
**SWAFEA**

***Sustainable Way for Alternative Fuels and Energy in Aviation***

# State of the Art on Alternative Fuels in Aviation

## Executive Summary

Submitted to the European Commission as part of the "State of the Art" report
under the contract for the SWAFEA study[i]

# 1. Introduction

Currently, the aviation sector uses petroleum derived liquid fuels as the energy carrier of choice for flight. In light the present environmental, economical and political concerns as to the sustainability of this energy source, the question of which alternatives the aviation sector should pursue in the future has emerged. Among these concerns, the environmental impact of fossil fuel use on global warming and air quality is of major importance, while the impact of volatile oil prices and the need for a sustainable supply of fuel are strong drivers for the economies of fuel users.

In this context, the European Commission's Directorate General for Energy and Transport has initiated the SWAFEA study to investigate the feasibility and the impact of the use of alternative fuels in aviation. SWAFEA's goal is to develop a comparative analysis of different energy/fuel options on the basis of an assessment of the available data. It also seeks to create a vision and possible roadmap for future deployments of alternative fuels and, in this regard, SWAFEA will provide policy makers with information and decision elements.

This paper summarises the findings from the SWAFEA preliminary state of the art study[ii]. It covers trends in aspects of future air transport, potential candidate fuels and associated feedstock along with sustainability and economical issues relevant for alternative fuels in aviation.

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[i] **Disclaimer**



[ii] This work, coordinated by S. Blakey (University of Sheffield) and Ph. Novelli (ONERA), has involved Ph. Costes (AIRBUS) - S. Bringtown (AIR FRANCE) – D. Christensen, B. Sakintuna, C. Peineke (ALTRAN) - R.E.E. Jongschaap, J.G. Conijn and B. Rutgers (DLO, PLANT RESEARCH INTERNATIONAL) - Lombaert Valot, E. Joubert, Jean-François Perelgritz (EADS-IW) - A. Filogonio (EMBRAER) - Th. Roetger (IATA) - A. Prieur, L. Starck, N. Jeuland (IFP) - P. Bogers, R. Midgley, J. Bauldreay (SHELL) - G. Rollin (SNECMA) - Lucas Rye, Chris Wilson (University of Sheffield).

# 2. Context for alternative fuels in aviation

Presently, aviation is considered to represent 2% of the world global CO2 emissions. It is nevertheless anticipated that the global demand for air travel will continue to increase throughout near to mid term up to 2030 albeit reaching market saturation in various regions of the world. Although the long term growth of commercial aviation is a positive factor since it's a significant contributor to the economies of European member states, it also means that the environmental impact of aviation in terms of its green house gas (GHG) emissions is likely to increase.

Studies completed before the current economic downturn suggest a continued rise in demand in line with the activities of the early 2000's at between 3.5 and 5% increase in passenger km flown [1,2,3,4,5]. Studies since the current economic downturn, and thus including the current stagnation of demand, suggest that demand will recover to the previous rate once the current economic climate improves around 2010 [2,6]. A similar trend is predicted for the demand in air freight, although this sector has seen a more drastic decline in demand due to the current economic climate [2].

Up to 2030, it is anticipated that the resulting increase in fuel consumption of the sector will be at a lower rate than the increase in passenger demand. This is primarily due to two factors: increases in fuel efficiency of the aircraft fleet (around 1.2% reduction per annum) [2,7], and secondly through the optimisation of air traffic management (ATM) through various initiatives, such as the European SESAR project, and elsewhere in the globe (total improvement of 5%) [8]. However, the rate of improvement due to fleet renewal is still under debate within the literature, also the rate of fleet renewal policy of airlines may be altered under the current economic climate [5,6,9]. This rate of improvement is slower than needed to achieve the Advisory Council for Aeronautics Research in Europe (ACARE) targets of 2020 for the complete fleet although new aircraft should meet these goals [5,10].

Taking all these factors into account, the International Air Transport Association (IATA) predicts an increase in aviation fuel demand from around 190 million tonnes in 2009 to between 300-350 million tonnes by 2030 [2], inducing a proportional increase of its CO2 emissions.

The European Community has long recognised the need to further promote renewable energy given that its use reduces greenhouse gas emissions and also contributes to security of supply, economic growth, competitiveness, regional and rural development along with the development of a knowledge based industry creating jobs [11]. The European Union (EU) Renewable Energy Directive establishes an overall binding target of a 20% share of renewable energy sources in energy consumption and a 10% binding minimum target for energy from renewable sources in all forms of transport to be achieved by each Member State by 2020. As part of its climate change mitigation efforts, the European Union has also decided to extend the European Emissions Trading Scheme (ETS) to aviation from 2012, which will add to the cost of jet fuel. The trading allowance price has been very volatile, and although it reached US$40/t $CO_2$ in December 2008 it has seen values as low as US$10/t. The latter is expected to double by 2030 and, if it does not restrict demand, it may become a driver for more rapid uptake of new fleet technologies [2].

As well as the environmental sustainability of commercial aviation, the availability of crude oil is a concern as peak oil is approaching and presents a major risk to an industry in which there are presently no commercialised substitutes for fossil fuels. Several alternative jet fuel products which are derived from other fossil fuels (coal, gas) are emerging and it is felt that their production processes will in time offer routes to produce high quality liquid fuel from more sustainable feedstocks.

Jet fuel is a hydrocarbon product refined as a middle distillate between gasoline, which is lighter and more volatile, and diesel which is heavier and more prone to waxing at low temperatures. Traditionally aviation kerosene is around 10% of the crude oil cut globally, the majority of the remainder being diesel and petrol. The percentage cut of the various products is dependent on their daily prices, the chemical limitations of the crude oil and the refinery configuration. A maximum of between 13% and 15% of the crude can be used for aviation depending on the oil field [12] and refinery capability, although it is seldom economical to produce this quantity to the detriment of diesel and petrol.

There is a significant Atlantic divide for road transport fuels, with a bias towards diesel demand in Europe and gasoline in the United States. This difference in vehicle fleet causes a structural shortage of middle distillates and kerosene capacity in Europe, making the European Union a net importer of jet fuel. The demands for diesel and, to a lesser extent, gasoline are expected to continue to rise in the mid term as peak oil is approached and the global automotive market continues to develop [6]. In the longer term, this rise will continue until technology for electric vehicles (hybrid power, battery and fuel cell technologies) becomes mature to the point that they start to contribute significantly to the automotive sector [6,13].

