IMPACT OF ALTERNATIVE FUELS ON ENGINE PERFORMANCE AND CO_2-EMISSIONS

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Abstract

Besides technological innovation in the fields of aircraft and engine technology, alternative fuels are a major potential contributor to secure future energy supply, combat oil price volatilities and reduce greenhouse gas emissions from aircraft engines. In this study, the impact of alternative fuels on engine performance, fuel consumption and CO_2 emissions is analysed on engine and flight mission levels. Direct effects from the combustion of alternative fuels are simulated by creating an alternative fuel model based on a simplified fuel reaction mechanism. By means of this model, both the fuel heating value and the chemical composition of different fuels can be considered during engine simulation. To evaluate the impact of alternative fuels on engine performance, two engine models are applied representing common engines used on short-haul and long-haul aircraft. Besides covering direct effects of alternative fuels on engine emissions, the benefits in terms of life cycle emissions are presented based on a literature review. Life cycle emissions of alternative fuels are discussed on an equivalent CO_2 basis and are compared to conventional kerosene. Finally, short- and long-haul flights are simulated to consider the impact of alternative fuels on fuel consumption and emissions on flight mission level.

Nomenclature

CR	Cruise
EI	Emission Index
FAR	Fuel to Air Ratio
FHV	(lower) Fuel Heating Value
FL	Flight Level
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GWP	Global Warming Potential
H	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids
ILUC	Indirect Land Use Change
LCA	Life Cycle Assessment
LUC	Land Use Change
SPK	Synthetic Paraffinic Kerosene
TA	Transition Altitude
TTW	Tank-to-Wake
WAR	Water to Air Ratio
WTT	Well-to-Tank
WTW	Well-to-Wake

1 Introduction

Worldwide aviation contributes about 2 % of today's man-made emissions of carbon dioxide (CO_2) [1]. According to market forecasts of major aircraft manufacturers, global air traffic is expected to grow by about 5% per year within the next decades ([2], [3]).

With respect to the growing sensibility for environmental balance, the aviation industry has taken responsibility by proclaiming ambitious goals for reducing aviation's environmental impact (e.g. [4], [5], [6]).

Besides innovations in the fields of aircraft and engine technology, alternative fuels are seen as a major contributor towards reaching these goals.

Today, commercial aviation relies on a single fuel, i.e. fossil crude oil derived kerosene. Alternative fuels have the potential to secure future energy supply and to combat oil price volatilities.

Synthetic Paraffinic Kerosene (SPK) derived from biomass feedstock is seen as one of the most promising alternative fuels in the near-term. SPK is virtually sulphur free and has a higher hydrogen-carbon ratio, which is assumed to improve engine performance and emission characteristics. Moreover, snowball effects on flight mission level in terms of reduced fuel flow and hence reduced take-off weight are expected to enhance fuel efficiency.

This study evaluates both qualitatively and quantitatively the effects of alternative fuels on engine performance and direct combustion emissions of CO_2 by analysing short-haul and long-haul flight missions. The evaluation is performed by means of DLR's performance synthesis program GTlab and DLR's aircraft performance tool VarMission.

Synthetic fuels from renewable sources such as biomass are expected to reduce aviation's environmental impact primarily by capturing CO_2 during cultivation. Considering the life cycle, the CO_2 release during combustion is balanced by CO_2 which has previously been captured. To quantify these potential benefits, also life cycle emissions are taken into account.

2 Alternative Fuels for Aviation

In 2008, air traffic consumed about 240 million tons of aviation fuels [7]. The primary type of kerosene used in commercial aviation is Jet-A1, defined in specifications like D1655 by ASTM International [8]. International air traffic demands fuel with specific requirements to cope with an aircraft's particular operation environment, e.g. high energy content (min. 42.8 MJ/kg) and density (775 to 840 kg/m³), low freezing point (min. -47°C) and good cold flow properties (max. 8 mm²/s at -20°C). The specification defines limits for certain fuel properties, based on experiences with crude oil derived kerosene, rather than defining a specific composition of jet fuel. Therefore additional fit-for-purpose tests for alternative fuels are required taken different production pathways and feedstocks into account, which makes the certification process of alternative fuels very extensive [9].

Within the last years the development of alternative fuels for aviation has accelerated impressively and the technology of processes has matured. The focus is set on "drop-in" fuels, i.e. fuels being fully compatible with conventional jet fuel, which do not require any adaptions on the aircraft and engine sides. Due to long hardware life, worldwide operation and costs, non "drop-in" fuels, like e.g. cryogenic hydrogen, are regarded as not viable in the near to mid-term. Moreover, blending with conventional kerosene may ease the introduction and ramp up of alternative fuels.

Since 2008 several demonstration flights proved the technological feasibility of alternative fuels in aviation (e.g. [10], [11]). As a consequence, two synthetic alternative fuels have been approved under ASTM D7566 in 2009 and 2011 for use in aviation as 50/50 blends with conventional kerosene. This refers to the following types of fuel:

- Synthetic Paraffinic Kerosene derived from Fischer-Tropsch (FT) Synthesis and
- Hydroprocessed Esters and Fatty Acids (HEFA).

