Alfa-Bird

Alternative Fuels and Biofuels for Aircraft Development

SYNTHESIS

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3 Airbus Central Entity, **Airbus CE**, France
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Glossary

ACI	Airports Council International
ALFA-BIRD	Alternative Fuels and Biofuels for Aircraft Development
ASTM	American Society for Testing and Materials
BtL	Biomass to Liquid
CAAFI	Commercial Aviation Alternative Fuels Initiative
CANSO	civil air navigation services organisation
CtL	Coal to Liquid
EEFAE	Efficient and environmentally friendly aircraft engine
ETK	Ethanol To Kerosene
EU	European Union
FAE	Fatty Acid Esters
FRL	Fire Resistance Level
FSJF	Fully Synthetic Jet Fuel
FT-SPK	Fischer-Tropsch synthetic paraffinic kerosene
GtL	Gas to Liquid
HEFA	Hydrogenated Esters and Fatty Acids
HiReTS	High Reynolds Number Thermal Stability
HPLC	High Performance Liquid Chromatography
IAB	International Advisory Board
IATA	International Air Transport Association
ICCAIA	International Coordinating Council of Aerospace Industries Associations
JFTOT	Jet Fuel Thermal Oxidation Tester
LCA	Life Cycle Analysis
LUC	Land Use Change
MCDM	Multi-Criteria Decision-Making
NBR	Nitrile butadiene rubber
NGO	non-governmental organization
OEM	Original Equipment Manufacturer

RQL	Rich Burn, Quenching, Lean Burn
RQL	Rich-queched- lean
SP	Subproject
SPK	Synthetic Paraffinic Kerosene
SWAFEA	Sustainable Way for Alternative Fuel and Energy in Aviation (EC Study)
TRL	Technology Readiness Level
WP	Work Package
WtL	Waste to Liquid
XtL	“From anything” to Liquid

1 SOME KEY MESSAGES

In July 2008, the ALFA-BIRD (Alternative fuels and biofuels in aviation) program started. Its main purpose was to develop a general and complete assessment of a selection of alternative fuels for aviation. The main results obtained are presented in this report.

ALFA-BIRD is a R&D project with the objective of looking forward at sustainable and alternative fuels, including their technical performances, their industrial production processes and market integration.

Some key points:

- The aeronautics industry requires the "drop-in" fuels according to existing standards at this time
- There will not be a "bad or good" alternative fuel, only a mix of solutions and strategies for implementation will be proposed
- Some fuels (HEFA, XtLs) have passed the certification but there is still a need of research about other options (feedstock, process, different blends...)
- Follow-up is required, in parallel, for the alternative fuels introduced in the fuel market and consideration of the evolution of the engine and fuel overall environmental performance
- The need to investigate the ASTM limit such as minimum of aromatics to allow other alternative fuel solution and improvement of already "almost suitable" fuels is important
- The need to develop a new kind of certification with additional protocol before the official ASTM one: quicker, cheaper (in term of volume) was consider important

  => further candidates require future investigation
- The need to give feedback and results to the ASTM in order to improve/adjust the specification to new alternative fuels
- Is the "drop-in" view compatible with the sustainability constraints?
  - Limitation of feedstock
  - Efficiency of the processes to produce the fuel

2 INTRODUCTION

1. Context

Presently, aviation represents approximately 5% of global fossil oil consumption and is responsible for 2% of total anthropogenic CO_2 emissions. However, air traffic will double in the next 15 years and it also assumes that fuel consumption and CO_2 emissions will more than double in 25 years. Furthermore, according to some specialists, we are past the oil peak and fuel price will increase more and more.

In this context, new objectives are envisaged to reduce the impact on the environment and to be more independent from fossil resources. IATA (International Air Transport Association), ACI (Airport Council International), CANSO (Civil Air Navigation Services Organization) and ICCAIA (International Coordinating Council of Aerospace Industries Associations) are targeting a carbon neutral growth by 2020 and a reduction by half of CO_2 emissions by 2050 based on 2005 levels. In 2011, the European Commission (EC) services, in close coordination with Airbus, leading European airlines (Lufthansa, Air France/KLM, and British Airways) and key European biofuel producers (Neste Oil, Biomass Technology Group and UOP), have launched an exciting new industry wide initiative to speed up the commercialization of aviation biofuels in Europe (Biofuel Flightpath). To reach these targets, we need to have a profound overview and knowledge for every possible alternative fuel regarding technical compliance, environmental performances and economics.

2. ALFA-BIRD's mission and consortium

ALFA-BIRD (Alternative Fuels and Biofuels for Aircraft Development) was a project partially funded by the EU in the 7th Framework Programme for Research and Technological Development, under grant n° 213266. It commenced in July 2008 and lasted four years. ALFA-BIRD's objective was to investigate and develop a variety of alternative fuels including biofuels that could gradually replace crude oil based Jet A1/Jet A, which is currently in use in civil aeronautics. The main motivation was the need to ensure a sustainable growth of the civil aviation with regard to the impact of the use of fossil fuels on climate change and air quality besides the context of oil prices that are highly volatile and increasing in the long term.

One of the main challenges in the project was to propose fuels that meet the environmental European objectives, the very strict safety and operational constraints in aviation (e.g. safe flight under very cold conditions), and that are compatible with current civil aircraft, which is a must due to their long lifetime of up to about 30-50 years. New alternative fuels should also meet the economic and trade constraints to integrate the market.

To address this challenge, ALFA-BIRD gathers a multi-disciplinary consortium composed of 24 members with key industrial partners from aeronautics (engine and aircraft OEM) and fuel industry, and from research organizations covering a large spectrum of expertise in such fields as biochemistry, refinery, combustion, aircraft systems or industrial safety, to name only a few. The ALFA-BIRD program was consequently dedicated to the selection and the evaluation of the alternative fuels with a short to long term perspective. In order to do so, the expertise of all partners was gathered and the evaluation was done on a technical basis: physical properties, combustion behaviour, and material compatibility and security aspects, but also on economic and environmental aspects (life cycle analysis).