The reduction in automotive demand for conventional liquid fuels due to the uptake of electric vehicles, combined with the rapid growth of aviation will result in an increase of the proportion of jet fuel demanded from the refining industry. Today this proportion is less than 10% but it could increase and exceed the refining capability to produce kerosene form crude oil beyond 2020. This occurrence of a peak in the demand for the kerosene cut (Peak Cut) might restrict the growth of the aviation sector at some future point unless the gap between supply capacity and demand requirements can be bridged by fuel from a non-conventional source.

In addition to the growing concerns about the environmental sustainability and worries about the security of supply for all transport sectors, the awareness that growth in aviation may become restricted by Peak Cut provides additional incentive for the uptake of bio- and alternative fuels.

# 3. Aviation fuel requirements

The main purpose of the technical requirements for jet fuel is to guaranty the safety of air transport. Therefore commercial jet fuel must meet precise technical and operational specifications and jet engines are designed to work with fuel having these specific characteristics. The relatively slow rate of renewal of the aircraft fleet and the global nature of the aviation sector demand that any bio- and alternative fuels which could be used in aviation meet the specifications of crude oil derived jet fuel and result in the same overall performance. As such the use of an alternative fuel would represent no change or challenge in the ground and supply infrastructure, airframe or engines. This is the definition of a “drop in” fuel.

A “non drop in” fuel would conversely imply new aircraft and infrastructure and would represent a substantial investment in a supply system which should be kept independent of the one for conventional jet fuel. In addition, the engine technology should be tailored for this fuel. Presently, it is felt that no manufacturer of aircraft or engines is going to limit the use of their equipment to a particular fuel or way of operating. All this suggests that in the near to mid term any alternative fuel for aviation will be “drop in”.

However, in the longer term, non "drop in" solutions should not be systematically rejected but their evaluation requires a careful balance between their potential advantages from efficiency, environmental or economical point of view and their approval and implementation costs.

Presently, a fuel used in commercial aviation has to meet the specification for civil jet fuel, which is ASTM (American Society for Testing and Materials) D1655 and the UK DEF STAN (Defence Standards) 91-91, both of which are globally accepted [14].

The specification comprises a list of minimum and maximum allowable values for a number of fuel properties, thus providing a relatively quick laboratory check to verify that each batch of fuel is “fit for purpose”, i.e. that it matches all requirements for use in an aircraft. The properties cover the ground handling safety of the fuel, the suitability of the fuel for storage, the stability of the fuel as a liquid over a range of operating temperatures and some physical characteristics. The latter can be used to empirically predict low temperature and combustion performance. These tests have been developed over many years to ensure safety. Specifications also stipulate the origin of the fuel which was until recently limited to crude oil.

Since the early 1990s Sasol (South Africa) has developed and produced a synthetic CtL (Coal to Liquid) kerosene fuel approved for use in aviation. This work has pioneered the route to approval for any potential “drop in” aviation fuel production process as detailed in the ASTM D4054 standard, and DEF STAN 91-91 appendix D.

The approval process to establish if a potential “drop in” fuel can be classified as a “drop in” and included in the specifications, includes additional testing. These tests are known as “fit for purpose” tests and represent the conclusions of 18 years of research into the approval of Sasol’s CtL fuel for use in commercial aviation [15]. The approval process also involves a review and formal agreement by the OEMs (Original Equipment Manufacturers) who can decide if additional testing (in particular components or engine testing) is required,. A 50% blend of Sasol CtL and crude kerosene and a 100% synthetic product from Sasol were the first alternative fuels approved for use in aviation. As a “drop in” fuel, these fuels require no recertification of any other components in the engine, airframe or supply infrastructure.

With a view to future fuel candidates however, the fact that a fuel doesn't comply with all the specifications of ASTM D4054, and could thus be seen as non "drop-in", doesn't necessarily prevent it from being approved. In this case the demonstration program will nevertheless be heavier and more expensive, with probably extensive testing, and the risk for the fuel to be finally rejected will be higher.

50% blends of Fischer-Tropsch (FT)[iii] derived fuels with conventional jet fuel have now been approved in 2009, and a new specification, ASTM D7566, is being issued to cover FT fuels. The specifications include the source and allowable processing routes of jet fuel. When the production process fits within the ASTM and DEF STAN definition of Fischer-Tropsch and meets the associated specifications, any company could produce a FT derived jet fuel for use in aviation without the need for further “fit for purpose” testing. Hydrotreated Vegetable Oil (HVO) derived fuels (in a 50% blend) are also going through the approval process, due for completion in 2011.

Importantly, it is the production pathway for fuels and the resultant product composition and performance properties which are approved, not the specific feedstock.

# 4. Liquid fuel production pathways

in addition to refining conventional crude oil, many production processes for liquid fuels have been proposed. These can largely be organised into the following families of pathways:

1. Traditional crude oil refining,
2. Gas to Liquid (GtL), Coal to Liquid (CtL), Biomass to Liquid (BtL),…, Anything to Liquid (XtL) through Fischer Tropsch process
3. HO (Hydrotreated Oils; typically from vegetable feedstocks, hence Hydrotreated Vegetable (HVO), or animal fat) also known as HRJ (Hydrotreated Renewable Jet),
4. Sugars conversion to alkanes or other hydrocarbons (terpenes) either by catalytic fermentation or thermochemical process.
5. Direct liquefaction: Naphthenic compounds,
6. Fatty Acid Esters (FAE),
7. Alcohols,
8. Furane derivatives,
9. Succinic acids derivatives.

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[iii] Fischer-Tropsch (FT) is a catalytic chemical production process for synthetic fuel based on processing of a synthetic gas obtained from gasification of a feedstock .

10. Cryogenic fuels: Liquefied Natural Gas (LNG) and liquid Hydrogen

The order of this listing does not imply any technical, economic, environmental or societal advantage of one production process over another. However, it is not far from indicating the level of maturity of the production process for its use in aviation as a potential drop-in fuel. However, concerning Fischer-Tropsch fuels, it should be that the the maturity of the process is not the same depending on the feedstock: CtL is at the industrial production stage while BtL is only at the demonstration stage.

