Sustainable Way for Alternative Fuels and Energy in Aviation

Final Report

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PREAMBLE

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This final report of the SWAFEA study makes the synthesis of a wide scope of analyses performed on different topics related to alternative fuels introduction in aviation by a team of 20 members of a consortium gathering different skills and backgrounds from industry, airlines and research.

Considerable efforts have been made to assure the quality of the information contained in this publication. However, neither ONERA nor any company participating in the SWAFEA study can accept liability for any loss, damage or injury whatsoever that would be alleged to result from any use of this synthesis and/or information.

The report represents a collective work and a general agreement on the high level conclusions derived from the outcomes of the parallel works carried out by different organizations or corporations in the frame of the study. As such, it does not engage the individual responsibility of each of these organizations and corporations on any and all the topics covered by the study.

The contents or any views expressed herein have not been adopted or in any way approved by the European Commission and should not be relied upon as a statement of the Commission's or DG Mobility and Transport's views.

Summary

Introduction

In February 2009, the European Commission's Directorate General for Energy and Transport initiated the SWAFEA study to investigate the feasibility and the impact of the use of alternative fuels in aviation. The goal is to provide the European Commission with information and decision elements to support its future air transport policy, in the frame of the European commitment to promote renewable energy for the mitigation of climate change, security of supply and also to contribute to Europe's competitiveness and economic growth.

The current report provides a synthesis of the results of the study and proposes an outlook with recommendations for further development of alternative fuels in aviation.

Context

The reduction of greenhouse gas (GHG) emissions has emerged as a major driver for the introduction of alternative fuels in aviation. Continuous air traffic growth, with its related increase in GHG emissions, has led to the consideration of the contribution of aviation to the 10% target of renewable energy in transport set by the Renewable Energy Directive (RED) for 2020. Furthermore, integration of aviation in the Emission Trading Scheme (ETS) in 2012 will be an incentive for the introduction of fuels with reduced carbon footprint. The aviation community itself has also called for a reduction of the sector emissions with the aviation industry targets to cap the emissions at their 2020 level and further to halve the emissions level in 2050 compared to 2005[1].

At the same time, increasing prices of crude oil and their high volatility are having a critical impact on airline profitability. Fuel has become their first source of expense (representing up to 30% of direct operating costs) with unpredictable, large fluctuations that are difficult to manage. In the longer term, security of supply is an issue for a sector which today fully depends on liquid hydrocarbon fuel.

Compared to other transport modes, the introduction of alternative fuels in aviation requires careful consideration due to the particular requirements of aviation fuels (low temperature properties, high energy content, etc.) that exclude the use of the fuels currently deployed for road transport. In addition, aviation fuels need to be approved to international standards by all stakeholders before being deployed.

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[1] Emissions capping at 2020 level may be obtained initially through economical measures. This target has been taken over in Resolution 17/2 of the ICAO 2010 Assembly.

Candidate alternative fuels for aviation

The field of alternative fuels is moving fast. As the SWAFEA study was progressing, the landscape of alternative fuels in aviation has significantly evolved with the approval by ASTM[2] of the first alternative fuels for aviation, the Fischer-Tropsch synthetic paraffinic kerosenes (FT-SPK). These FT-SPKs can be made from coal (CTL), gas (GTL) or biomass (BTL), all of which are now approved for commercial use in blending ratio up to 50% with Jet A-1. Hydroprocessed oils (HO), producing synthetic paraffinic kerosene from plant oils or animal fats, which are often referred as Hydroprocessed Renewable Jet (HRJ)[3], are presently following the same track and have already undergone numerous flight demonstrations. These fuels are said to be "drop-in" since they are fully compatible with today's aircraft engines and fuel systems as well as with the current fuel supply infrastructure, and can be blended with conventional Jet A-1. Fischer-Tropsch fuels are already at the production stage from coal and gas but still at demonstration stage from biomass. Hydroprocessing of oil is a mature process but limited production capacity today exists (mainly targeted towards diesel fuel).

A first purpose in SWAFEA has been to identify further needs beyond the on-going approval of these emerging solutions and to consolidate the knowledge about their impacts for aviation. Further, the focus was to identify additional fuel production pathways and fuel types that could be of interest for further research and development for aviation.

Drop-in fuels are the only current candidates for aviation: any perceived production cost advantages of non-drop-in fuels do not stack up against costly incompatibilities with the current equipment and infrastructure. In the short term, the focus is to increase the use of blend stocks which copy the molecules already present in conventional fuels. These include at the present time the Synthetic Parafinic Kerosene (SPK) obtained from Fischer-Tropsch process and oils hydroprocessing, and in the very near future may include synthetic aromatics.

The analysis shows that, even though a reduced content in aromatics is favourable for engines particulate emissions, using pure SPK (that are aromatics free) may result to incompatibility with seals[4] on current aircrafts and to operational problems because of the low density of SPK[5]. From the work performed within SWAFEA, synthetic aromatics (liquefaction/pyrolysis etc) are a viable blend stock. However, further study is needed in order to demonstrate the principle.

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[2] Formerly known as the American Society for Testing and Materials, ASTM is today an international organisation in the development and delivery of international voluntary consensus standards (www.astm.org)

[3] Recently the designation HEFA (Hydrotreated Esters and Fatty Acids was also introduced by ASTM

[4] Seals in the fuel systems of current aircrafts need a certain aromatic content to prevent leakage

[5] The density of SPK is below jet fuel specification. Although the energy content per unit of mass is slightly higher than in Jet A-1, this results in a reduced volumetric energy content that decreases the energy contained in the tank, which is an issue for flights at maximum aircraft range requiring the maximum energy content.

On the other hand, the SWAFEA study evidenced the economic interest in an initial period, during which biofuel availability will be limited, to consider a low incorporation in Jet A-1 of SPK with higher freezing point than those currently approved (while keeping the blend freezing point specification unchanged). Increasing the freezing point decreases the level of processing of the SPK which induces higher yields[6] and a better profitability.

Another point evidenced for these short term SPK solutions is that the increased use of SPK based blends will change the fuel average properties compared to the current Jet A-1 even if current specification limits remain. Future studies should thus examine the longer term implications of such changes on engine certification, performance, maintenance and cost of ownership.

Work also demonstrated that oxygenated molecules such as fatty acid esters present significant challenges and are not viable in the near to mid-term.

Due to their novelty, the sugar derived hydrocarbon routes could not be assessed within SWAFEA. Following recent announcements and the progress made by US biofuel start-ups such as Virent, Amyris and Gevo whose fuels are now considered by ASTM, these pathways are certainly to be included in future studies.

With a view to the introduction of new fuels beyond the current Fischer-Tropsch and HRJ SPK, the consensus-driven ASTM approval process and the ASTM and DEF-STAN[7] specification controls appear suitable and robust and the report recommends their continued adoption.

The importance of the implementation of a rigorous quality control is also underlined as the introduction of totally new fuels will induce a new supply chain involving a probably larger number of actors with new comers that are not used to aviation requirements.

Life cycle of alternative fuels

Biofuels have the potential to significantly reduce greenhouse gas emissions.

Mitigating greenhouse gas emissions through the use of alternative fuel needs a careful evaluation of the emissions produced through their entire life cycle ("Well or Field to Wake"). Indeed, if combustion emissions are neutral for biofuel since it is biomass carbon, the production and distribution of the fuel induces GHG emissions.

With view to the climate change mitigation target, CTL and GTL, which are fossil fuels, have no potential for reducing greenhouse gas emission and generally even increase these emissions (in particular CTL). High efficiency carbon capture and sequestration is in any case required to contain the emissions induced by CTL or GTL production. These processes are also feedstock intensive.

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[6] kg of total liquid product vs. Kg of feedstock

[7] DEFSTAN 91-91 has issued its 7th edition which incorporates the generic FT approval but also additional guidance on traceability.

However, these technologies are today mature and deployed at industrial scale (South Africa, Malaysia and Qatar) and they allow a diversification of the fuel supply to cope with an increasing demand. They also present the same atmospheric advantages as BTL and HRJ due to the lower particulates emissions induced by SPK use. The market may naturally push for the emergence of these fuels with increasing prices of crude oil or concerns about crude oil scarcity.

From the climate change point of view, the recommendation is thus to focus on biofuels which have the potential to significantly reduce life cycle GHG emissions especially in case of BTL. For HRJ, the ability to reach the RED's reduction threshold of 60% compared to kerosene will require a careful choice of crops and an optimisation of the cultivation step. In any case, critical attention will have to be paid to land use change for the cultivation of energy crops as it is potentially the dominating effect in the whole emissions chain.

A major issue is the assessment of indirect land use change (iLUC) for which today no methodology or certification approach exists. There is thus an urgent need for methodological studies on the way to address iLUC and on suitable policy measures to control it.

Finally, aviation being a global activity and aviation fuel a global commodity, there would be a strong benefit from an alignment on a globally recognised methodology for Life Cycle Analysis in order to avoid the necessity of multiple assessments and certifications of the fuels. This would also provide a clear view of the ability of a given fuel to comply with the existing national or regional regulations

Feedstock and sustainability issues

Availability of large quantities of sustainable biomass may be the main bottleneck to reach industry targets. For biofuels, availability of feedstock and the related possible environmental and societal impacts are key issues.

From the assessment performed within SWAFEA, it was concluded that, with the current transformation processes (Fischer-Tropsch and oils hydroprocessing), an excessive fraction of the traditional biomass (from agriculture and forestry) possibly produced in 2050 would be required in order to achieve the aviation industry target of halving emissions in 2050 compared to 2005.. Radically more efficient biomass or processes and also revolutionary aircraft technologies would be necessary to meet this goal.

The target of stabilising emissions at their level of 2020 before 2050 ("carbon neutral growth") appears as more feasible without considering very radical innovation. Such a target is already demanding but preserves biomass availability for other applications rather than transport.

If this target is technically possible, it is underlined that it requires a significant effort and investment in agriculture, cultivating a large amount of lands not cultivated today, the availability of fertilizers and of manpower. Indeed agriculture appears as the main potential source of biomass. From the yield increase technical point of view, meeting the demand for biomass seems feasible by 2050. However there is a significant challenge to achieve the foreseen development of the production in the next 40 years. Reaching a carbon neutral growth at 2020 emissions level from 2030[8] would for example request a rate of increase of the biomass production between 2020 and 2030 that appears extremely hard to achieve. This means that achieving carbon-neutral growth at 2020 levels will depend on economic measures beyond 2030.

Looking at the limitation of traditional biomass with regard to emissions reductions targets, developing additional source of biomass is an important axis for biofuel deployment. Algae appears as a particularly interesting candidate since they promise higher yields than terrestrial crops and have modest requirements on land quality, avoiding a direct competition with food. Research is nevertheless required before confirming the potential of algae, the main research challenges being to confirm at large scale the high performances obtained in laboratory or pilots, and to reach competitive production costs for energy production. To maximise their performance, algae also call for a high integration of the process and the development of synergies with other application (for example for sourcing the required CO_2 and nutrients) and co-products. The co-production of high value biomass is essential to support the commercialization of algae based fuels. The risk of proliferation of modified algae species with improved resistance and productivity may also be a major issue. Last, there is a debate concerning whether algae fuel should be accounted as a biofuel or not when fossil carbon is used for algae culture[9]. The conclusion and the way combustion emissions are accounted for may have a significant impact on algae development.

Sustainability of the feedstock production is usually raised as a major concern for biofuel production. With the exception of competition with food, potential environmental and societal impacts don't appear to be intrinsic features of either biofuels or crops used to produce them. Risks are mostly relevant of agriculture management and development policy of the interested countries. The fact is that biofuels development may put additional pressure on existing trends linked to intensive agriculture development (deforestation, water demand, etc.). Concerning competition with food, the Food and Agriculture Organisation (FAO) opinion is that, at world scale, the net effect on food security in the short term is likely to be negative, mainly due to the impact of biofuels production on food price. In the longer term, positive effects could be obtained if biofuels production contributed to the general development of agriculture. This underlines the critical attention to be paid to agriculture development and feedstock production along with the development of biofuels.

Existing sustainability frameworks such as the RSB[10] catch most of the sustainability issues and are quite comprehensive. If efficiently and rigorously applied, these certification schemes should provide

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[8] Note that the high-level industry and ICAO goal to achieve carbon-neutral growth includes the possibility of economic measures (carbon trading and offsets). The scenario described here (carbon-neutral growth from 2030) refers to “physical” emissions and does not correspond strictly to industry and ICAO goal. In that sense the 2030 timeframe is not related to industry or ICAO goal.

[9] SWAFEA final conference - Toulouse, 9 & 10 February 2010.

[10] Round Table for Sustainable Biofuel, http://rsb.epfl.ch/

guardrails for the potential impacts of the development of biofuels, in aviation and other sectors. The main weakness of certification framework today is related to the handling of indirect effects (such as iLUC) that can be hardly addressed at the producer audit level. As with LCA, harmonisation of international regulations, for example at ICAO level, would probably facilitate the deployment of biofuels though it seems difficult to achieve.

Atmospheric impacts

Aviation emissions and the type of fuel used have an impact on atmospheric chemistry and on the radiative balance of the atmosphere beyond the CO_2 effect. For example, contrails formed by condensation of water vapour onto exhaust aerosols, including soot particles, may trigger the formation of induced cirrus clouds. Emissions of nitrogen oxides perturb the natural chemical cycles, lead to ozone production or destruction depending on latitude and altitude, and modify methane time of residence in the atmosphere. These indirect effects from burning fuel at cruise altitude provide further contributions to the greenhouse effect in addition to CO_2 emissions.

From literature data and from the tests performed within SWAFEA, the use of alternative fuels such as the 50% SPK blends with Jet A-1 leads to significant reduction in engine soot and SO_x emissions due to the reduced content of aromatics and sulphur. Other species are less affected and their emissions changes may depend on the combustion chamber technology (NO_x, CO, UHC) while the lower consumption associated to higher energy content of SPK is a factor for NO_x and CO_2 emissions reduction.

Primary and secondary particles as well as sulphur oxides emissions reduction in exhaust plumes should have a positive impact on local air quality. In addition, the simulations performed in SWAFEA show that the reduced soot concentrations may affect significantly contrails properties and possibly reduce their radiative impact in the atmosphere. Additional studies on alternative contrail formation mechanisms are clearly recommended as current conclusions on contrails remain preliminary.

A global simulation performed for a traffic forecast in 2026 with a 50% SPK blend with Jet A-1 show that global emissions changes may modify aviation produced ozone concentration (a reduction was obtained for the simulated fleet mainly due to NO_x decrease associated to fuel consumption reduction). This change is expected to remain modest, considering the limited influence of alternative fuel on NO_x, and below natural ozone variability. Additional experimental data on engines emissions with alternative fuels would be required to conduct additional simulations with an increased level of confidence.

Economics

Currently identified aircraft and engine technology improvements don't offer sufficient potential for achieving the aviation industry GHG emissions reduction target without biofuels use, but biofuels lack of competitiveness is a barrier to their deployment.

Under the assumption that only one fuel solution is used to meet European demand, approximately 80 HRJ production plants or approximately 300 BTL production plants would be required to halve emissions in 2050. Independently of the fuel solution, this indicates that a large and immediate technological and financial effort would be required to ramp up production capacity at sufficient pace to meet the set targets with alternative fuels.

The economic analysis shows that neither BTL nor HRJ solutions are initially cost competitive with conventional jet fuel (initial price is about 160% higher than jet A-1[11]). Specific measures are needed to enforce their deployment. In the longer term, their viability depends heavily on the possibility to secure "low price" feedstock supply.

HRJ exhibits the highest dependence on feedstock price and cost competitiveness in the medium to long term cannot be reached unless cheap and abundant sources of sustainable oils can be secured.

BTL is initially dominated by capital investment. With learning, the specific investment cost may drop and BTL fuels will eventually become cost competitive when a large number of plants have been built. Since the feedstock for BTL is comparably cheap and varied, cost improvements may be expected at the pace of technological development, giving BTL fuels a financial advantage in the medium and long term.

In the hypothesis that "cheap" feedstock supply could be secured, policy measures and incentives are required to initiate the deployment of biofuels.

Under the current open ETS system, in which biofuel use is free from emissions allowances need, and without further incentives to use biofuel, airlines would clearly buy carbon credits in the initial period and biofuel production would not start up. ETS systems are coupling the price of alternative fuels to non-fuel-related mitigation measures, thus initially setting a benchmark for the price for alternative fuels at the price of Jet A-1 plus the price of carbon. In the longer term, unless competition on the supply side emerges, there is a significant chance that prices for fuels remain pinned at this level, even if production cost for alternative fuels are dropping.

A quota mandate on aviation fuel suppliers, offers the higher certainty to deploy the biofuel production capacities necessary to reach the emissions reduction targets but raises the issue of the impact on fuel costs for airlines (and of the control of fuel prices, airlines being in a captive situation). As a reference, a simplified simulation assuming a benefit margin for fuel producers limited to 25% (as a proxy to more complex market mechanisms), shows that if a quota mandate of 5% was introduced in

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[11] For a Jet A-1 reference price of 550 €/ton.

2020, the increase of airlines fuel bill for the year 2020 would be in the order of 3% under the application of the current ETS system.

The production of biofuels for aviation is nevertheless also linked to the production of biofuels for other transport mode and in particular road transport but also maritime transport. Indeed, both for technical and economic reasons, it would not make sense with BTL and HRJ process to target only jet fuel production[12]. Conversely, producing only automotive fuel is both technically and economically possible. The profitability of biofuels in the other transport modes is thus an important parameter of the jet biofuel business case. The biofuels incorporation strategies for road transport and air transport are nevertheless different due to the available road transport lever of substantial duty and tax reductions. The existence of such lever is also likely to favour road transport in the access to biofuel, knowing in addition that aviation requirements induce higher production costs. A proper policy is thus required to secure aviation access to biofuels.

Other renewable sources of energy

The maximum theoretical potential for fuel savings with an alternative energy system is limited to 3% and determined by the reduced power (and/or bleed-air) off-take from the main engines. In practice this saving will be reduced by the extra mass of the new and main-engine-independent power system.

State-of-the-art secondary batteries as electric energy carriers are too heavy. Fuel cell using hydrogen may be a solution, in particular if combined with other functions of the aircraft, such as producing water in flight, which provide weight-saving synergies. Another group of options is the permanent operation of a highly-efficient internal combustion engine or fuel cell as “improved APU system” that complements or substitutes the electric energy and bleed air off-take from the main engines.

With fuel cell systems the main engine kerosene consumption can be reduced by 2 – 3%, and ground operations fuel efficiency can be improved by 1 – 4% of mission fuel, depending on the mission duration. Estimated net benefits are 0.7 – 3.5% total mission fuel saving.

As a conclusion, the potential for conventional kerosene savings in the main engines is possible but theoretically and practically very limited as presented here in the context of other renewable energy systems.

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[12] The targeted ratio affects the type of co-products and their potential value on the market. Increasing the ratio of jet fuel tends to increase the ratio of other co-products than diesel (light distillate and heavy compounds) the value of which is lower than the one of diesel. For BTL, a "reasonable" ratio is about 25 to 30%. For HRJ, the ratio can be 30% or 70%, but the choice of the highest ratio makes the valorisation of the co-products more difficult.

Conclusions and deployment outlook

Although the aviation sector has a good track record in reducing its environmental impact through efficiency gain[13], it is highly unlikely to reduce or even stabilise its emissions through this means alone.

Biofuels present a real potential for reducing GHG emissions, provided that the feedstock production step is well mastered. However, if at least BTL and HRJ pathways will be available in the short term to produce jet quality fuels, they face a lack of competitiveness with conventional jet fuel that is likely to hinder their development, even with the exemption of biofuels use from ETS. In addition, biomass availability and production development appear as the critical bottlenecks for biofuel ramp-up and for achieving emissions reductions targets.

Both biomass availability and economics evidence the need for more efficient processing pathways, with higher transformation yields and reduced costs, and for new sources of feedstocks. In that field, algae today appear as a promising axis of research. A higher economic efficiency is also expected from the sugar derived hydrocarbons pathways, the yields of which are nevertheless today still low. Emergence of these new solutions is likely to require about 10 years.

Contrary to other modes of transport, aviation has no other energy solution in view than liquid fuels and it is questionable for its long term development whether it would be socially accepted if aviation does not reduce its emissions. Biofuels provide a solution for aviation emissions reductions and also for the diversification of its fuel supply. Achieving significant reduction will nevertheless need time and a determined policy, meaning also that aviation will have to offset a part of its emissions beyond 2030. Initiatives have to be decided from now to start the process and generate the learning and technological progress which is required for a faster future deployment in order to achieve emissions reductions targets.

To initiate the start-up of production, it is suggested that defining minimum challenging but achievable goals for phased introduction into aviation towards a 2020 target is used to set policy measures. No single measure available today seems adapted to achieve the production target while ensuring a significant involvement of multiple stakeholders in biofuel production. Therefore a combination of measures will be required. In particular an overall field to wing strategic plan could be an efficient approach which would push for the emergences of a number of "end to end" projects addressing the complete production chain from feedstock to fuel. This is a way to reach the minimum production target while favouring technology development and diversity along with the development of sustainable energy biomass production. Means of funding that should include the possible use of revenue from ETS auction. To complement this, the potential of a quota mandate policy could be investigated, in a "push and pull" approach which guaranties that the deployment occurs and that may also offer possibilities to distribute the funding on a wider range of payers.

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[13] Including aircraft drag and mass reduction, engine technology and efficiency improvement, etc.

To support the deployment policy, the demonstration of the regular supply of an airport would be a helpful initiative to identify and assess in real situation all the practical issues induced by the introduction of new fuels. It would bring learning and solutions to pave the way for a future large deployment in European airports.

In any case, early deployment should definitely go with an intensification of the research on innovative processes and feedstocks, and should be considered in synergy with other sectors and in particular with the automotive industry.

Main recommendations

Economics and policy

- Define an initial moderate goal for biofuel in aviation by 2020 (defining the precise blending value, for example 2%, requires further analysis).
- Set-up an incentive policy encouraging "end to end" deployment projects, multiple actors' involvement and technology development and diversification. A public support to a number of "end to end" intermediate size demonstration projects through a combination of various financial tools (co-funding of investment through "private public partnerships", incentives to biomass and biofuel production) could be the way to promote such initial deployment. It should also be investigated whether it makes sense to possibly combine it with the introduction a limited quota mandate by 2020 in a "push and pull" approach.
- Propose to the Member States to invest part of the ETS auction revenues to support biofuels development in aviation.
- Promote harmonisation of policies, in particular for biofuel sustainability recognition, at ICAO level.
- Adapt ETS application to the specifics of aviation (report of biofuel use by airlines should be done on the basis of biofuel purchase rather than on the basis of the fuel burned in the aircraft).
- Improve stakeholders' awareness of the possibility for aviation biofuel to contribute to the 10% target of renewable energy in transports of the RED.
- Define a long term strategy for the production of biomass and use by the different end user sectors, including aviation.

Sustainability

- Consolidate the assessment of biomass availability for all type of resources (agriculture, forestry, waste, unexplored sources,…) and propose guidelines to help the selection of the most suitable biomass and cultivation practices at Europe’s regions scale.

- Harmonise sustainability requirements between the different European regulations and policies (possible introduction of the RED sustainability criteria in the ETS for biofuel to be credited of zero emissions).
- At international level (ICAO), propose the harmonisation or the alignment of the various LCA methodologies and a harmonisation of sustainability criteria in order to facilitate a worldwide certification of aviation fuel.
- Support research on methodological approach of indirect Land Use Change and associated policy measures.
- Investigate further the environmental and societal impacts and acceptance of intensive energy biomass production.

Research and Development

- Carry out research programs to improve yields of energy crops (plant breeding) which are still at an early stage compared to food crop.
- Demonstrate energy crops performances under controlled agricultural practices ensuring sustainability.
- Intensify research on algae with demonstration at significant scale and study of integrated projects.
- Intensify research on novel pathways (feedstock + processes) likely to produce drop-in fuels (in particular research effort in bio-chemistry and thermo-chemistry with view to the development of higher efficiency processes for SPK) and improve the understanding of fundamental aviation fuel requirements (further investigate the "drop-in" envelope of aviation fuels properties).
- Initiate a demonstration project for logistics and management of airport supply with biofuel.
- Conduct a project to evaluate long term impact of alternative fuel on aircraft engines and systems.
- Include alternative fuels in research programs on atmospheric impacts of aviation to more completely assess their impacts compared to conventional Jet A-1.

European Networking

- Set up a European network of excellence for alternative fuels in aviation to bring together technical expertise and provide an integrated approach to alternative aviation fuels including sustainability, regulatory aspects and economics.

- Beyond SWAFEA, establish a coordination structure for aviation biofuels development in close connexion with the existing European Biofuel Technology Platform. Such a coordination structure could be opened to international cooperation and international partners. It could contribute to the further definition and implementation of the Strategic Transport Technology Plan currently built by the European Commission.

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Glossary

- CTL: Coal To Liquid (synthetic liquid fuel produced from coal through Fischer-Tropsch process)
- ETS: Emission Trading Scheme
- GHG: Green House Gas
- GTL: Gas to Liquid (synthetic liquid fuel produced from gas through Fischer-Tropsch process)
- HO: Hydroprocessed Oil
- HRJ: Hydroprocessed Renewable Jet
- IATA: International Air Transport Association
- ICAO: International Civil Aviation Organisation
- iLUC: indirect Land Use Change
- Jet A-1: the conventional kerosene based fuel used for aviation
- LCA: Life Cycle Analysis
- LUC: Land Use Change
- RED: Renewable Energy Directive
- RSB: Round Table for Sustainable Biofuel
- SPK: Synthetic Paraffinic Kerosene (synthetic kerosene consisting only of paraffin, i.e of alkane chains)
- UHC: Unburned Hydrocarbons

1 Introduction

Commercial aviation is a global business of around 23,000 aircraft currently operating on a single fuel product which is presently sourced from fossil fuels, contributing around for 2 to 2.5% of global carbon emissions.

As with the road transport, the use of alternative fuels in the aviation sector has been considered in order to relieve the environmental, economic and political concerns that have grown concerning fossil fuels. The most pressing threat is probably the impact of fossil fuels combustion on climate change through the Green House Gas emissions and the long term human and economic consequences it implies. Sensitivity to atmospheric pollution with its impacts on health has also become more acute with the increase of road and air traffic and the development of large conurbations. At the same time, relative growth of the sector and the high volatility of oil prices has demonstrated critical impacts for airlines and in the longer term security of supply may become an issue.

In February 2009, the European Commission's Directorate General for Energy and Transport initiated the SWAFEA study to investigate the feasibility and the impact of the use of alternative fuels in aviation. The goal is to provide the European Commission with information and decision elements in order to support its future policy in the field of air transportation, in the frame of the general European commitment to promote renewable energy for the mitigation of climate change and also to contribute to Europe's competitiveness and economic growth. The study has thus developed a comparative analysis of different fuel and energy options on the basis of the present knowledge and proposes a possible vision and roadmap for their future deployment.

The various aspects of alternative fuels introduction in aviation have been addressed. A first focus was the technical analysis of the introduction of new fuels in aviation and the evaluation of the possible candidate fuels with respect to the aviation fuels requirements. Concurrently, the environmental and societal implications of going to non-conventional fuels, and in particular to biofuels, have been assessed in terms of resources availability, actual life cycle emissions and sustainability. Last the economics of the new fuels have been analysed in order to assess their viability and the most appropriate implementation strategies to promote their deployment.

The study has been carried out by a team of twenty partners representing stakeholders from the various links of the aviation fuel chain[14]. This team involves major European actors of the sector but also the leading Brazilian aircraft manufacturer and the International Air Transport Association.