Theses fuels are considered as "drop-in" fuels and can be used without restrictions on aircraft or engine operability. However, some technical issues, like seal swelling to prevent leakage or fuel density, are strongly affected by aromatics, which do not occur in neat SPK. Currently a minimum aromatic content of 8 %-vol. is required by certification requirements and, consequently, only the use of fuel blends up to 50%-vol. is approved. The addition of synthetic aromatics may avoid these issues and the approval for neat synthetic paraffinic kerosene is currently on going. Moreover, other pathways are under consideration including Direct Sugar-to-Hydrocarbon (DSHC) and Alcohol-to-Jet (ATJ) routes based on sugar cane or chipped wood [12].

The present investigation focuses on biomass feedstocks. The considered alternative fuels are summarized in Table 1.

Feedstock	Process
Switchgrass	FT Synthesis
Forest residue	FT Synthesis
Jatropha	HEFA
Camelina	HEFA
Algae	HEFA

Table 1: Evaluated alternative fuels.

Although most of these fuels and pathways are technologically mature, they are not yet mass-produced. Availability of biomass feedstock, production capacities and fuel production at competitive costs become key issues for the successful deployment of alternative fuels in aviation. Biomass cultivation for fuel production must not compete with freshwater needs, food crop production or biodiversity. In addition, air traffic is facing competition for biomass with other sectors like e.g. road transportation.

3 Modelling Alternative Fuels

For an evaluation of alternative fuels the DLR gas turbine performance tool GTlab [13] is used. The working fluid is modeled as a perfect gas, assuming heat capacity as a function of temperature only:

$$c_p = f(T) \neq f(p) \qquad (1)$$

Within GTlab exchangeable fuel performance maps are applied, allowing the flexible use of arbitrary fuels. These maps consider gas properties in terms of thermodynamic functions like isobaric heat capacity c_p, enthalpy h, entropy function ψ and heat addition tables, representing the temperature rise ΔT as functions of fuel to air ratio FAR, water to air ratio WAR, temperature T and inlet temperature T_{in} and pressure P_{in}, respectively:

$$\begin{aligned} c_p &= f(T, FAR, WAR) \\ h &= f(T, FAR, WAR) \\ \psi &= f(T, FAR, WAR) \\ \Delta T &= T_{out} - T_{in} = f(T_{in}, P_{in}, FAR, WAR) \end{aligned} \qquad (2)$$

The free chemical kinetic software package Cantera [14] was used to generate the fuel performance data for this study. The gas composition is calculated assuming chemical equilibrium. The temperature rise is defined by the equilibrium temperature, taking dissociation effects and enthalpy of vaporization into account. The thermodynamic data for gas properties is derived using NASA 7-term polynomials [15].

3.1 Methodology and Assumptions

The fuel model delivers the gas properties and temperature rise characteristics within the thermodynamic engine performance program GTlab. Lee et al. [16] proposed a reduced five-step fuel kinetic mechanism for jet fuel simulation, where the surrogate fuel is composed of an aromatic ($C_{10}H_8$) and a paraffinic ($C_{13}H_{28}$) compound only.

Based on this simplified fuel composition generic fuel models have been created representing Jet-A1 as the baseline reference (JetRef), neat SPK (SPK100) and a 50/50 blend of Jet-A1 and SPK (SPK50) as two alternative fuel configurations.

The fuel models were calibrated to meet the respective average hydrogen (H) mass content of the fuel, whereas any sulphur content within the fuel was neglected. Fuel specific gravity was not explicitly modeled and is just mentioned for the purpose of comparison.

As proposed e.g. by Rachner [17], Jet-A1 normally has an average hydrogen mass content of about 13.9 %. The average lower fuel heating value (FHV) is typically about 43.26 MJ/kg and the specific gravity is about 807.5 kg/m³ (at 15°C), representing the mean value of the permitted range within Jet-A1 specification [17].

The properties of the Jet-A1 reference fuel model used in this study are presented in Table 2.

Parameter	Unit	Value
H	[wt-%]	13.9
H/C ratio	[vol./vol.]	1.92
FHV	[MJ/kg]	43.25
Specific gravity @15°C	[kg/m³]	807.5

Table 2: Properties of reference Jet-A1 fuel model JetRef.

SPK either derived from FT Synthesis or via HEFA has a slightly different chemical composition. Although SPK is a drop-in fuel with almost similar properties to conventional Jet-A1, its deviating chemical composition results in a different thermodynamic behavior in terms of burned gas properties and energy density.

Neat SPK fuels do not contain any aromatics and therefore reveal a higher hydrogen-to-carbon ratio. Eliminating the aromatic species the neat alternative fuel model consists only of the paraffinic compound. The hydrogen mass content of neat SPK is in the range of 15-15.5% ([10], [18]). The lower fuel heating value is in the range of 44-44.3 MJ/kg and the density at 15°C in the range of 749-753 kg/m³ [10].

The properties of the neat SPK model are presented in Table 3 and are well in line with the aforementioned data from literature.

Parameter	Unit	Value
H	[wt-%]	15.3
H/C ratio	[vol./vol.]	2.15
FHV	[MJ/kg]	44.04
Specific gravity @15°C	[kg/m³]	750

Table 3: Properties of neat SPK alternative fuel model SPK100.

The fuel models for Jet-A1 and neat SPK were mixed together to generate the 50% blend SPK. The resulting hydrogen mass content and lower fuel heating value do well agree with publicly available data. Quoted values are about 14.6 % hydrogen mass content [18] and a lower fuel heating value in the range of 43.5-43.7 MJ/kg [10]. The SPK50 has a specific gravity in the range of 779-789 kg/m³ at 15°C [10].