3. ALFA-BIRD project organization

In operational terms, ALFA-BIRD addresses the following objectives:

- To identify and evaluate potential alternative fuels to petroleum kerosene, considering the whole aircraft system
- To assess the adequacy of a selection of up to 5 alternative fuels with aircraft requirements, based on series of tests and experiments
- To evaluate the environmental and socio-economical performance of the selected alternative fuels
- To set the path towards industrial use of the "best" alternative fuels

To reach these objectives, several subprojects were designed. Figure 1 shows the relationship between the different subprojects.

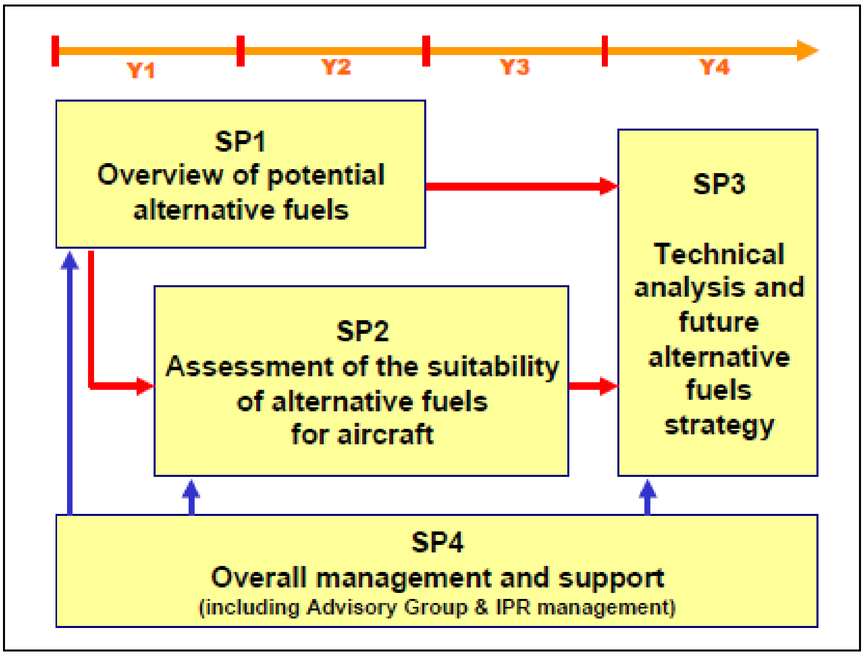

Figure 1 : Relationships between the different ALFA-BIRD subprojects.

The present report describes the main tools and methods used in each subproject and their important results.
The selection of alternative fuels which have been studied is explained in the first part (SP1), then the results of technical (SP2) are provided, environmental and socio-economical assessment (SP3) in order to discuss a possible ranking of the tested fuels and their strategy for implementation on the market (SP3) are discussed finally. SP3 also included environmental and socio-economical assessment.

3 SELECTION PROCESS OF ALTERNATIVE FUELS (SP1)

As planned originally in the ALFA-BIRD program, the fuel selection process is divided into two steps/phases. In March 2009, the consortium has completed the first step, which consisted in evaluating 12 blends in terms of their quality as jet fuel based on standard characterization tests only (Table 1). An exhaustive list of fuel options was proposed by IFPEN following their state-of-the-art study and discussed amongst partners. The selection of 12 candidate fuels to be tested in this first step was then voted by ALFA-BIRD's Steering Committee on April 2009.

Table 1: Description of the 12 fuel blends investigated in SP1

Fuel number	Description (volume % blends)
1	FSJF
2	FT-SPK
3	FT-SPK + 50% Naphthenic cut
4	FT-SPK + 20% Hexanol
5	FT-SPK + 10% Furane
6	FT-SPK + 20% Furane
7	FT-SPK + 30% Furane
8	FT-SPK + 10% FAE
9	FT-SPK + 20% FAE
10	FT-SPK + 30% FAE
11	FT-SPK + 50% HEFA
12	FT-SPK + 75% HEFA

This proposed list of 12 Jet-fuel candidates was built around three axes, covering a wide range of alternative fuels. Regrouping these alternative fuels by chemical family, we have:

- paraffinic compounds
- naphthenic compounds
- oxygenated compounds.

The paraffinic compounds are produced by Fischer-Tropsch synthesis (FT-SPK) and from Hydroprocessed Esters and Fatty Acids (HEFA). The naphthenic compounds represent products that come from direct liquefaction/pyrolysis of coal or biomass. Concerning the oxygenated compounds, the study of their potential use in aeronautics is very original and has been explored in ALFA-BIRD. Each selected chemical family is described and discussed in the following paragraphs.

1. The reference fuel: the Fully Synthetic Jet Fuel from Sasol

The selection process adopted in ALFA-BIRD was a direct comparison of each fuel candidate with a well characterized and a certified reference fuel rather than a relative comparison between each candidate. Therefore, the reference fuel needed to be identical for all tests and all partners.

Jet A-1/Jet A is the conventional fuel for civil aeronautics and therefore it was considered as a reference in this study. However, this product has a large variability according to the crude oil and the process (sweetening, hydroprocessing, among others). This implies for example a variation in the level of aromatics and sulphur.

ALFA-BIRD has chosen the Fully Synthetic Jet Fuel (FSJF) from Sasol as the reference fuel for several reasons:

- To place the study in a long-term view if CtL is developed in the future
- To have coherence and to be complementary with respect to other EU and international initiatives (SWAFEA[1], CAAFI[2])
- To have a constant and controlled quality reference that could also be obtained for future studies.

The FSJF is a fully synthetic jet fuel and consists of 50% FT-SPK and 50% of an aromatics-containing stream derived from severely hydro-treated coal tar kerosene. This product has a well-defined composition due to the fact that it comes from an identified refinery with a controlled process. Moreover, a synthetic fuel contains inherently less chemical families with a narrower distribution of components within each family, compared to Jet A1/A. These attributes made the selected fuel an excellent reference as it is less prone to source/process-dependent variations than Jet A-1.

2. The paraffinic compounds

A promising alternative fuel is FT-SPK. The Fischer-Tropsch synthesis is described as follows: The raw material (e.g. coal, natural gas, biomass and waste, ..) is broken down at high temperature to basic molecules (mostly CO and H_2 – this mixture is called synthetic gas or syngas), chemically cleaned, and rebuilt into a synthetic crude which is then refined into different products, from a blend stock which allows a range of final products including jet fuel. This process makes mainly straight chain of hydrocarbons (paraffinic compounds). The advantage of the FT-process is the large variability of the sources (CtL from coal, GtL from natural gas, WtL from wastes, BtL from biomass, or XtL from anything) that could be used. The process is well established for conversion of coal and gas, in future it will be developed further to use biomass or biogenic waste and side products as a feedstock.