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[14] The SWAFEA team gathers under the leadership of Onera: Altran, Bauhaus Luftfahrt, DLR, IFPEN, University of Sheffield, Airbus, AirFrance, Cerfacs, Concawe, DLO/Plant Research International (WUR), EADS-IW, Embraer, Erdyn, IATA, Ineris, Rolls-Royce plc, Rolls-Royce Deutschland Limited, Shell and Snecma

Exchanges were also organised with other initiatives such as the ALFA-BIRD program of the 7th European Framework Program[15], in which many SWAFEA partners are also involved, and the US CAAFI initiative[16]. Two "Stakeholders Conferences" and a final international conference have been held to exchange with the community, in order to enlarge the basis of information and to debate some of the major questions related to alternative fuels introduction in aviation[17].

The findings of the technical, environmental and economic analysis have been presented in dedicated reports. The purpose of the present synthesis report is to build on these thematic analysis and assemble the key results in order to answer the central question of the SWAFEA study which can be summarized as: "*What are the most promising alternative fuels for aviation (in terms of environmental, economic, and technical performance), and what does EU industry and science think would be an appropriate roadmap to provide a stimulus to the EU's competitiveness in this marketplace?*".

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[15] in the frame of the 7th Framework Program of the European Commission's Directorate General for Research, the ALFA-BIRD program investigate the development of alternative fuels for aviation with a long term perspective

[16] Commercial Aviation Alternative Fuel Initiative – www.caafi.org

[17] SWAFEA Stakeholders Conference: Brussels, April 2009 [1] and Munich, July 2010 [2].
SWAFEA Synthesis Conference – Toulouse, 9-10 February 2011 [3].

2 The alternative fuels issue in aviation

2.1 Context

A strong driver for alternative fuels in aviation is environment and climate change. It is associated in Europe with the commitments to take an active role in climate change mitigation by the promotion of secure, sustainable and competitive energy which contributes to the reduction of Green House Gas (GHG) emission together with reducing energy dependence, increasing security of supply and contributing to economic growth.

In 2007, the Renewable Energy Directive set a binding target of 20% in 2020 for renewable energy use in the Community. It also set a specific 10% target for transport. As far as biofuels are concerned, these targets come with additional requirements on the CO_2 emissions on a life cycle basis that should be at least 35 % less than for conventional fuels, and at least 60 % lower from 2018. The Directive also defines sustainability criteria these fuels should respect to be accounted for in the Directive application.

If aviation is today considered to represent only about 2 % of the world global emissions, its contribution is nevertheless anticipated to increase in the coming years. Indeed, the reduction in emissions that can be expected through the technological progress will not compensate the effect of the increase of the air traffic that is predicted by all future air traffic forecasts. An increase from 204 millions of tons of aviation fuel consumption in 2006 to about 300 to 350 millions of tons twenty years later seems to be a reasonable estimate [1]. Such an increase may significantly undermine the reductions of emissions made by the other sectors to combat climate change. Sustainable alternative fuels are seen as a way to decouple the environmental impact of aviation from this traffic growth and the European Commission thus considers that aviation can make a significant contribution to the 10 % target. It could also help to overcome the technical restriction in automotive industry that in the short term could limit the proportion of biofuels in gasoline and diesel below this 10 % limit.

The willingness to include aviation in the general effort of greenhouse gas emissions reduction is also marked by the decision to introduce aviation in the Emission Trading Scheme (ETS) from 2012. The consequence will be the capping of aviation emission at 97% (then 95% from 2013) of their level in 2005 and the necessity for airlines to buy 15% of their allowances through auctions. This will add to the direct cost of jet fuel for aircraft operators. Thus ETS may become a driver for introduction of new technologies on aircraft but also for the use of alternative fuels, with lower carbon impact, such as biofuels.

This GHG emissions reduction target is mostly shared by the end users, many airlines being involved in initiatives or demonstrations to reduce aviation environmental impact. In June 2009, IATA, as the worldwide association of airlines, also adopted a number of high level goals for the reduction of aviation CO_2 emissions that were endorsed by the aviation industry[18] in the joint industry submission to ICAO in September 2009:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020;
- A cap on aviation CO2 emissions from 2020 (carbon-neutral growth);
- A reduction in CO2 emissions of 50% by 2050, relative to 2005 levels.

The first two goals were included in ICAO’s Resolution on Climate Change in October 2010. The use of sustainable alternative fuels for aviation, particularly the use of drop-in fuels[19] in the short to mid-term, was also endorsed in November 2009 as an important mean of reducing aviation emissions at the Conference on Aviation and Alternative Fuels in Rio de Janeiro.

In addition to the strong adhesion of the aviation world to the limitation of its environmental impact, a major interest of airlines for alternative fuels also stems from the critical economic impact of fuel cost and especially of its volatility on their business. Fuel has become the first source of expense for airlines (representing up to 30% of their operational costs) and managing unpredictable large fuel cost fluctuations, as the ones seen in 2008-2009, is extremely difficult. Airlines thus expect from alternative fuels a stabilization of the fuel prices at a moderate level and the avoidance of excess volatility that makes their business uncertain.

After the downturn of 2009, fuel price is forecasted to increase continuously in the next 20 years[20]. If it seems that there has been a "bubble" in oil price in 2008, the cost of producing oil is increasing due to sharp rise in the cost of finding and extracting oil from new sources. Oil cost could also remain significantly above production costs because of the respective evolution of demand and production, with an increase of the demand from the developing countries and a relatively stable production level. In this context of expensive oil, additional pressure may arise on kerosene with the increased proportion of jet fuel demanded from the refining industry due to the rapid growth of air traffic and also to emergent demand of other sectors[21].

2.2 Aviation fuels technical requirements

The need for a specific study to address alternative fuels for aviation is directly linked to the particular requirements of aviation fuels and of their approval processes and specifications as described in previous SWAFEA reports [1] [5].

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[18] represented by the world associations ACI (airports), CANSO (air navigation service providers), IATA (airlines) and ICCAIA (manufacturers)

[19] A "drop-in" fuel is a substitute for conventional jet fuel, which is fully compatible and interchangeable with conventional jet fuel. Such an alternative fuel doesn't require any adaptation of the aircraft or of the infrastructure.

[20] IEA World Energy Outlook 2008 & IATA Economics

[21] Marine may turn toward kerosene because of proposed environmental legislation forcing the marine sector to use distillated fuels rather than heavy fuels oil as currently.

To summarise, there are three main categories of properties that are required for an aviation fuel. The first is associated to the particular conditions of storage of the energy onboard an aircraft and to the high altitude conditions of use. The second is related to the operation requirements in turbojet engines and the last one is defined by safety considerations.

The primary energy storage function is constrained on aircraft both by mass and volume restrictions that lead to a minimum value for fuel energy content (42.8 MJ/kg) and restrictions for its density (between 775 kg/m^3 and 840 kg/m^3). The aircraft flying at high altitude, fuel storage takes place at low temperature. The freezing point of the fuel should thus be below -47℃ and low temperature viscosity should be low enough (below 8 mm^2/s at -20℃) to allow pumping of the fuel.

Injection and combustion of the fuel in the engines induce constraints on fuel viscosity, volatility and composition. Aromatics content is in particular limited due to particle formation during combustion.

Fuel is also used on aircraft as a cooling fluid and a lubricant which introduces additional requirements for thermal stability and lubricity respectively. From the lubricity point of view, aromatics and, to a much greater extent sulphur, play an important role and a too low concentration may induce problems in this area. A minimum aromatics content is also required for the seals swell and the avoidance of fuel system leaks.

Last, safety and maximising hardware life impose specifications on volatility, flash point, electric conductivity and compatibility with materials.

All these properties are defined by specifications, the main ones being the DEF-STAN 91-91 and the ASTM D1655. They have now been complemented by the new ASTM D7566 for the introduction of Synthesized Paraffinic Kerosene (presently Fischer-Tropsch fuels, approved in 2009, and soon hydroprocessed oils, known commonly as HVOs or HRJs, that are expected to be approved in 2011). Theses specifications don't define the precise composition of the fuel but the limit values for a number of its properties and also the nature of the product and of the process for its manufacturing. Before being introduced in the specification, the fuel has to undergo an approval process that checks a wider number of properties through additional tests (the "fit-for-purpose tests") and demonstrates there is no harm to use it in existing hardware. The fuel being approved, the verification of the limited number of properties of the specification is enough to guarantee that a fuel batch is compliant with specification and is fit for use in aviation. ASTM has now defined the D4054 for such an approval process.

Considering these specific requirements, it should be underlined that none of the biofuels presently deployed for road transport, ethanol and fatty acid esters (generally referred as biodiesel) are suitable for aviation. Even the fuel produced through Fischer-Tropsch synthesis or vegetable oil hydroprocessing are not directly usable for aviation and need further upgrading to match the severe specification of aviation.

2.3 Current situation of alternative fuels in aviation

During the last three years, the period of time covering the SWAFEA study initiation and achievement, the landscape of alternative fuels in aviation has significantly evolved.

The major evolution has been the first approval by ASTM of a new fuel family[22] in addition to the traditional Jet A and Jet A-1 recognized for years by the D1655 specification. Fischer-Tropsch synthetic paraffinic kerosenes (FT-SPK), made from coal, gas or biomass, are now approved for commercial use up to blending ratio of 50% with Jet A-1. Hydroprocessed oils (HO), producing synthetic paraffinic kerosene from plant oils or animal fats and often referred as Hydroprocessed Renewable Jet (HRJ), or or Bio-SPK, are presently following the same track and have already undergone numerous flight demonstrations[23].

The initial question whether there was technical alternative solutions for aviation has thus been answered The fuels produced by Fischer-Tropsch or hydroprocessing, when blended with Jet A-1 up to 50%, are "drop-in" fuels meaning that they can be used just as if they were conventional Jet A-1, without any limitation, special handling or re-certification of aircraft.

If the first alterative fuels have now been approved, this doesn't mean that they are already available for commercial deployment and use by the airlines. The production capability indeed remains very low in regard to the aviation needs. It consists mainly of Fischer-Tropsch fuel from coal and gas, the BTL process (Biomass to Liquid) being still at the production demonstration stage. Most of the production is targeted to automotive industry and commercial aviation use has been limited to a number of flight demonstrations. The largest production capability for hydroprocessed oils is under development by Neste, while projects are announced in the United States.

During the course of the study several demonstration flights have been successfully completed by airlines in conjunction with engine and airframe manufacturers and fuel suppliers, all proving that flights could be made with fuels derived from sources other than petroleum crude. Currently, the activity in the sector has moved to the demonstration of economically sustainable production and use.

Lufthansa’s burnFAIR project, in conjunction with the German government, DLR and Neste Oil are undertaking a demonstration on a commercial aircraft route from April 2011 as part of the German aviation research program, LUFO. The route between Hamburg and Frankfurt, will involve refuelling at Hamburg only with a 50% blend of biofuel and conventional Jet A-1 for one engine of an Airbus A321. This will form a longer term study on the effect of bio-derived fuel on the aircraft engine maintenance and engine life. This programme will be reliant on the certification of the fuel before it can commence.

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[22] Sasol semi-synthetic and synthetic fuels had been previously approved but only as specific fuel from one production unit.

[23] The approval of HRJ was initially expected in 2010 and then at the beginning of 2011. End of 2010, negative votes at ASTM from engines manufacturers, EASA and USAF Petroleum Agency have nevertheless call for further inquiry before approval. Unexpected behaviour has been encountered recently at low temperatures.

Other projects looking towards the commercialisation of alternative fuel production are being developed by fuel producers in partnership with specific airlines and specific airports in order to ensure supply of sustainable jet fuel.

For example Solena and British Airways plan to provide 2% of BA's fuel requirements at Heathrow in 2014 in a reported $300million programme. Once operational the plant will provide 16 million gallons annually to BA until 2024. Solena is also using this model in partnership with Quantas at Sidney Airport and although less advanced, a consortium with Easy Jet, Ryanair and Air Lingus based in Dublin.

Air France is also strengthening its implication in biofuels through a concrete and innovative initiative aiming at producing biofuels from forestry waste. Air France is entering the demonstrator project initiated by the CEA (Atomic and Alternative Energy Authority) which will produce 20 000 tons/year of BtL. This project seeks to demonstrate the technical feasibility of a full BtL production chain in France. From 2014, 10% of the production will be available to supply Air France's aircraft. Air France will also participate in the company SYNDIESE in charge of the industrialisation of this production.

Finnair had also announced in November 2010 their aim to be the first user of bio-Jet on regular flights in conjunction with Neste Oil from 2011. Later in February 2011, they nevertheless postponed their decision explaining that "*the price of the fuel and its sustainability measured against all criteria is not at the level that we would have gone into it at this point. There are various research projects in progress, and it is in our interests to use a fuel produced from local raw materials*". They are now looking for biofuel made from local raw materials[24].

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[24] www.greenaironline.com

3 Candidate alternative fuels for aviation

3.1 Introduction to SWAFEA assessment

A first purpose in the SWAFEA study has been to review and compare the possible options for alternative fuels in aviation. The assessment was first done from the technical point of view of the fuel suitability with the aviation requirements [7].

Upstream of the candidate fuels evaluation itself, a "high level" question had to be addressed, which plays a major role in the selection of possible options and future development of aviation fuel. It concerns the "drop-in" or "non drop-in" characteristic of the fuel. Major conclusions about this fundamental point are presented before reviewing the fuels assessment carried out in SWAFEA.

With view to the technical suitability of new fuels for aviation, a first concern in SWAFEA has been to identify possible further needs behind the introduction of the emerging "drop-in" solutions that Fischer-Tropsch SPK and HRJ fuel constitute, and to consolidate the knowledge about their impacts for aviation.

A first question was whether there was any remaining unknown and important development to carry out for their introduction. Part of it was the evaluation of their impact on combustion performances and emissions of lean-burn low NO_x combustion systems under development for the new engine generations. Considering the limitations put on the blended SPK in the current approval process, the target of which was an immediate approval of mature solution with "no harm" for use in existing hardware, the next question was the possibility for an increased flexibility in the SPK specification, in order to facilitate their deployment. This included the analysis of the fundamental limitations in blending ratios (50% in the current specification) and in particular the question of the aromatics and the possibilities either to do without aromatics or to find a substitution component. Further the possibility of compromises between the product quality and the economic efficiency of the process was investigated, being identified that the high requirements of aviation induce a handicap for the fuel introduction on this limited market compared to the use in other less demanding sectors.

Beyond these identified routes to "drop-in" alternative fuels, the question of the additional pathways and fuel types that could be of interest for aviation was the next point for the fuels assessment. Three different directions were mainly considered:

- The potential for petroleum based aromatics substitution of naphtheno-aromatics compounds that can be obtained from liquefaction or pyrolysis (and which could possibly also bring an improved economic efficiency for blend stock production);
- The emerging "sugar to hydrocarbon" routes which are new pathways for producing hydrocarbon from sugar or from lignocellulose (through an intermediate transformation in sugar) with the expectation of higher economical performances than Fischer-Tropsch;

- The consequences of considering an oxygenated molecule through low blending ratio of Fatty Acid Esters (FAE) that are presently already widely produced for diesel application and could thus constitute an additional relatively cheap source of fuel[25].

The investigations carried out on the different types of fuel to answer theses question were mainly based on an experimental testing program through which the properties of the fuel and their potential compliance with aviation requirement were analysed.

The industry evaluation and approval process is defined within ASTM D4054 [12]. However, within the frame of the SWAFEA test programme it was not possible to complete the very rigorous and lengthy process as defined in ASTM D4054. Further, SWAFEA testing was not intended to be an approval program; rather relevant directions for further works to near term sustainable fuel solutions were targeted. Considering the balance between the targets and the constraints, the SWAFEA programme has included the following elements[26]:

- Testing which includes elements of the ASTM D4054 requirements and is a selection of important tests within the 3 tiers considered in ASTM approval process (specification compliance testing, "fit for purpose testing, component or engine testing);
- Test of new blend material (and associated processing) in neat form and in trial final blends;
- Optimised selection of which fuels are subjected to specific testing to ensure that maximum benefit from the programme is achieved - in other words, fuel/test combinations have been selected which are of most interest and relevance rather than doing every fuel in every test.

Fuels tested are therefore outside the current planned approval process within ASTM and Defence Standards committee programmes but are within a scope that is believed to have potential, and, provide potential benefits over those fuels currently within ASTM scope.

In this experimental approach however not all the fuels of interest could be analysed because fuel samples could not be made available. That was in particular the case for the sugar to hydrocarbon routes.

3.2 The "drop-in" fuels

From the most general point of view, a "drop-in" fuel is a substitute for conventional jet fuel, which is fully compatible and interchangeable with conventional jet fuel. Such an alternative fuel doesn't require any adaptation of the aircraft and of the infrastructure, and doesn't imply any restriction on the domain

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[25] These last oxygenated molecules are generally not considered as potentially "drop-in", in particular because the presence of oxygen atoms represents a significant deviation from the conventional fuel chemical composition. Oxygen has several impacts such as a decrease in energy content, an increased water affinity and a different behavior with aircraft materials.

[26] The detailed test program has been described in [5] and [6]

of use of the aircraft. It can be used just as conventional jet fuel and doesn't require any new certification of the systems. The "drop-in" property is today seen as a major requirement for any new fuel in aviation and has been the target of the development and approval of the first alternative fuels in aviation.

It should be underlined however that a "drop-in" fuel should not be assimilated to a fuel matching the present specifications. Indeed, the recent approval programs had as main objectives the evaluation of fuels for immediate approval. Thus, in a conservative approach aiming at preserving safety, these fast tracks have limited the scope to well-established processes and to final products that clone crude-oil based kerosene molecules. This does not mean that, later, the specification may not evolve and be enlarged to include additional fuels with possibly larger deviation from current kerosene.

A "non drop-in" fuel would need to be handled separately from conventional jet fuel, thus requiring a parallel infrastructure to be built up at all airports. Costs of such large parallel infrastructure networks are prohibitive: virtually all large airports are supplied by pipelines from refineries; which cost roughly 1 M$ per km for cross-country sections, and a multiple of this on and around airport sites. The network of fuel quality control points, which has been optimized in a long evolutionary process over the last decades, would also have to be doubled, together with the changes in quality control processes. In addition, incompatible fuels would require segregation of storage tanks and doubling of the airport distribution network of pipelines to the hydrants at the different parking position.

From an operational point of view, no aircraft is dedicated to a specific route and there is a permanent optimization of the fleet use, which is a requirement to insure the profitability of the company. Consequently, the new fuel distribution network would have to be deployed worldwide and it would be necessary to maintain different networks until the new fuel production covers 100% of the needs, knowing that average aircraft lifetimes exceed thirty years. The worldwide availability of the resource for a fuel that could not be mixed with Jet A-1 or other drop-in fuels would also be an issue for the deployment.

In addition, the investments for the new storage and distribution systems shall be made before the entry into service of the first aircraft dedicated to the use of "non drop-in" fuel. From the manufacturers' point of view, the guarantees that such investments will be made in a sufficient number of airports shall be obtained before any decision for launching the development of the first dedicated aircraft. In any case, it seems that there could be a maximum of one alternative "non drop-in" fuel family.

Finally, airlines are also not ready to compromise with certain aircraft performance attributes. In particular noise is today very sensitive on many airports. Introduction of a new fuel should not induce change in aircraft's trajectories that would increase noise for residents around airports or expose them to an increased pollution. Furthermore, a change in the fuel performance, even if the fuel remains compatible with the aircraft from a chemical and physical point of view, is likely to induce the requirement of a separate handling. In particular, an energy density below the specification requirement would not allow the aircraft to reach its maximum range and would require to be supplied separately in order for the pilot to calculate the exact energy content of the fuel tank.

Today, the "drop-in" feature has been demonstrated for 50% blends of Jet A-1 with Fischer-Tropsch Synthesized Paraffinic Kerosene and is expected for hydroprocessed oils (also often referred in the U.S. as HRJ, Hydroprocessed Renewable Jet") which should also be approved by 2011 for 50% blends with Jet A-1. Works are also undergoing on fully synthetic alternative fuels[27]. In this context, with view to the complexity and huge potential cost of its introduction, a "non drop-in" fuel would only be justified if it promises considerable advantages in terms of economics and sustainability in comparison to FT and HRJ solutions. These advantages are likely to come mainly from the production process. Indeed the review of the candidate alternative molecules, as illustrated by Figure 1, shows that the feedstock for the presently identified "non drop-in" routes can also be processed in potential drop-in fuels by other processes.

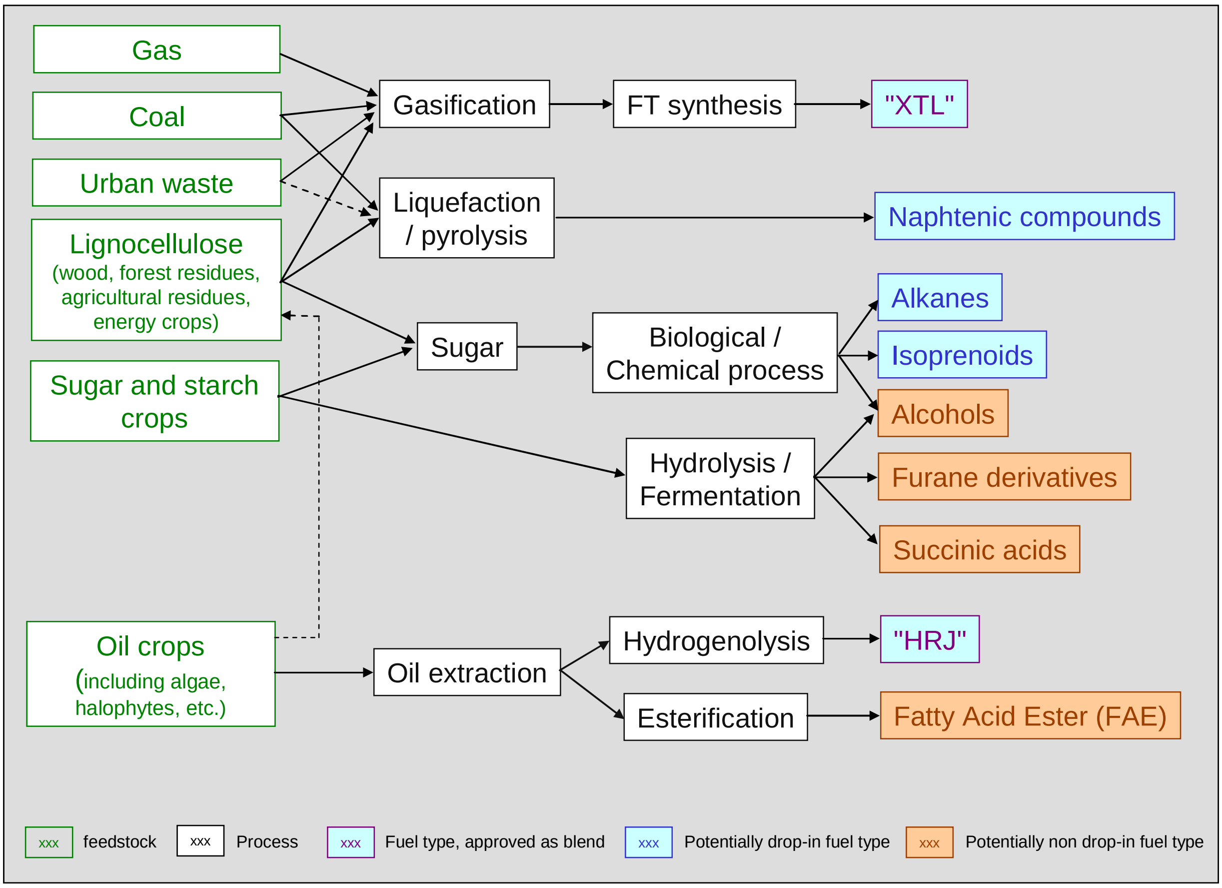

Figure 1: Feedstock, processing pathways and fuel types for candidate alternative fuels

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[27] Approval of "neat" Fisher-Tropsch Fuel is targeted for 2012, and of "neat" hydroprocessed oils in 2013 according to the same roadmap - CAAFI Annual General Meeting, 30 September 2009. "Neat" doesn't necessarily mean that the fuel is purely obtained from Fischer-Tropsch or hydroprocessing; synthetic aromatics may be added.

In the progress of the SWAFEA study, no such promising non "drop-in" fuel has clearly been identified from the current available information. The technical analysis of the possible candidate fuels for aviation has thus been oriented towards fuels that were believed as potentially compatible with the present system and that have a chance to be integrated in an evolution of the specifications.

3.3 Synthetic Paraffinic Kerosene (SPK) derived from Fischer-Tropsch and hydrotreated oils

Analysis on SPK have been carried out in SWAFEA on the basis of HRJ fuel samples but considering the proximity of both FT-SPK and HRJ, most of the conclusions also apply to FT fuels.

Overall, the performed testing has not raised any major issue and confirms that inclusion of SPK is a short to mid term viable option.

Combustion studies, performed on lean-burn low NO_x combustion systems for which little to no data was available in the literature, confirmed the trend of smoke and particulates reduction with increasing levels of HRJ already observed for classical combustion systems [8]. The impact on NO_x and unburned hydrocarbon is not solely related to the fuel composition thus no clear trend demonstrating the fuel impact could be observed. Further, other combustion properties including laminar flame speed and ignition delay time are within expected bounds. Changes in emissions profile are due to the complex interactions of properties-dependent physical processes during fuel delivery from injector into the combustion zone (influenced by physical properties such as density, viscosity etc) and during combustion where characteristics such as aromatics levels relate to smoke/particulate production and energy density affects flame temperature and position.

Although such benefits are clear, what must also be considered is the potential changes within the current specification limits. Impact on specification and also impact on engine if fuel population changes occur must be considered separately. More testing would be required at rig and/or engine level to determine the long-term risks and benefits of operating fuels with typical average values which are different from today's observed ones. However, it should be noted that fuels which are currently or soon to be approved have been shown to have properties that are sufficiently similar to conventional such that the need for additional maintenance to maintain current levels of safety is today not seen as a strong risk. Further consolidation would nevertheless contribute to increase the confidence of users, investors and insurances regarding the risk to go for alternative fuels.

Increasing the blending ratio with conventional fuel over the current 50% limit induces change in the typical fuel properties that have to be considered. The current limitation stems from the lack of aromatics in FT fuels that makes them not matching the specification for density, lubricity and compatibility with some polymer materials[28]. Currently, fuels with less than 8% aromatics cease to be “drop-in”[29].

Beyond the possibility to completely eliminate fossil fuel (which is nevertheless also highly depending on biomass availability), the reason for looking for higher blending ratio is linked to production and logistics aspects. Indeed, the blending requirement induces constraints on the production organization such as the requirement to either collocate alternative fuel production with a refinery or to create dedicated hubs to achieve the blending, with transportation infrastructure for the blend stock. Flexibility could be gained if a fully synthetic fuel could be used, also allowing complete turn to alternative fuels in some places where there is a real opportunity for it. Combustion tests have also shown that a potential benefit of increasing SPK blending ratio would be the reduction of particulates emissions that decreases with the aromatics content.

From the engine point of view, initial testing beyond 50% HRJ shows that fuels may fall outside specification but the feeling is that many of the problems may be resolvable with further study.

By far the most obvious problem is the impact on seals. Low or zero aromatic fuels represent an unknown with significant risk of causing seals leakage. Experience and test evidence have shown this to be true[30] but there is currently not sufficient knowledge to quantify the risk such that a limit below the “safe” 8% minimum can be defined at this time. Additives could be imagined that induce the swell which therefore simulates the presence of aromatics for the benefit of the elastomeric materials. Currently no significant studies are being undertaken (apart from initial feasibility) to develop such additives and define dosage rates. Further, the approval of such additives would have to go through the ASTM D4054 process which incurs significant effort, cost and timescales. In the long term, it can be imagined that "zero aromatic tolerant" seals are implemented on engines and aircraft. They would allow a shift to zero aromatic fuel once the older aircraft are retired from service. Indeed, the retrofit of existing fleet is not seen as a viable solution with the regard to the added value of such a modification considering the cost of the retrofit and of the associated probable recertification of the fuel system. Options which allow the aromatics limit to remain, including the production of synthetic aromatics, are seen as more viable.

