in ASTM D7566 were determined in order to monitor possible changes), mixing behavior under realistic conditions, compatibility with the fuel supply infrastructure, and operational use of the multiblend JET A-1 in an aircraft. The SAF, which were available in the context of this project, were alcohol-to-JET (ATJ)-SPK, hydrotreated esters and fatty acids (HEFA)-SPK, and synthesized *iso*-paraffins (SIP). The multiblends produced during the pre-investigations provided the basis for the determination of the fuel quantities required for the demonstration.

Moreover, Fischer-Tropsch (FT)-SPK, based on a power-to-liquid (PTL) approach, was investigated on the laboratory scale. To do this, an intermediate FT product from a PTL demonstration plant was upgraded by isomerization and hydrocracking in different modes in order to meet the ASTM requirements.

2.2 Demonstration

A laboratory analysis alone does not suffice to comprehensively answer these questions, since the realistic conditions in a fuel depot and in the fuel supply infrastructure can lead to effects that cannot be simulated in a laboratory environment. Moreover, the application of existing legal and regulatory requirements and identifying obstacles for improvement were part of the demonstration.

For this reason, a large-scale demonstration was carried out, including the transport of several hundred tons of SAF HEFA-SPK and ATJ-SPK, as well as JET A-1, for the production of about 600 t of Multiblend JET A-1 and supply of this amount to the infrastructure of a major airport.

As part of this demonstration, the influence of the multiblend JET A-1 on local emissions at the airport was investigated as well. Comparative emission measurements were carried out on an aircraft turbine in an engine testing facility at the Leipzig/Halle (LEJ) airport. Two ground runs were conducted based on a fixed measurement protocol that included a fossil JET A-1 reference measurement and a measurement of the multiblend JET A-1.

2.3 Accompanying R&D

The project also provided the opportunity to tackle further outstanding questions directly linked to the introduction of sustainable aviation fuels. These included:

- An LCA of the different sustainable aviation fuels and the different kinds of multiblend JET A-1. Various individual LCA were developed for environmental issues and costs for the SAF, which were used to investigate three different scenarios (linked to the demonstrated case and the assumption that an airport will be supplied with multiblend JET A-1 on a commercial scale). The LCA for the environmental impact assessment was based on two methodical approaches: (1) an attributional LCA based on the international standards ISO 14040 and 14044, and (2) a method for calculating GHG emissions for biofuels as defined in the EU Renewable Energy Directive (2015/1513). The life cycle costing analysis included the production and transport costs over the whole supply chain.
- Development of viable sustainability documentation procedures and requirements for various SAF feedstocks (e.g., no deforestation, protection of highly biodiverse and high-carbon stock areas worldwide). Further, the focus was on documenting the traceability and transparency of the respective sustainability information along the entire supply chain and on determining the respective interfaces with emission trading accounting systems and their verification. All aspects were set in context to current national and international regulatory frameworks.
- Weaknesses and limitations of the existing accounting system for SAF in in the European emissions trading system (EU ETS) were derived. On this basis, conceptual designs of different approaches/methodologies for accounting SAF in the EU ETS were developed. Furthermore, the research demonstrated that SAF accounting involves various industry/regulatory stakeholders without a single responsible party, which indicates the necessity to pursue the matter of implementing a suitable accounting concept for SAF on a regulatory level.

3 Results and Discussion

The key results of the DEMO-SPK project are briefly discussed below.

3.1 Fuel Properties

The first step was to design and produce four different multiblends that contained the maximum amount of SAF and which continued to meet all requirements stipulated by ASTM D7566. The multiblends were mixed on a laboratory scale (4 L per multiblend), and the relevant physicochemical parameters were determined. The analysis confirmed that ASTM D7566-compliant fuels had been obtained. This means that it is possible to produce on-spec, semi-synthetic fuel mixtures from several different synthetic fuels.

This was followed by a 6-month storage stability test in a fuel depot, using the same four multiblends produced at a scale of hundreds of liters. Samples were taken from each fuel mixture at the beginning and end of the storage period, and the fuels underwent a full analysis to determine possible alterations in fuel quality. No changes of the chemical-physical parameters (in particular: existent gum, acidity, thermal stability) were observed. This means that no deterioration in the fuel quality was found to have occurred. Additionally, samples at different fuel levels were taken during the storage period. These samples were analyzed to rule out the unlikely event of segregation.