The relationship between the various production pathways and the fuel product produced from biomass feedstocks is illustrated on *Figure 4.1*.

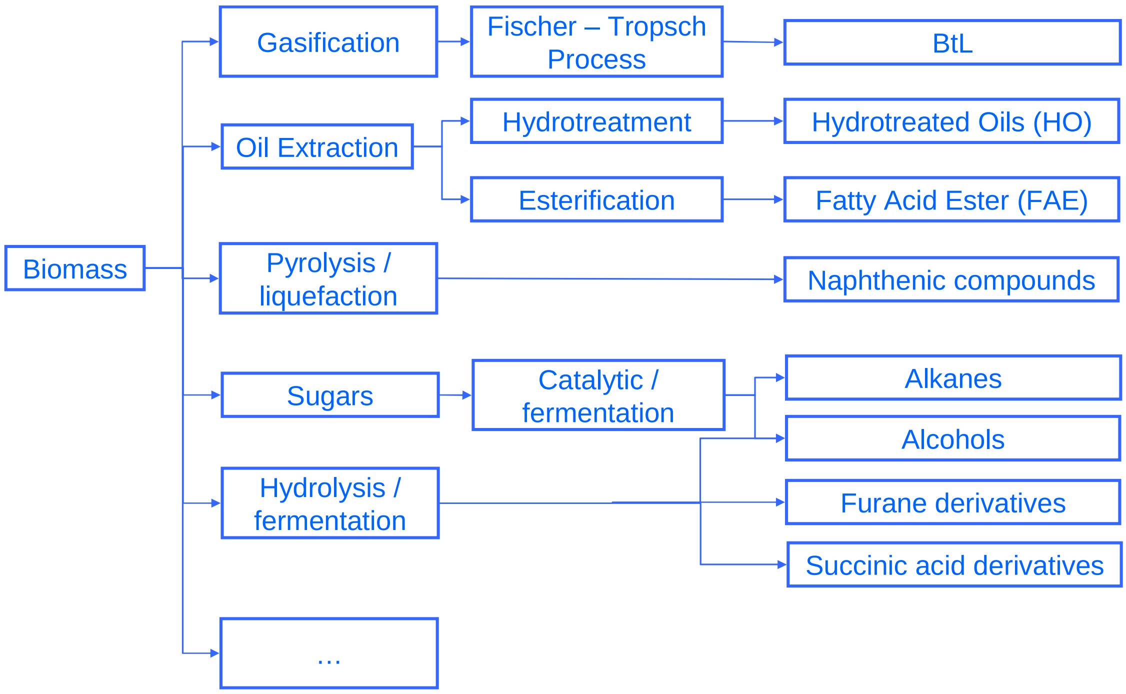


*Figure 4.1 Pathways and products from biomass*

## 4.1. Potential “drop in” production pathways

The rising demand for high quality automotive diesel is accelerating the development of Fischer-Tropsch (XtL) fuels and hydrotreated oils (HO) which are currently at the point of leaving pilot plant scale and scaling up for commercialisation with proprietary production and post processing technologies. CtL and GtL are the most advanced of the FT group.

The production of fuels using the Fischer-Tropsch (FT) process can be subdivided into three 'steps':

- production of synthesis gas (syngas) which by gasification of any carbonaceous material like natural gas, coal, biomass, or their combination;
- Fischer Tropsch catalysis which makes mainly straight chain hydrocarbons;
- Post processing (cracking, isomerizing) to adapt the fuel property to the need (for example improve cold flow properties in case of aviation).

As synthetic fuels, FT fuels properties can be tailored for application and can meet or exceed the current specifications. In addition, properties only depend on the process, not on the feedstock. Their chemical composition makes them quite close to the paraffinic part (linear alkanes) of the traditional Jet-A1.

As already mentioned, FT fuels have been approved in the frame of the ASTM for blending with Jet-A1 at a 50% ratio. The reason for blending is that FT fuels do not contain aromatics required for lubricity and seals swelling in aircraft systems and engines (Sasol Fully Synthetic Jet Fuel is an exception - it combines a FT fuel with a synthetic aromatic stream the output of which is approved as neat product).

Before the current economic downturn, GtL global capacity was set to go from 150 000 bbl/d[iv] in 2006 to 900 milion bbl/d (or approximately 48 million t/a) in 2020 [16] (most of this production serving the automotive market. There are no approved CtL plants in the world today other than the existing SASOL plant. World scale (70 000 bbl/day) projects take around 7 years from agreement and the current economic situation is not favourable for capital intensive projects such as these. The current market price for CtL equivalent to petroleum oil is between 130 and 200US$ per barrel [2].

In addition to the recovery of capital investment, the costs of Fischer-Tropsch process fuels are also dependent on the primary energy which must be expended to produce syngas from the feedstock: ranging from almost zero for natural gas to substantial expenditure to produce a syngas from lignocellulosic biomass (wood, grasses and waste products from agriculture amongst others [17]). In addition GHG emissions are also highly dependent on the feedstock used. (For BtL, land use change must be duly accounted for [18]). The CHOREN BtL plant in Germany uses wood and is built to produce 0.2 million t/a. Although the FT processes can be used on a range of feedstocks, the life cycle emissions vary significantly as does the amount of water needed.

Hydrotreated oils are obtained from direct hydrogenation (more precisely, hydrogenolysis) of vegetable oils or fats. It is possible to use processes and catalysts similar to those used for crude oil middle distillate hydro treatment, the so called HO pathway. The liquid fuel produced is comparable to Fischer Tropsch fuel, however, HO products tend to have a narrower distillation curve than FT fuels [19]. One of the advantages of HVO over FT is that the feedstock could be co-processed with middle distillates from crude oil, the technology for which is already mature; this process is being investigated in Brazil by Petrobras and TecBio. Compared to esterification (that is largely used for biodiesel), hydrotreatment is much more costly.