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[28] Aromatics are required for swelling of fuel system seals, particularly in case of aged seals. Lack of aromatic may induce leakage.

[29] This current minimum is based on years of experience with crude-oil based Jet A-1 where values below 8% were never observed. The 8% minimum was therefore instituted to keep these new blends within experience. It is not the result of a progressive testing protocol and, during the ASTM discussions, it was always recognized that this limitation needed to be addressed by further work

[30] The AAFEX tests for example, performed on a CFM-56 engine installed on a NASA DC-8, report leakages that occurred, not on the engine but from a tank, during the test due to the lack of aromatics

In the short term, the question of the use of a neat SPK is thus not relevant, but there would be an interest to identify the minimum aromatic content with view to the particulate emissions from engine.

A second aspect to consider with neat SPK is their density which is below the specification and makes them non "drop-in" from the operational point of view. Density impacts the maximum range of the aircraft. Although the energy content per unit of mass of neat SPK is slightly higher than in Jet A-1, the low density results in a reduced volumetric energy content that decreases the energy contained in the tank, which is an issue for flights at maximum aircraft range requiring the maximum capacity. It should be noticed that only a small proportion of the flights are limited by the maximum range. However the reduced density of a neat SPK would introduce a limitation on aircraft use which is to be considered with airlines. Possibilities of increasing SPK density could be investigated through an optimisation of its formulation (balance between the mean carbon chains length and the isomerisation of the fuel to ensure good cold flow properties[31]). Synthetic aromatic is also a mean to produce a neat synthetic fuel that complies with density requirement.

In order to increase flexibility in alternative fuels introduction, the possibility of compromises between the blendstock quality and its production cost have also been investigated, while still remaining within the specifications for the final blends (which thus remains "drop-in").

Ongoing programs within CAAFI, USAF, and ASTM, have as main objective the evaluation of aviation alternative fuels for immediate approval which has limited the scope to well-established feedstock and processes and to final products that clone crude-oil based kerosene molecules. Consequently and in the particular case of HRJ blend stocks, high quality and high level of processing were sought in those programs to guarantee the approval. Such a high level of processing impacts the achievable yields and the economics of the process. It was anticipated that lowering it would increase the yield from a given amount of biomass and increase the overall fraction available for commercial aviation, while reducing capital and operational costs of HRJ production units.

In order to investigate the relationship between process costs, process yield, HRJ quality, and blending rate, IFPEN and Shell have joined their expertise to produce for the purpose of SWAFEA two different qualities of HRJ from the same original oil. Between the two, the level of hydroisomerisation that is applied to hydroprocessed oil in order to improve their low temperature properties[32] was varied. One production has been made with a measured freezing point of -24℃, while another production has been made with a freezing point of -50℃. Lowering the quality requirement, regarding the freezing point, from -50℃ to -24℃, results in an additiona l jet fuel yield of about 10% in mass relative to the oil. For the first product, blends with Jet A-1 with incorporation rates from 10% to 30% have been tested

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[31] Longer carbon chains length translate in a degradation of low temperature properties.

[32] Hydroprocessing produces most exclusively linear paraffins in the range of diesel fuel, which present low cold flow properties. Hydroisomerisation improves these properties by converting the linear chain in branched paraffins.

against the standard properties; they proved to match the specification for blending ratio up to 15 to 20% depending on the Jet A-1 quality.

These preliminary tests have consequently shown that the proposed blending strategies can have a potential in order to enhance the incorporation rate of HVO in conventional jet fuel. The blending of high amount of a low freezing point HVO could allow higher incorporation rates in the long term, while the incorporation of high freezing point HVO in small amount could allow to initiate the incorporation in the short term, while optimising the process yield. Nevertheless, it has to be outlined that these are only preliminary results and need an important validation work before going in the certification process and being industrially used.

3.4 Other processes of interest for aviation fuels

3.4.1 Naphthenic compounds

Naphetheno-aromatics[33] produced through coal or biomass liquefaction have been identified in the state of the art [1] as a candidate that could present interest both from the production point of view and for the substitution of aromatics.

The production potential of coal direct liquefaction (DCL) is considered as high because the yield of the process is significantly higher than the one of Fischer-Tropsch with a lower cost. Capital cost is of the same order of magnitude. First industrial production units are starting in China (Shenhua) where the coal reserves are significant[34]. The technology could also be applied to biomass (DBL) but DBL process is currently at research level.

In the same time, one of the next candidates for evaluation and approval within ASTM is a sustainable source of aromatics. This is because the availability of such products would increase the maximum level of sustainable product within jet fuel by substituting the (essential) conventional aromatics within the blend. Indeed, with the right raw materials and process capability, it is expected to produce a 100% drop-in jet fuel, and further, at one location. A single location has the benefit of removing the need to transport and off-site blend products which have a cost, environmental and, quality assurance benefits[35].

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[33] Also called cyclic alkyl aromatics

[34] It can be also noted that Axens and Headwaters Incorporated have signed an agreement to form a strategic alliance to provide a single-source solution for producing ultra-clean fuels by direct coal liquefaction (DCL) alone or in combination with refinery residues or biomass.

[35] ASTM is currently creating a working group or groups looking at synthetic aromatics (as of Dec 2010). Potential routes includes liquefaction, pyrolysis and/or derived from alcohol intermediates. There is also the possibility of allowing aromatics within synthetic paraffinic kerosene by changing hydrogenation process conditions.

The product used within SWAFEA is referred to as naphthenic cut. This is in fact not a real sustainable product but a substitute for liquefaction product which was purchased from chemical industry due to the non-availability of an actual liquefaction product. It contains some aromatics (~10weight%) but also a high percentage of cyclic hydrocarbons (naphthenes).

SWAFEA testing demonstrated that the inclusion of such products with HRJ is a viable option and that physical, chemical and performance properties are very much as would be predicted. No show stopper was identified within SWAFEA regarding the approval as a blendstock for aviation fuel (which is also confirmed by parallel investigation from IFPEN [13]). The product presents also some potential for aromatic substitution in SPK fuels. Aromatics being not exactly the same as in conventional kerosene, more detailed investigation are required, including fit-for-purpose and component testing. This is also needed to better understand the influence of the cyclic hydrocarbons.

SWAFEA testing was done on a substitute material, and testing was limited. The evaluation of real sustainable aromatics products is thus required for a full conclusion about naphtheno-aromatics. Further studies are thus recommended to assess their suitability for aviation, as this is a feasible and useful new option to increase the scope and maximum sustainable content of jet fuel. In addition, developments on the process are currently carried out by companies with also other applications.

3.4.2 Fatty Acid Esters

A blend containing about 10% of FAE with Jet A-1 was tested within SWAFEA in order to study some consequences of an oxygenated molecule and also the potential of FAE as a blendstock for aviation fuel. Indeed the FAE production for automotive diesel engines is already well developed which could have provided a relatively cheap source for initial introduction of biofuels in aviation.

Neat FAE properties are not suitable for aviation use, especially concerning the cold flow properties, the thermal stability and their energy content. Within SWAFEA, the candidate FAE was selected for presenting short carbon chains lengths likely to improve these properties, and the blending ratio was selected at the limit where previous studies indicate FAE blends with Jet A-1 match the specification properties.

However, standard analysis of the 10% FAE+ Jet A-1 blend concluded that the blend had significant failing properties. Further, some of the measurement methods applied to conventional jet fuels was not applicable to this blend. Of particular interest is the reduction in energy density, which would have an adverse effect on aircraft loading and increase fuel consumption and the fact that measurement methods for this critical property do not give accurate results in the presence of oxygenates.

This blend also showed an impact on elastomer permeability[36]. This limited testing may indicate non-compatibility of FAE with current elastomeric materials which could be a risk.

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[36] It should be noted that this may have been due to the presence of n-heptane (19.3vol.% of the neat FAE) which was not expected in the sample

3.4.3 *Sugar derived hydrocarbons*

Different pathways are under development for the use of sugars as an intermediary for the conversion of biomass such as cellulose to ethanol (Logen) or leading directly to hydrocarbons via micro organisms (Amyris Biotechnologies, California), a process which produces isoprenoids, or catalysis (Virent Energy Systems Inc. Wisconsin) which produces Alkanes [1]. The latter two are potential jet fuels and are considered for the ASTM D4054 approvals process.

The Virent pathway incorporates the more traditional bio-catalytic production of ethanol from carbohydrates with aqueous phase reforming (AFR) to generate hydrocarbons. The feedstock for this process is from the plant sugar once it is reduced to its water soluble form. Samples of jet quality product have been produced from this production pathway and submitted for assessment against the ASTM D1655 specification test. In a similar way to the FT and HVO SPKs, the Virent product unblended is beyond the density limit of the specification due to the low levels of aromatics. The flash point is also below the specification but the lab scale results suggest that lighter products can be removed in the final distillation of the product which will increase the flash point [14]. Virent pathway is currently at the laboratory scale.

Amyris Biotechnologies developed, using biological synthesis, a process to produce a surrogate to jet fuel from sugar cane. Basically, this process uses a GMO to convert sugar into isoprenoids molecules. Isoprenoids, also called terpenes, are unsaturated hydrocarbons, made of a number of isoprene ($CH_2{=}C(CH_3)CH{=}CH_2$) units, which can be linear or cyclic. Since the building blocks are isoprenes (C_5H_8) there are only two (three at the most) molecules that are within a kerosene cut: $C_{10}H_{16}$ and $C_{15}H_{24}$. For the jet fuel, a blending of C10 and C15 molecules with 50% of Jet A1 is a target, and it is expected that this blending will meet the ASTM D 1655 requirements. According to Amyris' Brazilian Branch, its production of diesel and jet fuel is nowadays in the pilot scale. Presently diesel has the priority (large scale production in 2012) and jet fuel production is expected for 2014-2015[37].

No samples of this kind of fuel were made available for SWAFEA. No assessment of their suitability for aviation use could thus be performed.

3.5 Other outcomes from the fuel assessment program

In the frame of the fuels assessment performed within SWAFEA, a paper study on the relevance of current standard test methods and analysis for novel fuels has highlighted that while fuels remain wholly hydrocarbon in composition current standard test methods are relevant. However, care has to be taken to ensure these remains true for any future products. Indeed testing of products outside the current specification limits showed some limitations in test methods. Particularly relevant is measurement of products which contain non-hydrocarbons (in SWAFEA this was a 10% FAE blend).

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[37] Amyris acquired a 40% of a sugar cane mill (in association with a of Brazilian production leader). The media has announced others agreements among Amyris and three other ethanol production groups.

Results clearly show that methods designed for hydrocarbon jet fuel have the potential to give very misleading results (highlighted properties included in particular Lower Heating Value, which has to be measured and not estimated, and compositional measurements).

The SWAFEA test program has also allowed to identify some test methods that could provide complementary data to that from the ASTM D4054 data set and that could be incorporated into the palette available to ASTM groups working on novel fuels (Table 1).

Type of property	Measurements
Combustion	Laminar flame speed Ignition delay time
Material compatibility	Elastomer permeabilitty
Stability	High Reynolds Number Thermal Stability Cocking tests
Safety	Explosion and fire tests

Table 1: fuel characterisation methods recommended for inclusion in ASTM palette

3.6 Conclusions and recommendations

A first conclusion is that, at least in the near to mid term, the introduction of alternative fuels into aviation fuels should be based on "drop-in" fuels since currently no non "drop-in" solution has been identified for which the production advantage could overcome the costly drawbacks of being not compatible with current systems and operations. In the short term, this is likely to be done by an increased use of blend stocks which copy the molecules already present in conventional fuels (thus guaranteeing that the fuel is “drop-in”). These include at the present time, Fischer-Tropsch derived Synthetic Paraffins and Hydrogenated Renewable Jet, and in the very near future may include synthetic aromatics, in line with the approach and processes being used by ASTM and Defense Standards groups.

The analysis shows that, even though a reduced content in aromatics is favourable for engines particulate emissions, it cannot be considered to use pure SPK in the short to mid-term because of non compatibility with seals on current aircrafts and because of the low density of SPK that induces operational problems. From the work performed within SWAFEA, synthetic aromatics (liquefaction/pyrolysis etc) are a viable blend stock. However, further study is needed beyond the preliminary testing performed in SWAFEA with an artificial substitute in order to demonstrate the principle.

Conversely, the SWAFEA study evidenced the economic interest in an initial period, during which biofuel availability will be limited, to consider a low incorporation in Jet A-1 of SPK with higher freezing point than those currently approved. Increasing the freezing point decreases the level of processing of the SPK which induces higher yields and a better profitability.

Another point evidenced for these short term SPK solutions is that the increased use of SPK based blends will change the fuel property population within the jet fuel pool (even if current specification limits remain). Future studies should examine the longer term implications of such changes on engine certification, performance, maintenance and cost of ownership.

Work also demonstrated that oxygenated molecules such as fatty acid esters in the kerosene cut (as opposed to biodiesel which include longer carbon chains) present significant challenges and are not viable in the near to mid-term. In addition, testing of products outside the current specification limits showed some limitations in test methods, particularly where non-hydrocarbon molecules were present.

The sugar derived hydrocarbons routes could not be assessed within SWAFEA. Looking at the works performed in the United States and knowing that these routes are now under consideration by ASTM, these fuels are certainly to be considered in future studies. These fuels may induce specific questions such as a reduced number of molecules, with consequences on distillation properties, which are worth studying.

With view to the introduction of new fuels beyond the current Fischer-Tropsch and HRJ SPK, the ASTM approval process and specification controls appear as quite suitable and the report recommends its adoption. To enable EU centric approvals requires the creation of a new capability and knowledge network which should integrate and complement ASTM, Defence Standards and other specification group activity rather than compete with them. Included in this should be test capabilities used within the SWAFEA programme that have provided new insights into fuel performance, and importantly, testing capability for future engine technology to ensure new fuels are “future proof”.

4 Life cycle of alternative fuels pathways

In the presentation of the context for alternative fuels in aviation (chapter 2.1), we underlined the major importance of the Green House Gas (GHG) emissions reduction in the motivation for going to alternative fuels.

The relevant criterion for assessing the actual emissions of a fuel pathway is to evaluate the total emissions along the complete life cycle of the fuel from the production to its final use. The environmental efficiency of the whole chain depends on the combination of the feedstock type, the conditions in which it is produced, the conversion pathway (including the logistics from the production place to the processing plant) and finally the emissions from the combustion of the fuel. It can be captured through the Life Cycle Analysis (LCA) which not only allows to capture the GHG emissions but can also be applied to evaluate the energetic efficiency of a pathway.

Based on the methodological guidelines set by the European Directive on the promotion and use on renewable energy (2009/28/CE), assessments have been made within the SWAFEA study on greenhouse gases (GHG) emitted for the production and use of alternative fuels and on energy consumption associated to the various steps of the whole life cycle. The analysis has been focused on the processes that are supposed to be relevant for the European Union in the middle term (~2020-2030), mainly the Fischer-Tropsch and the hydroprocessing processes which are presently the more mature ones for which data are also available. For these processes, different pathways have been analysed corresponding to different feedstocks[38]:

- Conventional Jet fuel and FT fuel from natural gas (GtL);
- Hydrotreated Renewable Jet (HRJ) fuel from rapeseed, camelina, oil palm, jatropha and algae;
- FT fuel from lignocellulosic biomass (BtL) including miscanthus, switchgrass and wood from short rotation coppices (SRC).

Complementary results are also available from the PARTNER study [15], which has also considered aviation fuels, and from road transportation studies (JEC, RENEW).

A synthesis of the results is presented on Figure 2 (detailed results are available in [16]).

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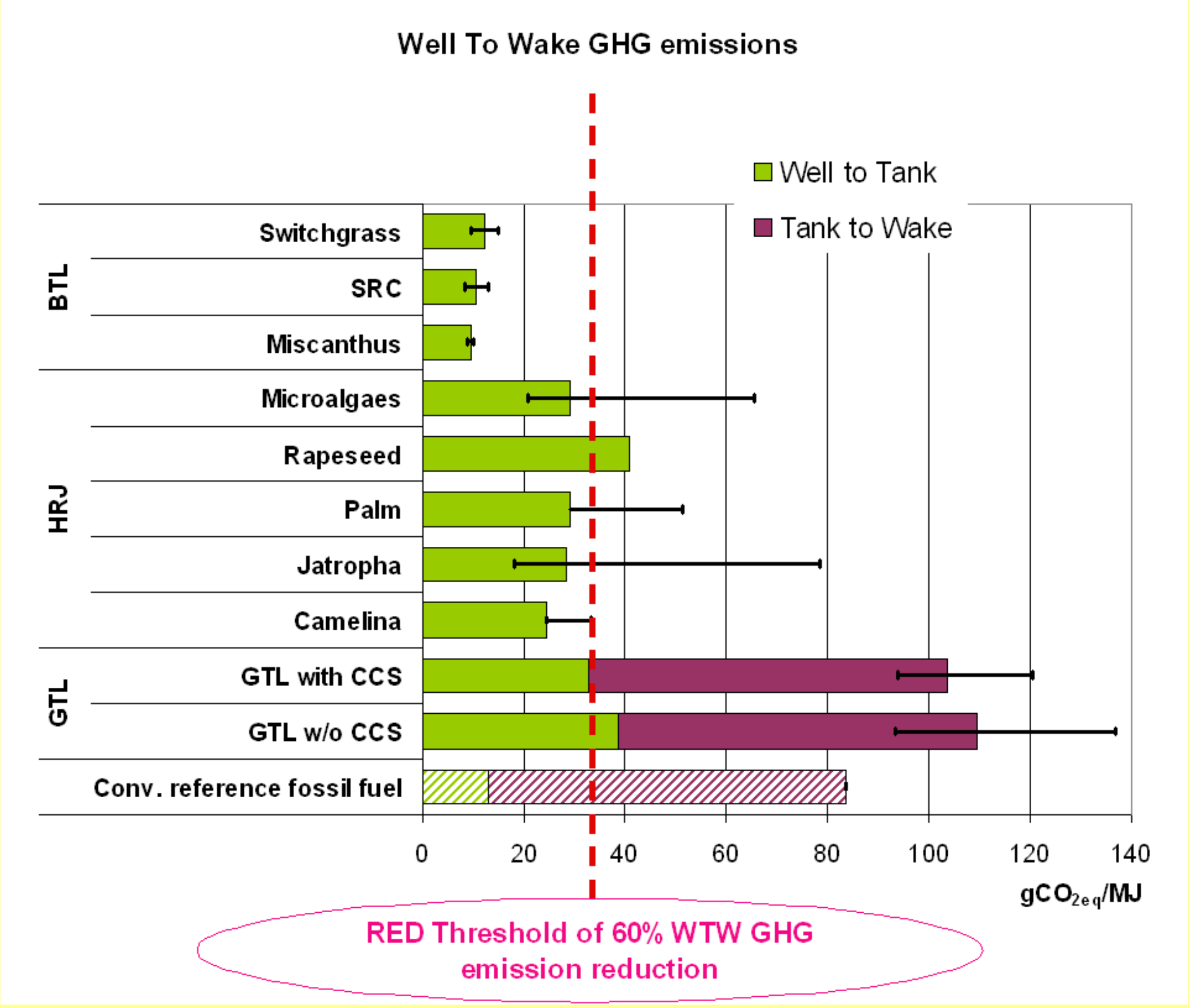
[38] For biofuel pathways, the feedstock analysed in the LCA correspond also to feedstocks that were considered in the biomass production scenario presented in next chapter about feedstock and sustainability issues.



Note:

- The reference pathway considered for algae corresponds to autotrophic algae with average characteristics from literature data. Microalgae are grown in open raceways mixed with wheel paddles in a facility covering about 100 ha. Pounds are located near an electrical plant in order to recycle the flue gases with 15% mass of CO_2. A purification step of flue gases is required in order to extract CO_2 and to feed algae on it. To carry out photosynthesis, microalgae use sunlight energy, CO_2 and nutrients. These nutrients are supplied by sludge from waste water treatment plant considered as a waste.
- Reference processes data are from NextBTL for HRJ, RENEW for BTL and IFPEN and Shell for GTL
- Uncertainty bars correspond to sensitivity to the inputs data range found in literature.

Figure 2: Results of SWAFEA life cycle assessment – GHG emissions

4.1 Life Cycle Analysis of fossil based alternative fuels

There are presently two fossil based alternatives to conventional kerosene: the Fischer Tropsch synthetic fuels obtained from coal (CTL) and from gas (GTL). From the analysis performed within SWAFEA (GTL with and without carbon capture and sequestration – CCS) and additional results from literature (PARTNER [15], JEC [17]), it turns out that:

- CTL use leads to more than doubling the GHG emissions compared to conventional kerosene; significant emissions reduction can be obtained with CCS but the emissions remains higher than for kerosene;
- GTL imported to Europe from a remote production facility is likely to have higher GHG emissions compared to the current EU Jet A-1 baseline (14 to 51%) - CCS can be applied but even the most complex and costly measures are unlikely to give a net reduction in carbon emissions relative to today's benchmark.

In addition, the total expanded energy in the process is significantly increased compared to conventional kerosene. In the best investigated case, GTL produced from Qatar, the expanded energy is 0.55 MJ per MJ of fuel produced, to be compared to 0.11 MJ/MJ for conventional kerosene. This expanded energy is directly non renewable energy stemming from the gas itself. Applying CCS increases the energy consumption to 0.79 MJ per MJ of produced fuel, for the same case of GTL from Qatar. This results in a low efficiency in the use of a fossil resource.

On the single criterion of life cycle emissions, none of theses alternative fuels thus qualify for bringing the targeted emissions reduction, especially when one has in mind the emission reduction threshold set in the RED for biofuel which is 60% in 2018. It should be noted that when compared to non conventional petroleum like oil shale or tar sands, the picture is less severe for GTL[39] which could then present an advantage.

Development of CTL and GTL would thus not contribute to a GHG emissions reduction policy. These fuels mainly bring the opportunity to diversify the supply sources for aviation fuels and so to answer the demand increase and also the oil price increase (but at the cost of low efficiency in terms of fossil resources use). However, from an environmental point of view, the analysis shows that FT fuels (including CTL, GTL and BTL), like HRJ, reduces the level of particulates emissions of the engines thank to the reduction of the content in aromatics which presents an advantage from the local air quality point of view and is also likely to reduce the impact of contrails formation on radiative forcing.

4.2 Life Cycle Analysis of biofuels

In opposition to CTL or GTL, all the evaluated biofuel pathways demonstrate a potential for significant GHG emissions reductions. Nevertheless, their ability to reach the RED's threshold of 60% in terms of

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[39] Based on PARTNER's results for oil shale and tar sands

emissions reduction depends strongly on the process, the feedstock and also the cultivation pathway which is generally the major contributor (in particular due to the use of agrochemical inputs, especially N_2O).

BTL pathways are able to reach the RED GHG reduction threshold. They are the pathways leading to the strongest emissions reductions, which can reach up to 90% with the best evaluated feedstock (miscanthus). In case of BTL process, the life cycle emissions are dominated by the emissions from the feedstock cultivation (Figure 3). Indeed, emissions associated to the process consist of CO_2 from biomass and are thus "neutral". In addition the evaluated lignocellulose feedstocks also demonstrate low cultivation emissions compared in particular to many oil seeds.

If BTL performances from GHG emissions point of view are quite interesting, the process demonstrates a poor energetic efficiency which is in fact linked to its low yield (about 25% in mass of product[40]). The process doesn't ask for large amount of non renewable energy but consumes in itself a large part of the biomass. This has direct negative consequences on the need for biomass and following on the amount of lands required to produce this biomass. Nevertheless, the biomass production simulation performed in SWAFEA shows that BTL process associated to lignocellulose feedstocks cultivation leads to a higher global production of fuel than the use of hydroprocessing with oil seeds [10].

HRJ pathways produce higher emissions than BTL. One reason is the requirement for hydrogen in the process, hydrogen which is presently produced from non renewable sources (natural gas reforming). The other reason is that the evaluated oil seeds generally produce higher cultivation emissions than lignocellulose crops. The ability of HRJ to match the RED's target finally depends on the feedstock and on the emissions associated to the cultivation pathway. Camelina for example demonstrates better performance than rapeseed because of a lower inputs requirement. Jatropha illustrates the importance of the cultivation practices: LCA emissions may be low, and compliant with the RED, when the crops residues are returned to the land for replenishment rather than removed which induces the need for fertilizers. The sensitivity analysis shows that the optimisation of the cultivation steps will be very important for the compliance of HRJ pathways with the RED.

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[40] 1 t of dry biomass produces 0.25 t of final fuel.

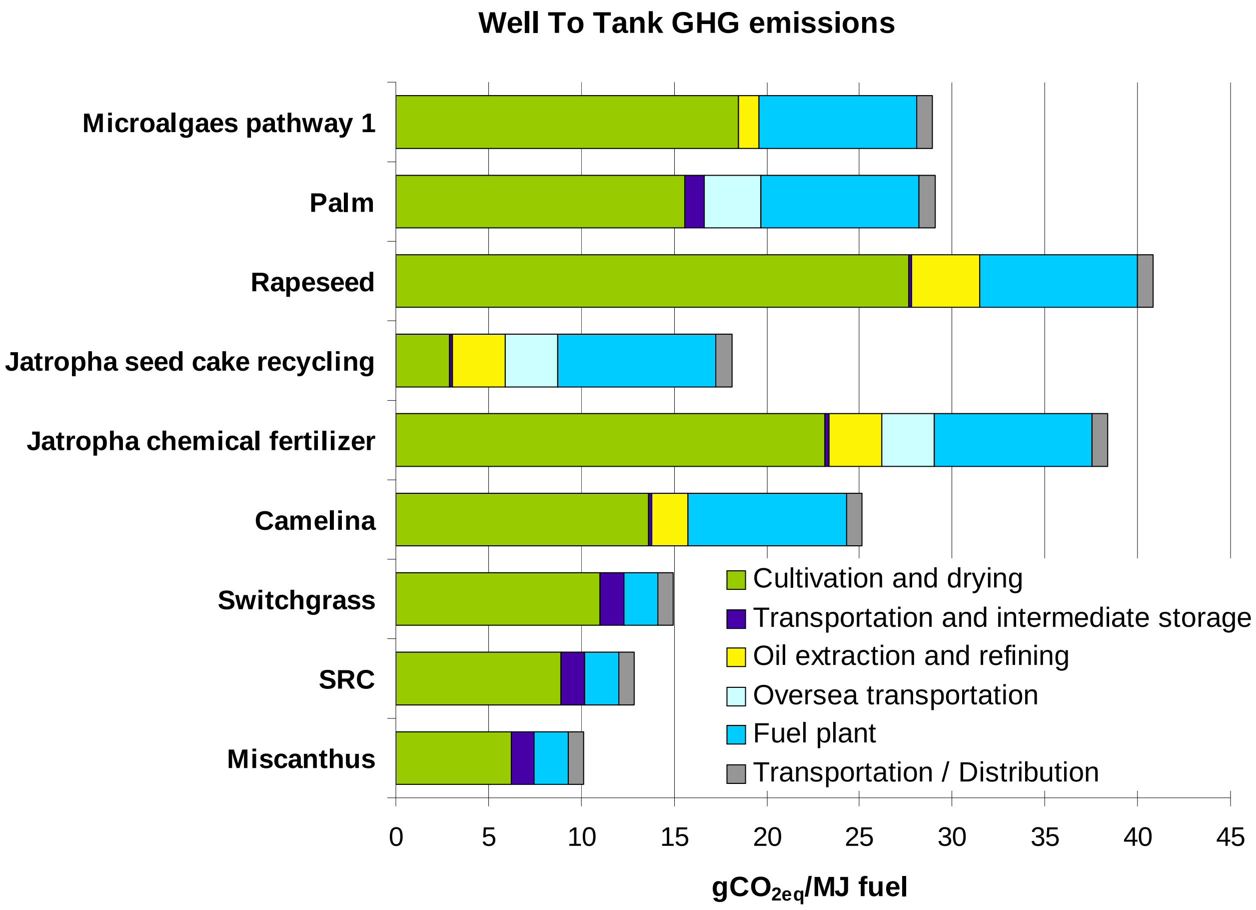

Figure 3: Contribution to biofuels life cycle emissions (SWAFEA assessment)

The consideration also applies for algae for which obtaining low emissions requires a careful optimisation of the different steps of the algal oil production (Figure 4). The best performances are obtained when considering integration of the production with other applications producing CO_2 or nutrients sources. A important point should also be underlined concerning algae: LCA emissions reductions can be obtained for algae when they are considered as biofuels because the carbon released by combustion is then considered as "neutral". However, as it was raised during the SWAFEA final conference, if the carbon used to grow the algae comes from a fossil source, like the flue gas of a power plant, algae fuel may not be considered as a biofuel. Since algae allow to make a double use of the fossil carbon, credits could be allocated to algae fuel for this but may still result in a significant increase of algae LCA emissions. Algae ability to comply with the RED thresholds will thus also depend on the regulations that will be defined.