FT-SPK was used in ALFA-BIRD as a blend stock; consequently, this product was also tested neat in order to have the possibility to clearly identify the fuel impact on gas

[1] SWAFEA for Sustainable Way for Alternative Fuel and Energy in Aviation; see www.swafea.eu

[2] CAAFI for Commercial Aviation Alternative Fuels Initiative; see www.caafi.org

turbine operation. There are currently no industrial BtL plants, consequently, the FT-SPK used in ALFA-BIRD was a GtL delivered from Shell. The different XtLs (GtL, BtL, CtL, etc.) are assumed to be similar because the same process is used and because the composition of a FT-SPK is known to be mostly dependent on the process and on the raw materials.

The FT-SPK (GtL) used in the ALFA-BIRD project was within SPK specification limits (ASTM[3] D7655). It should be noticed that a SPK generally has no aromatics (less than 0.5% mass), whereas the ASTM D7655 specifications indicate a minimum of around 8% vol. of aromatics in the final blend (Jet + FT-SPK).

HEFA is also a paraffinic product. Its chemical composition and its physical properties are close to FT-SPK, provided they meet the same D7655 requirements. The potential of HEFA has been explored in ALFA-BIRD by performing standard characterization.

The first step to produce HEFA is to have an important oil feedstock. In ALFA-BIRD we envisaged the possibility to produce large quantity of oil using yeast. The results are really promising: we obtained an accumulation of 70% of lipids in the microorganism which corresponds to 88% of maximum theoretical yield. A lot of improvements can be done in this field such as yield increase and optimization of the lipid profile in order to afterwards fit better to hydro cracking and hydro treatment finishing processes.

Very high-quality diesel (and kerosene) can then be obtained by subsequent hydrocracking of the primary product. A large variety of vegetable oils including domestic types, animal fats and cheaper vegetable oils can be processed to yield the same final, high quality product.

Industrial hydrogenation plants are currently under construction. Neste Oil has developed the NExBTL® Process. In the hydrotreatment conditions, unsaturated fatty chains are hydrogenated. The resulting straight chains, mainly Cl2 to C18, are wholly paraffinic. Such fully saturated compounds have excellent cetane index but generally poor cold flow properties compared to corresponding esters, which may require an additional hydro isomerization step. This produces branched (iso) paraffins which have the superior low temperature properties required to achieve jet fuel freeze point.

UOP developed a process to make HEFA derived from plant oils such as Jatropha. This process consists of hydrocracking /isomerisation of vegetable oil (~ C9 paraffinic blend). The addition of aromatic compounds is required in order to adjust the density – the only approved way of achieving this is by blending with conventional fuel. In France, Axens also sells a fully validated HEFA process (Vegan® process)

Properties of this product are very similar to synthetic blend stocks coming from the FT-process. HEFA contains no sulphur, oxygen, nitrogen or aromatics. The heating value is similar or better than the one of jet A-1,its storage stability is good (when the required antioxidants are present) and water solubility is low. The high n-paraffin composition might lead to problems with cold flow properties. However, process is adjusted in order to obtain correct cold flow properties.

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[3] ASTM for American Society for Testing Materials. ASTM D7566 is a new specification for certifying a 50% blend of Jet A-1 and SPK produced from biomass using a Fischer-Tropsch process.

HEFA is a high quality, high purity product and presents similar properties compared to jet A-1; however, its cold flow properties and lubricity have to be controlled. Regarding the process, there is a need to check the availability, the investment cost and the dependency of feedstock on oil composition.

It was decided to choose FT-SPK, representing paraffinic compounds, as the selected fuel in the second phase of ALFA-BIRD, mainly because of the availability of this product, and also, to be complementary with respect to other initiatives (SWAFEA, CAAFI).

3. The naphthenic compounds

The naphthenic or naphtheno-aromatic compounds can be produced from direct liquefaction of coal (nowadays) or biomass in the future (sustainable). This kind of molecule has some characteristics that seem to be suitable for jet fuel use: good cold flow properties as well as good energy content in volume, in particular. Some elements need to be checked like the behaviour in combustion, the pollutant emissions, and the material compatibility, in agreement to ALFA-BIRD's mission: to revisit the fuel specifications and reconsider the whole aircraft system composed by the triplet fuel, engine and ambience.

The main effect of adding naphthenic or naphtheno-aromatic to FT-SPK is to bring the FT-SPK blend into the Jet A-1 specification limits (ASTM D7655), mainly in terms of minimum aromatics contain (8% in volume by IP 156) and density (775 kg/m^3 as a minimum by IP 365). The last point, in particular, was observed within the first phase dedicated to standard characterization of a blend of FT-SPK and 50% of naphtheno-aromatic cut.

With these benefits, it seemed advisable to explore the potential of this blend (FT-SPK and 50% of naphtheno-aromatic cut) in more detailed tests.

4. The oxygenated compounds

The presence of oxygen in the chemical structure is expected to affect key fuel properties including: energy density, volatility, corrosion ability, material compatibility, and combustion properties. This is why the oxygen containing compounds cannot be used as a blending component in a substantial volume. However, one of the non-negligible interests to have oxygen in the molecule structure could be the reduction of the particulates emissions in order to reach the environmental objectives. Potential oxygenated fuels envisaged in the first step are listed below.

- ***Alcohols***

Alcohol - for fuel - is produced from the fermentation of sugars by micro-organisms catalysed by different enzymes. The feedstock might be sugarcane, sugar beet, wheat, barley or corn. Presently, the process of fermentation cannot make use of the whole biomass, and significant research is underway to improve this. Moreover, the modification of the enzymes to allow the production of other alcohols such as hexanol is an area of active research.

The interest – and the need - to use in aeronautics a different alcohol than ethanol, is to fit with specified jet fuel properties such as energy density, flash point, water solubility... Some of these drawbacks existing in case ethanol, a C2 alcohol, would be used can be overcome by the use of higher alcohols (means higher carbon number): as the increase of the carbon number will allow an increase of e.g. the energy density as well as the flash point. However, the increase of energy content is limited even when using heavier alcohols. Therefore, any blending proportion with actual jet fuel will lead to an increase of the volume capacity required in plane, which is not conceivable.