The properties of the surrogate 50%-blend SPK alternative fuel model are presented in Table 4.

Parameter	Unit	Value
H	[wt-%]	14.6
H/C ratio	[vol./vol.]	2.04
FHV	[MJ/kg]	43.65
Specific gravity @15°C	[kg/m³]	780

Table 4: Properties of 50%-blend SPK alternative fuel model SPK50.

3.2 Fuel Model Analysis

The derived performance maps show deviations between the fuel models in terms of temperature rise and gas properties. Figure 1 depicts the temperature rise as a function of fuel to air ratio for given inlet temperature and pressure of 800 K and 40 bar respectively.

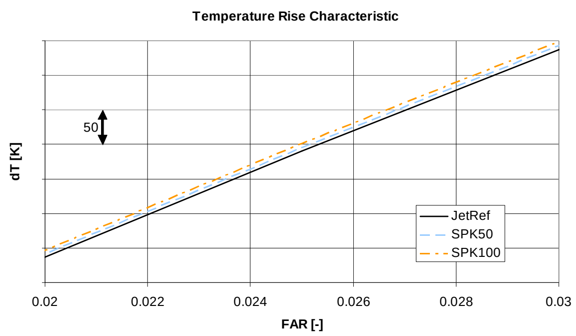

Figure 1: Comparison of temperature rise characteristics in fuel performance maps of modeled fuels.

The SPK50 and SPK100 fuel models need a lower FAR and hence lower fuel amount to achieve the same temperature rise as the JetRef model fuel due to their higher hydrogen content and thus increased fuel heating value.

Isobaric specific heat capacity was chosen as representative for gas property deviations originating from different chemical fuel compositions. Figure 2 shows c_p as a function of gas temperature at a constant FAR of 3%.

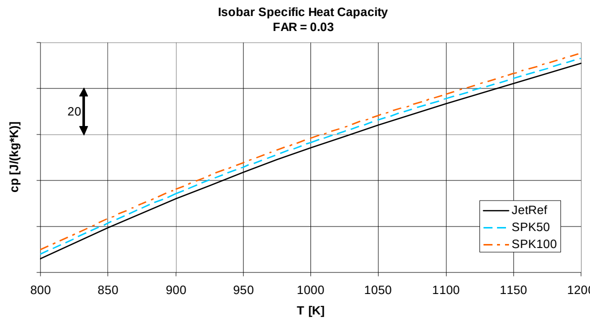

Figure 2: Isobaric specific heat capacity characteristics of fuel models at a fuel to air ratio of 3%.

The SPK fuel models have a slightly higher isobaric specific heat capacity compared to the JetRef fuel model. Since the work output W of an expansion process is proportional to specific heat capacity given by

$$W = c_P \cdot (T_2 - T_1) \tag{3}$$

the increased isobaric specific heat capacity raises the power output of the turbines and thus improves the overall jet engine cycle.

4 Engine Design and Mission Calculations

4.1 Engine Performance Simulation

Engine performance modelling is exercised by means of DLR's in-house gas turbine simulation program GTlab. For the present investigation two engine models were created: A two spool turbofan for short-haul applications (engine1) and a three spool turbofan applicable to long-haul aircraft (engine2). Engine design parameters are chosen to be similar to existing engines, namely the IAE-V2500 and the Trent 700 series. The models are based on publicly available data such as certification data sheets ([19], [20], [21]) as well as manufacturer specifications and common literature (e.g. [22]). The engine models are created following the approach described in [23] utilizing standard performance maps to simulate engine performance characteristics.
A summary of key engine parameters for both engines at take-off condition is given in Table 5.

Parameter	Unit	engine1	engine2
Net Thrust	[kN]	111.2	300.3
OPR	[-]	26.8	33.9
BPR	[-]	4.8	5.1
Fuel flow	[kg/s]	1.1	3.0

Table 5: Summary of selected parameters of simulated engine models.

4.2 Flight Mission Calculations

For investigations on flight mission level, DLR's aircraft performance tool VarMission is used [24], which is coupled to the GTlab engine simulation software. VarMission aircraft models are represented by characteristic aircraft weights (empty weight, maximum take-off weight etc.) and Mach number dependent lift-to-drag characteristics for different aircraft configurations. Generic aircraft are simulated that resemble real aircraft types.
A flight mission is simulated as a sequence of flight segments, namely:

- Taxi-out and taxi-in with engines operating at idle thrust.
- Climb at two different airspeeds with an acceleration phase on flight level (FL) 100.
- Constant Mach number cruise at constant FL.
- Descent at constant Mach number (above transition altitude (TA)) and at constant airspeed (below TA) with a deceleration before reaching FL 100.

Departure and approach segments are simulated on basis of the so-called ATA and low-drag-low-power procedures respectively. Typical reserve fuel policies are assumed considering 5% of the trip fuel as contingency, flight to an alternate airport at a distance of 200 nautical miles and 30 minutes of holding at low altitude.

Two flight missions are simulated for this study, a short-haul mission by a generic narrowbody aircraft and a long-haul mission by a widebody aircraft. Aircraft specifications resemble an Airbus A320 for the short-haul flight and an Airbus A330 for the long-haul mission. Table 6 shows the mission characteristics assumed for this study.