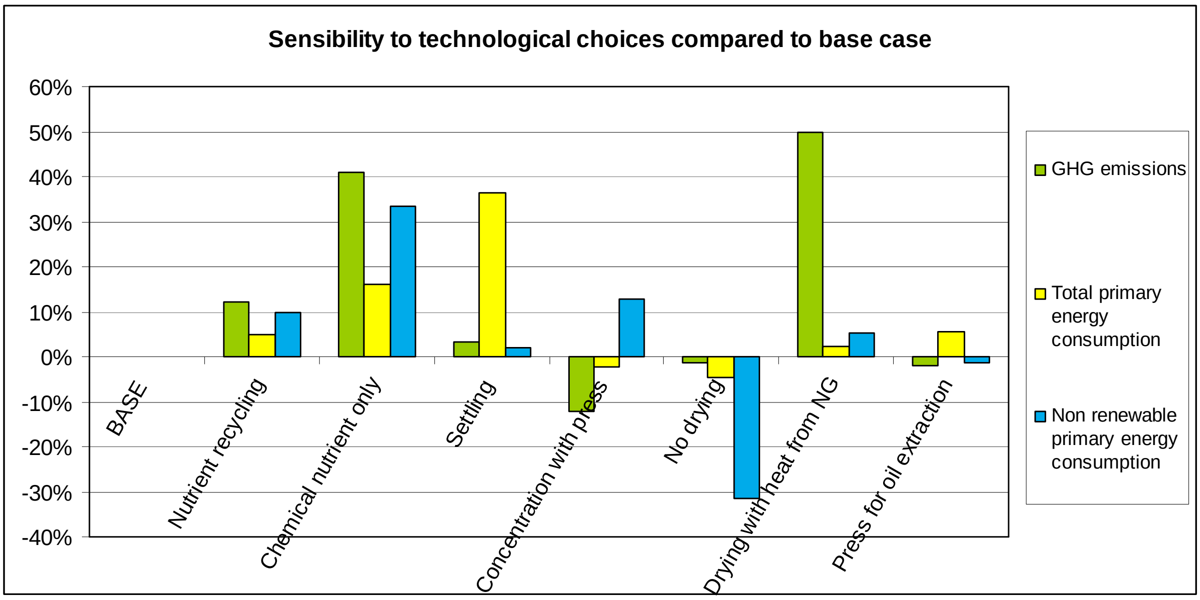

Figure 4: sensitivity of algae LCA to technical options of the pathway

From an energetic point of view, HRJ pathways are less demanding than BTL but require more non renewable energy mainly because of the cultivation step (needs for fertilizers and diesel) and of the hydrogen production from natural gas. Non renewable energy consumption may be particularly high for algae due to drying, harvesting and cultivation (per order of magnitude importance). Again, the production process has to be particularly optimised for algae.

The previous consideration about life cycle GHG emissions stand for situation where no land use change is considered for the cultivation of the crops. Like many other recent studies, the evaluation carried out within SWAFEA shows that the contribution of land use changes may offset all benefits from a given alternative fuel if the biomass is grown on a land formerly covered by vegetation with high carbon stocks. This is in particular the case if forests are converted, a case which was excluded from the SWAFEA study since it doesn't comply with the RED or with sustainability frameworks like the RSB's one[41]. Examples of land use change impact, computed in relation with the definition of a biomass production scenario within SWAFEA, are given in Table 2. They show that land use change may easily have a dominating effect over the whole production chain, but that in some case this effect may be positive for example when perennial crops are cultivated on converted grasslands. Then a positive effect on GHG balance is obtained as the cultivated species store more carbon than the reference considered land. Land use change is thus a parameter of major importance for energy crops cultivation.

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[41] Round Table for Sustainable Biofuels - http://rsb.epfl.ch/

Reference land use considered		**Grassland**		**Cropland**		**Grassland**	
Climate region ***Soil type***		**Warm temperate, dry** ***High activity clay soils***	**Cold temperate, moist** ***High activity clay soils***	**Warm temperate, dry** ***High activity clay soils***	**Cold temperate, moist** ***High activity clay soils***	**Tropical Dry** ***Sandy soil***	**Tropical moist** ***High activity clay soils***
Annual Feedstocks	Camelina low case	79,7	277,2	-	-	-	-
	Camelina high case	63,0	192,9	-	-	-	-
	Rapeseed	40,0	122,4	-	-	-	-
Perennial Feedstocks	Miscanthus	-11,8	-7,9	-28,3	-63,7	-	-
	SRC	-17,3	-11,5	-41,5	-93,4	-	-
	Switchgrass	-16,6	-11,0	-39,8	-89,6	-	-
	Jatropha	-	-	-	-	-254,7	-328,6

(CO_2 emissions from LUC have been distributed over 20 years)

Table 2: Carbon stock evolution in soils expressed in CO2eq per MJ of Fuel (positive values means that soil destocks carbon, negative values means that soil stores carbon)

4.3 Methodological issue with Life Cycle Analysis

Methodological assumptions used in LCA, and in particular the way allocations are done for the co-products, are often cited as a very sensitive parameter for the results. The use of a given methodology may also be enforced by regulations. The RED, for example, defines a methodology for LCA which was basically used for the SWAFEA evaluations. It implies, in case of co-products, to use an allocation of the emissions on the basis of their energy content[42]. Other approaches consider an allocation on the basis of the mass, the economic value or the use of a substitution method which is based on the evaluation of possible displacements of products and co-products uses. This last method is also recognised as an appropriate method by the RED for the purpose of policy analysis, while it is the selected approach in the U.S. RFS regulation. Methods also differ in the various existing certification schemes [18]. Other methodological aspects can differ between the various analyses, for example the way to account for N_2O emissions[43], and the reference value for kerosene may also vary.

Mass allocation is the most favourable option, economical value may be changing over time, while energy allocation often provides results close to the substitution method [1]. In the substitution method however the choice of the substitution may have a strong influence. For example, in case of production of electricity in BTL, if the substituted electricity is produced from coal, the BTL pathway gets very high GHG credit considering the high emissions of electricity from coal. Depending on the

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[42] More precisely on the basis of their Lower Heating Value.

[43] IPCC methodology was used in SWAFEA which is not always the case in PARTNER study.

reference taken into account (electricity produced in France, Europe or United States of America), the results may thus change.

Despite these methodological differences, similar tendencies are observed between PARTNER's results and SWAFEA's assessment. However the quantitative values regarding the fuel production impacts are sensitive to the considered methodology. This can be a concern for the fuel qualification under several regulations. For some cases, a fuel may comply with the emissions reductions thresholds under certain regulations or certification frameworks only. The existing differences also lead to the requirement for multiple assessments depending on the place where the fuel will be used (as a consequence RSB is currently implementing various methodologies in its LCA tool).

An additional methodological issue regarding LCA is related to indirect land use change (iLUC). Land use change may indeed result as an indirect consequence of the deployment of biofuel and may not be immediately visible. Indirect land use change results from the displacement of cultures because of the deployment of energy crops on areas that were used for other purposes and especially for food production. iLUC is difficult to observe and evaluate as it is an indirect process with a temporal and geographical shift. It's also something difficult to control through certification schemes since it falls outside of the control of the audited companies (agricultural producers). Currently neither the RSB nor the RED have introduced iLUC in their standards and there is today no consensus on a methodology to address iLUC in LCA.

4.4 Conclusion and recommendations about Life Cycle Analysis

As a conclusion, with view to the climate change mitigation target, it appears that CTL and GTL have no potential for reducing green house gas emission and generally even increase these emissions (in particular CTL). High efficiency carbon capture and sequestration is in any case required to contain these emissions. These processes are also feedstock intensive. However, these technologies are today mature and deployed at industrial scale (South Africa, Qatar,…) and they allow a diversification of the fuel supply to answer an increasing demand. The market may naturally push for the emergence of these fuels with increasing prices of crude oil or oil scarcity situations.

From the climate change point of view, the recommendation is thus clearly to look at biofuels which have the potential to significantly reduce life cycle GHG emissions especially in case of BTL. For HRJ, the ability to reach the RED's reduction target will require a careful choice of crops and an optimisation of the cultivation step. In any case, critical attention will have to be paid to land use change for the cultivation of energy crops as it is potentially the dominating effect in the whole emissions chain.

A major issue is the possibility of indirect land use change for which today no methodology or certification approach exist. There is thus an urgent need for methodological works on the way to address iLUC and on the suitable policy measures to control it.

Last, aviation being a global commodity, there would be a strong benefit from an alignment on a global recognised methodology for Life Cycle Analysis in order to avoid the necessity of multiple assessments and certifications of the fuels. Though probably not easy to achieve, such harmonisation would also provide a clear view of the ability of a given fuel to comply with the existing national or regional regulations.

5 Feedstocks and sustainability issues

The preference for biofuel being established from the climate change mitigation point of view, the next issue is related to the availability of the feedstock for the production of these biofuels and to the associated potential environmental and societal impacts.

5.1 Feedstock availability

There is a limited variety of biomass categories behind the different pathways considered for aviation: lignocellulose and oil for currently available processes (BTL and HRJ), lignocellulose and sugar for possible future processes. Sugar is currently used for automotive industry but the tendency is to develop the so called "2nd generation" routes producing sugar from lignocellulose as an intermediate product (lignocellulose ethanol).

An analysis of the potential availability of what could be called the "traditional" biomass was carried out within SWAFEA [10]. This includes biomass from agriculture, forestry and waste, corresponding to the already existing streams of biomass. A proper assessment was achieved for the agriculture biomass production, based on a simulation of the world agriculture production capability [11]. For forestry and residues, the analysis stands on literature data (in particular Smeet for forestry).

Potential availability should be understood as the total amount of biomass that could be produced on earth under given assumptions, mainly technical and ecological. The analysis doesn't constitute a prediction of the biomass production that is likely to be seen in 2050, but an estimate of the possible production from a "technical" point of view. Thus the result should be understood as a "maximum" biomass production capability assuming that the conditions for production are achieved and also that given sustainability constraints are enforced. Finally, at the different steps of the assessment, conservative choices were systematically done when a choice was possible.

The major constraints which were enforced for the assessment are:

- No competition between food and fuel, meaning that in the agriculture production scenario, lands are dedicated in priority to food production and that energy crops are only grown on remaining lands;
- No deforestation, meaning that only croplands and grazing lands are considered for energy crops production and that forest exploitation should only use the yearly increment (i.e the maximum amount of wood that can be harvested without reducing the stock);
- No negative land use change impact, meaning that only perennial crops are considered for cultivation on grazing lands;
- Preservation of a minimum amount of grazing lands (set to 30% of the remaining grazing lands when food demand is satisfied) and of undisturbed forests.

The agriculture possible rain fed production was assessed taking into account the available resources of cropland and grazing land in the world, their climate and soils, and projections on how much of these would be required for food security and the preservation of biodiversity. Productivity of food crops was extrapolated from the analysis of productivity increase over the last 30 years, with a limitation to current North America observed yields. Selected energy crops yields, including both lignocellulose and oil seeds, were estimated from agronomical considerations and the crops with the highest performances were regionally selected for the production scenario. To maintain flexibility for instantly returning to food crops if required, only annual crops were considered on croplands[44].

It should be noted that marginal lands were not considered in the assessment because their properties are not well enough characterised and it is often not possible to clearly know why they are considered as such (soil quality, slope, etc.). Productivity on such land would be in any case lower which also raises the concern of the profitability for the farmer.

From this assessment, agriculture appears likely to be the main potential contributor to energy biomass production (Table 3). Forestry biomass presents a potential from a technical point of view, but the introduction of economical[45] or ecological[46] constraints drastically reduce it to logging residues, even leading to a shortage of wood for industry and woodfuel when the highest projection of wood demand in 2050 is selected. For residues, the largest contributor is also agriculture (while urban wastes appear as a marginal contributor).

EJ/y	Agriculture	Forestry	Residues	Total
Primary energy	162.2	4.6	16.6	183.4

Table 3: Total biomass primary energy potential in 2050[47]

This potential biomass availability has to be assessed against the global energy demand as projected in 2050. The projections from the International Energy Agency have been used as a reference (**Table 4**) along with aspirational scenarios for aviation fuel demand: a physical carbon neutral growth of aviation (without economic measures) from 2030 at the emissions level of 2020[48], and the more

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[44] For more details about the agriculture production scenario, refer to [10]

[45] "Economical potential": the technical potential that can be produced at economically profitable levels

[46] Introduction of constraints such as restriction of exploitation to already disturbed forests in order to preserve biodiversity

[47] Biomass potential is expressed in energy equivalent due to the different type of biomass included which haven't the same energetic content. Expressing biomass in Mt, which seems to be a more natural unit, would thus be meaningless.

[48] This is more constraining than the mid-term high-level industry goal, which allows offsetting by economic measures

ambitious IATA target of a 50% reduction of the emissions in 2050 compared to 2005 (Table 5). A preliminary remark is that both targets represent an enormous challenge. Limiting aviation to its emission level of 2020 from 2030 implies a very strong ramp-up of biofuels production by 2030 to provide, only for aviation, the equivalent of 170% of the current total biofuel production, meaning 31% of the biofuels production projected by IEA at that time in its Scenario 450[49].

		Reference Scenario		Scenario 450	Blue Map Scenario
EJ/year	2009	2030	2050	2030	2050
Primary energy demand	502	705	977	604	750
Primary biomass demand	*51*	67	90	82	150
Biomass share	10%	10%	9%	14%	20%
Final energy demand	347	482	664	427	443
Transport final energy demand	95	140	204	126	112
Biofuels demand in transport	2.2	5.6	4.5	11.7	29.1
Share of biofuels in transport	2%	4%	2%	9%	26%

Table 4: Projection of energy demand

Reference scenario: continuation of present policies

Scenario 450: voluntary scenario limiting CO_2 in the atmosphere to 450 ppm and temperature increase to 2℃

Blue Map: scenario reducing emission by 50% in 2050 compared to current levels

EJ/year	2010	2030	2050
Total final energy consumption	8.6	14.7	24.4
"IATA carbon neutral growth" from 2030			
Biojet consumption	0	4.6	16.7
Biojet share	0.0%	31.3%	68.4%
IATA 50% reduction target in 2050			
Biojet consumption	0	4.6	24.4
Biojet share	0.0%	31.3%	100.0%

Table 5: Projection of aviation energy demand

(Assuming life cycle emissions reduction of 80% for biofuels)

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[49] This is the reason why a carbon neutral growth target from 2020 was not retained in the study, since it would correspond to an unrealistic development of biofuels production by 2020. The gap with IATA and ICAO target to cap aviation emissions from 2020 may be filled by economic measures.

Compared to the primary energy demand, the biomass potential represents 19% of the total demand in the reference scenario, and 24.5% of the aggressive "Blue Map" scenario. This is a significant percentage which nevertheless evidences the strong need for other energy sources.

If fully converted into biofuel, assuming BTL process and oils hydroprocesssing[50], this biomass can produce about 112 EJ/y of final energy, which represents 17% of the final energy total demand of the reference scenario, and 25% of the Blue Map's one. This potential biofuel production would cover the total transport final energy demand of this second scenario, and is significantly higher than the contribution of 29 EJ/y projected by IEA for biofuel in transport.

From the 112 EJ/y of biofuels, up to 32 EJ/y can be jet fuel if jet fuel is targeted in priority in oils hydroprocessing[51]. These figures have to be compared with the jet fuel demand ranging from 16.7 EJ/y for the carbon neutral growth scenario, and 24.4 EJ/y for the 50% emissions reduction target, when a 20% "carbon intensity" is assumed for biofuels[52], which is already an aggressive value with view to the results of the life cycle analysis.

Finally with this 20% biofuels "carbon intensity" assumption, reaching the 50% emissions reduction in 2050 would imply to use about 76% of the total biomass potential to make biofuels.

In such a scheme, 24.4 EJ/y of jet fuel would lead to the production of 61 EJ/y of co-produced non jet fuels, nearly the double of the projected biofuel contribution in transport of the IEA's Blue Map scenario. More generally, using the BTL conversion ratio, the Blue Map scenario projects only the use of 54 EJ/y (i.e. 36%) of the biomass primary energy for biofuels, meaning that 96 EJ/y (64%) of the primary biomass demand is dedicated to other uses. When 76% of our assessed biomass is used for biofuels, only 43 EJ/y are left for other uses. Reaching the IATA 50% reduction target thus means to displace a significant part of the other world biomass demands toward other sources of energy.

From this point of view, the carbon neutral growth scenario is probably more realistic whilst still very demanding. With 16.7 EJ/y of jet fuel, it requires 52% of the biomass to be processed into biofuels which is much closer to IEA's projection. This scenario would lead to 41.6 EJ/y of co-produced biofuels, a global share of biofuel in transport final energy demand of 52%, and would let 88 EJ/y for other uses.

When applied at European level, the analysis shows that for the same assumptions (carbon neutral growth from 2030 at 2020 emissions level, use of 52% of the available biomass to produce biofuels), Europe could be able to produce about 38% of its biofuel needs for aviation (meaning 38% of the amount of biofuels blended in the jet fuel uplifted in Europe).

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[50] Mass yield is 25% for BTL and 85% for vegetable oils hydroprocessing.

[51] Jet fuel ratio is about 25% for BTL and may be up to 70% in hydroprocessing.

[52] Emissions from biofuel = 20% of kerosene emissions

There are obviously uncertainties in such an assessment of the biomass availability. For example there are strong uncertainties on wood demand in the long term and the authors indicate a poor quality of the available data. Current waste use is also not precisely estimated. That's the reason why in the assessment, the most conservative value from the chosen evaluation were selected.

For agriculture, the assessed biomass production is "technical", meaning that the land is there to produce the amount of biomass with "reasonable" technology assumptions (yields) in agriculture. This does not mean that achieving this level of production is easy. It implies to push the technology development in all the geographic areas and to put in cultivation large amounts of lands that are not cultivated today. This requires investment in agriculture, education of the farmers and also the involvement of the required manpower. The assessed production also requires that the fertilizers are there. Last, if the yearly increase in yields considered in the study seems to be realistic considering the evolution over the last 30 years, it does not mean that the foreseen development of the production can be achieved in the next 40 years. In such technology development scenario, it is also possible that the diet developments change more rapidly than projected, thereby consuming part of the achieved increase in biomass production for food products.

Additional learning from the simulation of agriculture production is that the scenarios favouring the production of lignocellulose biomass lead to the highest production of primary energy from biomass and also to the highest potential production of fuel[53]. Associated with LCA evaluation, lignocellulose thus appears as a better choice from an environmental point of view. Oil seeds should nevertheless not be systematically rejected depending on the area; there are also required to ensure rotation on croplands where the choice was to grow annual crops in order to preserve flexibility. With view to emergence of new processes such as the "sugar to alkanes", the biomass availability assessment could also be complemented by the evaluation of a scenario favouring sugar crops and starch crops.

A final observation is that in the longer term, the analysis shows that there is a need for either a revolution in aircraft efficiency and energy sources or the identification of additional sources of biomass. Indeed the biomass availability is projected to decrease over time, while in 2050 the current projections do not see any stabilisation of air traffic and fuel demand.

5.2 The additional potential of algae

The satisfaction of energy demand by biomass introduces severe requirements and is likely to add to the pressure on agriculture production which would support both food and energy, with the risk of "bad years".

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[53] These scenario are nevertheless scenarios in which the choice to favor lignocellulose is done globally and not regionally optimized, results could be optimized by adapting the choice depending on the area – in particular in the oil palm belt

In addition to the classical raw materials considered in the assessment of biomass availability, new type of feedstocks can be expected in the future, in particular through the development of algae that promise higher yields than terrestrial crops and induce low requirements on land quality, avoiding a direct competition with food.

Algae are nevertheless still at research and development stage, the main challenges being to confirm at large scale the high performances obtained in laboratory or pilots, and to reach competitive production costs for energy production. Reaching these goals implies progress at all the steps of algal oil production chain, harvesting of algae and extraction of the oil being often recognized as the most pressing technical challenges. It also calls for a high integration of the process and the development of synergies with other application and coproducts. Indeed, economic, environmental and energetic balances of the production can be greatly improved if the CO_2 required for algae growth comes from flue gases and if the nutrients can be obtained from wastewater. The co-production of high value biomass is also essential to support the commercialization of algae based fuels.

The risk of proliferation of modified species with improved resistance and productivity is also raised by algae. The containment of the culture may be a major issue.

As a conclusion, considering the early stage of algae production, drawing conclusion about their future contribution to biofuel production seems premature. Research and demonstration at significant scale are still required and emergence of commercial large scale production may take time. However, their potential advantages clearly justify the continuation and the development of research in the field.

Last, it should be noted that most of the reported effort on algae is dedicated to autotrophic algae which use photosynthetic energy, CO_2 and nutrients for their growth. The heterotrophic pathways, in which algae grow on natural carbon source such as sugar and for which solar energy is not necessary, could also present some interest with view to the use of low value co-products from other industry (glycol for example). A deeper analysis would be required to evaluate their potential.

5.3 Sustainability issues

The product of biomass as a raw material for fuel production raises a number of significant sustainability issues. These concerns are at the origin of the various sustainability frameworks and certification schemes that have developed.

Sustainability issue covers:

- environmental impacts with the risks on deforestation and biodiversity, the impacts on water and the risk of proliferation of modified or invasive species;
- societal impacts, the first of which is certainly the risk of competition with food, with also the consequences on access to land and the protection of local population or small holders against the development of large plantations, and also the changes in practices or in the environment (creation of infrastructure for forest exploitation for example).

These potential environmental and societal impacts don't appear to be intrinsic features of either biofuels or crops used to produce them, if we except competition with food. Oil palm is for example not intrinsically a "bad" crop (from the productivity point of view it is even the ideal crop). Deforestation, water use, risks of pollution or societal impacts exist for traditional agriculture and are mostly relevant of agriculture management and development policy of the interested countries. The fact is that biofuels development will put additional pressure on existing trends.

Concerning the competition with food, the simulation of the potential biomass production tends to show that biofuel production is possible while preserving the priority for food. This simulation was of course done in a theoretical manner assuming the existence of a high level control on the repartition of crops production between energy and food crops. The reality may of course be different depending on the market forces that will drive the priority development of one or the other sector. Considering the multiple interactions that exist on food market and its global dimension, it is not clear that the food security issue may be tackled only through the certification schemes. FAO feeling is that, at world scale, the net effect on food security in the short term is likely to be negative, mainly due to the impact of biofuels production on food price. In the longer term, positive effects could be obtained if biofuels production contributed to the general development of agriculture, bringing technology and improved practices in developing countries that also benefit to food production. In any case, such progresses in agriculture are definitely requested in order to reach the biomass production potential required to satisfy biofuels needs.

Existing sustainability frameworks such as the RSB catch most of the sustainability issues and are quite comprehensive. If efficiently and rigorously applied, these certification schemes should provide guardrails for the potential impacts of the development of biofuels, in aviation as in the other sectors. In any cases, there is currently no clear alternative to such certification schemes.

5.4 Conclusions and recommendations

From the assessment performed within SWAFEA, it has been concluded that, with the currently available technologies and with "traditional" biomass only, the industry target of reducing aviation emissions by 50% in 2050 compared to 2005 levels would probably be too ambitious regarding the estimated biomass availability. This would call for an excessive share of the total biomass to produce biofuels.

The target of stabilizing emissions at their level of 2020 ("carbon neutral growth") appears as more easily feasible with view to the biomass potential availability in 2050. Such a target is already demanding but preserve biomass availability for other sectors than transport. It is thus more in line with the projection made International Energy Agency for the global demand.

If this target is technically possible, it is underlined that it requires a significant effort and investment in agriculture, putting in cultivation large amount of lands that are not cultivated today, the availability of fertilizers and of manpower. If it seems feasible by 2050 from the yield increase technical point of view, it does not mean that the foreseen development of the production can be achieved in the next 40 years.

Considering the level of uncertainties associated to any biomass availability assessment due to the complexity of the problem, the number of parameters to take into account, the uncertainties on many data, further consolidations of such evaluation are certainly required with view to the long term management of biofuels production development. Looking at the various existing studies and the spreading of the results which is also connected to the differences in the considered assumptions, a recommendation is to create a network of the relevant experts in Europe to link the involved teams, make them confronting their approaches and hypothesis, and initiate specific studies to clarify the uncertainties in a coordinated manner.

Further research on the impacts of the considered scenario should be pursued to analyse the consequences of the fertilizers needs and use, and also the environmental and societal impacts (with for example the question of the acceptance of such intensive use of lands).

To consolidate the biomass potential estimation, demonstration of energy crops performances under controlled agricultural practices ensuring sustainability and on various typed of lands should be initiated. This goes with an improvement effort of yield increase for the energy crops which are currently at a much lower step of development than food crops that benefit of centuries of improvement.

An analysis at a more regional scale the biomass production would also allow to better take into account local conditions and possible environmental impacts. It could be imagine to define on such basis a kind of guidance scheme for energy agriculture at regional scale.

Research on algae is an important axis to diversify sources of biomass and relax the pressure on agriculture. They should be oriented toward demonstrations at significant scale, to confirm yields and scalability of the production, and toward the study of integrated projects in order to maximise the potential benefit and minimize the life cycle impact on both emissions and energy.

To insure that aviation biofuel production will develop in a sustainable manner, environmental certification of biofuels following certification schemes such as the RSB or other similar frameworks appears as the main existing tools. If bilateral agreements between the European Union and third countries (as described in the Communication from EC on June 2010[54]) are likely to be the relevant level to address political aspects of sustainability, they should probably not necessarily exclude certification of the producers considering the local character of sustainability.

Concerning the aviation sector, the feeling in the SWAFEA team is that the inclusion of aviation in the RED should be more clearly stated and communicated. Indeed, in the course of the study, it appears that the RED application to aviation was not clearly understood by the stakeholders, many even

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[54] 2010/C 160/01 Communication from the Commission on voluntary schemes and default values in the EU biofuels and bioliquids sustainability scheme

believing that aviation was not concerned by the RED. It seems also that the present European regulations should be harmonized to enforce more efficiently the sustainability of aviation biofuels. In particular, while the RED introduce sustainability criteria and life cycle emission thresholds for biofuels, these biofuels qualify for zero emissions in the ETS application without any consideration of their actual sustainability and life cycle emissions.