Neste Oil of Finland is building full scale plants at several locations globally, with the goal of producing 1.7 million t/a by 2011 [20]. UOP is developing hydrotreated oil with hydrocracking and isomerisation of oils from the Jatropha plant; this fuel, after the addition of aromatics was flight tested in a 50% blend by Air New Zealand in December 2008 [21].

Rather than using intermediate oils or syngases, direct liquefaction mixes a powdered feedstock with hydrogen prior to hydrotreatment and hydrocracking. This produces a highly naphthenic liquid fuel, which is unsuitable for automotive applications. The yield of the process is significantly higher than for Fischer-Tropsch, and the cost lower. In principle this may offer an alternative approach to the FT / HO lighter hydrocarbon products, whose approval is only in blends as their density is too low, although unblended the liquefaction product would have too high a density to meet the aviation fuel spec. This pathway may offer the potential for the development of an entirely bio-jet “drop in” fuel through the blending of FT/HO products with a bio-derived naphthene. This is of particular interest as its use would not compete with the automotive market. In addition, the lubricity of a naphthenic cut could compensate for the low lubricity of FT and HO fuels.

[iv] Barrels per day (bbl/d) a commonly used measure of production capacity.

The direct liquefaction of biomass has a low level of technological maturity and is still at the stage of research. Large scale direct coal liquefaction plants are being built in China; a 20,000bbl/d plant was launched in 2008, with projected expansion to 70,000bbl/d by 2015 (1 and 3.4 million t/a, respectively).

The use of sugars as an intermediary from cellulose to ethanol and hydrocarbons is also under investigation. Two routes suitable for aviation fuels are currently being explored, one through fermentation conversion with micro-organisms to produce terpenes (Amyris) and the other through catalysis to produce alkanes (Virent). These routes are the next pathways to be considered for approval by ASTM. They are promising because they associate relatively cheap process with low cost feedstock.

## 4.2. FAEs and Alcohols

Oils can be converted to their fatty acid esters (FAE) by trans-esterification in the presence of a catalyst using methanol (methanol is the M in FAME, potentially fuels could be produced from other alcohols). FAEs from this pathway, within the diesel cut, are established in the automotive market. Fuels produced by this process do not meet the Def Stan and ASTM specifications for jet fuel as they are not pure hydrocarbon products. The incorporation of such products would require significant effort to overcome the technical challenges resulting from the FAE chemistry. It should be noted that, due to contamination by FAME of jet fuel supplied through multiproduct pipelines, an approval of 100ppm FAME content in jet fuel is currently being reviewed against the fit for purpose tests, [22].

Common alcohols such as ethanol and butanol do not meet the energy density requirement for jet fuel. However, higher biosynthetic pathways may present a route to produce linear alcohols such as hexanol, octanol and even dodecanol [23]. Recent tests under the French CALIN program have shown that hexanol can be blended with Jet A-1 up to 10% and still meet the Table 1 requirements of ASTM 1655 [24]. A major issue with such a fuel for aviation is the affinity with water, as OH compounds are hydrophilic. The development of the higher alcohol processes is still at a research scale.

Most of the existing alcohol feedstocks are presently food crops. The production of ethanol from cellulosic biomass is an alternative pathway, which is receiving significant attention [25]. Several pilot plants are under construction or in the early stages of industrialisation, in particular in the United States and in Europe. However, no production is commercially available yet [26].

## 4.3. Other fuels

It is possible to produce a similar flashpoint and boiling point to jet fuel by reacting ethanol with succinic acid produced from sugar fermentation. This produces a diethyl-succinate (DES). Bioamber has a pilot plant producing 40 000L per annum (or 0.04 million t/a) in Bazancourt, France.

Other oxygenated molecules can be produced from biomass or the isomerisation of glucose by first converting them to fructose and then producing a dimethylfuranes (DMFs) using a metallic catalyst. This has been extensively studied as a potential alternative fuel for spark-ignition engines. DMF molecules have a higher energy density and boiling point than ethanol and are not soluble in water; in addition, the cold flow properties and flash point are comparable with those of jet fuel.

For completeness, liquid hydrogen and Liquefied Natural Gas (which is predominately methane, an energy source but also a significant GHG) should finally be mentioned. They have significantly lower densities compared to conventional jet fuel. Hence even in liquefied form, they cannot be considered potential “drop in” fuels. Most of the technical considerations and design requirements for liquid hydrogen aircraft also apply to LNG, although LNG aircraft are less demanding. Their use would necessitate the redesign of all aircraft and airport facilities as discussed previously. In addition, efficient and environmentally sustainable large scale production of hydrogen has not yet been achieved.

# 5. Feedstocks

Fuels can be categorised into one of two groups; depending on whether the product may provide a reduced environmental footprint (“environmental sustainability”) or essentially increases supply security (“security of supply”). Reduced environmental footprint is mainly expected from biomass feedstock while, for security of supply, fossil resources other than crude oil can be used.

As with crude oil, the majority of the feedstock for both groups of products is destined for the automotive market in the form of diesel. In addition, there will also be competition for certain types of raw biomass suitable for co-feeding with power stations or other stationary facilities and also with the chemical industry. The resources accessible to biofuel, and moreover to jet fuel, is difficult to assess and will depend on economical factors and political choices.

Most of bio derived fuels produced up to now, and often designated as "first generation" (though this term has no rigorous definition) have been manufactured from sugar plants, cereals and oils plants: bioethanol from maize, sugarcane, wheat and sugar beet (representing 12% of global sugar production and 3% of cereal production), and bio diesel from rape, soy, sunflower, palm and to a lesser extent, coconut and babbassu (5% of total oil production). These crops represent the world’s most significant agricultural crops, and, either in a raw or processed state, they play a major role in the food and feed markets.

For various reasons, there is now a trend to develop other crops for biofuels. These reasons include the search of species that could be grown with less fertilizers (Camelina), or water resources (Jatropha, Moringa) and eventually on marginal land (Jatropha, Pongamia-Milletia), the adaptation to climate (especially for the northern hemisphere), increased yields (Macauba) or avoiding competition with food, either directly through the food and feed markets, or indirectly through the displacement of food crops. Whether the farming of these new crops can offer improved sustainability without competing with existing crops is still a major area for investigation as production is scaled up. For example reaching high yields with Jatropha may require more water than previously reported ([27],[32]). In addition many of these new crops have only been farmed on a small scale; they are not yet well known nor optimised as food crops have been for more than a thousand years. Their economical viability and environmental credentials could also depend on the valorisation of their coproducts (for example Jatropha toxic residues). As dedicated crops, they however offer the potential for specific optimisation for fuel production.