In conclusion, ethanol is available worldwide, but presents severe drawbacks. The use of higher alcohols could have a potential, provided that viable production pathways are found. Moreover, the CO_2 balance could be beneficial. Consequently, higher alcohols are considered to be an alternative fuel interesting for R&T for aircraft but in a long term view. Alcohols could not be used as a blending component in a *substantial* volume, mainly to avoid the critical decrease of the energy content. A blend of FT-SPK and 20% hexanol gave promising results in standard characterization and the ALFA-BIRD team decided to go further in detailed experimentations.

- ***FAE (Fatty Acids Esters)***

FAE is commonly referred to as "biodiesel" and is used as blending components for diesel fuel, in accordance with the EU legislation, the majority of which is the methyl derivative (FAME). However, FAME is used as an extender and limited to a few percent in automotive fuels. The question arises whether FAE could also be considered as a possible alternative fuel to conventional Jet fuel.

Esters have chemical and physical properties that are similar to conventional fossil fuel; but these properties depend on the starting material: esters can have different numbers of carbon atoms and varying degrees of unsaturation (number of carbon-carbon double bonds).

Due to their properties, FAE could not be directly used as a blending component for Jet fuels in *significant* volume. However, there exists a possibility to improve the properties of FAE for jet fuel use by the selection of the raw material (chain length / insaturation rate trade-off, use of another type of alcohol for trans-esterification process...). Additionally, FAE presents high availability due to a well-known production process and to large production plant investments. Yeast can also be used to produce FAE, but it appeared an issue in FAE freezing point. We succeeded in modify this freezing point using long chain alcohols and enzymes to perform the esterification of the yeast oil. This is a very encouraging development representing a potential improvement.

In the first step (standard characterization) of the ALFA-BIRD project, blends of FT-SPK and FAE in different amount (10, 20 and 30%) have been produced and analysed. It was observed that the addition of FAE implied an increase in acidity, in corrosion, and poor cold flow behaviour. On the other side, the addition of FAE to a FT-SPK had a relative positive effect on the density.

Nevertheless, ALFA-BIRD did not explore any deeper the use of this type of compounds due to the technical risks and problems identified.

- ***Furans***

Furans are produced from carbohydrate components that can be found in lignocellulosic biomass, in sugar beet and in sugar beet pulp. The production method still in the early stages of development is the subject of several research programmes. In spite of a high density, the cold flow properties as well as the boiling and the flash point of this kind of molecule are in the range of a Jet fuel.

Note that the oxygen content of this molecule implies a low energy density in mass that can to some extent be compensated by a high density, and consequently a correct energy density in volume may be achieved. The material compatibility needs also to be checked.

The potential of furans, more precisely tetrahydrofurfuryl ethyl ether, was explored in ALFA-BIRD – within SP1 tests - by studying blends of FT-SPK with 10, 20 and 30% of furans. Nevertheless, ALFA-BIRD did not explore any deeper the use of furans.

Some significant and useful findings from this assessment should be mentioned. The characteristics of some furanic were studied, in particular 2,5-dimethyl furan, often called 2,5-DMF and hydroxymethylfurfural, HMF or 5-(hydroxymethyl)furfural. The molecules that seemed to have a potential for aircraft application were 2-(methoxymethyl) tetrahydrofuran and 2,5-bis(methoxymethyl) tetrahydrofuran. In spite of a high density, the boiling point, the cold properties (viscosity at -20°C) and the flash point were in the range of a jet fuel.

To conclude, the main advantages and drawbacks of 5-HMF as a fuel are given in Table 2.

Table 2: Advantages and drawbacks of 5-HMF as a fuel.

Advantages of 5-HMF	Drawbacks of 5-HMF
- High flash point (around 80°C) **- Presence of oxygen can decrease particulates emissions**	- Very low heating value due to oxygen content Nevertheless, the very high specific gravity of the fuel (1.29) allows compensating this oxygen content as far as volumic energy content is concerned - Oxygen and aldehyde function can induce some issues concerning the material compatibility (especially elastomers) - Very high specific gravity (1.29), due to the presence of oxygen leading to the formation of H-bonds in the fuel - Very high melting point (around 35°C)

As a consequence, even if some production pathways would exist, 5-HMF seems not to be suitable as an alternative jet fuel because the drawbacks would lead to too many issues to solve.

It is clear that oxygenated compounds are not "drop-in" fuels; but ALFA-BIRD, as a research project looking also in a long term perspective, decided it was important to look at these oxygenated compounds and to evaluate their potential. **From all the oxygenated compounds, it was decided to select the blend of 20% of hexanol in FT-SPK in order to perform the more detailed investigation within the second step in the selection process. This hexanol blend has been chosen as a model fuel for oxygenated non drop-in fuels.**

The characterisation of the 12 alternative fuels and their comparison therefore leads to the down selection of 4 promising pathways described further that were assessed in terms of technical performances, environment and economics, within the subprojects SP2 and SP3.

4 FUEL SUITABILITY ASSESSMENT (SP2)

1. Methodology

For all of the reasons mentioned above, ALFA-BIRD's Steering Committee has decided, after the consultation of the Advisory Group in November 2009, that four promising fuels would be further tested in the second phase within ALFA-BIRD, the assessment of the suitability of alternative fuels for aircraft. This selection was based on the standard characterization done on the initial fuel list (12 blends) in the subproject 1, SP1.

The 4 fuels proposed for the technical, environmental and economic detailed testing in ALFA-BIRD second part (SP2 and SP3) were:

- **FSJF (CtL from Sasol)**
- **FT-SPK (GtL from Shell)**
- **FT-SPK + naphthenic cut (50%)**
- **FT-SPK + hexanol (20%)**

The technical tests were performed in four different work packages in the subproject 2 – SP2- focusing on:

- **Injection and combustion**

  Experimental behaviour, under simulated engine conditions; model validation
- **Engine systems integration**

  Experimental assessment of compatibility; search for improved materials
- **Aircraft systems integration**

  Experimental assessment of compatibility
- **Safety, standards, regulations**

  Towards certification (regulations, standardisation)

Concerning injection and combustion, the selected alternative fuels had to release the energy necessary to power aircrafts' engines. Therefore, the tests were directly related to the elementary physical phenomena occurring in the aircraft engines: atomization, single droplet, and spray evaporation, vapour mixing, ignition, heat release and combustion, with FSJF from Sasol as a reference. Results collected from these experiments were, for example, the evaporation rates of monodisperse streams of droplets evaporating in different pressure-temperature conditions; auto ignition delay time, laminar flame speed and product pattern of the combustion for a wide range of parameters. These data allowed input to support work on chemical models to describe these kinds of characteristic combustion properties.