Parameter	Unit	Short-haul aircraft	Long-haul aircraft
Max. take-off Weight	[kg]	77,000	230,000
Empty Weight	[kg]	42,000	121,000
Payload*	[kg]	18,400	29,300
Range of simulated mission	[km]	860	6,200
Altitude@CR	[ft]	35,000	37,000
Mach number@CR	[-]	0.78	0.82
**short haul: 164 passengers + 2,000 kg of freight *long haul: 253 passengers + 4,000 kg of freight (assuming 100 kg per passenger incl. luggage)*			

Table 6: Summary of selected parameters of short- and long-haul mission.

5. Evaluation of CO_2Emissions

5.1 Direct combustion emissions

Direct combustion emissions of CO_2 from aircraft engines are considered in this study. The CO_2 emissions correlate with the amount of carbon in the fuel and hence are coupled to fuel consumption. The emission index (EI) method is applied to calculate corresponding emissions from different fuels. An emission index specifies the amount of emissions per kg of fuel. Assuming complete combustion and neglecting sulphur content CO_2 and H_2O emission indices for the fuel models can be calculated following equation 4

$$C_mH_n + \left(m + \frac{n}{4}\right)O_2 \rightarrow mCO_2 + \frac{n}{2}H_2O \qquad (4)$$

The emission indices of CO_2 ($EICO_2$) and H_2O (EIH_2O) agree well with those quoted in [25] for conventional kerosene Jet-A1. The $EICO_2$ of the fuel models are summarized in Table 6.

Fuel	$EICO_2$ [kg/kg]
JetRef	3.16
SPK50	3.13
SPK100	3.10

Table 6: CO_2 emission indices of JetRef, SPK50 and SPK100 fuel model.

5.2 Life Cycle Analysis

Life Cycle Assessment (LCA) is a systematic iterative technique to consider the environmental impact of a product throughout its entire life cycle so-called Well-to-Wake (WTW). The approach of a LCA has not yet been established by an international standard, but there are supporting standards and guidelines defining principles and framework of a LCA (e.g. [26], [27]).

Regarding aviation fuels, five life cycle stages need to be analyzed, i.e.:

1. Raw material acquisition
2. Material transport
3. Fuel production
4. Fuel transport and distribution
5. Fuel use (combustion)

The first four stages are often referred to as Well-to-Tank (WTT) analysis while the combustion step is defined as Tank-to-Wake (TTW).

From a life cycle perspective biomass derived fuels have zero net TTW emissions. Due to the ability of plants to absorb CO_2 from the atmosphere during cultivation, CO_2 release during combustion can be offset by CO_2 which has previously been captured.

In some instances land use change (LUC) or indirect land use change (ILUC) emissions have the potential to dominate the environmental impact of the product [28]. These additional CO_2 emissions are induced by the cultivation of energy crops due to change of natural lands, which store CO_2 in their soil and biomass. If such land use changes occur somewhere else due to increased demand in biomass, the effects are referred to as indirect. As uncertainty regarding LUC and ILUC effects is large, LUC related aspects are not considered in the following sections.

Greenhouse gas (GHG) emissions of a production pathway include emissions of CO_2, CH_4 and NO_X. For the purpose of comparison, emissions are expressed in terms of equivalent CO_2 emissions per energy of the final product (g CO_2eq/MJ fuel) using the 100-year global warming potential (GWP) index [29].

Studies assessing life cycle aspects of alternative fuels include the European SWAFEA project [30], the PARTNER project in the USA [28] as well as the report for the Committee on Climate Change (CCC) by E4tech [31].

All studies agree that some assumptions have to be made. As a consequence there are uncertainties in the results which are expressed in terms of error bars or by defining different scenarios (e.g. low, baseline, high). However, in the interest of clarity, only baseline or average values are quoted in this study.

5.2.1 Conventional jet fuel from crude oil

Conventional Jet-A1 derived from crude oil is used as the reference fuel in this study. Energy demand and emissions of crude oil extraction vary between production fields, primarily due to different flaring and venting rates, but also because of gas field properties like reservoir pressure, rock type, permeability and accessibility.

Pipelines, road or rail transport and ocean tankers are used for transportation of crude oil feedstock.

Processing of crude oil mainly consists of distillation and upgrading steps for finalizing the product. Processing efforts depend on feedstock quality, while process emissions also depend on infrastructure for energy supply.

Finally, jet fuel is distributed from the refinery to bunkers and airports for refueling via pipelines, trucks and sea tankers.

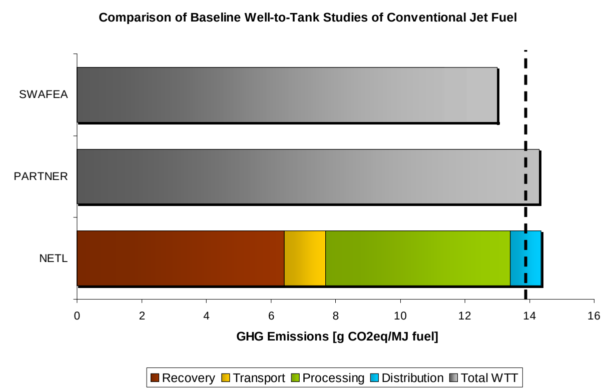

Figure 3: Life Cycle Well-to-Tank GHG emissions for conventional jet fuel supply from literature.

The overall energy efficiency for conventional crude oil processing is about 90%, i.e. 1MJ of crude oil feedstock results in 0.9 MJ of jet fuel products [28]. For conventional jet fuel the E4tech study uses the results reported by the National Energy Technology Laboratory (NETL) [32]. The results of conventional kerosene life cycle emissions are summarized in Figure 3. The mean value is indicated by the dashed line.