Another area of significant research is the use of algae for oil production and substantial effort is currently being made to achieve industrial scale algae production. This is primarily as its yield could be between 20 and 100 times greater per hectare per year than land based crops such as rapeseed. Algae can either be produced directly from sunlight, or grown from sugar plant products. In the latter case it has substantially higher yields, but requires a feedstock itself. Actual yields and mass production still have to be demonstrated while harvesting and processing also require research and development.

As discussed in section 4, biofuels can also be produced from lignocellulose, which is the major component of cell walls, through Fischer-Tropsch process and in the future through biomass liquefaction or enzymatic pathways. This opens the way to a wider range of feedstock including trees, short rotation coppices, perennial grasses (Switchgrass and Miscanthus which are well adapted to temperate latitudes, being the geographic regions between the tropics and the polar circles) but also agricultural co-products and waste such as straw or harvest residues. The use of agricultural or forest waste should nevertheless be considered carefully. Studies have evaluated that no more than 33% of agricultural waste could be used in a sustainable manner [28,29], the remainder being required to maintain soil fertility (similarly for forest residues). Collection and transportation of the residues are also great issues which restrict their use to their locality, particularly if efforts are made to reduce the overall environmental impact of their use. At the same time, the technology required to convert these feedstocks is characterised by significant economies of scale. Logistics and conversion thus work against each other.

A final source of feedstock could be municipal solid waste. However, the potential of this source is difficult to assess as it depends strongly upon assumptions about economic development and consumption of materials, with some issues related to high variability of these materials and also health hazards [18].

The selection of a sustainable feedstock should encompass global fuel production capability, covering different aspects such as land availability for farming, agricultural and feedstock yields, and the efficiency of the conversion process. The RES Directive implies that the EU will not be self-sufficient if plant oil is uses as a feedstock as insufficient land area is available and the most productive oil plants are tropical [28].

Biofuels represented about 1% of total road transport fuel consumption in 2005 [30]. Achieving a higher percentage for biofuels would require developing biomass production whilst also meeting the growing demand for food and feed, in particular the increasing consumption of animal protein in developing countries (the ratio of raw vegetable material to produce one ton of animal product is generally high).

Various studies have evaluated the land area that could be made available for biomass and hence biofuel production capability. Potential improvement through agricultural efficiency should nevertheless also be kept in mind. In particular, Sub Saharan Africa, South America and ex USSR zones offer the potential for expansion of farming not only in terms of new agricultural land availability but also in terms of potential yields increase, values from these lands being currently very low. Many studies assume that most of the increasing food demand for cereals and oilseeds will be met by an increase in agricultural productivity, which has been the case since 1970. This continuous improvement is however not considered as sufficient to face the biofuel demand growth which is anticipated to be significantly higher than the traditional rate of increase of demands and yields [31].

Forecasts of new available land for agriculture depend on scenarios, particularly the use of pastures and meadows. From FAO data, Sub Saharan Africa and South America have 830 and 320 million hectares of potential arable land[v] for seasonal crops without the use of existing forest lands. Use of these lands would represent an 80% increase in global arable land that is presently around 1.4 Gha (in comparison between 1974 and 2004, the annual rate of increase of arable land was 1.7% [32]). Other studies calculate between 250 and 440 million hectares of additional land for agriculture could be used [33,28], considering for example an increase in grassland in answer to diet preference trends towards more animal products.

There are also uncertainties about the capabilities to actually make use of these lands. In any case, about 80% of the available land is split between Africa and Central and South America while the growth potential is limited in Europe. The use of marginal land is not accounted for in these figures and may provide an additional production capability with specific crops. Further, some studies predict that by 2030, the demand for land will be much greater than the amount of land remaining [33]. This will result in an increase in pressure on the world's forests as a result. However, the destructive expansion of palm oil plantations into forests of East Asia, which took place between 1990 and 2005 destroyed large parts of a diverse ecosystem [34] and demonstrates the environmental risks of this approach. The experiences gained from the expansion of palm oil illustrate the need for criteria for the required forest area and the preservation of biodiversity, criteria that are not presently well established.

There are also large discrepancies reported in the primary energy potentially available from biomass on these additional lands, with projections varying from 54 GJ/ha/y to 330 GJ/ha/y in 2050 [28]. More generally, the reported total potential primary energy available from biomass

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[v] Arable land is defined as the difference between agricultural area and permanent crops, meadows and pastures – agricultural area being land area minus forests and other lands.

exhibits a wide range from 100 to 1500 EJ/y[vi] for 2050 when combining all the hypothesis on land use, types of biomass used, yields etc [29]. A more reasonable estimation seems to be between 200 and 500 EJ/y by 2050 by which time the world energy demand would be between 600 and 1040 EJ/y[vii].

The part of this biomass primary energy that can be actually used depends on the conversion efficiency and, ultimately, also from the sharing between the various use of biomass (energy production, chemistry,…). This illustrates the number of uncertainties in estimating the potential global production of biofuels. With the assumption of half of the biomass to be dedicated to biofuels, 440 Mha of new land available, an intermediate value of primary energy from biomass of 190 GJ/Ha/y and a conversion efficiency of 35% (sugarcane to ethanol), Doornbosch & Steenblik estimate that biofuels could cover 23% of world liquid fuel demand in 2050 [28].

Up to now, the need for security of supply has dominated the development of alternative liquid fuels for aviation. Currently, rises in the price of oil and security of supply issues mean the uptake of CtL and GtL has become profitable. This is illustrated by the expansion in this sector though the CtL production pathways described above have been shown to consume more energy than conventional refining whereas GtL pathways are, within the limits of estimation, equivalent to crude oil. As with conventional crudes, the GtL and CtL pathways also result in the releasing into the atmosphere large quantities of green house gases [35].