PTL-SPK was produced for the first time using an FT raw product from a PTL demonstration plant that produces PTL diesel. A key result of the comprehensive investigation was that an SPK yield of more than 60 wt % could be obtained with the chosen upgrading process steps; the related hydrogen demand is about 0.5 g per 100 g feed. Finally, an SPK quality compatible with key ASTM D7566 requirements could be proven and the process conditions to achieve this could be verified. PTL-SPK was produced for the first time with an FT raw product from a PTL demonstration plant. A major result of the comprehensive investigation was that more than 80 wt % of the middle distillates and waxes in the feedstock can be converted to SPK with the chosen upgrading process steps; the related hydrogen requirement is about 0.5 g per 100 g feedstock. The quality of the jet components obtained meets the ASTM requirements (Tab. 1) and the process conditions required for this have been verified.

Table 1. FT-SPK properties compared to ASTM requirements.

Parameter	ASTM D7566	FT-SPK
Freezing point [°C]	max. –40	–42.9
Initial boiling point[a] [°C]		172.2
10 % recovered [°C]	max. 205	174.3
50 % recovered [°C]	report	189.7
90 % recovered [°C]	report	220.5
Final boiling point [°C]	max. 300	234.4
Flash point [°C]	min. 38	51.5
Density (15 °C) [$\mathrm{kg\,m^{-3}}$]	730–770	744.5
Acid number [$\mathrm{mg\,KOH\,g^{-1}}$]	max. 0.015	0.006
Kinematic viscosity (–20 °C) [$\mathrm{mm^2 s^{-1}}$]	max. 8	3.8

[a] Boiling behavior according to ASTM: "Physical Distillation"; data for FT-SPK: "Simulated Distillation".

3.2 Demonstrated Supply Logistics and Production of Multiblend JET A-1

The next step of the DEMO-SPK project was to create a multiblend JET A-1 and to supply it at the Leipzig/Halle airport using the existing airport infrastructure. Due to safety regulations, blending could not be performed directly on the airport premises and was instead done at an external tank farm. Composition and blending procedures had to comply with existing regulations, some of which currently do not explicitly cover multiblends.

Fig. 2 illustrates the supply chain. The individual types of kerosene were transported in different ways as they were manufactured at different locations. The fossil JET A-1 was produced in Germany and, hence, simply transported by rail tank car to the blending site. The sustainable aviation fuels were produced in the USA and, hence, had to be shipped to the port of Hamburg in ISO tank containers and from there (partially via a container terminal) trucked to the blending site.

Two different kinds of SAF (HEFA-SPK and ATJ-SPK) certified according to ASTM 7566 were purchased and used for blending. It would have been beneficial to source at least one additional type of SAF but, in spite of sourcing worldwide, the two fuels used were the only ones available anywhere at scale. With respect to the fossil fuel, care was taken to source a conventional JET A-1 with low sulfur and medium aromatics content to avoid distorting the emissions measurements. Blending was performed at Speyer tank farm. As blending of kerosene is normally not performed for fossil fuels, some infrastructure adjustments had to be made first at Speyer tank farm (dedicated pipes for SPK, equipping one tank to perform the actual blending).

After mixing, the multiblend JET A-1 was loaded onto tank cars and transported to Leipzig/Halle (LEJ) airport.

3.3 Turbine Emissions

Previous studies have shown a reduction in soot released from aircraft engines when jet fuels with higher hydrogen contents are used [2]. For the emission measurements in DEMO-SPK, an Airbus A300/600 aircraft and facilities for engine test runs on the premises of LEJ airport were used.