5.2.2 Fischer-Tropsch Fuels from Biomass

The Fischer-Tropsch process is an indirect liquefaction process, producing liquid hydrocarbons like diesel and jet fuel from almost any carbonic feedstock. The products are often referred to as XTL ("anything-to-liquid") or CTL, GTL and BTL, depending on the initial feedstock, which is either coal (C), natural gas (G) or biomass (B).

Feedstock recovery is mostly affected by biomass cultivation, especially in terms of fertilization and herbicides. Short truck routes are typically considered for feedstock transportation as BTL plants are assumed next to feedstock cultivation sites [28].

The Fischer-Tropsch fuel production consists of three main production steps:

- Syngas production,
- Fischer-Tropsch Synthesis and
- Hydrocracking

Syngas (CO, H_2) is generated by gasification or steam reforming of carbon feedstock [33]. The syngas is cleaned to avoid catalyst deactivation before feeding the Fischer-Tropsch Synthesis. Therefore the final Fischer-Tropsch products are virtually free of any contaminants, e.g. sulphur and nitrogen.

The Fischer-Tropsch Synthesis converts syngas into liquid hydrocarbons using metal catalysts, typically based on iron or cobalt. The carbon chain length is adjusted by hydrocracking, whereas long chain hydrocarbons (paraffins) are fragmented to the desired chain length. Hence the final FT-fuel characteristics are independent of the initial feedstock and only depending on processing parameters.

Process efficiencies are typically assumed of about 45-50%. Most of the internal energy demand of the BTL process can be provided by the biomass itself, which results in low CO_2 emissions of the production process. A summary of the baseline GHG emissions for FT fuels production pathways are summarized in Figure 4.

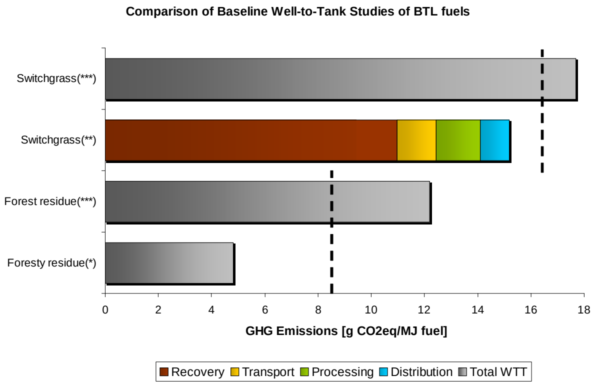

Figure 4: Life Cycle Well-to-Tank GHG emissions for alternative FT jet fuel supply from literature.
(*) E4tech, (**) SWAFEA, (***) PARTNER

5.2.3 HEFA Fuels

The production of HEFA fuels is also referred to as bio-SPK or Hydrogenated Renewable Jet (HRJ). These fuels are derived from vegetable oils.

Oil can be plant-derived or sourced from animal fats. The present study considers jatropha, camelina and algae as feedstocks. Production pathways for aviation fuels from algae are currently immature. The high interest in algae biomass is attributed to the very high yield per area due to the fast growth rates of algae. Moreover, algae are non-competitive to food production.

Oil extraction is based on mechanical or chemical methods. Biomass oil mostly consists of triglycerides, combining a glycerol and three fatty acids. These oils were cleaned to eliminate impurities before they are further processed. The cleaned oils are deoxygenated in presence of a catalyst by reactions with hydrogen. They are finally cracked and isomerised in a second reaction to paraffins in the diesel and jet fuel range. Therefore HEFA fuels properties are quite similar to FT fuels.

The GHG emissions for HEFA fuels are summarized in Figure 5.

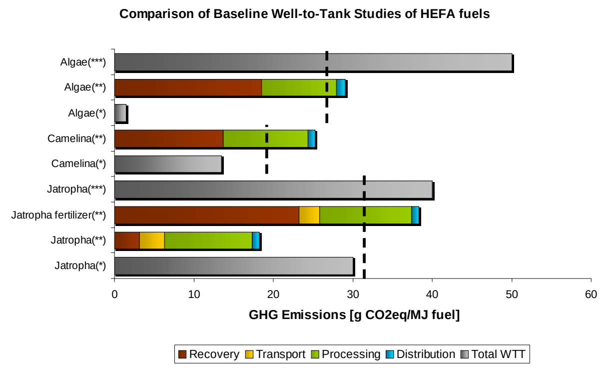

Figure 5: Life Cycle Well-to-Tank GHG emissions for alternative HEFA jet fuel supply from literature.
(*) E4tech, (**) SWAFEA, (***) PARTNER

The PARTNER report assumes that suitable growth of algae is assured by feeding the algae with additional CO_2 from electricity production.
The emissions for the algae pathway according to the E4tech study differ significantly from the PARTNER report. Within the E4tech study algae residues are assumed to produce methane, which is used for both internal and external electricity production [31].

6. Results

6.1 Impact on engine performance

To evaluate the impact of alternative fuels on engine performance, two engine models have been designed.

The simulated fuels are compared at two operating points representing take-off and mid-cruise operating points.