In terms of energy content, the world estimated coal reserves amount to about 2.7 times the oil reserve. In addition their geographic distribution is significantly different from oil with large reserves in United States (29%) and China and India (21%) whereas these countries have less than 8% of the oil reserve. The European Union amounts for about 5% of the world coal reserve and 1.5% of the oil reserves. Based on this figures, CtL appears clearly as a security of supply fuel.

Natural gas reserves are presently estimated around 180 $tm^3$ which in term of energy content is a bit lower than oil reserves. 56% of the reserves are concentrates in three countries, Russia, Iran and Qatar, while just 25 fields over the world hold almost 50%. According to IEA, these reserves correspond to around 60 years of current production.

# 6. Sustainability issues: environmental and societal impacts

Sustainability has three dimensions: the environment, the society, and the economy. The later is addressed in section 8 and we focus here on the first two aspects.

Various initiatives, such as the SAFUG[viii], RSB[ix] or RSPO[x], along with the European Directive on Renewable Energy Sources (RES) have contributed to the definition of sustainability criteria. They result in a list of impact categories that can be grouped in a set of six sustainability criteria: emissions, biodiversity, resources use (water, energy, soil and waste), competition with food, socio-economic criteria (such as impact on economy, rural development, etc.) and uncertainties related to feedstocks and technologies. The RES Directive provides quantified objectives for Green House Gas (GHG) emission, that should be at least 35% lower for biofuels than for

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[vi] 1 EJ = $10^{18}$ J

[vii] It's interesting to note that [29] estimates that the demand for energy from biomass will be lower than the possible supply estimates due to competition with other energy sources that could be more attractive if the cost of biomass increases.

[viii] Sustainable Aviation Fuel User Group

[ix] Round Table for Sustainable Biofuels

[x] Round Table for Sustainable Palm Oil

petroleum fuels, and prohibits the use of raw materials obtained from land with recognized high biodiversity value or high carbon stock.

Behind many of these criteria is the issue of land use change which should be considered from a global point of view since it may be direct or indirect. Indeed, the allocation of existing agricultural lands to biofuels crops may induce transformation of pastures or forests elsewhere to food crops, or the transformation of forest in grasslands.

Life Cycle Assessment appears as the right methodology to account for the global emissions associated with any energy source (LCA will be addressed in next section).

Impacts on biodiversity are clearly illustrated by examples such as the deforestation of regions like the Amazon, whose rainforests are home to a large variety of flora and fauna species. In the events of grassland conversion to crops production, a loss of biodiversity would also occur since the grasslands had dozens of varieties of plants, while the cropland is usually limited to very few. Agricultural practices may also endanger the remaining flora and fauna. Biodiversity decline is now the object of two United Nations Conventions (Biological Diversity and Climate Change), and is a priority of European Union, but is not easy to define and measure. Efforts tend to define several complementary indicators to monitor human impact and forecast future developments. However, results may conflict between the various indicators. The final impact of biofuels on biodiversity may depend on the long term positive effect of reduced future climate change and the short-term negative effect of land use change, climate evolution being also a potential threat for the extinction of species [29]. Loss of biodiversity can also be linked to a reduced number of crops species [31]. Raw materials for biofuels are often based on a unique species which induces a limited genetic diversity with a consequence for its resistance to new pests and nuisances. Concerning lignocellulosic feedstock, special attention should be paid to the invasive character of some variety such as Miscanthus.

The food versus fuel debate has grown with the strong increase of food products price in 2008. The debate centres on the idea that biofuels are competing with food for valuable arable land, reducing the amount of land available to grow food and driving up food prices. There is some controversy over the exact reasons for the food price hikes. Although there is general agreement that biofuels do contribute to this increase, there is considerable disagreement over the magnitude of the effect because many factors are involved. For example the strong economic growth in China causing increase in demand for food (milk, meat, etc.) or the price of oil (which affects farmers costs as well as transportation of the food). With international crisis, food prices dropped again but FAO considers that biofuels will continue to push them up. It's worth noting also that high agricultural prices have in reverse an impact on biofuels competitiveness and could limit their development.

Biofuels can also compete with traditional cultivation through access to water resources. FAO estimates that the scarcity of water could be in many cases the limitation for biofuels production rather than the availability of land [31]. Already 70% of the consumed fresh water is dedicated to agriculture, competing with industrial and domestic use. Obviously, the situation depends heavily on local conditions but the climate change could also add pressure in certain areas. Furthermore, aspects, such as water pollution due to fertilizer run-off or pesticides use, should not be ignored.

In the short-term, the price increase of agricultural products should have a negative impact on countries that import their food and on the poorest part of the population. In the longer term, high agricultural prices could in contrast, favour rural development in developing countries. Production of raw materials for biofuels could also provide revenue sources to these countries. As many developing countries lie in tropical zones, the climate conditions are often conducive to the growth of bioenergy crops. Local policy support may nevertheless be required to develop infrastructure, funding and legal systems.

Attention should also be paid to the sharing of the benefits from biofuel market. Agriculture markets are often dominated by a small portion of the population and private investors may buy up large amounts of land in poor countries to grow products for their own markets, forcing small scale subsistence farmers into marginal land [36].If the feedstock is processed into an added value product within the country of origin, this may be also beneficial for the producing country as it may create jobs and infrastructure [37], and also reduce energy dependence of poor countries.

# 7. Life cycle analysis

Currently only a few studies have considered the green house gas effects of $CO_2$ throughout the life cycle of aviation fuel [35,38]. As with all such studies, many assumptions are made so that emissions from integrated production cycles can be accounted for in single product streams. Accounting for whole life cycle GHG emissions is of increasing importance, as there is a strong will at the world scale, and in particular at European level to set minimum targets for GHG reduction associated to the use of alternative fuels in general, and of biomass-based fuels in particular. The recent EU Directive on the use of renewable energies [11] sets such a minimum target at 35% GHG emission reduction compared to fossil-based fuels and gives default values for GHG balances of ground transportation fuels, based on LCA calculation.