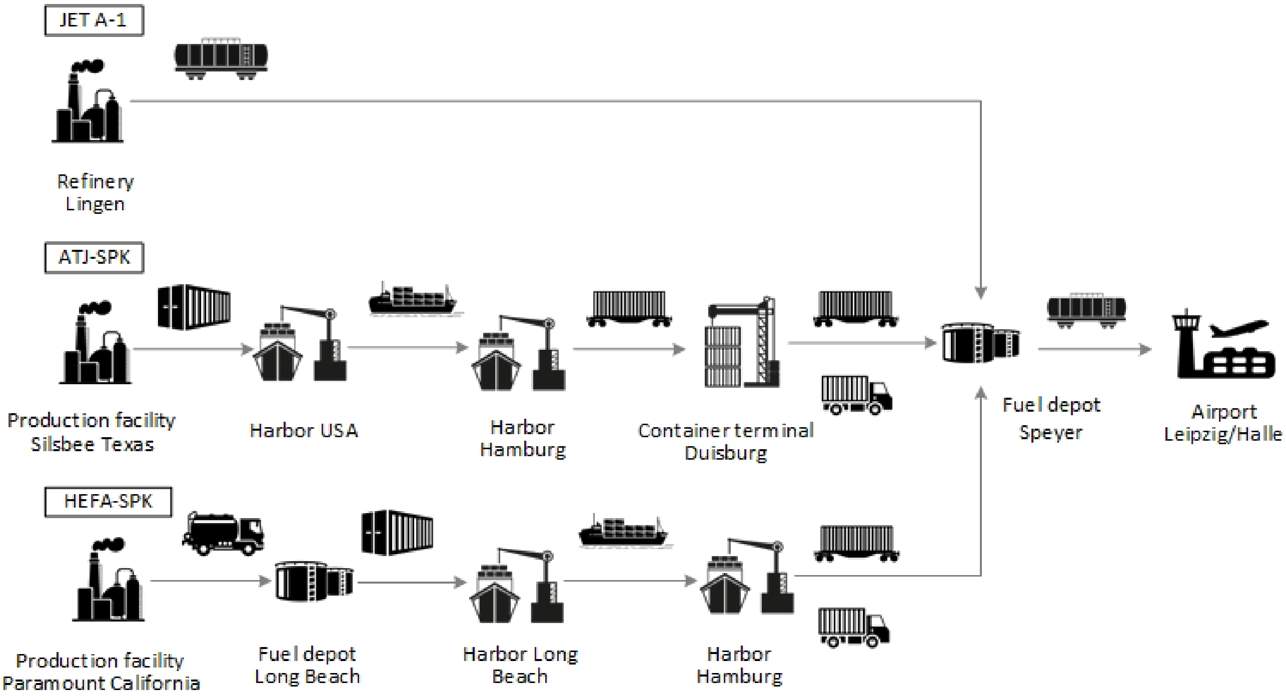


Figure 2. Demonstrated supply logistics.

On arrival, the aircraft was fueled with the reference JET A-1. After emission measurements were completed, the aircraft was moved from the engine test run facility to a parking position. It was defueled and then refueled with the multiblend JET A-1. A second emission measurement was then performed back at the engine test run facility. Prior to each ground run, samples were taken from the wing tanks for analysis.

Several particle counters and other instruments, like an Engine Exhaust Particle Sizer (EEPS; TSI Inc.), a Scanning Mobility Particle Sizer (SMPS; TSI Inc.), a UV-IR Black Carbon monitor (MA-200; Aethlabs), and a mobile Fourier transform infrared spectrometer (MKS) were used to record the emission profile of the engine. The instruments were operated with a thermal denuder to remove the volatile particle fraction of the aerosol. The remaining non-volatile particles (nvPM) show a significant emission reduction in case of the multiblend fuel. In order to demonstrate the effects of the multiblend in an application-related context, the measured emission indices were interpolated (Fig. 3) and transferred to a standardized scenario based on the ICAO landing and take-off (LTO) cycle. The interpolation of the measured data was based on fuel consumption and used to calculate the total amount of released particle mass at the four LTO power settings. When looking at the total emissions derived from the LTO cycle, the application of the multiblend JET A-1 led to a 37% reduction in the released particle number and a 29% reduction in released particle mass. During the LTO cycle, a total of 95 g of particulate mass was emitted (approx. 0.01 wt % of the fuel used), which translates into a reduction of 28 g for just one of the aircraft turbines.

In addition, also CO and NO_x emissions were measured. As expected, CO emissions are similar for both fuels (reference JET A-1 and the multiblend) and NO_x emissions show a stronger dependency on the ambient conditions than on the fuels itself.