As expected from fuel model analysis, the use of alternative fuels improves fuel consumption in both operating points. The fuel flow benefits in comparison to JetRef are presented in Figure 6.
It can be observed that fuel flow reductions are somewhat lower than suggested by the deltas in terms of heating value and gas properties. These deviations are not significant and may be smaller than model uncertainty. It may be possible, however, that these deviations are caused by engine re-matching, since the operating point of the engine model was iterated to match a given thrust. Engine component performance deviates due to different gas

properties and fuel flows. As a consequence, operating points shift in component performance maps. These very small deviations may cause penalties or improvements in terms of component efficiency, pressure ratio, mass flow, etc., which in total seem to reduce the previously gained performance benefits. However, these effects depend on specific engine characteristics and hence may not show the same implications on all engine types.

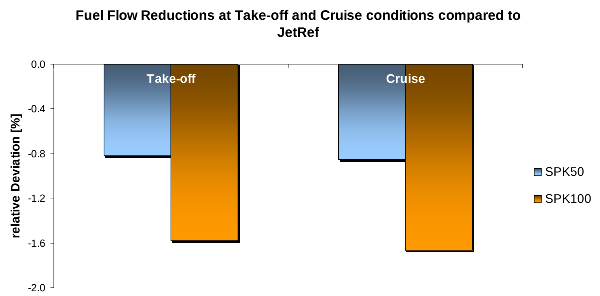

Figure 6: Fuel flow reductions of SPK50 and SPK100 fuel models at take-off and cruise conditions compared to JetRef on engine1.

6.2 Impact on CO_2 emissions on flight mission level

Improved fuel consumption on engine level reduces the required fuel amount for a flight and hence decreases take-off weight. Reduced take-off weight on the other hand has an additional effect on fuel consumption. These snowball effects are taken into account on mission level calculations. Two flight missions are simulated representing a typical short-haul and a long-haul flight mission.

6.2.1 Short-haul Mission

A typical short-haul flight mission profile of 860 km was defined, similar e.g. to a flight from Berlin (TXL), Germany, to Paris (CDG), France. Flight mission profile and corresponding fuel consumption of all three fuel models are illustrated in Figure 7.

For this mission a fuel consumption of 3654 kg JetRef is calculated. When using the SPK50 fuel model, a fuel consumption of 3620 kg SPK50 is obtained. With SPK100 fuel on the short-haul flight mission, a fuel amount of 3588 kg is required.

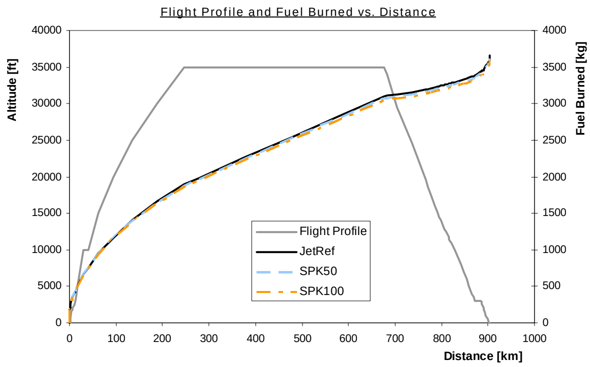

Figure 7: Short-haul flight profile and fuel consumption of all three fuel models.

The reduction in fuel consumption compared to JetRef results from improved engine performance in combination with an indirect effect from a reduced take-off weight. A summary of the results for the short-haul flight mission simulation is given in Table 7.

Fuel	Fuel consumption total [kg]	Fuel consumption reductions to JetRef [%]
JetRef	3654	-
SPK50	3620	0.9
SPK100	3588	1.8

Table 7: Fuel consumption results of short-haul flight mission.

To consider direct combustion emissions, the EIs for the fuel models are applied to the fuel consumption. The resulting CO_2 emissions are presented in Table 8.

Fuel	CO_2 emissions total [kg]	CO_2 emissions reductions to JetRef [%]
JetRef	11547	-
SPK50	11331	1.9
SPK100	11123	3.7

Table 8: CO_2 emissions of short-haul flight mission.

Taking life cycle emissions into account, the reduction of equivalent CO_2 emissions is even larger. The TTW CO_2 emission for biomass derived alternative fuels is assumed as zero. For conventional kerosene TTW emissions of 73.1 g CO_2eq/MJ are obtained from equation 4.

$$CO_{2,TTW} = \frac{EICO_2}{FHV} \tag{4}$$

Figure 8 illustrates the CO_2 reduction potential for neat SPK and blended SPK on flight mission level.

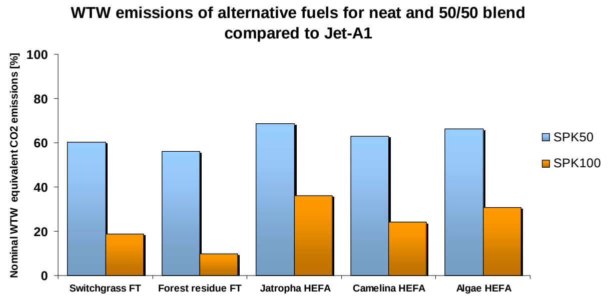

Figure 8: WTW emissions of alternative fuels in comparison to conventional Jet-A1 on short-haul mission.

6.2.2 Long-haul Mission

In order to assess the dependency of potentially effects on the flight distance, a long-haul mission was also simulated.

The long-haul mission over 6500km resembles a flight from Berlin (TXL), Germany, to New York (JFK), USA. Flight mission profile and corresponding fuel consumptions are presented in Figure 9.