Concerning the engine systems integration, most of the safety aspects of using the selected alternative fuels have been assessed. Any Jet fuel will come into contact with a variety of materials, both metallic and non-metallic. Hence, some tests analysed the fuel's property to act as a hydraulic fluid and as a heat sink in the engine control system. Therefore, static and dynamic tests have been undertaken on the non-metallic materials found within the engine. Also, the effect of the fuels on selected wetted metals found in the engine has been studied. Further investigations were focusing on the hot end materials found in current engines. The main purpose of these hot-end tests was to ensure that no hazardous effect would occur to turbine blades, as a result of some – possible - reactions of combustion products of alternative fuels or from any traces of unknown compounds present. The thermal stability of candidate alternative fuels has been evaluated, for example, on the performance of the control system as well as the fouling propensity of the fuel i.e. from gums and lacquers in the engine fuel injectors (polymeric materials).

Concerning aircraft system integration, the selected alternative fuels have been tested on existing fuel systems. Issues were related to: sealing, corrosion, pumping, filtering, water compatibility, microbial contamination, gauging and permeability, among others. Effects of temperature, altitude, water content/icing on general pumping performance, gravity feed and ice blockage of inlet strainers were also studied. Further investigations dealt with a more general material compatibility with fuel in the aircraft.

Concerning safety, standards and regulations, all the data and experience gained in producing, handling and testing the alternative fuels have been collected and analysed, with the main focus on safety issues. Examination of the potential impact on the regulation and standardisation schemes in an operational environment has been carried out, also.

All the technical assessments were performed according to the ASTM specification tests where applicable and the results were gathered in a matrix to obtain a general overview of technical fuel performances and suitability for use in aircraft.

It should be noted that even if technical assessment is better standardized than for instance environmental or economical assessment, there are many different parameters and properties which change when testing alternative fuels compared to conventional Jet A-1. The operating conditions for the same experiments may evolve when changing fuel to test. This can lead to some results which are not always directly comparable and make the fuel ranking difficult.

2. Results

From the technical assessment, several important points were highlighted. Table 3 shows the technical issues for each selected fuels compared to CtL delivered from SASOL.

Table 3: ALFA-BIRD alternative fuels compared to CtL (FSJF) within the technical and regulation assessment

Testing category	FT-SPK (GtL)	FT-SPK + 50% NC (Naphthenic cut)	FT-SPK + 20% Hexanol
Technical & Technological	11 X 24 X 2 X -Stress relaxation O-ring NBR -NBR elastomer swelling	9 X 23 X 3 X - Stress relaxation O-ring NBR - NBR elastomer swelling - Gauging issues	8 X 14 X 10 X -NBR elastomer swelling -NBR elastomer tensile -NBR elastomer hardness -FVMQ elastomer hardness -NBR elastomer permeability -FKM elastomer permeability -FVMQ elastomer permeability -Stress relaxation O-ring NBR -Stress relaxation O-ring FVMQ -Gauging issues
Regulation	1 X 3 X	4 X	1 X 2 X 1 X -Explosivity

X : better than CtL (FSJF) ; X : worse than CtL (FSJF) ; X : as good as CtL (FSJF).

Similar properties and criteria have been assessed for all fuels to make the comparison possible (except when experience was not feasible or failed for a fuel). The failed tests are described in red to identify the technical issues in this synthesis table. We found that FT-SPK + 20% Hexanol has much more technical and technological problems compared to CtL (FSJF) especially within material compatibility than the other fuels.

We noticed that the main technical problems we observed were related to the **percentage of aromatics** which have an important impact on elastomer compatibility, but also have a link with density. We know from the ASTM specification that at least 8% of aromatics are needed based on in-service experience to date. In future, we need to assess more clearly the optimized aromatics quantity and chemical composition to define the minimum requirement volume to add for a blend with a paraffinic cut. Indeed, although aromatic compounds are responsible of the good fuel density, they create pollutant emissions such as soot hence they are issues for environment and health.

The aromatics effect leads also to material incompatibility which is critical (elastomer tests). For instance, the NBR, the most used nitrile elastomer in aeronautics, is very sensitive to all ALFA-BIRD alternative fuels.

GtL seems to have better technical performances (except for stress relaxation of nitrile O-ring) compared to GtL + 50% NC and GtL + 20% hexanol.

GtL + 50% naphthenic cut is a very interesting fuel. It has a similar chemical composition to Jet A-1 and therefore comparable properties such as good cold flow properties and specific density. However, gauging and stress relaxation on nitrile O-ring tests were different and need to be addressed in future.

GtL + 20% hexanol received a large number of red crosses in the technical & technological category. ALFA-BIRD testing confirmed that oxygenated fuels are not "drop-in" because of the critical failures in the ASTM tests due to the oxygen presence (material compatibility and explosivity?, in particular). However, it was worthwhile to study because we discovered some improvements compared to CtL in fuel properties (thermal stability, soot concentration profile, flame temperature, pool fire). Some technical barriers such as the freezing point for fatty acid esters might be broken (showing rooms for improvements for the future [1]). Additional tests should be performed in order to assess the full potential of those oxygenated fuels. Nevertheless, these preliminary results show that their use might be compromised because too challenging for the moment considering the aircraft/engine architecture.

The **regulation** assessment did not show critical issues for the alternative fuels, expect for the blend with hexanol which failed in the "explosivity" critical criteria. No major concerns in terms of security and safety for the selected ALFA-BIRD fuels (neat GtL and GtL+NC) were identified. But please note: if a new alternative fuel enters on the market, all safety standards must be review with the new operating conditions it implies.

Project members performing the technical assessment highlighted also a problem with **fuel storage time**. Different results can be obtained depending of the fuel age. Important improvement in terms of storage should be evaluated in future projects. Furthermore, fuel and fuel container cleanliness were found to be critical as fuels are sensitive to trace contaminants. Future programmes should learn from ALFA-BIRD experience.