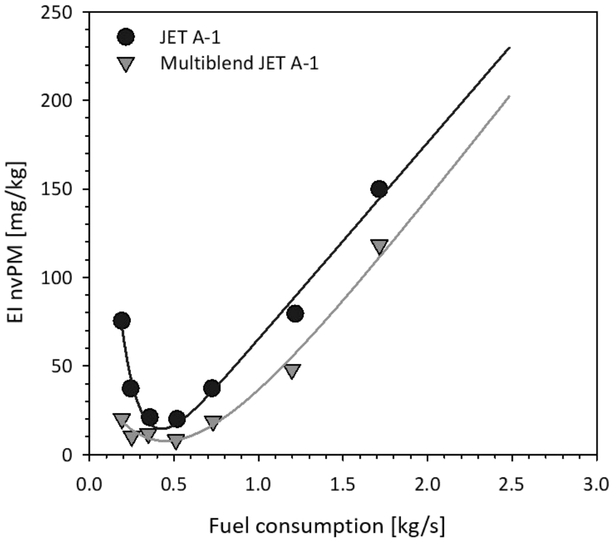


Figure 3. Emission index of the non-volatile particle mass at seven different engine power settings for multiblend JET A-1 and the reference kerosene (instrument: MA-200 aethalometer, AethLabs).

3.4 Life Cycle Analysis and Life Cycle Costing

Based on the assessment of the different types of renewable kerosene and the assessment of the fossil JET A-1 supply chain, life cycle assessments were carried out for manufactured multiblends, including transport from the fuel depot to LEJ airport and its use in the aircraft. Therefore, three different cases were analyzed. Case A depicts the supply chain demonstrated in the DEMO-SPK project. Case B represents the supply chain with a multiblend JET A-1 consisting of four components. In case C, the theoretical, large-scale production of the synthetic components was calculated.

Fig. 4 shows a considerable reduction in GHG emissions of up to 35 % for the multiblends compared to fossil JET A-1. The biggest contributor to the total GHG emissions is the combustion in the aircraft engine. The greenhouse effect of the emissions at high altitudes was not taken into account. Simplistically speaking, it can be assumed that the effects of all the SPK and multiblends tested would be the same. Since the biogenic CO_2 emissions are not incorporated in the GHG balance, the GHG emissions from the combustion of fossil JET A-1 is to be considered as the main contributor. This can be seen when comparing the higher GHG emissions in case B with the lower emissions in cases A and C. This difference in GHG emissions

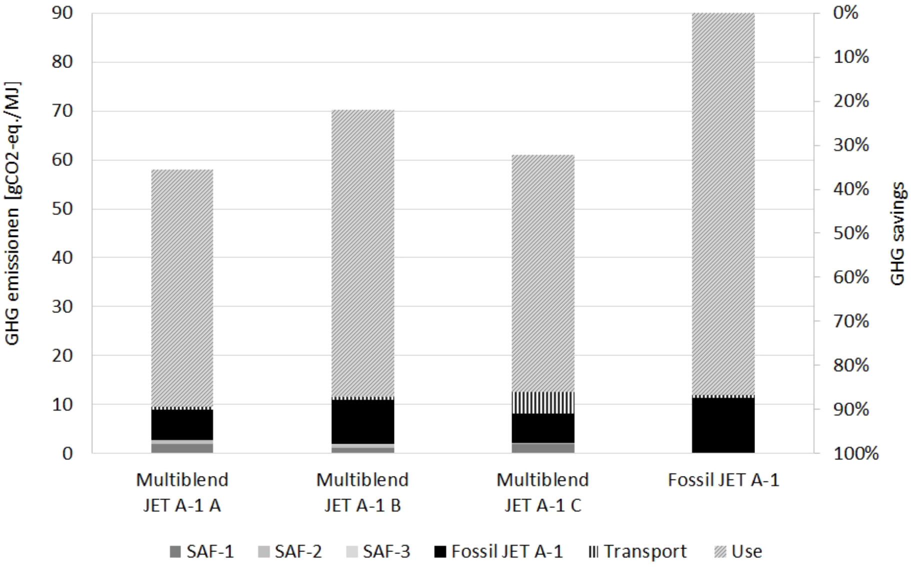


Figure 4. GHG emissions and GHG savings of multiblend JET A-1 compared to fossil JET A-1 for different scenarios.