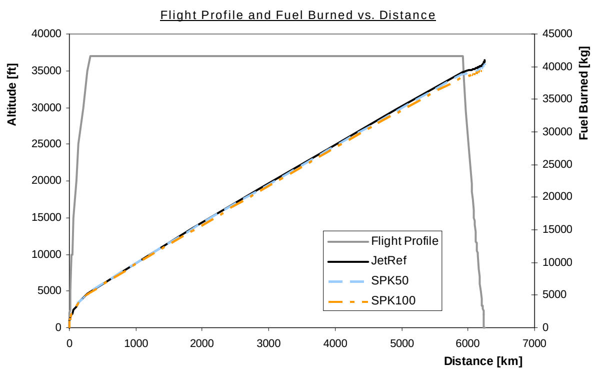

Figure 9: Long-haul flight profile and fuel consumption of all three fuel models.

A fuel consumption of 40978 kg Jet-A1 was calculated for this mission. Flying this mission with the SPK50 blend, only 40547 kg fuel is required. Using SPK100 fuel, a fuel consumption of 40139 kg is obtained for the long-haul mission.The fuel consumption results are summarized in Table 9.

The fuel flow reductions are somewhat larger than on the short-haul mission, since snowball effects are more emphasized on long-haul flights.

Fuel	Fuel consumption total [kg]	Fuel consumption reductions to JetRef [%]
JetRef	40978	-
SPK50	40547	1.1
SPK100	40139	2.0

Table 9: Fuel consumption results of long-haul flight mission.

The $EICO_2$ of corresponding fuels are considered for the evaluation of the direct combustion emissions of the long-haul flight mission and are presented in Table 10.

Fuel	CO_2 emissions total [kg]	CO_2 emissions reductions to JetRef [%]
JetRef	129490	-
SPK50	126912	2.0
SPK100	124431	3.9

Table 10: CO_2 emissions of long-haul flight mission.

From a life cycle perspective, the reduction potentials are very similar to those obtained on the short-haul mission. Figure 10 shows results for the SPK100 and SPK50 models respectively.

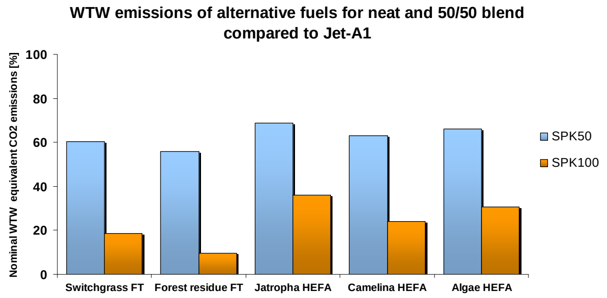

Figure 10: WTW emissions of alternative fuels in comparison to conventional Jet-A1 on long-haul mission.

The simulations suggest that only a small additional effect from a decreased take-off weight can be expected on flight mission level. Improvements of fuel efficiency and (direct) CO_2 emissions by alternative fuels are in the order of a few percent. The potential benefits from reduced life cycle emissions, on the other hand, are of considerable magnitude.

Impact of specific gravity of alternative fuels was not explicitly considered. However, the results from flight mission simulation indicate that the smaller fuel density of alternative fuels could not fully be compensated by improved fuel consumption. This may have small effects on aircraft range.

7. Conclusion and Perspectives

Today, only two alternative fuel types meet the specifications for aviation fuels and are approved for use in aircraft engines. Although other pathways are currently under consideration, SPK from Fischer-Tropsch Synthesis and HEFA are the most promising candidates in the near- to mid-term future.

The present study quantifies the potential benefits of these alternative fuels with respect to engine performance. By using neat SPK, engine performance can be enhanced resulting in a fuel consumption improvement of up to 2% on a typical long-haul mission. Since only 50/50 blend ratios are approved, the fuel consumption gain for blended SPK is about 1% on flight mission level.

Different chemical compositions and higher hydrogen to carbon ratio of SPK result in lower $EICO_2$, i.e. fewer emissions of CO_2 per kg fuel of up to 2% compared to Jet-A1.

In total, a reduction of direct CO_2 emissions of about 4% could be reached by the employment of alternative fuels. According to the simulations, the snowball effects on flight mission level from a decreased take-off weight are rather small.

Despite these effects, the key advantages of alternative fuels are reduced greenhouse gas emissions throughout the entire fuel life cycle. From a life cycle perspective, direct combustion CO_2 emissions from biomass derived fuels are considered zero, assuming that all carbon released during combustion has previously been captured. Consequently, all alternative fuels from renewable resources have lower life cycle GHG emissions (up to 90% for forest residue FT) than conventional crude oil derived kerosene. Using 50/50 blends of SPK, the life cycle GHG emission reductions are in the range of 40%.

Especially when considering biomass products, LUC or ILUC effects may mitigate these benefits. However, no international standard on LCA has been established yet and life cycle emissions inventories still struggle with major uncertainties. Further investigations are needed to standardize LCA approaches and to reduce uncertainties.

For future deployment of alternative fuels, availability of biomass and production capacities are bottlenecks. Doubts exist, whether there will be enough biomass available for aviation without compromising food production or biodiversity [30]. Besides, aviation is facing competition for biomass with other sectors. From a global point of view, life cycle benefits of alternative fuels take effect independent of the field of application. Furthermore cost competitiveness of alternative fuels is not yet achieved.