To conclude, from the technical assessments above, ALFA-BIRD proposed **a first assumed ranking** according to the "Fail or Pass" criteria for each test. Weighting criteria is a limitation for this king of assessment and this first ranking did not take into account the weighting here.

The assumed ranking from the technical evaluation compared to CtL (FSJF) is:

GtL > GtL + 50% NC > GtL + 20% hexanol

(“>” meaning “better than”, according to the tests led in the frame of the ALFA-BIRD programme”)

This ranking could change considering economic and environmental assessment that we be reviewed in the following sections.

5 ENVIRONMENTAL/ECONOMICAL ASSESSMENT (SP3)

1. Objectives of SP3

The subproject 3 is related with the environmental and socio-economical evaluation of the four alternative fuels selected in SP1 and technically assessed in SP2. The assessments supported providing a global conclusion of the ALFA-BIRD fuels some elements to implement a strategy for fuel and integration within the future.

Integration of alternative fuels is not only a technical stake. To perform a global assessment by review of each production pathway of alternative fuel environmental and socio-economical evaluation is mandatory. In addition to the technical issues, ALFA-BIRD had to deal with trade, political and environmental constraints such as productivity, price and resource availability which may be predominant within a decision-making process.

However, this kind of assessment was not easy compared to technical evaluation which is standardized and guided by the ASTM specification tests. Many different specialist fields are involved in an environmental and socio-economical assessment; forecasts are difficult because of the uncertainty of prediction. Moreover, there was a wide maturity difference between the tools and methodology used**.**

In ALFA-BIRD, we gathered competent and complementary organizations to deliver a general and as complete as possible assessment of the selected alternative fuels and their production pathways. This assessment helped to develop a decision-support methodology (for assessing and balancing gains and losses) and to provide resources to decision-makers to decide whether or not to support alternative fuel integration.

As the prime purpose of integrating alternative fuels is related to climate change, the main evaluation in this subproject was performed considering the environmental impact. The improvement from standard fuel practices was assessed, taking into account the global lifecycle (LCA), and considering all the environmental concerns related to air transport. This evaluation included key parameters such as fuel production and distribution, combustion within engines, and some aircraft mission profiles.

Additionally, an economic evaluation provided some insights for the related costs and expected availability. The socio-economic assessment took into account social aspects by delivering insights to the relationship between the selected alternative fuels and their cost parameters. In this evaluation field, a dynamic and technology-competition model based tool was developed by EU-VRi and R-Tech to give prediction on aviation biofuel market up to 2050 according to different scenarios.

The participants in this sub-project were mainly DLR Köln, EU-VRi, Technical University of Graz and IFPEN (but all other members contributed to by giving data and/or complementary the expertise).

This global evaluation, combined with the chemical formulations and manufacturing processes developed within the remaining activities, are the main result of ALFA-BIRD: an innovative set of aircraft fuels implying reasonable ownership costs and guaranteeing sustainable aviation.

The present report will define the methods and tools used in the environmental assessment and then give the main conclusions from all technical, environmental and economic test results.

2. Environmental and energy balance

This assessment aimed at performing an emissions-related evaluation of the alternative fuels. The candidates that have been selected within SP1 and SP2 were assessed, in a global lifecycle analysis (LCA), and considering all the environmental concerns related to air transport (CO_2, NOx, particles…). This evaluation included key parameters such as fuel production and distribution (well-to-tank), combustion within engines (tank-to-wing), and flight mission profile. Finally, we tried to model a scenario involving the whole aircraft fleet in order to provide a global view of the environmental problem and the impact of alternative fuels was modelled.

Results

Life cycle analysis showed that neat GtL and CtL, even considering carbon capture sequestration, are not performing better, but possibly worse, than Jet A-1, in terms of CO_2 emissions.

Using GtL+hexanol reduces CO_2 emissions and- in that sense - has less impact on the environment. But because of a lack of data on this fuel (especially production process), we could not quantify the reduction percentage. We also did not realize a life cycle analysis for GtL+NC, NC coming from biomass, for the same reason. Nevertheless the naphthenic cut might come from sustainable feedstock (biomass liquefaction/pyrolysis) in the future, hence it could decrease the negative impact of GtL fuel use on the environment, with respect to CO_2 emissions.

ALFA-BIRD also added in the LCA analysis results for BtL and HEFA from SWAFEA study to go further within the alternative fuels comparison. These fuels seem very promising depending on the feedstock. They should reduce CO_2 emissions by more than 50%. Nevertheless, ALFA-BIRD LCA study highlighted that **LUC (Land Use Change)** issue for biomass feedstock could have a strong impact on LCA and it was not taken into account in the project because assessment method is not reliable currently unclear. Indeed, this could change the trend of a better environmental impact for the fuels made from sustainable feedstock. Further knowledge and experimental data is needed to fully quantify the LUC (direct and indirect) impact and confirm the interest to pursue with alternative fuels from biomass. Collecting these data is not easy because of the result variability which strongly depends on the geographical location. iLUC and LUC assessment need therefore a frame of a methodology global agreed at European or worldwide level (e.g. RSB standards) to be applied with the least bias possible

The study highlighted that **fuel flow reduction** is expected when using alternative fuels with higher lower heating value per unit mass (LHV). At flight mission level a potential snowball effect from the fuel flow reduction was noted. Indeed, fuel payload at take-off is lower and therefore aircraft will consume less jet fuel reducing total weight etc… This effect is more important for long duration flight at or near the maximum aircraft range. However, it is important to note the fact that a fuel flow reduction can lead to a volume increase hence to a non-negligible important fuel storage volume issue for the aircraft.

This work package was also evaluating the CO_2 and NOX emissions at operating level then at flight mission level. CO_2 emissions depend of fuel composition (C/H ratio). Therefore, CO_2 emission reduction can easily be predicted. For NOx emissions, which are mainly depending of the temperature in the combustion chamber and engine technology, results should be proportional to the fuel flow. However, discussions within ALFA-BIRD highlighted that a higher heating value may lead to a higher temperature and so might balance the emission reduction due to a fuel flow decrease as we explained previously. More research and especially experimental testing with chosen alternative fuels would be helpful to understand and clarify the NOx formation rates for different fuels.