As it has already been raised for LCA, aviation fuel being a global commodity, a harmonisation of sustainability regulations would help and should be searched at ICAO level for a worldwide application in accordance with ICAO's resolution on climate change.

6 Atmospheric impacts of alternative fuels

Aviation emissions have an impact on atmospheric chemistry and on the radiative balance of the atmosphere. For example, contrails formed by condensation of water vapour onto exhaust aerosols, including soot particles, may trigger the formation of induced cirrus clouds. Emissions of nitrogen oxides perturb the natural chemical cycles, lead to ozone production or destruction depending on latitude and altitude, and modify methane time of residence in the atmosphere. Along with sulphate aerosols formed in aircraft plumes, these indirect effects from burning fuel at cruise altitude provide further contributions to the greenhouse effect in addition to CO_2 emissions. The most recent evaluations of these in-flight effects estimate that the overall radiative forcing is 2 to 3 times higher when all emissions and induced effects are taken into account than it could be from CO_2 emissions alone.

Given the forecast of the air traffic increase, it is anticipated that air traffic may double in the next twenty years compared to the present situation. The contribution of air traffic to climate change would then be more significant..

Use of alternative fuels may reduce the overall impact of aviation on the atmosphere. But evaluating aviation atmospheric impacts requires to consider a lot of processes, each of them being dependent on the used combustion technology, on operations and on natural variability of the atmosphere. However general trends and preliminary conclusions can be drawn.

6.1 Emissions

The studies initiated in SWAFEA have been carried out considering Synthetic Paraffinic Kerosene (SPK) blends with Jet A-1 which are currently the main candidates for aviation alternative fuels.

From literature data and from the combustion tests performed in the frame of SWAFEA, the most notable impact of SPK blends on engines emissions is a strong reduction of particulate matter. Primary particles (soot particles) are mainly reduced due to lower fuel aromatics content. Available data indicate that soot initial concentration at the engine nozzle exit may be reduced by 30% to 90% at cruise conditions. Secondary particles, mostly volatile, are also significantly reduced as alternative fuels contain much less sulphur, which is responsible of new particle formation in the exhaust.

General trends are more difficult to establish for gaseous emitted species since some of them strongly depend on the combustion technologies, on the engine types and on the used settings. Some compounds emission indices may increase such as unburnt hydrocarbons and water vapour but this may, on a larger scale, be partly compensated by the fuel consumption reduction. CO_2 emissions will finally be reduced through the reduction of both the emission index and fuel consumption.

6.2 Aerosols and contrail formation

With reduced sulphur and aromatics contents, combustion of alternative fuel produces less primary and secondary particles. Apart from benefits on local air quality (potential reduction of respiratory diseases), such properties are likely to modify the processes of contrail formation, and therefore the impact of aviation on climate change.

Assuming that contrail formation is driven by condensation and deposition processes of water vapour on pre-existing aerosols, the reduction of these, using alternative fuels, tends to modify the contrail properties: crystals number density, mean size and optical properties are all significantly changed.

The sensitivity of contrail properties in the aircraft near-field to the initial concentration of exhaust particles was analysed within SWAFEA by numerical simulation [20]. It included the mean radius, the total mass of condensed vapor and the contrail optical depth. Computation were performed considering a CFM56 engine fuelled with a 50% blend of SPK with Jet A-1 for which literature data indicate a reduction of soot particles in the range between 30 and 50%.

The simulated impact of soot concentration on the optical depth of near field contrails is illustrated on **Figure 5**. The optical depth strongly decreases with soot concentration and the radiative forcing of the contrails decrease accordingly. A reduction of 30% in the emitted number of soot particles would translate in a reduction of the optical depth of the order of 40% and the radiative forcing of the contrails would decrease accordingly.

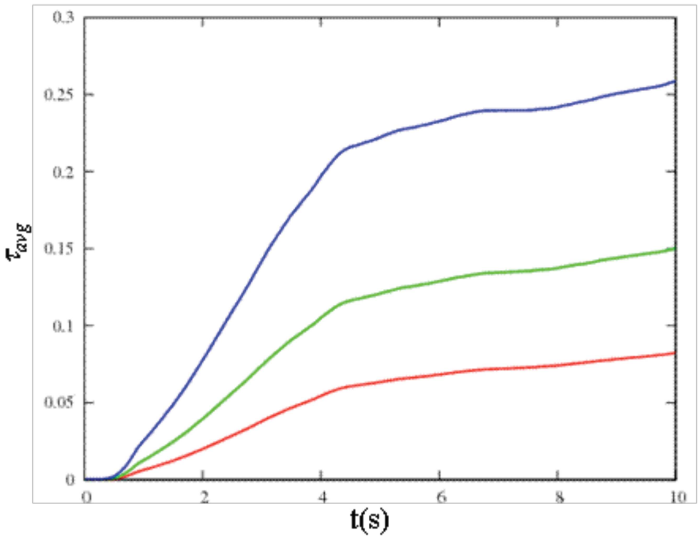

Figure 5: Contrail optical depth in an aircraft plume.

Blue: Initial soot concentration; Green: 50% reduction in soot; Red: 75% reduction in soot.

The radiative global forcing for contrails just after their formation is evaluated to be about 12 mW/m2 for the present day fleet compared to a forcing of 28 mW/m2 due to the CO2 aircraft emissions [21].

According to our results the forcing due to young contrails would be reduced to 7,2 mW/m2 for identical air traffic conditions if blended fuels are adopted.

However, the calculations have been performed for young linear contrails a few seconds after engine emissions. It remains to be seen how the optical depth will evolve for older contrails, when the water vapor used for ice crystal growth comes from the atmosphere rather than from the engine exhausts.

In addition, some other contrail formation mechanisms need to be carefully reviewed, as even in the absence of soot particles some alternative processes involving organic material from UHC and ambient aerosols may take over and produce contrails anyway.

As a conclusion, from the preliminary results of SWAFEA, alternative fuels with lower aromatics content may have a positive effect on contrails radiative forcing due to the reduction of soot emissions. Further analysis would nevertheless be required to draw complete conclusions.

6.3 Global impact

Expected changes in fuel consumption or emission indices from alternative fuels can be evaluated in terms of climate change and chemical perturbations of the atmosphere, especially regarding ozone concentrations.

The ozone perturbations for year 2026, have been compared for two different aviation global emissions scenarios: a reference case without use of alternative fuels and another one considering the use of a 50% SPK blend. These scenarios are based on a commercial air traffic forecast from AIRBUS which also includes a projected aircraft fleet (aircraft with more than 100 passengers only). They are used to build a global three-dimensional emissions map over the globe as an input for the atmospheric impacts simulations (Figure 6). Year 2026 was selected as a compromise between the available forecast and a time horizon at which alternative fuels may have reach a significant deployment.

37 existing or in-development aircraft were selected to represent the commercial fleet. Each aircraft is associated to a specific engine/combustor couple for which emissions when using Jet A-1 fuel are certified or given by engine manufacturers. Based on previous research projects, this commercial fleet should represent ~85% of total fuel burned by aviation in 2026, last part being made by smaller commercial aircraft (<100 pax), business aviation, general aviation and military fleet. Fuel burn and emissions were calculated along each mission by using industrial aircraft performance data, emission indices EIs and Boeing Fuel Flow 2 method.

For alternative fuels, emissions data introduced in the scenario were corrected mainly on the basis of the tendencies observed in literature data. Unfortunately experimental data are scarce and not available for all type of engines. For non already certified engines also, only tendencies can be given (based on preliminary engine data provided to Airbus by engine manufacturer). This introduces uncertainties in the results which are strongly linked to the considered engines fleet and emissions changes with alternative fuel.

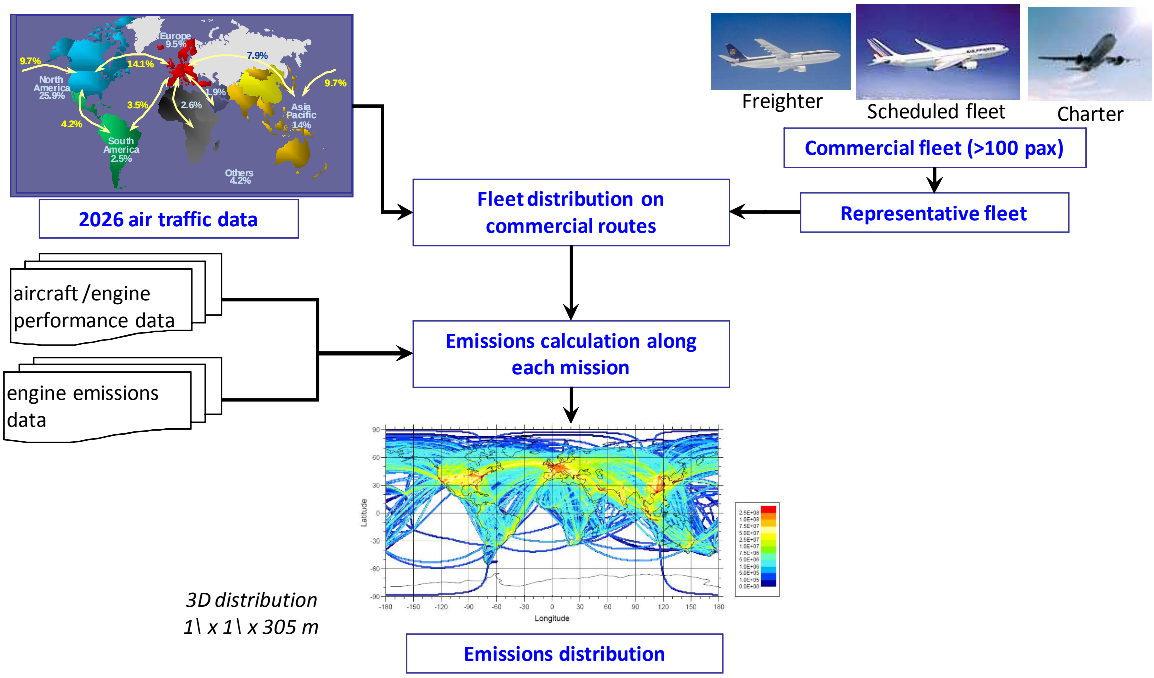

Figure 6: process for production of scenario fleet emissions with the ELISA tool (AIRBUS)

The global resulting emissions for the two scenarios are summarised in Table 6. The use of 50/50 SPK/Jet A-1 fuel conducts to a reduction of the fuel consumption for each mission. For the commercial fleet operating in 2026, this represents a global reduction of ~1.1% in fuel consumption and a reduction of ~1.7% in CO_2 emissions, when the H_2O emissions increase of ~3.7%. Strong reduction in SO_X emissions is also expected due to the low sulphur content of this alternative fuel.

The reduction of the fuel consumption conducts also to a change in the aircraft take-off weight, and so in the vertical profile that the aircraft makes along each mission. As consequence, more emissions are produced at higher cruise altitudes. Such variations could have some impacts that need to be quantified on the occurrence rate of persistent contrails.

The variations of NO_x and CO emissions are limited. The reduction of NO_X emissions results mainly from the fuel consumption reduction rather than from the changes in engine emissions indices (note that the engines selected to represent this commercial fleet have a strong influence on the final result). The increase of unburned hydrocarbon (HC) is more significant. NO_x and CO emissions contribute to ozone production.

Emissions in MT/year	NOx	HC	CO	CO_2
2002 emissions	2.06	0.013	0.338	
Reference 2026 (no alternative fuels)	5.31	0.034	0.871	1030.8
Alternative fuels 2026	5.23	0.038	0.872	1013.6
$\Delta_{\text{alternative/ref}}$	- 1.41%	+ 11%	+ 0.16 %	-1.13%

Table 6: Total aviation emissions for the 2002 case, the 2026 reference case and the 2026 alternative case

The impact of using alternate fuels on ozone formation has been simulated using a 2D photochemical model. The 2D model is a (latitude, altitude) mode; data are thus average in longitude.

The impact of alternative fuels can be first seen on the NOx atmospheric content (Figure 7, left panel). At the 2026 horizon, the NOx content would decrease by about 2% at cruise altitude in the Northern hemisphere. Consequently less ozone would be produced by the NOx aircraft emissions. In relative terms the ozone production would decrease by about 2.4%, with little seasonal and latitudinal variations (Figure 7 right panel).

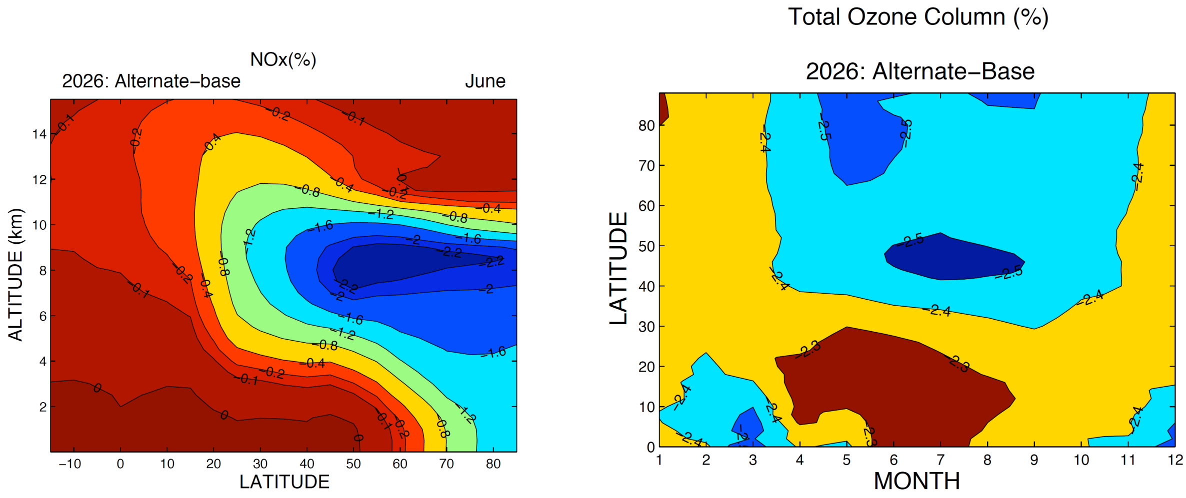

Figure 7: NO_X and O_3 variations due to the use of alternate fuels at the 2026 horizon

With the hypothesis used for the simulation, the use of alternate fuel should have a very modest impact on the ozone atmospheric content. According to the model calculation, the ozone production at the 2026 time horizon would decrease by about 2.4 % when alternate fuel is used. This is a very small number that is at least one order of magnitude lower that variations due to natural variability or change that are expected to follow the decrease in the stratospheric chlorine loading. In addition, this result is quite uncertain because the NOx index of emission for alternate fuel appears to be very variable from one engine type to another, and also according to the power regime used. Thus the NOx emission reduction is result of a delicate balance directly related to the details of the fleet scenario. Most of the NOx decrease seems however to be related to the lowest fuel consumption in the alternate scenario compared to the reference one.

6.4 Local air quality

Local air quality simulations have been performed with a chemistry transport model in Paris area, including Orly and Roissy airports. Air traffic and aircraft emissions were provided by the same scenario than the one use to study the global impacts of alternative fuels and also correspond to the use of a 50% blend of SPK with Jet A-1. Anthropogenic gas emissions were taken into account at the European scale from various available inventories such as EMEP[55] or GlobCover.

Given a set of NO_x, SO_x, NH_3, PM, VOCs and CO emissions, the concentrations of 44 gas-phase and aerosol species have been computed. The results have been used to evaluate air quality indicators as defined in the Directives (Air quality Directive, Directive on National Emission Ceilings).

The reduction in particulates emissions associated to SPK use is a positive factor for local air quality since soots are considered as an important source of severe respiratory affection and sulphur oxidation leads in particular to sulphuric acid formation. However, aircraft soot emissions could not be introduced in the simulation because no extensive database is available for these emissions. Indeed, during engines certification, only smoke numbers[56] are collected for particulate emissions and there is no agreement on a relation between smoke number and soot particles size distribution or mass. Therefore, no data can be used from certification measurements. In flight measurements or ground level measurements have already been done on soot particles but no extensive set of data is available for different engines and operating conditions. A quantitative evaluation of the impact of soot emissions reduction is thus currently not possible.

The simulation results show that the impact of the use of a 50% SPK blend with Jet A-1 does not give any visible impact on local air quality for O_3 and PM10 concentrations. The SO_2 aircraft emissions decrease is significant but its impact is limited on sulphate concentrations since the SO_2 contribution of aircraft represents only 2 to 3 % of the total SO_2 emissions. In France, sulfate concentrations have mainly a regional or continental origin and a local measure on a low emitter has a negligible impact on local air quality.

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[55] www.emep.int

[56] The smoke number is measured by collecting soot on a paper filter. The color change of the filter gives yhe value of the smoke number.

6.5 Conclusions and recommendations for the atmospheric impact

The studies initiated in SWAFEA have been carried out considering Synthetic Paraffinic Kerosene (SPK) blends with Jet A-1 which are currently the main candidates for aviation alternative fuels.

From literature data and from the combustion tests performed in the frame of SWAFEA, the most notable impact of SPK blends on engines emissions is a strong reduction of particulate matters, both soots and aerosols, due to the lower contain of these fuels in aromatics and sulphur. Available data indicate that soot initial concentration at the engine nozzle exit may be reduced by 30% to 90% at cruise conditions.

This reduction in particulates emissions is a positive factor for local air quality. However a quantitative evaluation of the impact of the reduced soot emissions is currently not possible because no extensive database on aircraft soot emissions is available to perform simulations. The consequence of the reduced SO_2 emissions have been evaluated on the base case of Paris airports but the impact on local air quality turns out to be rather limited because aviation is not the main source of sulphate in France.

Particulate matters also influence the formation of contrails and of induced cirrus clouds which modify the radiative forcing of the atmosphere. Detailed simulations of a turbulent wake performed in SWAFEA show that reducing the soot emission index reduces the diameter of the ice particles that form on soots and following decreases the optical depth of the contrails. This is likely to reduce the effect of the contrails on radiative forcing and thus on climate. Additional studies on alternative contrail formation mechanisms are clearly recommended as current conclusions remain preliminary.

The impacts of SPK blends on other engines emissions, like CO, NOx or UHC, are much more limited. In particular, NOx are mainly dependant on the combustor configuration and for SPK fuel, the difference of fuel properties compared with Jet A-1 have only a second order effect. The impact may be positive or negative depending on the engine and thrust rate. Emissions variations are also induced by the consumption reduction due to the higher heating value of SPK.

The global emissions changes due to the combustion of a 50% SPK blend should modify the concentrations of the ozone produced by aviation but this change is expected to remain modest and below ozone natural variability, considering the limited influence of this fuel on NO_x. Additional studies may be conducted using more detailed 3D simulations when a more significant amount of data will be available for engines emissions with alternative fuels.

7 Economics of alternative fuels

An economic analysis has been carried out in the frame of SWAFEA to answer a number of questions about the economic viability of alternative fuels in aviation. These are:

- What are the economic realities influencing the feasibility of alternative fuels for aviation?
- How do these alternative fuels compare with the business-as-usual case of conventional fuels?
- To what extent might different (European) policies affect these economic realities?
- What are the key issues that need to be overcome for alternative fuels to be viable in the aviation industry and what strategies could be used to make it happen?

The analysis has been mainly focused on the current short term candidates for deployment which are BTL and HRJ. For less mature solutions that could emerge in a longer term, an economical assessment is more difficult because reliable publicly available data are lacking. The Sugar-to-alkanes routes were nevertheless also analysed but with a higher level of uncertainties and a more qualitative description.

The economical assessment has been centred on Europe and considers the supply chain for the aviation fuel uplifted in European countries (Figure 8). It has been built around the industry target of reducing by 50% the CO_2 emissions of the aviation sector in 2050 with respect to 2005 levels. This determine the ramp up of the industry and so the "learning" effect that can be expected from the production development especially concerning the processes and the industrial facilities. In this approach, it was assumed that there was no limitation regarding the resources (in terms of both feedstock, capital for investments or number of plants) and that fuel production plants were coming online whenever more production capability was required to carbon emissions reduction target. Since only "drop-in" fuel situations were considered, the implementation of alternative fuels doesn't imply any other extra cost for the end users than the additional cost of the fuel.

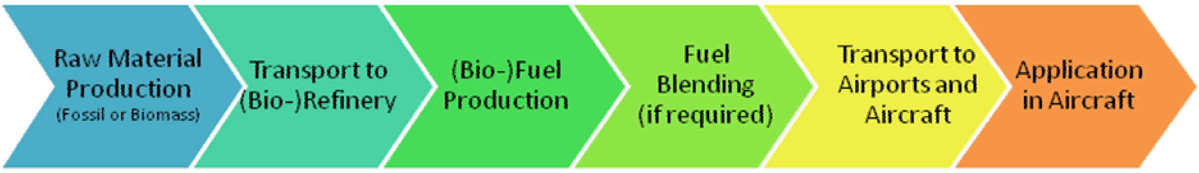

Figure 8: aviation fuel value chain considered in the economical analysis

The jet fuel demand considered in the analysis is in line with IATA projection [1] which sees a rise of the global demand from 200 Mt of kerosene in 2010 to 300 – 350 Mt by 2030 despite continuous improvements in fuel efficiency. To account for the maturity of the European aviation market, a

European market growth rate of one percentage point less than the global rate was assumed in this work. The following parameters have been used:

- European jet fuel demand in 2010 (52.65 million tonnes, equal to 2008 consumption);
- Annual air transport growth (3.5% in 2010, linearly decreasing to 2% in 2050);
- Annual fuel efficiency increase (1.8% in 2010, linearly decreasing to 1% in 2050).

Different projections for crude oil supply published by the U.S. Energy Information Agency (EIA), the Association for the Study of Peak Oil (ASPO) and historical data published by BP were extrapolated. Based on an economically obtainable jet fuel fraction of 15%, sufficient conventional crude oil based jet fuel can be produced to meet aviation demand and no supply restrictions for jet fuel were integrated in the analysis. The market price for jet fuel was extrapolated from data available from the US EIA.

As aviation will be included in the European Trading Scheme from 2012, carbon prices assumptions [19] were included in the study (Figure 9).

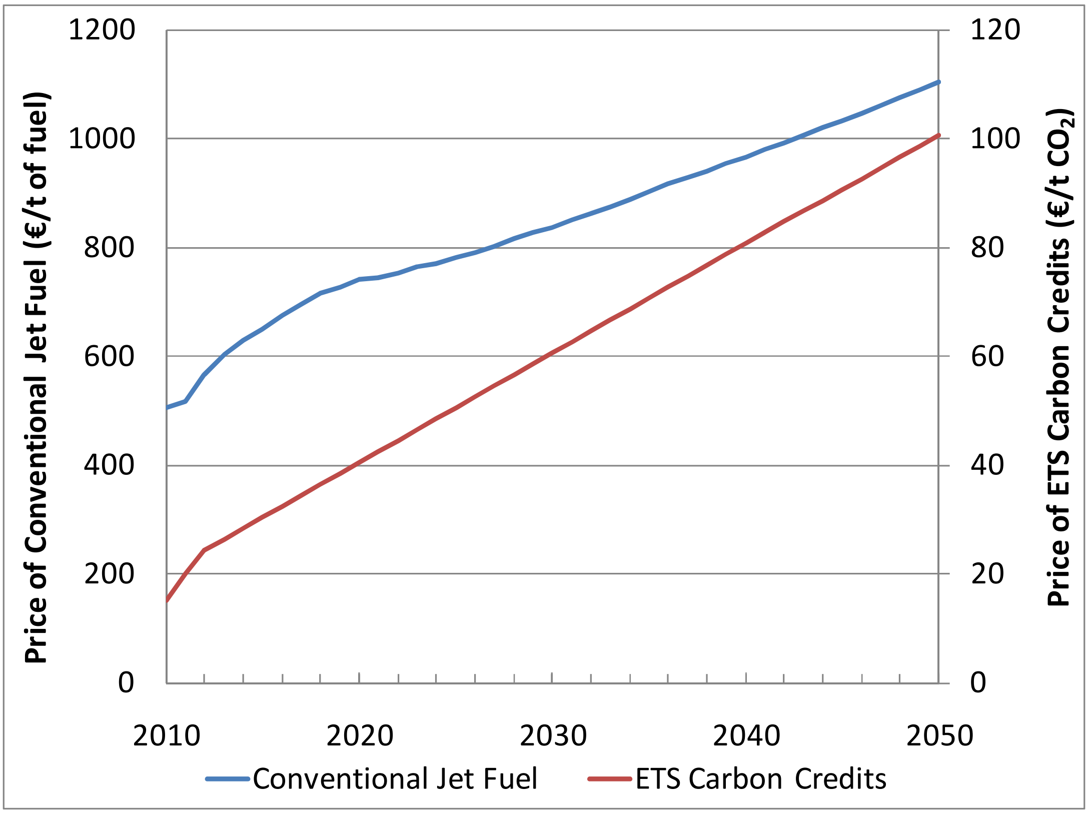

Figure 9: Projections for jet fuel and emissions certificates prices.

7.1 Cost trends for alternative fuels

In order to provide reference figures for the economics of alternative fuels, a reference development scenario was built for their production ramp-up. It assumes that the fuel production increases in such a way that it matches the emissions reduction target selected as a reference, a 50% reduction in 2050 with regard to 2005. The biofuel demand is then determined considering that:

- Before 2020, a slow take-off of biofuels is anticipated - the biofuel fraction thus increases linearly from 0% - 0.1%;
- From 2020 onwards the biofuel fraction is increased by 2.44% annually to reach 73.4% in 2050.

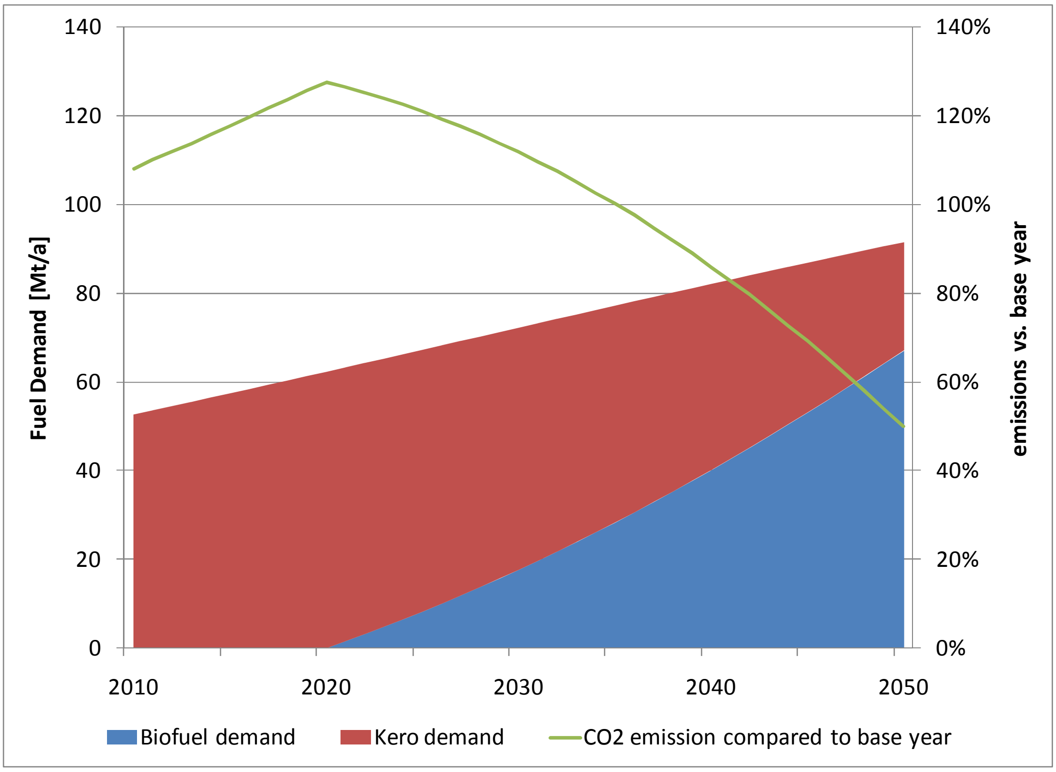

Figure 10: reference scenario for fuel cost evaluation

In this scenario, it is assumed that biofuel accounts for zero emissions, meaning that the actual life cycle emissions are not taken into account. In addition no limitation in blending ratio is considered with view to the fuel approval in aviation (which would require technological development to overcome the current limitation).