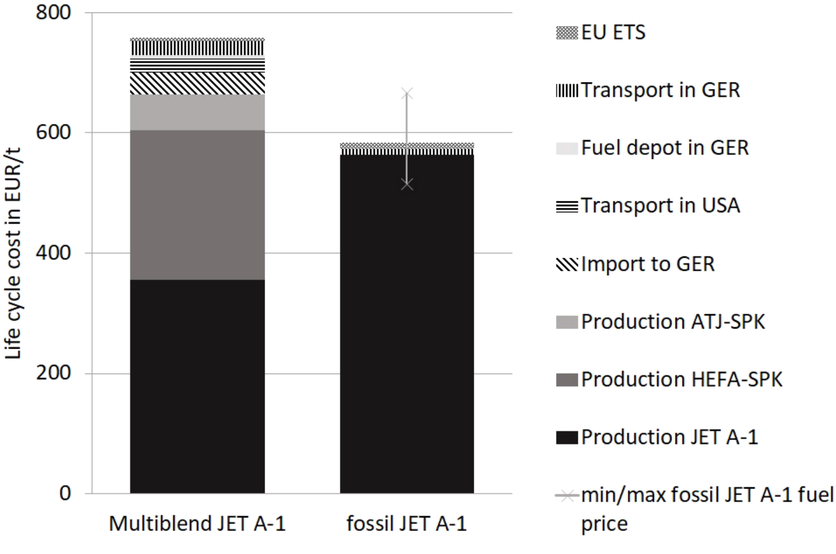


Figure 5. Life cycle costs of multiblend JET A-1 and fossil JET A-1.

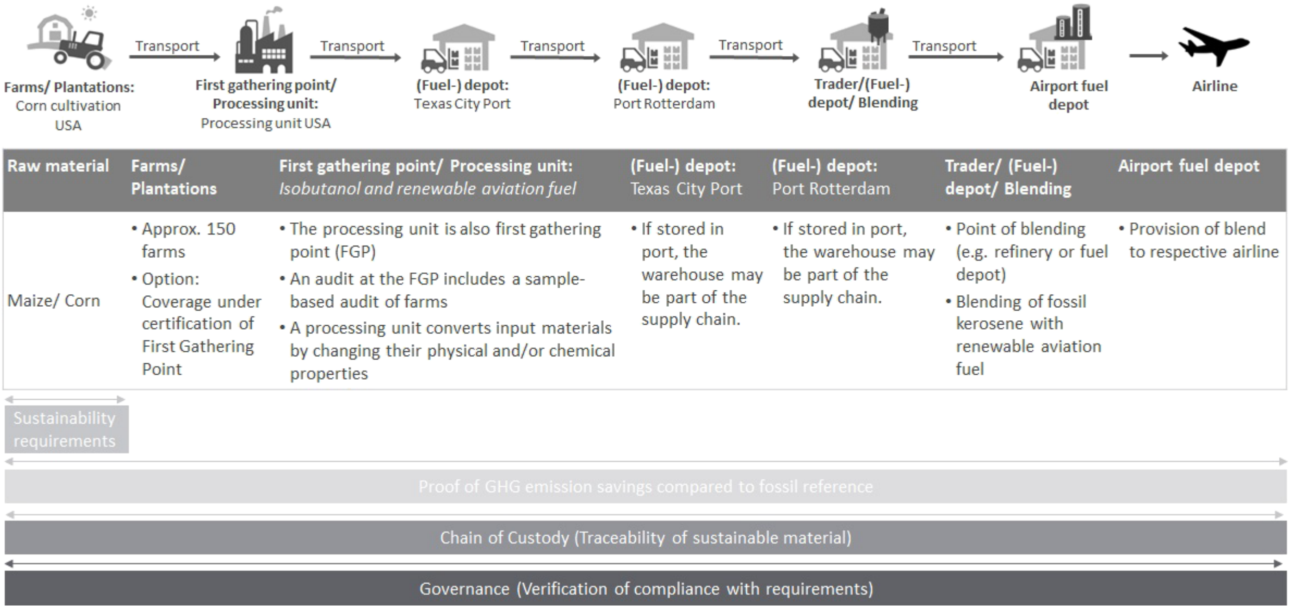
is caused by the lower ratio of renewable kerosene in this particular multiblend and the concomitant higher JET A-1 ratio. In this composition, the GHG emissions that occur within the supply chain of the renewable forms of kerosene have no significant effect on the overall emissions.

When acquisition and supply costs are combined, the total life cycle cost for the multiblend JET A-1 amounts to EUR 760 t^{-1}. In case C, the logistics and supply of the multiblend and the multiblend components amount to approximately 12 % of the overall life cycle costs (Fig. 5).