Particle and contrail formation are dependent on the atmospheric conditions and therefore are difficult to predict. Lack of data excluded the ability to form firm conclusion but it is possible to imagine that with less aromatic content, alternative fuels should be “cleaner” in terms of particles emissions. For contrails for instance, we know their formation are due to a condensate nucleus with high temperature and specific humidity air conditions but it is not known what the engine emission impact is.

The study intended to model scenarios to have an idea of the environmental impacts of all the aircraft fleet using alternative fuels. However, it was very difficult to conclude on environmental consequences of fuel emissions because modeling an entire fleet is very complex. Therefore we can give assumptions only on CO_2 reduction which have the same trends than within the LCA analysis.

Other pollutants such as NOx, CO, unburned hydrocarbon were not considered due to the lack of data at global level. Moreover, these emissions are depending on the engine technology; hence, it is even more difficult to predict.

To conclude about the environmental impact assessment, we observed a real potential for environmental improvement (reducing emissions) using alternative fuels. Nevertheless, we could not accurately quantify this effect at some points or forecasts all the consequences, especially on atmosphere primarily because of the lack of good quality data.

3. Economical evaluation

The economic analysis provided an insight into the relationship between the selected alternative fuels and their cost parameters. In a first step, the direct costs to produce, distribute and use the alternative fuel candidates previously assessed were evaluated, including revenues from by-products, and compared to their equivalent data regarding conventional fuels. Additionally, the fuel availability aspect has to be assessed since it plays a major role in the viability of a world-wide transportation device such as aircraft. The consequences on air transport market have to be deduced from the whole set of data.

Proposed solution of the methodology for economic evaluation of new alternative fuels is based on four notions: the overall S-curve model, decoupling indicators, LCC analysis and socio-economic analysis (SEA).

Results

The **economic assessment** was mainly performed by EU-VRi and R-Tech, with some significant contributions from the IFPEN team.

Jet A-1 is still the cheapest fuel in terms of production costs. For the alternative fuels, we obtained the following results presented in Table 4. Two different processes were assessed for Coal to Liquid production: Indirect Coal to Liquid (ICL) and Direct Coal to Liquid (DCL). The main difference between the two processes is the use of Fisher-Tropsch synthesis in ICL compared to the direct conversion of coal to liquid by hydrogenation and carbonization processes.

Table 4: Results from economical assessment:

Equivalent oil price to production cost for Jet A-1 and neat alternative fuels.

Fuel	Jet A1	BtL	FT-SPK (GtL)	FSJF (ICL)	DCL (NC)
Range possible for equivalent oil price to production cost ($/barrel)	80 to 150	159 to 259	42 to 104	60 to 140	57 to 117

We deduced comparing to oil price scenario (defined by a range of probability) that BtL production cost should be compatible with market price if the pathway is supported by policies speeding up the industrial development (specifications, tax differential, technology improvement).

GtL pathway is already viable in a range of cases but it will compete against traditional natural gas liquefaction. It seems that GtL production plants are not likely to be implemented in Europe because of low gas reserves. However, economics are very favourable in other countries such as Middle East, North America or parts of Asia.

CtL (DCL and ICL), is also an attractive case according to the geographical location and coal supply cost. It is currently cost effective and CtL production may be in competition with GtL in USA for instance. Nevertheless, future regulations on CO_2 could mitigate this economical interest in the future.

In general, economical assessment for these neat selected fuels is promising and supporting alternative fuel integration in the future if environmental incentives are set up.

4. Future alternative fuels strategy and implementation

This work package aims to make a synthesis of the previous results (with respect to environment and economy), completed by the technical data from SP1 and SP2. The risks and benefits are assessed, and a hierarchy will be established among the set of candidates.

To complement a scenario of implementation will be provided, which could combine some short-term and long-term solutions, with recommendations on the main actions/decisions to be performed, that will set the path to actual deployment of alternative fuels to air transport.

Finally, the potential to jointly improve combustion behaviour from (low Nox) to greenhouse gases reduction by a combination of new technologies and alternative fuels will be addressed, and related recommendations will be provided that could assist in the achievement of overall environmental objectives for aviation.

Results

The first ranking we proposed after performing SP2 (technical assessment) was then modified according to the inputs from SP3 (environmental and economic evaluation). Ranking was still implemented in comparison to FSJF which is the reference fuel in ALFA-BIRD due to its technical compliance with ASTM requirements (ASTM certification obtained for XtL in 2009).

This new ranking takes into account two main constraints, the technical compliance and the economical/environmental performance requirements within a long and short term perspective (see Table 5). However, this is not a definitive ranking, and some comments (see next paragraph) have to be considered. Besides, as it will be further explained, the ranking is valid if only considering the naphthenic cut coming from a sustainable biomass.

Table 5: Final ALFA-BIRD alternative fuel ranking according to the overall assessment (techniques, environment, and economics) and considering the naphthenic cut coming from biomass.

Rank	ALFA-BIRD alternative fuels
1	GtL + 50% NC (NC from biomass)
2	100% GtL
3	GtL + 20% Hexanol

As noted, **GtL + 50% NC** was almost "drop-in" due to the close replication of Jet A-1 fuel properties. Furthermore, the possibility to obtain the naphthenic cut from liquefaction/pyrolysis of biomass feedstock may reduce the negative impact on the environment. These facts illustrate why we considered GtL + 50% NC as the most interesting and promising fuel option.

100% GtL is also almost "drop-in" but the impact on the environment did not differ a lot from CtL, even with carbon capture sequestration. It would be difficult with this fuel to reach the environmental objectives fixed by IATA. However, GtL suitability with aircraft engine and structure is good and the production costs are already competitive with Jet A-1 cost, especially in some regions.

Finally, the study noted that **GtL + 20% Hexanol** is a "non drop-in" fuel, but interesting and surprising results (especially on thermal stability, or soot concentration profile for instance) make this oxygenated fuel an interesting choice from a R&T perspective. Clear risk and benefit assessment and a consistent evaluation with serious economic and/or environmental benefits would be necessary to perform to envisage a long-term application and to push further the development and the implementation of oxygenated fuel pathways.