7.1.1 BTL pathway

A number of assumptions are required to assess the economics of BTL.

Firstly, it was assumed that BTL plants are located close to the feedstock source to minimize feedstock transport cost. Indeed, only minimal processing at the source is taken into account. Hence the BTL feedstock typically has a rather low energy content, which implies that the feedstock has a low energy density in terms of volume and/or mass. The cost and efficiency of a Fischer-Tropsch plant increase with its production capacity. Therefore, there is a trade-off between the distance the feedstock has to be transported and the capacity of the plant. According to Boerrigter, BTL plants have an optimum production capacity between 0.5Mt and 1.5Mt of FT-products (diesel, jet fuel and light ends) per year. We therefore have assumed that the optimum production capacity is the production of 1Mt/a and that this plant size is reached through an intermediate size step with 0.5Mt/a production capacity in the first years due to the fact that, currently, only much smaller scale BTL plants are operational. The corresponding maximum transportation distance for the biomass varies between 80 km for the intermediate plant size and 115 km for the optimum size. The fuel blending with Jet A-1 takes place close to a conventional refinery.

For the feedstock, Short Rotation Coppices (SRC) are considered as example to represent the cost for the production of woody raw material.

Considering the uncertainties on future biomass prices, two different assumptions were used for feedstocks price development:

- An optimistic hypothesis, in which the feedstock price decreases in parallel with yield increases as described by Wit (Wit D.,2008)[57];
- A pessimistic assumption, in which the feedstock cost is assumed to increase at the same rate as crude-oil.

Market will have a strong influence on feedstock price making any prevision hazardous. There is no clear evidence of a direct link between feedstock price and crude-oil price in the long term but this assumption is made to show the influence of an increase in the cost of feedstock.

To estimate a market price for the BTL fuel, a fixed profitability margin of 25% was assumed for the fuel producer. Capital expenditures (CAPEX) are handled in the form of an equity charge on the investment. This means that the capital investment is repaid by an annual charge for a given time period. This basically reflects a financing plan, in which an investor buys an asset and receives annual payments from an operator. The reference equity charge is 12% of the CAPEX over 20 years; it results on a break even for the investor of about 8 to 10 years.

As typically jet fuel only accounts for 25% of the product mix, only 25% of the total capital cost is taken into account for the calculation of the jet fuel production cost. Co-products as electricity, which are not clearly related to any given product, are taken into account pro-rata.

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[57] In this assumption initial cost of feedstock is 4.3 €/GJ (76 €/ton) with a 12.5% margin.

Figure 11 shows the obtained results for the BTL fuel cost evolution over the period compared to the reference Jet A-1 price and Jet A-1 price increased by the ETS projected cost.

The results first evidences the very strong influence of feedstocks cost on the BTL price and the time at which an equivalence price with Jet A-1 may be reached. For the optimistic hypothesis this equivalence is reached around 2030 when the projected carbon price is added to jet fuel price, while it is delayed beyond 2050 with the worse hypothesis. Then economics viability is never reached within the timeframe of the study, demonstrating the major importance of achieving the required biomass production at a competitive price.

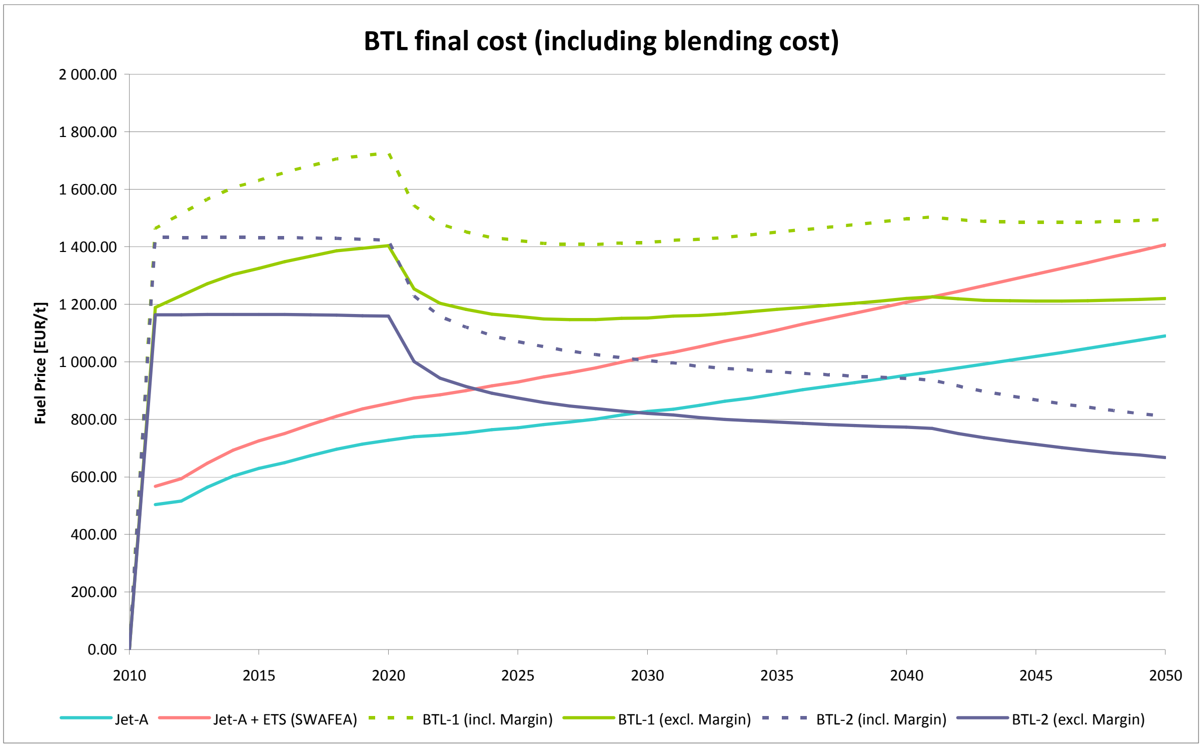


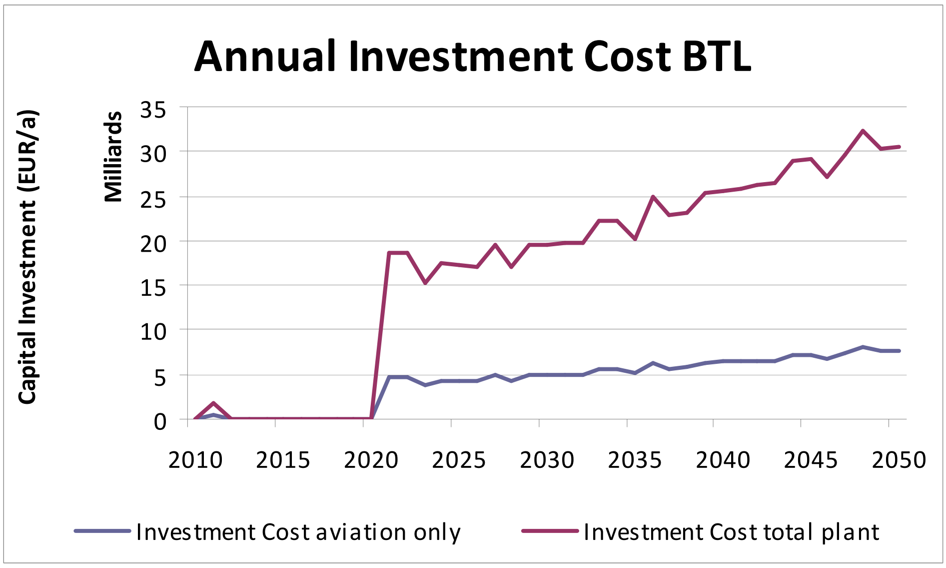
Figure 11: BTL delivery cost to airlines

(BTL-1: high feedstock price, BTL-2: low feedstock price, blending cost included)

A second result is that ETS, at the projected carbon price level, has an impact on the financial viability of BTL, advancing the price parity by about ten years. This is nevertheless far from sufficient to compensate the high production cost of BTL in the initial period.

The annual investment required to build the necessary plants is shown on Figure 12. Approximately 300 BTL production plants are required by 2050. In case of BTL, capital expenditures are very high due to a high complexity of the plants. As described above, only a fraction of the investment cost has to be covered by aviation, as the major share of the production will most likely be dedicated to road transport. Under these assumptions aviation would have to invest between 5 and 7.5 billion Euros per year over the investigated timeframe.

The question arises of the profitability of this high quality fuel in automotive industry which will have to support most of the required investments. Currently, road transport favours FAE which production cost is much lower than BTL or HRJ. However the FAE blending ratio in diesel is limited due to technical reasons that may be even more stringent with future high technology diesel engine. Higher blending ratio will require car industry to move to SPK fuel types all the more that some FAE may in addition not comply with the RED emissions reduction target. This would create a synergy with aviation, provided that automotive market doesn't monopolise all the production.



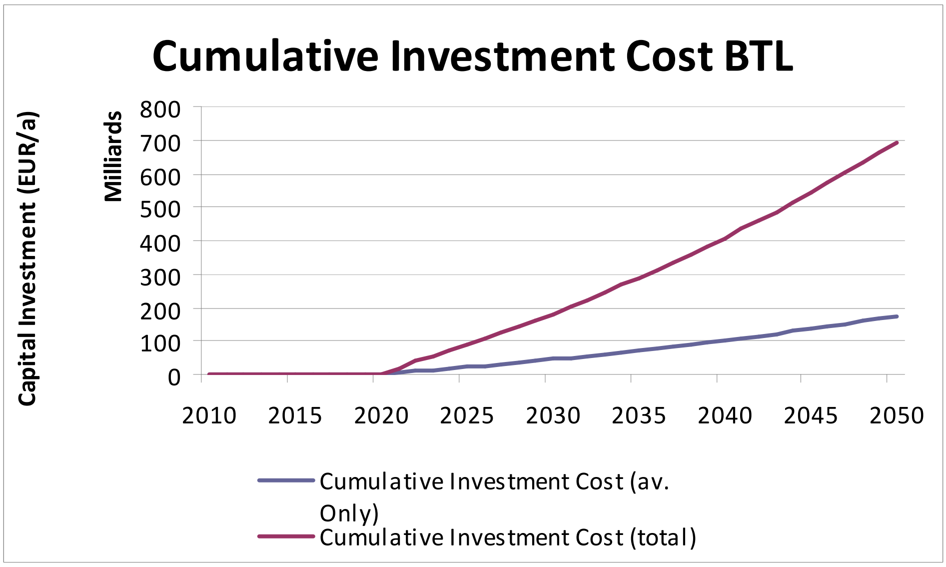


Figure 12: Investment required for BTL

Finally, for the two feedstock prices assumption, the cost breakdown of the fuel is given on Figure 13.

CAPEX is a significant contributor for BTL production cost. With the assumption of low cost feedstock, it's the dominant one over the entire period, representing more than 40% of the production cost. If increasing costs of feedstock are considered, it represents 36% in 2030 of the production cost and 28.5% in 2050. A quick estimate shows that, with this pessimistic assumption on biomass cost, reaching the parity of BTL price with kerosene (including carbon price) in 2030 would approximately require to halve the fuel transformation cost (including CAPEX plus operation and maintenance). This gives an estimate of the improvement of economic efficiency which is required on lignocellulose feedstock transformation processes in order to make them viable in a world of expensive biomass. A second way is to drastically increase the transformation yield.

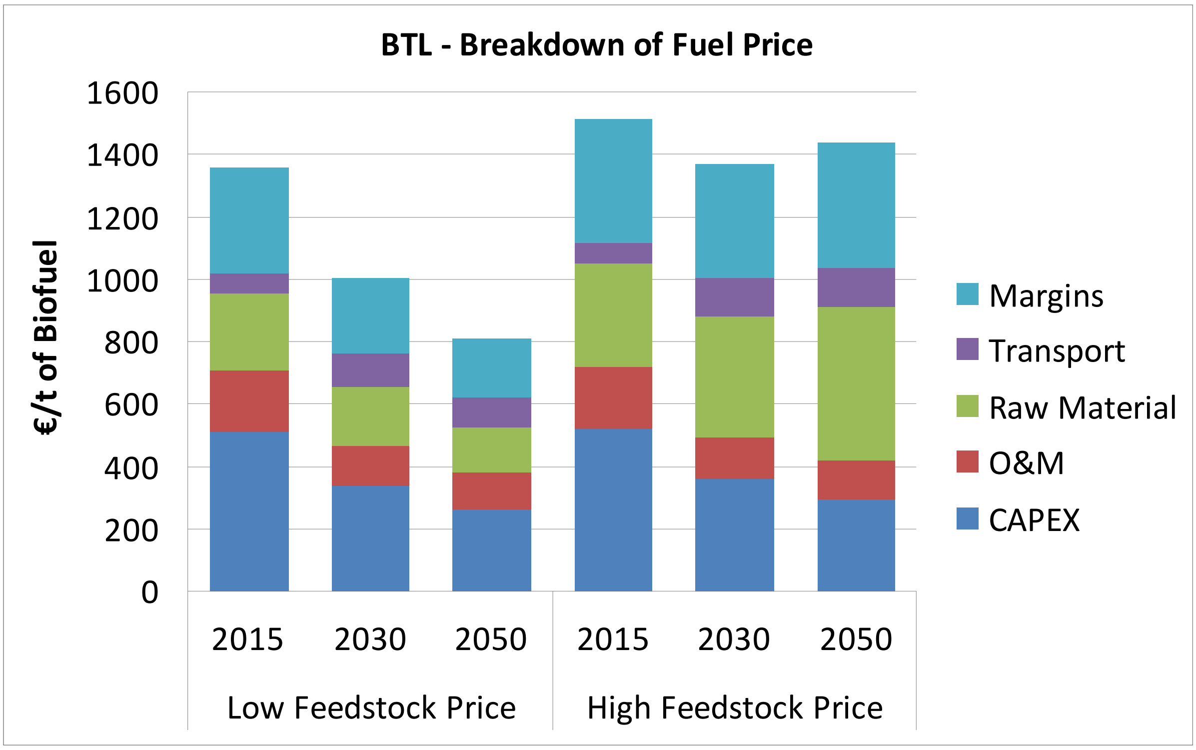


Figure 13: price breakdown for BTL

(All farming cost included in raw material – CAPEX including biomass preprocessing and fuel production)

7.1.2 HRJ

Vegetable oils are considered the main feedstock for HRJ and, because of their high energy density, it is economically viable to source the feedstock globally at world market prices and transport it to the processing facility.

Under these conditions, it seems favourable that hydrotreatment occurs in centralized, dedicated large-scale plants. Since the hydrotreatment process requires significant amounts of hydrogen input, it is assumed that these plants are located at or close to conventional crude oil processing infrastructure, which also guarantees access to the required transport infrastructure.

Because of the vicinity to conventional jet fuel production locations, the fuel will be injected in the conventional jet fuel supply chain directly at the plant gate.

The supply to large scale processing plants will most likely be based on global sourcing from different regions and oil crops. For the purpose of this study we have assumed the production cost of European-grown oil crops, such as sunflower and rapeseed, with modern highly-efficient solvent extraction mechanisms as a benchmark for future specific production cost, i.e., the production cost per unit of energy.

As for lignocellulose feedstock, two different assumptions were made for feedstocks price evolution:

- An optimistic hypothesis, in which the feedstock price decreases in parallel with yield increases as described by Wit (Wit D.,2008)[58];
- A pessimistic assumption, in which the feedstock price is assumed to increase at the same rate as crude-oil.

For oil even more than for lignocellulose, market will have a strong influence on feedstock price making any prevision hazardous. Again the evolution of price with crude oil gives an indication of the impact of an increase of feedstock cost even though no direct correlation is demonstrated between vegetable oil and crude-oil.

As for BTL fuel, a fixed profitability margin of 25% is assumed for the fuel producer. Capital expenditures (CAPEX) and co-products are handled in a similar way. Though the HRJ process allows the production of a large fraction of jet fuel, we assume that the total amount of liquid output is optimized from an economical point of view, which leads to a relatively low jet fuel fraction of 20%.Co-produced fuel is also treated in a similar way (a relatively low ratio of jet fuel, 20%, is assumed). By products from oil extraction (filter cakes) are sold at world market prices for animal feed and accounted for as a benefit for the feedstock producer.

Figure 14 shows the obtained results for the HRJ fuel cost evolution over the investigated timeframe compared to the reference Jet A-1 price.

The same trends as for BTL are observed. They result for HRJ in a even more uncertain viability. In the best case, in which an ETS scheme is in place and feedstock is low, price parity is not reached before 2041. For the high feedstock price assumption, ETS fails in providing economic viability for HRJ by 2050.

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[58] In this assumption initial cost of feedstock is 4.3 €/GJ (76 €/ton) with a 12.5% margin.

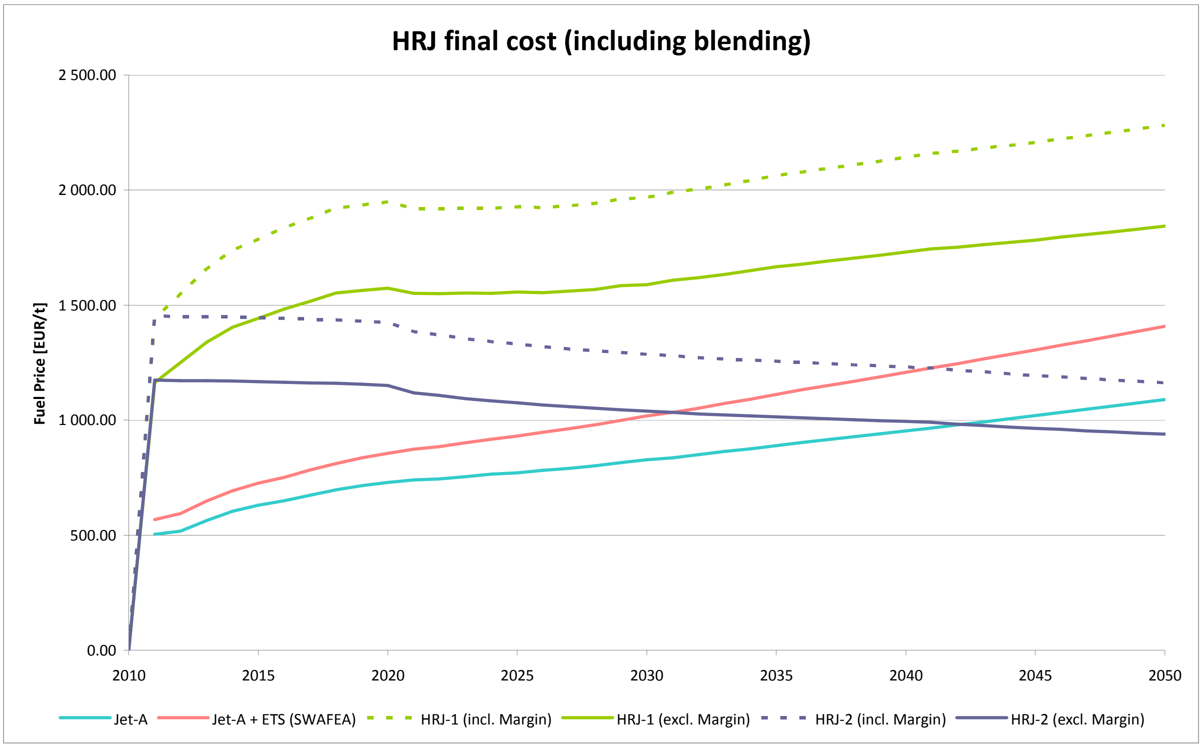

Figure 14: HRJ delivery cost to airlines

(HRJ-1: high feedstock price, HRJ-2: low feedstock price, blending cost included)

The required production capacity translates into approximately 80 hydroprocessing plants (Figure 15). The corresponding investment is much lower than the one needed for BTL due to the lower complexity of the plants. However this does not result in a better economic viability compared to BTL. HRJ cost is much more dependant from feedstock than BTL. Thus it also less benefits from learning and scaling.

The cost breakdown for HRJ is given on Figure 16. Even in the case of low cost feedstock, the production cost is strongly dominated by the feedstock price. This lets little hope for economic efficiency gains from the process improvement, especially in case of high prices feedstocks. Oil prices appear as a severe limitation for any biofuel technology based on vegetable oil.

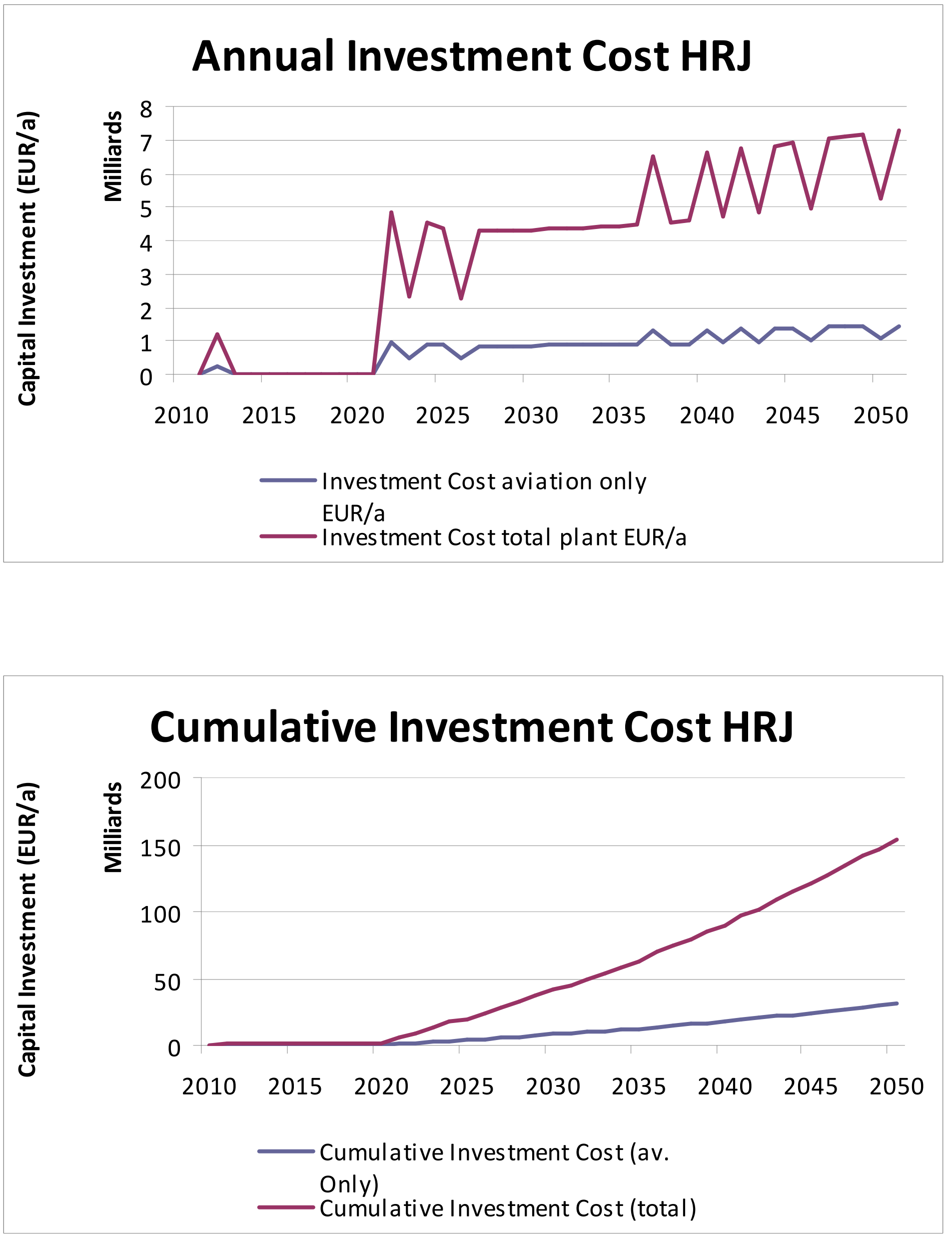

Figure 15: Required investment for BTL

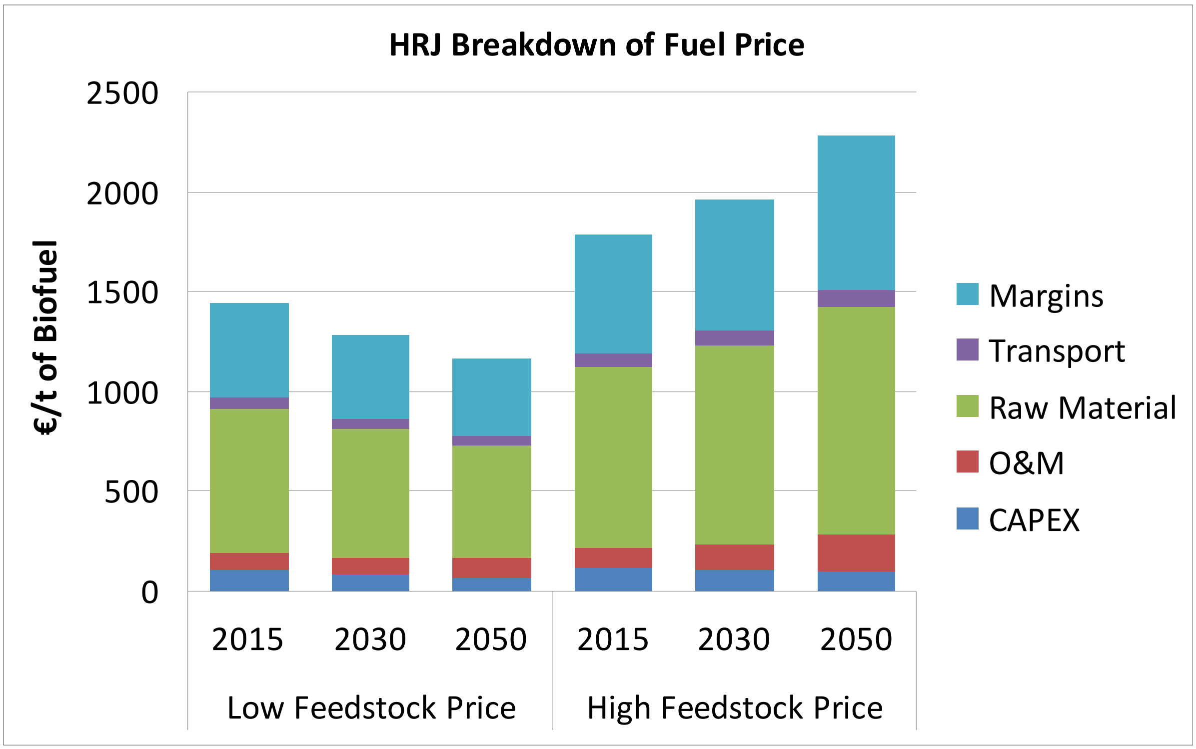

Figure 16: price breakdown for HRJ

7.1.3 Sugar to hydrocarbons

Currently the conversion from sugars and lignocellulosic material into hydrocarbons is still in the research/pilot phase and it is difficult to draw quantitative conclusions regarding the large scale economics of the processes. Nevertheless, the analysis has shown that under the given assumptions a significant potential exists to deliver a fuel comparable in price with BTL and HRJ. Two potential routes were investigated, one starting from sugar and using a chemical conversion, the second starting from lignocellulosic material and using bio-organisms to produce hydrocarbons.