In 2018, the price for fossil JET A-1 (ex refinery) was approximately EUR 560 t^{-1}, as reported in [3]. Considering a supply to LEJ airport, as assumed here, and the accounting of fossil fuels in the EU ETS, the life cycle costs amount to approx. EUR 580 t^{-1}. This would still mean 23 % less than the calculated life cycle costs of the multiblend JET A-1. Adding up the emission savings that accompany the implementation of the multiblend JET A-1, the life cycle costs of the multiblend and the fossil reference result in savings of EUR 128 t^{-1}, due to the reduction in CO_2 emissions.

3.5 Sustainability Certification of Aviation Fuels

It is possible to certify, within the scope of the EU Renewable Energy Directive (RED), all value-added chains involved in the production of sustainable aviation fuels and taken into account during this project. The certification systems recognized by the European Commission are applicable to all kinds of biomass and other renewable resources. Furthermore, the process technologies implemented in the value-added chains are equivalent to technologies that have already been certified. By individually auditing and certifying every element of the value-added chain, any random combination in a supply chain can be calculated. The documentation requirements for each of the elements guarantee uninterrupted traceability of the sustainability information. Finally, the methodology for calculating GHG emissions, as predetermined by the EU RED, provides flexibility, which enables the calculation and inclusion of new production methods at any given time. Fig. 6 presents examples of the requirements for sustainability documentation analyzed for an ATJ-SPK supply chain.



Raw material	Farms/ Plantations	First gathering point/ Processing unit: *Isobutanol and renewable aviation fuel*	(Fuel-) depot: Texas City Port	(Fuel-) depot: Port Rotterdam	Trader/ (Fuel-) depot/ Blending	Airport fuel depot
Maize/ Corn	• Approx. 150 farms • Option: Coverage under certification of First Gathering Point	• The processing unit is also first gathering point (FGP) • An audit at the FGP includes a sample-based audit of farms • A processing unit converts input materials by changing their physical and/or chemical properties	• If stored in port, the warehouse may be part of the supply chain.	• If stored in port, the warehouse may be part of the supply chain.	• Point of blending (e.g. refinery or fuel depot) • Blending of fossil kerosene with renewable aviation fuel	• Provision of blend to respective airline

Figure 6. Requirements for sustainability documentation analyzed for an ATJ-SPK supply chain.

3.6 Chain-of-Custody Options for Emission Trading

During the course of DEMO-SPK, different options for furnishing proof of implementation and accountability of sustainable jet fuels were discussed and illustrated [4]. This refers to both the traceability of each of the value-added chains of the SPK defined in this project and the need to transfer sustainability information about the injected renewable jet fuels after they are mixed with fossil JET A-1 into a blend/multiblend. Such a transfer of information needs to be guaranteed right up to the airport fuel depots and the subsequent fueling of the aircraft. For accounting purposes under EU ETS, the corresponding information must also be available to the airlines as the final fuel user. The three options for procedures in the documentation and accounting of sustainable aviation fuels are illustrated in Fig. 7:

- Option 1: Certification of the entire value-added chain of the renewable jet fuel under EU RED.
- Option 2: Transition from EU RED certification towards a "Book & Claim" system.
- Option 3: Transition from EU RED certification towards a "Track & Trace" system.

All three of these options essentially accomplish the desired goals. Therefore, it stands to reason that preferential options should be assessed in conjunction with additional administrative efforts.

The additional effort for implementing an established EU RED certification system includes certifying manufacturers and depots that have not conducted any prior transactions under EU RED, and setting up a mass balance for the EU ETS system.

The additional effort for the "Book & Claim" option is the Europe-wide registry (e.g. the European Central Registry) for purchasing, transferring and verifying Book & Claim certificates, so-called Guarantees of Origin. This task is expected to be assumed by an existing body. In this scenario, the additional effort lies in setting up and maintaining such a central registry (database).