According to ALFA-BIRD results, **GtL** could therefore be a good synthetic paraffinic base for alternative fuel if it is blended with naphthenic-aromatic cut from biomass feedstock. GtL may have also the advantage of being available soon on the market since the Fisher-Tropsch process is already well established.

Moreover, the study provided some interesting conclusions about **BtL and HEFA** (blends different from the 50% ASTM certification) which were included in the ALFA-BIRD matrix for some technical and environmental tests. HEFA and BtL are not "drop-in" fuels when used neat but their environmental assessment (based on LCA) described a real reduction for these fuels if they are produced from sustainable/biomass resources than for Jet A1, CtL and GtL. More research (including LUC) should be lead to confirm this positive impact on environment and assess more accurately their technical compliance to identify the issues and envisage solving them with maybe aircraft technological improvement if it is feasible. Finally, with some efforts and policy support, BtL production costs may become comparable with market price for conventional fuels.

Regarding the studies on the potential to improve combustion behaviour with new technologies, we found out that an optimization of the air-to-fuel ratio especially in the lean domain could reduce significantly the NOx emissions. A staged combustion could also lead to NOx emission reductions.

No contra-indication of existing low-NOx technologies was identified in ALFA-BIRD study. One promising solution, for instance, to use state-of-the-art RQL (Rich-queched- lean) technology in aero engines because it allies the simplicity of the RQL principle (single annular chamber, low-complexity injection compared to staged injection, stable combustion) with a decrease in its principal drawback, namely the soot production which would be avoided by the use of low or even zero aromatic (soot producing) compounds. Modify, difficult to get the point. Further studies and tests with the last generation of low-NOx technologies such as Lean Premixed Prevaporized, PERM or LDI explain strategies are recommended for the future.

Finally, the study attempted to establish a strategy of implementation of alternative fuels according to the actual market and actors. Some facts are important to consider when envisaging the alternative fuel integration.

No biojet fuels are available commercially today and several different pathways are in development with different level of maturity. The alternative fuels already available are only batch production and not continuous industrial production, except for GtL, CtL and HEFA (but HEFA is primarily dedicated at this time to diesel). This competition for product makes the market study quite difficult and subject to hypothesis.

Some types of fuel production (such as XtLs) could be implemented quicker because of the similarity to petroleum process. Others are more disruptive (yeast pathway for instance) and are therefore more technically challenging. Time scales are therefore important to take into account: time to establish a fully working unit plant is approx. 5 years and between 5 and 10 years for a whole process.

In any case, production processes for biofuel will be very dependent of the available feedstock. Biofuel projects have also a huge problem securing finance currently because of the high investment costs, but also uncertainties in the future about feedstock price, oil price, CO_2 price...

For the moment, it is difficult to determine the "best" pathway, each process has drawbacks and advantages which are difficult to balance. To make a rational decision, definition of what is the most important for the fuel development: yield (mass, energetic), cost, low investment or emissions is required with relative priority (weighting of importance). The importance of environmental policies which will design the market cannot be under estimated.

Finally, we also need international harmonization in order to avoid commercial distortions, for blending for instance which is complex and expensive. Besides, incorporation of alternative fuels will provoke issues in logistics. Developing the dedicated logistic associated with the deployment of biojet will be necessary, with associated quality assurance. The supply chain for future alternative fuels could be quite different to today's model of on-refinery production and transport/distribution to the airport. Control and regulation for the new "distributed", small scale production, distribution and off-refinery blending needs to be addressed.

6 CONCLUSIONS AND THOUGHTS FOR THE FUTURE

Useful scientific and technical outcomes for alternative fuels for aviation

The ALFA-BIRD project performed a robust, thorough and consistent technical, environmental and economical assessment of some of the most promising future alternative fuels for aviation. More than a simple characterization of the proposed fuels, ALFA-BIRD studied their production processes and their possible future integration on the market. Tackling the aviation alternative fuels issue with this global approach was a complete and challenging innovation for the whole ALFA-BIRD consortium. A challenge from which the 24 partners responded by working in a truly efficient and fruitful way.

It is important to note that the aim of ALFA-BIRD project was not to be a substitute for certification authorities and propose certification for new fuels or blends. Our objectives were to investigate options and to support the community with elements and methodologies for decision-making.

Numerous specialist fields were involved in this assessment; ranking and simple conclusions were difficult. Different degrees of maturity in assessments, tools and methods have to be taken into account in order to weight the different criteria in the most logical way.

Following test procedures developed by the ASTM (where relevant) also improved the degree of confidence in the results (storage, sampling) and would be recommended for future programmes.

Some important questions remain and further projects have to be dedicated to produce answers especially regarding environmental impact and consequences of using alternative fuels.

Further experimentation to develop models and collect data would require large quantities of fuel but such studies and testing would be very helpful in order to control and adjust the alternative fuel integration in aeronautics. Contribution and expertise from all aviation stakeholders such as engine manufacturers, aircraft constructor, airline companies or jet fuel producers will also be essential and bring the required skills, knowledge and expertise to bear on some of the remaining questions and challenges in alternative fuel development.

Finally, ALFA-BIRD identified that the jet fuel market is complex and new alternative biofuels would be in competition with biodiesel production. Production of biodiesel has a better cost/benefits balance compared to jet fuel production with existing technologies.

Conclusions on assessment

GtL and CtL are excellent fuels. They are compatible with already existing engines and the market forecasts for these technologies are positive.

However, considering the overall environmental and sustainable issues which is not the only but the main driver for fuel customers (airlines), they are not probably the best solutions.

Already certified at 50% BtL and HEFA should be a better alternative due to their positive improvement on environmental impact compared to conventional Jet A1. Moreover, ALFA-BIRD highlighted a good production process for HEFA lipid feedstock: the yeast pathway. Good results were obtained and more research would allow improvements supporting the development of the industrial process step. Issues in metal removal and lipid extraction have to be studied further (already started by Lesaffre).

Nevertheless a successful implementation of these fuels (HEFA and BtL) is envisaged only after land use change assessment related to biomass use and with some efforts from the industrial and political stakeholders. A global study on available biomass has to be completed first to define the optimum pathway to develop.

Significant technical challenges identified for non drop-in fuels such as oxygenated compounds by the ALFA-BIRD programme have demonstrated that they would need to show significant environmental benefits for raw material production and processing/blending before work to overcome these technical challenges for use in aircraft would be value added.

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