For aviation, emissions take place both on the ground and at altitude. Given the dispersive properties of the atmosphere in the corresponding altitude range, $CO_2$ emissions will not accumulate in the upper troposphere and can be considered as simply additive to the other sources from ground emissions. The other carbon emissions from aircraft are carbon monoxide CO, and the soot particles which have specific effects. CO is an ozone precursor in a NOx rich atmosphere and soot particles can trigger the formation of high altitude clouds, first in form of contrails that eventually form long-lived cirrus-like clouds if the atmosphere is supersaturated with respect to ice. Both effects contribute to the global warming by modifying the radiative balance of the atmosphere. Exactly how this should be evaluated as part of life cycle analyses is still under debate and is one of the areas which require further investigation.

In general terms, the “security of supply” fuels have the same (in the case of some GtL) or greater (in the case of CtL and oil sands) Green House Gas (GHG) emissions than conventional crude, and those related to bio derived fuels can be smaller. However, the emissions associated with bio derived fuels depend heavily on the feedstock used and whether the use of that source requires or leads to a change in land usage. Indirect effects and knock-on effects have also to be taken into account, but are more difficult to assess: accounting for such effects implies having an idea of the consequences of the conversion of land into cultivation dedicated to biofuel production on agricultural products markets and other agricultural soils. Also due to the differences in Technology Readiness Levels (TRLs)[xi], the uncertainties of the effects of bio derived aviation fuels are significantly larger.

Currently, life cycle analyses for algae based pathways present a wide range of uncertainty, reflecting the technological maturity of the feedstock. However, available data suggests that the best pathway based on terrestrial biomass (lignocellulose) has a better GHG assessment than algae based bio fuels [39].

Ideally, jet fuel LCA studies should consider other environmental impacts beyond GHGs, such as the EU RENEW project which has considered life cycle analyses of various BtL pathways for the automotive industries [40]. Any full life cycle analysis should also address other emissions that impact upon local air quality around the airport environment and can indirectly impact on climate change. Guidance for such LCAs is given by the European LCA methodology [41].

The results of those studies that also consider the water consumption in producing an alternative fuel highlight the need for a life cycle analysis to have a specific production route in mind. Some

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[xi] The Technology Readiness Level is a systematic metric from 1 to 9 indicating the level of maturity of a particular technology and allows the consistent comparison of maturity between different types of technology. Broadly, these phases of development can be categorised as: 1-4 laboratory and early development, 5-7 mid and full scale testing at prototype level, 8-9 demonstration and commercial application.

feedstocks will perform in certain zones of the globe, and water consumption is a considered a local problem related to feedstock production.

# 8. Economical sustainability

"Security of supply" petroleum products[xii] are starting to appear on the jet fuel market, and it is anticipated that this will continue throughout the mid term and beyond. It is still unclear whether environmentally sustainable products will see a similar level of investment.

The volatility in the price of petroleum oil has been part of the initiating factors in the development of "security of supply" fuels, and it is likely that environmentally sustainable fuels will not enter the market at a large scale until they are cheaper to produce than fossil derived fuels. For wood based BtL this price has been put at US$60/barrel [42], however this is almost certainly too low. At present it is difficult to be accurate about the long term crude equivalence of a mature BtL market.

As with conventional fuels, if a "sustainable" alternative fuel is available and in sufficient quantities, the aviation sector will have to compete with other transportation modes and/or sectors to secure this supply. Economics, in terms of the opportunity costs will most certainly prevail, meaning that biofuels will be used in the sector providing the best returns, which at the present time is the diesel / gasoline market. All future forecasts predict this dominance to continue at least beyond 2030 and the majority of alternative liquid fuels plants in existence or in the approval or build phases are to focus on the production of diesel for the automotive market. It is anticipated that aviation kerosene replacement fuels would catch a maximum of 15% of produced alternative fuels.

Typically there are four stages of development: laboratory scale, pilot plant, demonstration plant and commercial plant. A refining industry "rule of thumb" estimate on completion of the first three stages is around US$100M independently from the details of the pathway.

Many of the candidate fuels presented in section 4 are at a very low level of technological maturity and it is difficult for this reason to attribute a production cost at a suitable quantity of barrels per day to be economically sustainable. There are however, an increasing number of production scale plants coming online which provide an indication of the level of investment required to produce a liquid fuel from a non conventional source. To give examples, Sasol/Chevron GtL plant in Nigeria is estimated around 2000 M$ for a future production of 34 000 bbl/day and Choren investment in Germany is about 180 M€ to produce 4000 bbl/day of BtL.

With the current economic downturn, many of the planned GtL plants have been put on hold and it is more likely that production up to 2020 will only increase to 245 000 bbl/day total product. The CtL plants planned for future also have been put on hold and no further development is currently approved.

The production targets for the foreseen plants are significantly lower than those seen for conventional refineries and point towards the alternative liquid fuels market being far more decentralised than the existing crude oil based distribution system. Due to the lower feedstock energy density, the weight and volume of the feedstock supply is likely to be significantly larger than conventional crude oil. This will effectively limit the size of production at any plant because of the impact (economical, societal and environmental) of transporting increasing quantities of feedstock to the plant.

On a purely economic basis however, in a review of BtL plant sizing, Boerrigter calculates that the optimal size for a BtL plant is governed by the operational costs of converting the feedstock to a liquid fuel. The cost of transporting the low energy density feedstock is significant but increases more slowly than the cost of conversion process as the plant is scaled up, assuming the

[xii] A Security of Supply product increases the jet fuel supply diversity for a particular locality and hence lowers the unit cost of the fuel

feedstock is transported solely by road [42]. It should therefore come as no surprise that the two large scale hydrotreating facilities proposed by Neste (Singapore and Rotterdam) are sited near the worlds biggest harbours as the supply of sufficient feedstock represents a significant logistical challenge. From a general point of view, the scaling up of a production process should result in reductions in price per barrel of fuel produced.

There is a significant trade-off between pathways and feedstock. The choice for a prospective manufacturer is to either create a relatively cheap plant but with 85% of final product cost determined by feedstock acquired on an open market that is easily driven short of supply (HO), or a more omnivorous process such as BtL with cheap feedstock or even waste but a much higher initial capital investment that will need to be recovered in future product sales.