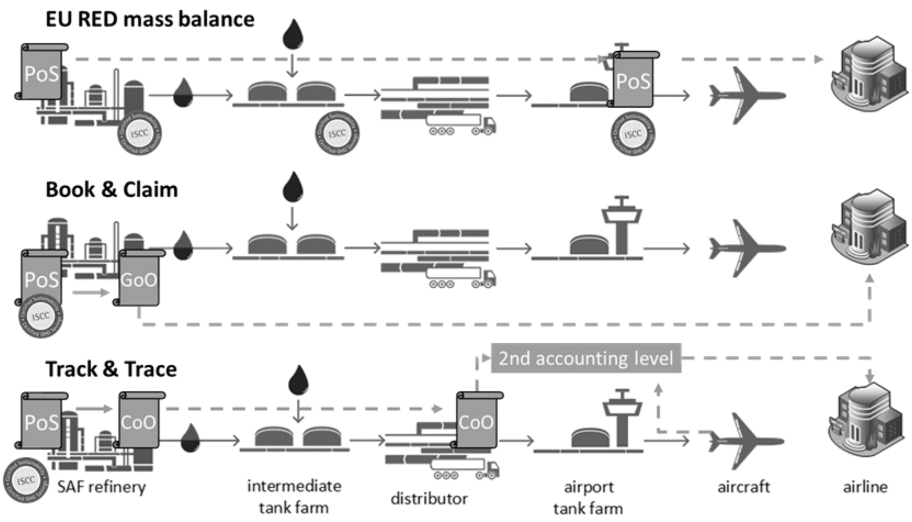


Figure 7. Chain-of-custody options.

With the "Track & Trace" option, the additional effort consists of establishing a European inventory management and reporting system (if applicable, an extension of the current capacities of the customs system) with the supply chain (database), and the additional maintenance and auditing tasks for the chief customs offices of the members states.

4 Conclusions

Thanks to the participation of more than 20 international partners from industry and science, DEMO-SPK has been the first of its kind to:

- verify that multiblends with different synthetic fuels also comply with the requirements of ASTM D7566,
- confirm that JET A-1 multiblends do not suffer from quality defects during storage,
- supply nearly 600 t of multiblend JET A-1 and to utilize this in flight operations at the Leipzig/Halle airport,
- through the use of multiblend JET A-1 in aircraft instead of pure fossil-based JET A-1 fuel (i) reducing particle emissions in ground runs by approx. 30–60 % and (ii) reducing CO_2 equivalent emissions by approx. 35 %,
- upgrade PTL-based FT-SPK to meet the key requirements of ASTM specifications,
- develop three different approaches for SAF sustainability verifications and SAF accounting aspects in GHG regulation systems like the EU ETS,
- make recommendations for improving the operational supply chain.

The pilot project has not only made numerous suggestions for operational project management but also identified concrete clarification needs, which is important for a successful implementation in the broader market. These include (i) the expansion of ASTM D7566 to include the simultaneous production of multiblend JET A-1, (ii) a simplified Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals (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 submitted 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 jet fuels as part of multiblend jet fuels 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) is 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 GHG.

Acknowledgment

The R&D project on the use of renewable kerosene at Leipzig/Halle airport (DEMO-SPK) involved the collaboration of more than 20 international partners from industry and science. It was initiated as a model project of the Mobility and Fuel Strategy (MFS) and financed by the Federal Ministry of Transport and Digital Infrastructure (BMVI). The project was coordinated by the DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH; partners included Adeptus Green Management GmbH, aireg e.V., ASG Analytik-Service GmbH, BP Europa SE, DHL/European Air Transport Leipzig GmbH, Dettmer Rail GmbH, Deutsches Zentrum für Luft und Raumfahrt (DLR) e.V., GEVO Inc., IFOK GmbH, knoell Germany GmbH, Meo Carbon Solutions GmbH, Neste Corporation, Petro Lab GmbH, Sunfire GmbH, Tanquid GmbH & Co. KG, TOTAL S.A., Technische Universität Bergakademie Freiberg, Technische Universität Hamburg, Varo Energy, VTG AG, Wehrwissenschaftliches Institut für Werk- und Betriebsstoffe (WIWeB), and World Energy LLC.

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Abbreviations

ASTM	American Society for Testing and Materials
ATJ	alcohol-to-JET
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ETS	emissions trading system
FT	Fischer-Tropsch
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LCA	life cycle analysis
LEJ	IATA code for the Leipzig/Halle airport
LTO	landing and take-off
MFS	Mobility and Fuel Strategy
PTL	power-to-liquid
R&D	research and demonstration
REACH	Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals
RED	Renewable Energy Directive
SAF	sustainable aviation fuel
SIP	synthesized *iso*-paraffins
SPK	synthetic paraffinic kerosene

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