The catalytic conversion route from sugars was considered similar to HRJ processing and closely linked to the price of feedstock and the capital cost for the installation. Because of the novelty of the technology, no reliable sources exist on capital cost for sugar to alkane conversion plants. However, it is expected that these plants have a similar complexity as HRJ plants, which are taken as a benchmark for cost, but increased by 50% to account for added processing of the final fuel. The price of sugar feedstock was extrapolated from historic data. This set of assumptions, less favourable than for HRJ and BTL fuels, leads to high initial prices. The current overall efficiency with respect to jet fuel is low due to the low selectivity of the catalytic conversion (6% from a white paper from Virent Technologies). The comparably high cost for the conversion in the catalytic process has limited potential for reduction, given the complexity of the operations.

The biological conversion route from lignocellulosic material on the other hand is based on a two step process, first breaking down the raw material into sugars, which then are converted into hydrocarbons by fermentation. The required processing technology is much less complex than a BTL plant but can use the same, relatively cheap feedstock. This combination promises a good potential for cost reduction. As it is expected that the plants have a similar complexity as lignocellulosic ethanol plants, these were used as a proxy for cost. A slightly higher price (+20%) was considered for feedstock considering the higher grade required for the material compared to BTL.

At the current development stage both processes make inefficient use of feedstock and it is questionable if sufficient sustainable feedstock is available to produce the required amounts of jet fuel. However, increasing efficiency, e.g., by selection of suitable bio-organisms for conversion, can help to solve the problem. The analysis shows that the production cost has the potential to drop below the cost of BTL fuels if efficiencies are increased.

Because the sugar to alkane process can run from waste materials from e.g. dry matter from vegetable oil production, a potential combination of processes can improve the overall use of feedstock material for fuel production.

Acknowledging the large uncertainties involved with benchmarking technologies in the development stage, it seems that lignocellulosic bio-conversion route is more promising from the economic point of view than the catalytic conversion, provided that the efficiency of the process can be significantly increased.

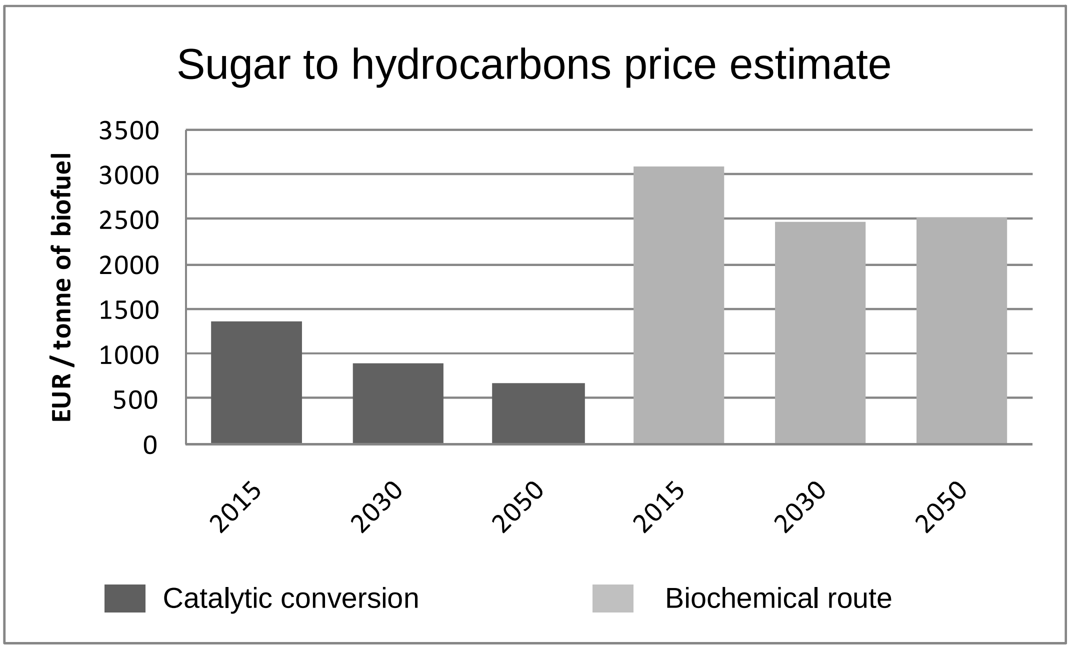

Figure 17: Price estimate for "sugar to hydrocarbons" pathways

7.2 Influence of incentive policies

Previous results show that neither BTL nor HRJ are cost-competitive with conventional jet fuel in the short term, even for the most favourable feedstock prices assumptions. Therefore, without any incentive policy, their deployment is not likely to take occur.

Different policy levers may be considered to support the deployment with view to the achievement of the environmental targets. Three scenarios have been investigated within SWAFEA to evaluate the influence of different approaches on the deployment of biofuels. This study was done assuming that "low" cost feedstock can be made available and hence that the competitiveness of biofuels can be reached after an initial period during which support is required.

The first one consists of a quota mandate which prescribes that a fraction of aviation fuel consumption must be met by biofuels. It considers a similar ramp up of biofuel introduction than the previously described reference scenario, except that it targets a linear increase of the biofuel fraction from 0% in 2010 to 5% in 2020. Then, until 2050, the biofuel fraction is increased by 2.28% annually to reach 73.4%, in order to meet the 50% emission reduction targets in 2050. In such a scenario, airlines being "captive" customers of biofuels, the risk is an uncontrolled increase of the fuel producer profitability margin. For the sake of the evaluation, this margin was nevertheless kept at 25%.

The second scenario relies on the assumption that the current ETS policy is extended up 2050. The approach makes use of tradable carbon credits, which means that CO_2 savings are decoupled from the emitter. Each party falling under the regulation is credited an emission allowance, which gradually is reduced over time. If a party manages to emit less than their allowance, they generate credits that can be traded in the form of certificates to other parties.

As from the fuels costs trends, ETS are not expected to be sufficient to make the deployment of alternative fuels happen in aviation, this second scenario aims at measuring the remaining gap between ETS and economic viability of biofuels. The strong assumption that the biofuels are sold at the Jet A-1 price increased by the carbon price was thus added. This allows to estimate the deficit to be covered by additional measures on top of ETS for the deployment to take place. This scenario is thus named "Limited biofuel price". The influence of the biofuel ramp-up, and associated learning effect, was also investigated through this scenario with a quite more aggressive take-off of the production leading to an already significant amount of biofuels in 2020 (in a purely theoretical approach, 25% of biofuel is introduced). Cost reduction by learning and scaling is thus achieved earlier.

In a third scenario, a limited carbon market was considered, in which emission credits are only tradable within the aviation sector and airlines have to pay penalties if their needs exceed their CO_2

allowances. This basically results in a higher possible sell price for the biofuels: biofuel price is in this case the conventional jet fuel price increased by the carbon price plus the penalties[59].

The economic consequences of these different scenarios are summarised in Table 7 for the most optimistic assumption concerning feedstock prices.

The associated cumulative cash flow during the initial ramp-up is given on Figure 18 and Figure 19.

Scenario	Fuel solution	Cumulative Profit 2050 (billions €)	Profitability time for Operator	Year of price parity with conventional jet fuel[i]	Jet fuel price (blend)	
					2030	2050
Quota mandate	BTL	+560	2010	2030	887	880
	HRJ	+870	2010	2041	960	1143
Limited biofuel price	BTL	+1100	2026	2021	933	1337
	HRJ	+870	2042	2034	933	1337
Limited carbon market	BTL	+2100	2010	2016	1190	2441
	HRJ	+2140	2017	2018	1190	2441

i: include the projected values for ETS and for penalties in corresponding scenarios

Table 7: Business case results for the considered scenario

(The reference price without ETS is 836 €/t in 2030 and 1104 €/t in 2050)

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[59] Penalties have been set at 100 € per ton of carbonin 2012 with a increase of 25% each subsequent 5 years period.

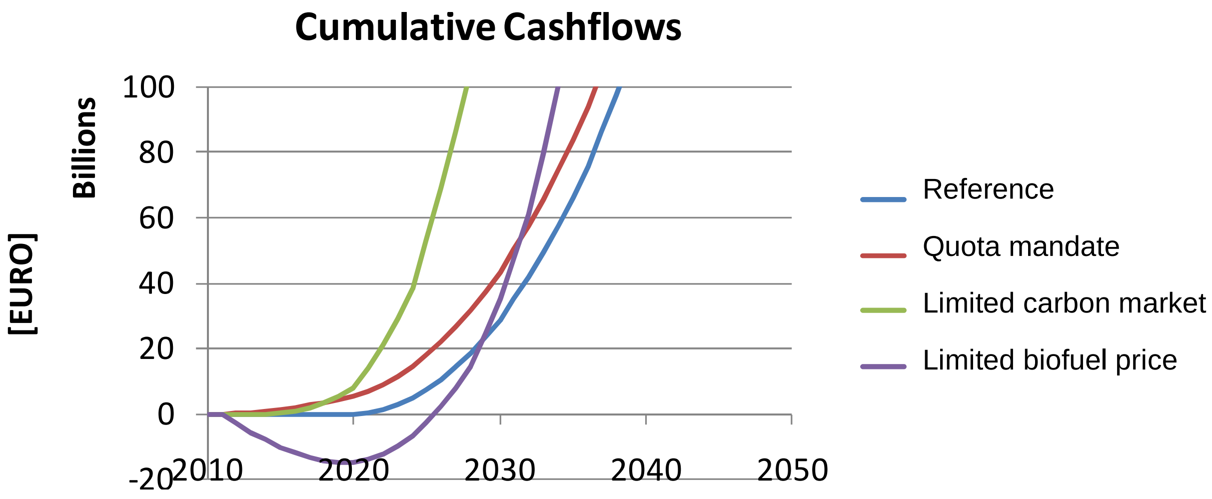

Figure 18: Cumulative cashflow for BTL

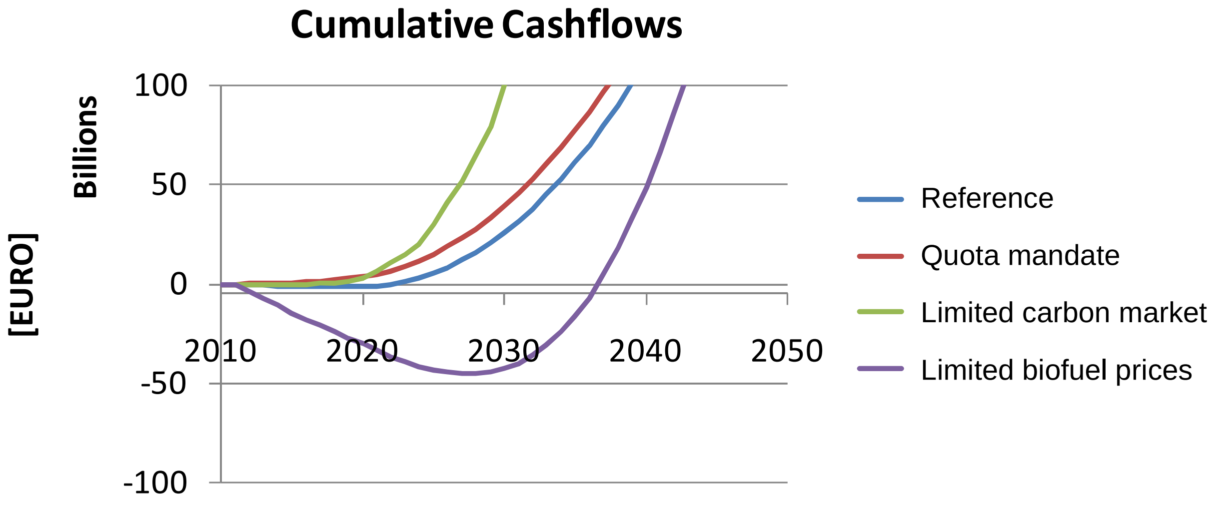

Figure 19: cumulative cashflow for HRJ

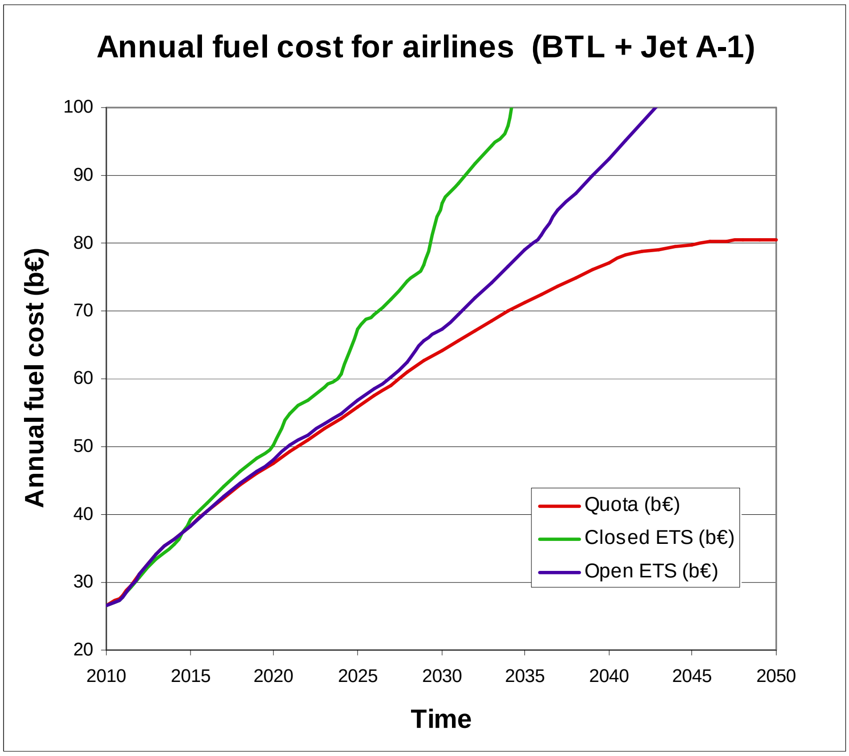

Figure 20: annual fuel cost for airlines (BTL)

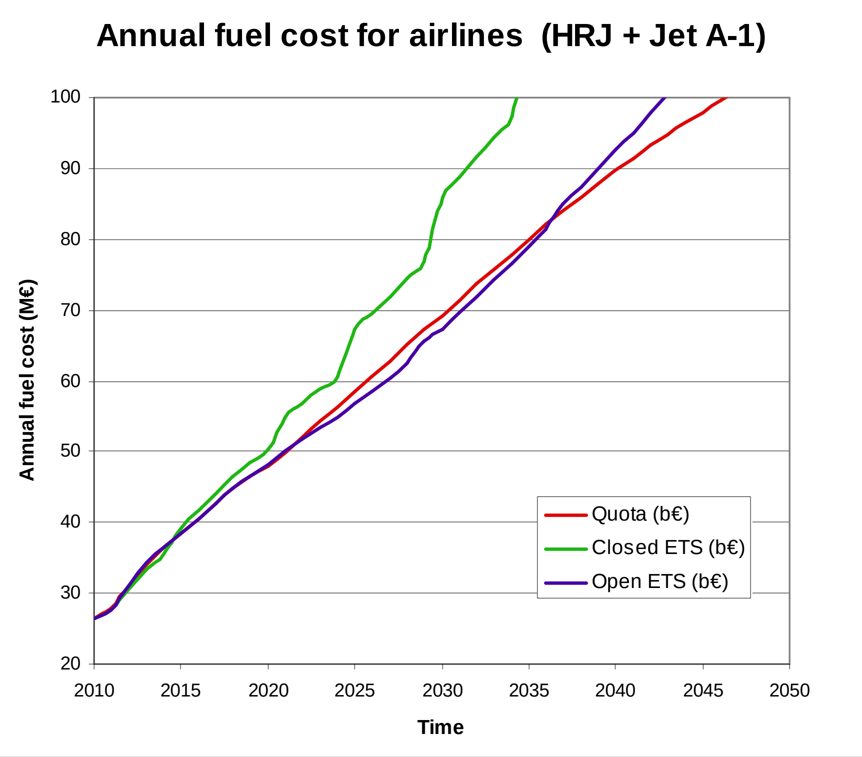

Figure 21: annual fuel cost for airlines (HRJ)

With the considered feedstock prices assumption, all the scenarios show profitability by 2050.

Nevertheless, as anticipated with an open ETS scheme, the price parity with conventional kerosene plus the carbon price is not reached before 2021 for BTL and 2034 for HRJ. During this period, airlines would thus not buy biofuels but rather buy carbon credits and aviation biofuels would not be deployed. A higher carbon price would help to reach the parity earlier. Nevertheless aviation is a small sector compared to the ETS global market with little impact on it and a higher carbon price would affect all the economic sectors.

In the Limited Biofuel Price scenario, the time evolution of the cumulative cash flow indicates the production costs that at least should be funded in order to ensure a competitive biofuel price at which airlines would be willing to purchase it. Once parity is reached, the profitability for fuel producers increases since the biofuel price is sticked to the kerosene price plus the carbon price, assuming that the ETS policy is maintained over the period and that the biofuel emergence (but also the emergence of other sources of energy in other sectors) has no strong influence on crude oil price. In this scenario, the cost for the airlines doesn't change compared to a situation where no biofuels are developed since the introduction of aviation in the ETS is already decided today.

From this point of view, the considered quota scenario appears as leading to a better situation for airlines in the long term with lower fuel prices. This is nevertheless strongly linked to the simplifying assumption of a 25% fixed profitability margin for fuel producers which may be unlikely in the captive situation enforced by quotas. Before the parity with kerosene is reached, the cost should be at the contrary higher for airlines who would fully support the cost for developing alternative fuels. Nevertheless, in this initial period, due to the low biofuel penetration, the resulting cost for airlines is not necessarily so large.

For BTL, the cumulated losses in the initial period of the deployment for the "limited biofuel price" scenario (which leads to the significant penetration of biofuel of 25% in 2020) is about 15 billion € in 2020, and have to be compared with the annual fuel cost of airlines which varies from 26 billion € in 2010 to 48 billion € in 2020 and which cumulated value on this period is 417 billion €. The negative cash flow thus represents 3.6% of airlines fuel costs. A sensitivity analysis shows that, if the equity charge could be reduced to 8%, the maximum cumulated losses would be reduced to 4.8 billion €, less than 1.2 % of airlines fuel bills. Such an equity charge obviously implies a lower profitability for investors which would then request at least a low level or risk. Government guarantees may help such reduction in profitability margins demanded by investors. However this estimate is done without introducing any profitability margin for the producer in the cost of the biofuel. Assuming the fuel producer would request a 25% margin to produce the fuel (in line with the other scenario), the negative cash flow to compensate by subsidies or other measures would be 57 billion € by 2027, representing about 7% of airlines 803 billion € fuel expenses during the same period.

In case of HRJ, the cumulated losses are higher, 45 b€, and the depth of the valley is reached later in 2028. These losses have to be compared to a cumulated fuel costs for airlines during the same period of 865 b€, meaning that they represents 5.2% of the fuel bill. In this second case, measures to support investment and reduce equity charge are not likely to influence the result since fuel cost is dominated by feedstock. If a 25% profitability margin is introduced for the fuel producer, the negative cash flow to compensate becomes 166 Md€ by 2037. It represents 10.7% of the airlines fuel expenses during the same period.

A similar estimation indicates that if a quota mandate of 5% was introduced in 2020, the total fuel cost increase for the year 2020 would be in the order of 2.4% of the airlines fuel bill in case of BTL, and 3.3% in case of HRJ (assuming a 25% profit margin for fuel producer and the application of the current ETS system). With fuel costs being around 25 to 30% of airline operating costs, this would represent roughly 1% of operating costs. These figures have to be compared with airline benefits that typically oscillated between +2.9 and -2.8% in the last 20 years[60]. Depending on the possibility or not for airlines to pass these costs to the passenger, the additional costs for biofuels might cancel their benefits.

From this analysis, the last scenario assuming closed ETS (and a level of penalties high enough to compensate for the biofuel higher cost) appears as non usefully expensive compared to the quota scenario.

Next to biofuel, the study also assessed the potential of additional technological or operational measures which are not included in the 1.5% yearly efficiency improvement of the fuel demand forecast. If early retirements of aircraft and engines upgrades appear as cost effective solutions compared to biofuels, they proved to have a limited impact on achieving the environmental targets that can be reached only through biofuels.

7.3 Other economical aspects

From the construction of the supply chain, the conventional fuel supply relies on few large companies supplying the fuel, which is produced from raw materials originating from few sources.

The alternative fuel supply chain on the other hand is – at least from the current point of view – very diverse and rather fractured. Fuel producers have to deal with a large number of suppliers, which deliver different types of raw material (e.g. different woods or oils) and different quality. Management of the feedstock supply is thus more labour intensive, but increases the robustness of the overall fuel supply.

Dependent on the fuel production process, the final product is more or less dependent on the composition of the feedstock and overall effort for quality control of the final product is more than for conventional fuels. Further downstream in the fuel blending step similar issues arise, though on different scale depending on the plant size/ the number of plants, respectively. As fuels from several

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[60] Source IATA

sources need to be blended, quality issues can potentially arise, leading to a higher risk of out of spec fuels, unless properly managed by quality assurance procedures.

On the other hand the more widely spread raw material suppliers and fuel producers lead to a more robust supply chain in terms of security of supply and dependence on geopolitical regions.

7.4 Business case conclusions

With view to the objective of reducing aviation GHG emissions, technology improvement, if cost competitive, doesn't offer the potential for achieving the industry emissions reductions target that can be reached only with involvement of biofuels.

To meet European demand, either approximately 80 HRJ production plants or 300 BtL production plants, or a combination of both, would be required. Independently of the fuel solution this indicates that a large and timely technological and financial effort is required to ramp up production capacity at sufficient pace to meet the set targets with alternative fuels.

Both BTL and HRJ solutions are initially not cost competitive with conventional jet fuel and specific measures are requested to enforce their deployment. In the longer term, their viability depends heavily on the possibility to secure "low price" feedstock supply.

HRJ exhibits a strong dependence on feedstock price and cost competitiveness in the medium to long term cannot be reached unless cheap and abundant sources of sustainable oils can be secured.

BTL is initially dominated by capital investment. With learning, the specific investment cost may drop and BTL fuels will eventually become cost competitive. Since the feedstock for BTL is comparably cheap and varied, cost improvements may be expected at the pace of technological development, giving BTL fuels a financial advantage on medium and long term.

In the hypothesis that "cheap" feestock supply could be secured, policy measures are nevertheless requested to support the initial deployment of biofuels.

With an open ETS system alone, airlines would clearly buy carbon credits in the initial period and biofuel production would not start up. ETS systems are coupling the price of alternative fuels to non-fuel-related mitigation measures, thus initially setting an upper boundary to the price of alternative fuels which also sets a benchmark for a potentially achievable price. In the longer term, unless competition on the supply side is large, there is a significant chance that prices for fuels remain pinned to the cost of the non-fuel-related mitigation measures, even if production cost for alternative fuels are dropping. Under these assumptions margins for biofuel producers would rise at the expenses of airlines.

A quota mandate on aviation fuel suppliers, would offer a higher certainty to deploy the biofuel production capacities necessary to reach the emissions reduction targets but raises the issue of the impact on fuel costs for airlines and of the control of fuel prices, airlines being in a captive situation. As a reference, a simplified simulation assuming a benefit margin for fuel producers limited to 25% (as a proxy to more complex market mechanisms), shows that if a quota mandate of 5% was introduced in 2020, the increase of airlines fuel bill for the year 2020 would be in the order of 3% under the application of the current ETS system (again this is only true if "low price" feedstocks are available). This represents around 1% of airlines total operating cost and is in the same order of magnitude than airlines benefits.

The production of biofuels for aviation is nevertheless also linked to the production of biofuels for other transport modes and in particular road transport but also maritime transport. Indeed, both for technical and economic reasons, it would not make sense with BTL and HTJ process to target only jet fuel production[61]. Conversely, producing only automotive fuel is both technically and economically possible. The profitability of biofuels in the other transport modes is thus also an important parameter of the jet biofuel business case. The biofuels incorporation strategies for road transport and air transport are nevertheless radically different. In particular, for road transport, the economical suitability is mainly obtained by specific tax reductions.

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[61] The targeted ratio affects the type of coproducts and their potential value on the market. Increasing the ratio of jet fuel tends to increase the ratio of other co-products than diesel (light distillate and heavy compounds) which value is lower than diesel. For BTL, a "reasonable" ratio is about 25 to 30%. For HRJ, the ratio can be 30% or 70%, but the choice of the highest ratio makes the valorisation of the co-products more difficult.

8 Other renewable energy sources for aviation

In addition to the analysis of alternative fuels, the SWAFEA study has reviewed the other renewable energy sources that could be introduced in aircraft energy systems in order to reduce fuel consumption and emissions by reducing the power extracted from engines for on-board energy production. The goal was to create a better understanding of their potential for aviation, their suitability for current aircraft energy systems and their requirements for introduction.

In the SWAFEA context, “other renewable energy sources” refer to renewable energy sources or energy carriers other than biofuels. The considered energy carriers using a variety of renewable primary energy resources such as solar power, wind and hydropower are mainly hydrogen and electric energy storage media.

The evaluation of other renewable energy sources or other renewable energy carriers focuses on energy options complementing existing aircraft energy systems (the engines) and thereby reducing the consumption of the traditional fuel (kerosene). The purpose is to identify the potential of overall mission fuel savings. Aspects of ground operations are also included.

The maximum theoretical potential of fuel savings of an aircraft with an alternative energy system independent (or partially independent) of the main engines is determined by the reduced power (and/or bleed-air) off-take from the main engines. Only a fraction of these theoretical savings can be realized with an alternative energy system that adds extra weight (and potentially extra drag due to larger wetted area) to the aircraft due to equipment for energy storage, harvesting and/or conversion. As a result, typically a theoretical potential of 3 % fuel savings from zero bleed-air and zero electrical power off-take can be expected, in practice reduced by the extra mass of the new and main-engine-independent power system.

The theoretical upper mass limit of an alternative independent power system is given by the mass-induced fuel burn penalty of less than 3 %. A conservative estimate, derived from the on-board power requirement and the theoretical mass limit, requires an alternative energy system to exhibit a power density of > 0.15 kW/kg in order to achieve net savings in the mission fuel burn. For a 4-hr flight, this translates into a requirement of an exergy[62] storage density of more than 0.59 kWh/kg.

This example clearly shows that state-of-the-art secondary batteries as electric energy carriers are too heavy (0.20 kWh/kg) for a 4-hr flight, while the power density of such batteries (> 1.0 kW/kg) is uncritical. New lightweight high-capacity low-power batteries with an exergy density far above the state of the technology have to be developed.

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[62] Exergy is defined as the fraction of energy that can be converted into useful work, i.e. the intrinsic exergy of a fuel is amount of mechanical (or electrical) work that can be maximally extracted from the system in a certain environment

Other renewable energy sources for onboard energy systems, such as hydrogen fuel and fuel cells benefit from a high exergy density of the fuel. Adding in weight-saving synergies with the aircraft system, such as the use of the water generated in flight in a “multi-functional” PEM fuel cell from burning hydrogen, are then a promising option.

One group of options for alternative on-board energy systems is the permanent operation of a highly-efficient internal combustion engine or fuel cell as “improved APU system” that complements or substitutes the electric energy and bleed air off-take from the main engines. The savings of conventional kerosene are due to either a significant improvement of the efficiency, even in the presence of a weight penalty, or due to the replacement of the APU kerosene with an alternative APU fuel, such as hydrogen.