One of the key findings of the State of the Art study work is the disparity between the expected timescale for the maturity of sustainable, low carbon fuels and the current activity in the field. Certainly, biofuels alone will not allow meeting the aspirational targets set by IATA and others. If the industry is to produce 225billion litres of low carbon fuel by 2030 in order to meet IATA's zero carbon sector growth targets, 225 plants of a similar scale to the Neste plants presently under construction must be on stream by 2030, or 10 plants a year from 2010 which is close to one every month. At current prices (500M€ per plant) this equates to an investment of 1.1trillion Euros in the next 20 years assuming 100% of the product of the plant be reserved for aviation.

Importantly, the majority of the "security of supply" and environmentally sustainable products produced today, and planned for the near term will be destined for the automotive market. The share of aviation of these greener fuels will be of a similar order of magnitude to substantially less than the current cut of crude oil for aviation. If the renewable energy contribution is to be expanded for aviation it will be necessary to put in place specific measures to make bio derived fuel production profitable. One such measure is the European Emissions Trading Scheme (ETS). The ETS aims to facilitate investments of aircraft operators in energy efficiency and emissions saving technology whereas previously there was no economic argument for doing so.

# 9. Alternative Technologies

Considering the readiness of revolutionary technologies, infrastructure, and economics, the dominance gas turbine engines consuming conventional aviation fuels will be likely to persist for the next couple of decades. However, alternative sources of energy could be introduced on board aircraft in a general effort to reduce aviation fuel demand. This is encompassed within the more electric aircraft (MEA) concept and is the next technology improvement. The more electric aircraft concept is anticipated to reduce the design complexity and weight of aircraft. This will increase the environmental benefits whilst reducing the liquid fuel consumption but demanding more on board energy production.

For the alternative systems, different combinations of energy sources are possible: power generation, conversion, or storage.

From the energy storage point of view, Li-ion technology represents the highest-energy-density battery, which means it offers the greatest development potential for future aircraft applications. Seeing the trend towards MEA in the future, the potential of fuel cell systems compared to conventional APUs or engine power extraction should be further investigated. Fuel cell technology is at a lower level of maturity than batteries, however demonstration flights have taken place with Fuel cell APU substitutes [43].An environmental impact analysis should be based on scenarios which define the production path of hydrogen and a model flight profile. The other systems of energy storage and generation should be considered against the background of shortcomings of these key systems e.g. storage systems for peak shaving.

Further evaluation of the interest of these alternative sources of energy will be performed during the SWAFEA study.

# 10. Conclusion

Current concern regarding climate change clearly demands the introduction of more renewable energy as targeted by the European Directive for Renewable Energy [11]. Due to its position at the leading edge of technological innovation, commercial aviation should also be considered as a contributor to the reduction of $CO_2$ emission which can be obtained through the introduction of alternatives fuels, along with reductions in airframe weight, engine improvements and the move towards more electric aircraft.

As the life times of aircraft brought into service in 2009 are into the mid term of 2030 and beyond, and considering the considerable investment in air transport infrastructure, effort towards alternative fuels is mostly targeted toward potential "drop-in" fuels fitting to conventional jet fuel aviation requirements as expressed by the specifications and approval processes.

Among candidate alternative fuels, a number are already seen as "drop-in" or potential "drop-in", the first families of which are reaching the final stages of approval as blends with conventional jet fuel. Beyond present approvals, further investigation and characterisation are still needed to introduce neat alternative fuels and to assess new pathways that are still being developed and could bring economical and environmental benefits.

A potential reduction in CO2 emissions is anticipated through the use of biofuels in jet fuel. A wide number of feedstocks can be used to produce these families of fuels, the various processes sharing in many cases the same type of raw materials. Most these feedstocks are presently produced from traditional agricultural crops. However there is currently a trend to develop new energy crops that could provide higher yields or allow exploitation of additional or marginal land. In the process also, the trend is to use a larger part of the plant and in particular lignocellulose, allowing making use of agricultural waste. In contrast to conventional agriculture, the use of algae derived fuels offers higher yields although this work is still very much at the research stage.

The ability of the biofuel production capacity to meet the total energy demand relies on numerous factors which remain uncertain at the present time. From a purely technical viewpoint, it seems that biomass can not be produced in sufficient quantities to satisfy the total energy demand in 2050. Practically however, the demand and supply of biofuel depends also on economical factors, biomass being in competition with other sources for energy production. Most of the projections do not forecast more than 20 to 30% of biofuels in transportation, including aviation, in 2050.

Many sustainability issues need to be incorporated into any analysis of this future production capacity and the identification of a production pathway meeting the sustainability criteria. First, existing Life Cycle Assessment results show large difference on Green House Gas emission depending on the processed biomass and on the conditions in which it has been produced. In particular land use change induced by the growing of the crops may have dramatic impacts on global GHG emissions for the fuel pathway. Land use change has also a direct impact on biodiversity and competition with food. Water use and pollution problems together with soil preservation are also important concerns and potential limitations for biomass energy production. All theses sustainability aspects are closely linked to local situations and conditions which restricts hopes for a single global solution. It is anticpated that different optimum feedstocks and production pathways will be suitable for different locations and conditions.

Economically, the most important considerations are the future production cost of biofuels and the large investments required to reach a significant production. Meeting IATA aspirational targets for zero carbon growth by 2020 will require much higher investments than the one presently going on in alternative fuels. Biomass production should also develop in parallel. For both processing and feedstock production, the scale up from lab and pilot to industrialised scale is a challenge, especially for low maturity pathways.

These problems are for most of them shared with other energy production from biomass. But due to its small share of the fuel market and of the additional cost of producing aviation fuels, aviation will face a specific difficulty in accessing the biofuels market which is likely to be dominated by automotive industry.

From this state of the art, directions of work for further assessment of alternative fuels in aviation can be outlined:

- Emerging new pathways that could provide economical and environmental benefits for the deployment of alternative fuels should be further investigated;
- LCA studies need to be complemented in particular for new pathways and also to integrate other impacts than GHG emissions – specifics of aviation with regard to atmospheric impact also need to be included;
- Availability of biomass and sustainability of alternative fuels production requires further analysis and various potential impacts of fuel production should be investigated though no global answer could be expected concerning sustainability;
- The business case of alternative fuels should be carefully analysed as a critical parameter of their deployment in order to identify the required implementation strategies and derive the various policy measures that could support this deployment.

The road to alternative fuels in aviation has now be opened with the first fuels approval but deployment remains a great challenge.

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