The air traffic sector has to be aware that considerable effort is required to reach the high-level goal of carbon-neutral growth. Alternative fuels are just one potential contributor and innovations in terms of aircraft and engine efficiency improvements are essential to enable sustainable air traffic growth.

References

[1] Barker, T. et al., *Technical summary, in climate change 2007: Mitigation.* Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change, UK and USA, 2007

[2] Boeing, *Current market outlook 2011-2030*, Seattle, 2011

[3] Airbus., *Delivering the future - Global market forecast 2011 – 2030*, Toulouse, 2011

[4] Argülles, P. et al, *European aeronautics: A vision for 2020 – Meeting society's needs and winning global leadership*, Report of the group of personalities, January 2001

[5] European Commission, *Flightpath 2050 - Europe's vision for aviation maintaining global leadership & serving society's needs*, Report of the High Level Group on Aviation Research, 2011

[6] International Air Transport Association IATA, *Aviation and climate change – Pathway to carbon-neutral growth in 2020*, July 2009

[7] International Energy Agency IEA, *Oil information 2010*, 2010

[8] ASTM Standard D1655 – 11b, *Specification for Aviation Turbine Fuels*, ASTM International, West Conshohocken, PA, 2011

[9] ASTM D4054 – 09, *Standard practice for*

qualification and approval of new aviation turbine fuels and fuel additives, ASTM International, West Conshohocken, PA, 2009

[10] Kinder, J., Rahmes, T., *Evaluation of bio-derived synthetic paraffinic kerosene (Bio-SPK)*, The Boeing Company, Sustainable Biofuels Research & Technology Program, 2009

[11] Lufthansa, *Biofuel in practical tests. We bring sustainability to the air*, Deutsche Lufthansa AG, Pure Sky, 2011

[12] International Civil Aviation Organization ICAO, *ICAO review: Sustainable alternative fuels for aviation*, 2011

[13] Becker, R.-G., Wolters, F., Nauroz, M., Otten, T., *Development of a gas turbine performance code and its application to preliminary engine design*, DLRK 2011, 27.-29. Sept., Bremen, Deutschland, 2011

[14] Goodwin, D.G., *An open-source, extensible software suite for CVD process simulation*, Proc. of CVD XVI and EuroCVD Fourteen, Electrochem. Soc., pages 155–162, 2003

[15] McBride, B.J., Gordon, S., Reno, M.A., *Coefficients for calculating thermodynamic and transport properties of individual species*, NASA-TM-4513, 1993

[16] Lee, C.M., Kundu, K., Ghorashi, B., *Simplified jet-A kinetic mechanism for combustor application*, NASA Technical Memorandum 105940, AIAA-93-0021, 1993

[17] Rachner, M., *The properties of Kerosene Jet A-1*, DLR-Mitteilung 98-01, 1998

[18] Corporan et al., *Emission characteristics of a turbine engine research combustor burning a Fischer-Tropsch jet fuel*, Energy & Fuels, Vol.21, No.5, 2007

[19] Federal Aviation Administration FAA, *Type Certificate Data Sheets (Make Model)*, http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgMakeModel.nsf/MainFrame

[20] European Aviation Safety Agency EASA, *EASA Engines Type Certificates*, http://easa.europa.eu/certification/type-certificates/engines.php

[21] International Civil Aviation Organization ICAO, *ICAO Exhaust Emissions Databank*, ICAO Doc 9646-AN/953, First Edition 1995

[22] Daly, M., Gunston, B. (Eds.), *Jane's Aero-Engines*, Issue Thirty, HIS Global Limited, 2011

[23] Kurzke, J., How to create a performance model of a gas turbine from a limited amount of information, ASME Turbo Expo 2005, 2005

[24] Schaefer, M., *Development of a forecast model for global air traffic emissions*, Dissertation, Ruhr-Universität Bochum, 2012

[25] Sutkus, D .J. Jr., Baughcum, S. L., DuBois, D. P., *Commercial aircraft emission scenario for 2020: Database development and analysis*, NASA/CR-2003-21331, 2003

[26] Allen et al., *Framework and guidance for estimating greenhouse gas footprints of aviation fuels*, AFRL-RZ-WP-TR-2009-2206, Aviation Fuel Life Cycle Analysis Working Group, Air Force Research Laboratory, 2009

[27] International Organization of Standardization ISO 14040:2006: *Environmental management — Life cycle assessment — Principles and framework*, 2006

[28] Stratton, R., Wong, H., Hileman, J., *Life cycle greenhouse gas emissions from alternative jet fuels*, PARTNER Project 28 report, Version 1.1, April 2010

[29] Intergovernmental Panel on Climate Change IPCC, *Climate change 2007: The physical science basis.* Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, 2007

[30] Novelli, P., *SWAFEA: a European study on the feasibility and impact of the introduction of alternative fuel in aviation*, SWAFEA, ISABE-2011-1409, 2011

[31] Bauen, A., Howes, J., Bertuccioli, L., Chusziak, C., *Review of the potential for biofuels in aviation*, Final report, For CCC, 2009

[32] Skone, T., Gerdes, K, *Development of baseline data and analysis of life cycle greenhouse gas emissions of petroleum-based fuels*, DOE/NETL-2009/1346, National Energy and Technology Laboratory, Pittsburgh, Pennsylvania, 2008

[33] Speight, J. G., Synthetic Fuels Handbook: Properties, Process, and Performance , McGraw-Hill, 2008

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