Fuel cells or Diesel engines (both having an efficiency of at least 40% and power-to-weight ratio of 1 kW/kg) as APU replacement or improvement (compared to a conventional APU turbine with less than 20% efficiency and 2 to 3 kW/kg) provide a higher efficiency at the expense of increased weight, volume and system complexity. The main benefit of such a system comes from energy savings and emission reduction during ground operations, and therefore has a higher benefit for short-range missions.

For ground operation, also electric wheel drive systems can be beneficial. Detailed specifications are not in the public domain but projected savings in fuel consumption of ground fuels and CO_2 emissions are both 66%, and reductions in hydrocarbon emissions of around 75%.

With fuel cell systems the main engine kerosene consumption can be improved by 2 – 3%, and ground operations fuel efficiency can be improved by 1 – 4% of mission fuel, depending on the mission duration. Estimated net benefits are 0.7 – 3.5% total mission fuel saving.

The integration of thermoelectric generators (0.5 kW/kg-module as state of the art) as a more radical energy option fulfils the power density requirement (0.15 kW/kg), however it can only be complementary to other renewable power systems due to the very limited application area with large heat gradients available in the aircraft engines.

Research and development for the reduction of the use of conventional kerosene should focus on the multi-functional fuel cell for on-board energy systems as this provides the largest theoretical system benefits. Critical technologies for alternative on-board energy systems are the fuel cell stack, the multifunctional integration of fuel cells and low-weight highly integrated hybrid power systems. Critical requirements for fuel cells are their development towards lower cost, longer lifetime, increased efficiency and power density. Cooperation between aviation and automotive sectors in the area of fuelling infrastructure would be beneficial. The development of renewable hydrogen production is also required.

To conclude, it is important to realize that the potential for conventional kerosene savings in the main engines is possible but theoretically and practically very limited as presented here in the context of other renewable energy systems.

9 Synthesis and deployment outlook

9.1 Synthesis

From this overall analysis of alternative fuels introduction in aviation, a first statement is that the key issue has moved over the last three years from the technical feasibility to the deployment of the fuels. Routes from both fossil feedstock and biomass are available or should be soon available. These are the Fischer-Tropsch thermochemical pathway from coal, gas or biomass, and the hydroprocessing of vegetable oils or animals fats. Beyond, other routes are under development and considered for aviation approval and in particular the so called "sugar to hydrocarbon" pathways which can produce hydrocarbon from sugar as a direct feedstock or as an intermediate step from lignocellulose. An approval process has also been defined in ASTM standards which provides the necessary guidelines for the introduction of new fuels.

Fischer-Tropsch is approved for aviation, already mature and deployed at industrial level from coal and gas and at demonstration scale for biomass. Hydroprocessing of oil is already mature and at an early industrial stage (also mainly for diesel) although it has not currently achieved its approval for aviation. When approved, both fuels will allow incorporation in Jet A-1 of up to 50% with fuel from conventional sources, while producing a fully "drop-in" fuel, i.e. fuels totally compatible with present systems. It should be noted that though these fuels are part of fuel families suitable for road transport, their use in aviation require further processing compared to their automotive version in order to match aviation specifications.

Fischer-Tropsch SPK fuels from coal and gas already have the potential to enlarge the aviation fuel supply beyond crude oil and thus can answer to the "security of supply" concern of the sector. Market trends may naturally push for their emergence with increasing prices of crude oil or reduced availability. In addition these fuels demonstrate high quality and in particular their lack of aromatics and sulphur (an intrinsic quality of both FT SPK and HRJ) reduces the particulates emissions of engines with positive impacts on air quality and, from preliminary results, also on contrail formation.

However these fuels don't meet the Green House Gas emissions targets set by both the European Union and the industry. From the fuel point of view, only renewable fuels such as biofuels are able to induce significant life cycle GHG emissions reductions. To this end, the biofuel feedstock production step has to be carefully tailored to minimise the cultivation emissions. Of utmost importance is the control of land use change for the biomass production, since either significant emissions or storage of carbon may be the possible consequence with a potentially dominating effect over the whole fuel production chain. Failing in controlling land use change would result in a great GHG emissions increase, and the opposite of the pursued target.

A move to biofuels obviously raises the issue of the availability of the biomass to produce them, with the critical issue of the competition with food which could result due to the limited amount of land available on earth. An assessment of the potential biomass availability for energy has been made within SWAFEA at a global scale for 2050, taking into account the need for food in an increasingly populated planet and the diet evolution of the population. Sustainability constraints in line with those of the European Renewable Energy Directive were enforced and credible yield increases were used. Energy crops were optimised for their suitability and productivity for local conditions.

Though such an assessment is recognised to contain significant uncertainties, it provides some measure against which the industry target for emissions reductions can be assessed, if they were to be met by biofuels only in addition to the presently anticipated aircraft and operation efficiency gain. In particular, it appears that the industry's target of reducing its emissions by 50% in 2050 compared to 2005 is too ambitious with the current processes and the use of traditional biomass only. Achieving a stabilisation at the emission level of 2020 would be a more achievable target that would already require a significant increase in biomass production and use, the acceptability and impacts of which certainly need further research. In particular, it should be noted that the major part of the biomass is likely to come from the conversion of what is currently grazing lands, as the potential from croplands in 2050 is quite limited.

This assessed potential availability should also not hide the significant challenge it represents in developing agriculture, putting lands under cultivation and mobilising the required manpower. Another challenge is also to make it happen in a controlled way in order to avoid competition with food under the market pressures. Indeed, from the biomass production presented in chapter 5, agriculture appears to be the first potential source of biomass.

With view to the limited amount of biomass potentially available and to the pressure its production will put on the agriculture, intensifying research on additional new biomass pathways must be recommended. Algae currently appear as promising candidate however their potential still needs confirmation at representative production scale and in economical viable conditions. Achieving good performances from the life cycle emissions point of view will also call for an optimised production process integrated with other activities. Additional biomass types (halophytes, etc…) should also be investigated. Maximising transformation processes efficiency and yield, and eventually radically new approaches to renewable fuels, are a second crucial axis of research to limit the requirement in biomass.

The challenge of developing biomass production is also a central question of the biofuel economic viability. The analysis carried out in the frame of SWAFEA converges with other studies on the fact that, with the current FT and HRJ technologies, biofuels will only be possible with "low cost" feedstocks. This is certainly the major issue with view to the eventual deployment of biofuels, especially looking at the repetitive tensions observed in 2008 and currently on the feedstocks market. A first requisite to obtain these "low prices" feedstock is a sufficient development of biomass production in line with the demand increase for biofuels, in order to avoid scarcity situations which would directly result in inflation with a direct impact on food security. Thus attention should be paid to the fact that biomass production does not follow a demand generated upstream by biofuel production but is really co-developed in a balance way. A second aspect of feedstock price is the productivity which has to be high enough to guarantee sufficient revenues for the producers.

The possibility of high biomass price has nevertheless to be considered. In such a situation, processes from vegetable oil seem to have a lower potential as oil price already represents the dominating contributor to the fuel price. Little gain can thus be expected from process improvement[63]. Lignocellulose feedstocks appear as more promising if significant progress can be achieved on the transformation process to reduce CAPEX and operation costs while improving yield to make a better use of the biomass. Again, for lignocellulosic feedstock, research on transformation process efficiency and yield appears of major importance. However the feedstock logistic aspect should not be forgotten since it has been identified as a major critical point for BTL plants[64]. As already mentioned, in the search for lower transformation costs, sugar to alkane routes have also to be considered (which also enlarge the type of feedstock to sugar and starch crops).

From the global assessment performed in SWAFEA, lignocellulosic routes can be seen as presenting a higher future potential than oil seeds routes, although from a technical point of view, both can provide a highly valuable fuel for aviation. Indeed, in addition to the economical results, lignocellulose crops assessed within SWAFEA have demonstrated lower greenhouse gas emissions than oil seeds, while BTL process also generates lower emissions than hydroprocessing[65] (such feature should also be considered for the development of new more efficient routes from lignocellulose). Moreover, the biomass availability coming mainly from converted grazing lands, the corresponding biomass is likely to be lignocellulose in non tropical or subtropical areas, due to the requirement to grow perennial crops on such lands to avoid land use change negative impacts[66]. However, from the feedstock point of view, oil seeds should not be excluded as they allow rotation with lignocellulose when annual crops are considered on croplands[67]. In tropical or subtropical areas, oils seeds can also present a regional advantage considering the climate. Considering the respective maturity of BTL and HRJ and these

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[63] The yield of hydroprocessing is already about 85% in mass for the total produced fuel.

[64] This was a major outcome of the RENEW study.

[65] BTL emits "neutral" CO_2 from the biomass while hydroprocessing emissions stem from the hydrogen which is currently produced from natural gas – things could be different if renewable hydrogen was used.

[66] Also, in the simulation of global biomass production, a higher biomass primary energy was obtained when lignocellulose was favoured. This result however needs further detailed investigation, since lignocellulose was favoured globally and not on a regional basis.

[67] Energy perennial crops on cropland were not considered in SWAFEA, in order to maintain flexibility for instantly return to food crop on croplands.

feedstock aspects, the two pathways are probably to have complementary roles in the implementation. Also, if algae are developed, hydroprocessing is the associated process.

At the interface between economy and sustainability, the questions of the feedstock type also interfere with the debate of the competition between food and fuel. It is clearly simplistic to reduce this debate to the question of the edible feature of the crop since a major aspect of the competition is through land use and depends on the respective area dedicated to each type of final use. From a theoretical point of view, the best policy is to favour the most productive crop in order to minimise the areas required for fuel. However in the short loop of crops cycle, the possibility to sell the crop on both markets is a factor of competition, while conversely it offers some flexibility to answer an unexpected need on one or the other market, for example to answer momentary low food production. If growing only perennial on grazing lands, this question mainly concerns croplands. The use of non edible crops in cropland could disconnect biofuel market from food market, with the possible economical advantage of a less fluctuating market for fuel production.

Growing dedicated energy crops implies a confidence of the farmers in such a market which will be a difficulty in the initial period when biofuel production is not well established. The settling of long term contracts with farmers is often proposed as a way to encourage the start-up of the production and to guarantee a certain stability of the prices.

The specific requirements of aviation have been emphasized in this report, leading to the use of processes that are not the ones currently deployed for road transport, even though aviation fuel are based on processes also suitable for car industry. There is nevertheless a strong link between aviation and road transport since diesel and lighter fractions are always co-produced with jet fuel with the current processes[68]. Producing the required volumes for aviation also leads to the production of a significant amount of fuel for road transport. The contrary is not necessarily true, the process producing basically fuel in the diesel range that needs to be upgraded in jet fuel. Thus aviation may have to compete with road transport to secure its share of the fuel production, but the production of its fuel may not happen without any synergy with automotive industry. This means that the produced fuels need to be viable on both markets.

Currently, road transport favours FAE which production cost is much lower than BTL or HRJ. FAE incorporation ratio in diesel is nevertheless limited due to technical reasons (that may be even stronger with future high technology diesel engine) and higher blending ratio will require car industry to move to SPK fuel type (some FAE may also not comply with the RED emissions reduction target). This is likely to create the convenient synergy with aviation. The biofuels incorporation strategies for road transport and air transport are nevertheless today radically different. For road transport, the incorporation rate is driven by mandatory minimum content (in line with the RED) and the economical

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[68] For HRJ, depending on the optimisation of the process, jet fuel fraction is typically 30% or 70%. For BTL, typical jet fraction is comprised between 25 and 30%.

suitability is mainly obtained by specific tax reductions. On aviation side, the tax lever today does not exist since aviation fuel has no taxes, in particular because of the Chicago convention.

If the shift to alternative fuel was driven mainly by economics, diversification and security of supply, thus probably favouring routes like CTL and GTL, one can fear that aviation would have higher difficulties in getting its share of fuel because of its higher requirements and small market size. It would probably have to pay a larger premium to obtain its fuel.

If the shift to alternative fuels in aviation is driven by climate change mitigation and GHG emissions reduction, a final question arises considering the best use of biomass and biofuels. Where is biomass use likely to produce the highest GHG emissions reduction with the highest economic efficiency? This lays outside the scope of SWAFEA, nor is the intention of the Consortium to enter in a holistic analysis of the energy use or to provide a global scheme for resources use. Beyond providing some facts about the use of biofuels in aviation, two sectoral considerations can however be given as inputs to this debate.

The first one is that in the 2050 perspective, it is not believed that aviation will be able to do without liquid fuels, and more over "drop-in" liquid fuels. Aviation thus has not the possibility of other sectors to move towards low emitting energy sources through the use of electricity. If aviation is recognised as an important pillar of the economy and exchanges, its liquid fuel supply has thus to be secured.

It could therefore be considered, if aviation was not seen at the best place where to use biomass, to preserve fossil fuels in priority for aviation, particularly if a complete decarbonisation through biofuel is not possible. However the long term sustainability for aviation of such a choice is quite questionable since it would then become the "red flag" of the GHG emissions, concentrating all the attacks about its environmental impact. It is thus believed in the sector that it should contribute to GHG emissions reductions and biofuels may be an effective means for this to be achieved as other currently anticipated technology improvements don't appear as sufficient to reach the target.

During the SWAFEA final conference, which gathered a wide range of actors including NGOs, there was a general consensus that biomass use should include aviation.

9.2 Deployment outlook

9.2.1 A initial target for aviation

From the outcomes and findings of the SWAFEA study, a possible outlook for the deployment of alternative fuels in aviation has been developed. It supports the major recommendations made by the SWAFEA team for future European policy.

To establish the "roadmap", a reference scenario has been analysed on the basis of both the environmental and the economic study.

Considering the European Union involvement in climate change mitigation and the aspiration of the aviation sector to limit its environmental impact, the main driver considered for the deployment outlook is the reduction of GHG emissions. Biofuel introduction is thus the main focus and target.

As it has been underlined, the industry target of reducing the GHG emissions level by 50% compared to 2005 needs efforts going beyond the current understanding of processing technologies and estimated availability of traditional biomass. Capping emissions at 2020 level is currently a more sensible objective.

Would such a capping be achievable from 2030 with technical measures only[69] (meaning without considering the economic measures associated to carbon credit market)?

The biofuel production required to match this target is illustrated on Figure 22. Life cycle GHG emissions associated to biofuels are assumed to be 20% of those of kerosene[70]. Considering the current uncertainties for aviation biofuel deployment, only a limited ramp-up of biofuels is targeted in this scenario for the initial period from 2010 to 2020, with a ratio of 2% of biofuels in aviation by 2020.

The corresponding requested biofuel production is summarised in Table 8 and compared to some projection for world biofuel production in road transportation[71] (source IFPEN).

Considering the current state of technology, it is assumed that no other pathways than HRJ and BTL will be industrially deployed by 2025. In the hypothesis that the bio jet fuel is produced through BTL or HRJ pathways, an estimate of the total volume of fuel produced to obtain this quantity of jet fuel is given in the table (assuming co-production of jet and other fuel with a share of jet fuel of 25% for both process). After 2030, other processes are likely to emerge and thus the given values should rather be seen as indicative.

The total amount of biofuel in 2025 is in the same range between our scenario and road transportation projections (though these last projections only consider a limited amount of BTL diesel). However the increase rate required to achieve the carbon neutral growth by 2030 is much higher than the production increase projected by road transport during the same period (and from a similar level of production).

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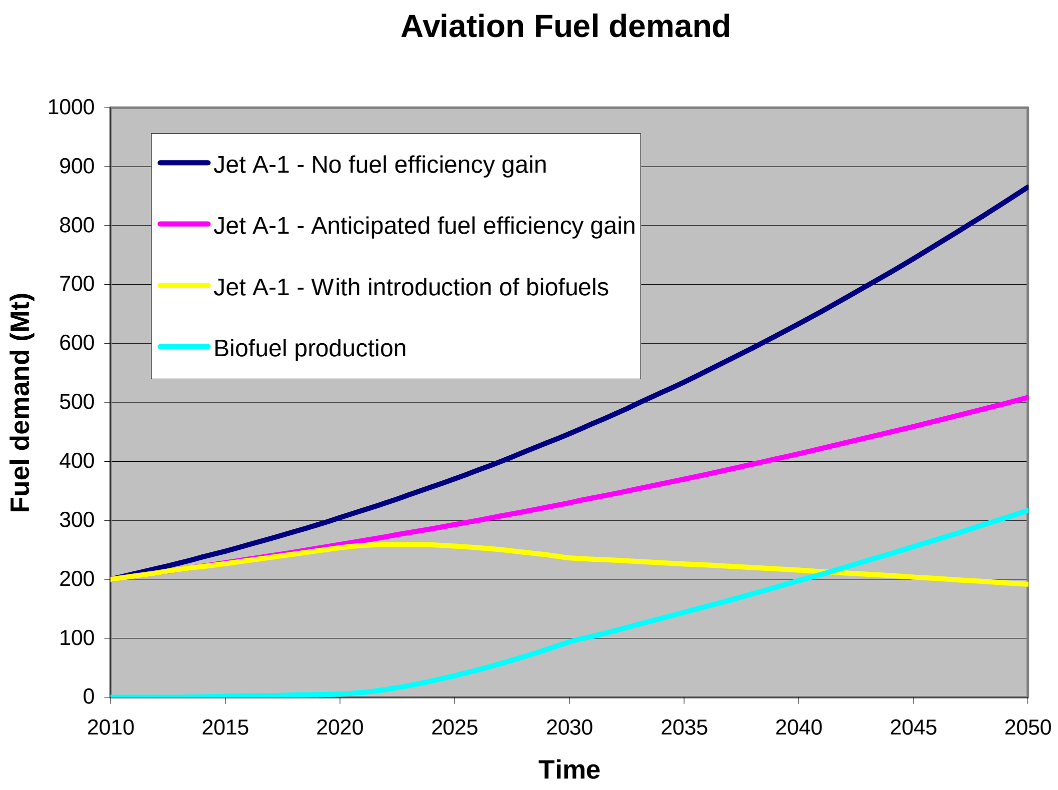
[69] Note that the high-level industry and ICAO goal to achieve carbon-neutral growth includes the possibility of economic measures (carbon trading and offsets). The scenario described here (carbon-neutral growth from 2030) refers to “physical” emissions and does not correspond strictly to industry and ICAO goal. In that sense the 2030 timeframe is not related to industry or ICAO goal.

[70] However such an assumption is recognized as highly uncertain taking into account the high variability of LCA results with the type of crop and the cultivation conditions..

[71] this projection include current ethanol and biodiesel ("1st generation") plus lignocellulose ethanol and BTL diesel ("2nd generation)



Assumptions: Global jet fuel demand in 2010 estimated to be 200 million tonnes;
Annual air transport growth of 4.5% in 2010, linearly decreasing to 3% in 2050;
Annual fleet fuel efficiency increase by 1.8% in 2010, linearly decreasing to 1% in 2050.

Figure 22: Aviation fuel demand for the reference scenario

			2020	2025	2030	*2040*	*2050*
Carbon neutral from 2030	Biojet	EJ/year	0.22	1.57	4.03	*8.47*	*13.59*
	Associated total biofuel	EJ/year	0.9	6.3	16.1	*33.9*	*54.4*
	Yearly increase	%	-	*47%*	21%	*16%*	*10%*
Road Transport projection	Road transport biofuel	EJ/year	4.93	5.76	6.82	-	-
	Yearly increase	%	-	3%	3%	-	-

Table 8: Scenario fuel demand and IFPEN projection for road transport (Axens, 2010)

In particular the required associated rate of increase of biomass production in this early phase looks extremely high. If the carbon neutral growth at 2020 emissions level may look compatible with the potential "technical" biomass availability in 2050, it is questionable whether the production can be increased quickly enough to reach it as early as 2030. Introduction of radically more efficient processes and feedstock, such as algae, would be required to achieve the goal.

As a reference, if a yearly production increase of 14.5% could be achieved from the production level in 2020 (2% of biofuel in aviation), then the ratio of biofuel in the total jet fuel would be 6% in 2030, instead of the 28% required to reduce emissions at 2020 level (14.5 is the yearly increase rate that leads over 30 years to reduce the emissions in 2050 at the level of 2020).

The conclusion is thus that the carbon neutral growth at 2020 emissions level is not expected to be achievable as early as from 2030 without economic measures.

This statement puts biofuel deployment in aviation into a longer term perspective. Before the introduction of new technologies, in particular for feedstocks, the ramp-up of biofuels is likely to be slow down by the capability to increase biomass production. Later, in particular if the promises of algae were confirmed and if significant increase in process efficiency could be obtained, a faster increase can be imagined. Also the emergence of processes yielding jet fuel without coproducing diesel or gasoline may be anticipated. Then producing the required jet fuel would not mean producing large quantity of automotive fuel and the global biomass demand could be lower if electrification progresses for automotive applications. However if electrification is likely to reduce light duty vehicles demand for fuel, a continued growth of the demand can be expected for heavy duty road transport which requires middle distillate-type fuels.

If one could call for a faster ramp-up of biofuels in aviation with view to climate change mitigation, the consequence of an excessive demand for biomass production has also to be considered from a sustainability point of view. A slower deployment is probably a guaranty with regard to the sustainability of biofuels development.

The consequence is that aviation emissions offsets will be needed beyond 2030 and that aviation will be a net carbon credits buyer in the coming decades.

Knowing that technology improvements will not be sufficient to achieve the targeted emissions reductions, it seems important nevertheless to initiate from now the deployment of biofuels even with a limited initial target. This is also a condition to generate knowledge, experience and future technical progress for a larger deployment.

In parallel, the research on new feedstocks and new processes has to be intensified in order to accelerate the emergence of new technologies that could greatly modify the perspectives.

For the initial low incorporation phase, the technical solution investigated within SWAFEA and consisting of relaxing the requirement on cold flow properties for the biofuel blendstocks is relevant and could help improving economic viability of aviation biofuels. Such a solution should be further analysed with view to a possible approval.

In this outlook, an emergence of aviation fuel supply from processes like CTL and GTL may also happen in answer to demand increase, prices increase or a supply scarcity situation. In addition, if the capping of aviation emissions at 2020 level was finally achieved in 2050 thanks to biofuel, 40% of the jet fuel would still come from fossil resources. The concern if CTL and GTL are developed will be to contain the GHG emissions of these processes at levels as close as possible to the one of conventional kerosene. Very high efficiency carbon capture and sequestration will then be required and research on this technology is certainly an important axis.

9.2.2 Some possible strategies to initiate the deployment.

The main challenge to initiate the deployment is to overcome the economical barrier of the low attractiveness of biofuels for investors.

Different means can be considered and are analysed here with view to a limited initial target for the deployment corresponding to a biofuel share of 2% in aviation (this value is indicative, further investigation would be required before fixing a precise value). This target represents the production of 1.25 Mt of aviation biofuel to be uplifted in Europe in 2020[72]. For the analysis, BTL and HRJ pathways are mainly considered which doesn't mean that new emerging pathways are excluded. BTL and HRJ are used to set some reference figures and because they are currently the most mature processes with view to a deployment by 2020.

9.2.2.1 Quota mandate

The introduction of a limited biofuel blend mandate on fuel producers is a first potential option to trigger the production of biofuels for aviation.

If low, such a quota may not be too demanding in term of biomass production, avoiding negative environmental and societal impacts, and the impact on airlines' fuel costs, and consequently on air transport demand, may also be relatively small.

On the basis of a typical biofuel production cost of 1200 €/ton[73] and assuming a profit margin between 15 and 25% for fuel producers, the acquisition cost of 1.25 Mt of biofuel is comprised between 1.7 and 1.85 billion € which would represent an increase of 1.5 to 1.8% of projected airlines fuel bill in 2020. Assuming that fuel represents 25% of airlines operating cost, this increase would translate in a 0.4% increase of operating cost and possibly also of ticket prices, depending on price and demand elasticity.

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[72] Based on fuel demand from Eurostat as used in the economic analysis.

[73] However corresponding to a favourable biomass price

It should be noted however that such an increase may be in the order of magnitude of airlines profitability margins (over the last 15 years, the average net profit margin of airlines has varied between -2.8% and 2.9% of their turnover, the 2008 crisis being excluded[74]). Further analysis, including the co-produced fuels valuation, is also required to more precisely evaluate the impact of a quota. In particular, the diesel co-produced with jet fuel will have a higher cost than the current biodiesel obtained from estherification which has to be taken into account into the global production scheme.

The main advantage of a quota mandate is that it is the policy measure that provides the highest guaranty that investment is done in biofuels implementation for aviation. It also not requires public funding even though it could be usefully accompanied by some supporting measures.

A first potential risk associated to a quota mandate is that there is probably little expectation to enforce it at a global level which could result in competition distortion between airlines. However, all airlines deserving routes to or from Europe would be in an equivalent situation on such routes if the quota is enforced on fuel production.

A second risk lies in the possible answer that will be chosen to fulfil the quota. Fuel producers have two options: either to develop their own production or to buy the biofuel from another producer. Considering the typical production capability of hydroprocessing plants, the 1.25 Mt of biofuel corresponding to a 2% quota could be produced with two HRJ plants. The situation may be that the quota is satisfied by the production of only one producer which already has a technology (Neste for example), the other buying the fuel. Then the quota is satisfied but the benefit for preparing further steps would be low since little actors would have involved themselves in biofuel production and technology development.

A last risk associated with quota is that it is likely to induce pressure on biomass demand if no accompanying measures are decided to develop in parallel biomass production (it should be avoided that biomass production answers the demand if inflation is to be avoided).

An alternative way to introduce a quota mandate in a more flexible approach can also be to define mandates for different types of fuel rather than for application sectors, as it has been done in the U.S. RFS2. A strong emphasis could then be put on drop-in hydrocarbon fuels, suitable for road transport without blending limits as well as for aviation.

9.2.2.2 Incentives for biofuel production or consumption

A second way to offset the biofuel initial lack of competitiveness could be to subsidy the production or the consumption to compensate the extra-cost for airlines.

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[74] Source: IATA

With the previous assumption, assuming a price of 800 € for kerosene[75], including carbon price, in 2020, the premium for 1.25 Mt of biofuel compared to kerosene is about 725 M€ (for a fuel profit margin of 15%). With no obligation for airlines to buy this fuel, this would be the cost to compensate to make biofuel competitive with kerosene. However, like for quota, the premium for the co-produced fuels has also to be taken into account, in particular on the automotive market.

Different incentive policies could be studied. It could be incentives to airlines buying biofuel or to company producing biofuels through various kinds of taxes exemptions (reduced taxes on benefits, taxes credit, airport charges or taxes exemption,…). The logic of giving taxes exemption to fuel producers is a priori that they are the ones which have the decision to invest in biofuels. An alternative or complementary approach could be to subsidise the biomass production.

Such an approach is more "positive" for fuel producers and airlines, without the risk associated to failing in achieving the threshold of a quota mandate.

The question is to know whether such a measure could be attractive enough for investors.

To provide some indicative references, Table 9 gives some approximate figures to compare investments in conventional refining, HRJ and BTL. For conventional refinery, the investment released for the announced Aramco/Total announced refinery in Jubail[76] has been taken as a reference. The figures are given in required investment per million ton of fuel produced per year. Associated revenues and return on investment are not quoted because of a lack of reliable data.

	Conventional refining	HRJ	BTL
Investment - M€ / Mt.y^{-1}	370	600	3800

Table 9: Required investment per unit of production

From this table, it turns out that, with public incentives, HRJ could be in the same range of attractiveness for investors than conventional refining. The investments required for BTL are one order of magnitude higher. With an incentive policy for biofuel production, it might thus be expected that only the HRJ pathway would be deployed.

The issue with the subsidising of the production is thus that it doesn't necessarily lead to the selection of the most efficient pathway. Due to the lower CAPEX required for HRJ, investors are likely to choose this pathway even though production cost may be higher in the longer term. Again this doesn't favour technology development and diversification.

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[75] Average value for 2020-2025 with the projection use for SWAFEA economical analysis

[76] Aramco & Total refinery, Jubail - http://www.bloomberg.com/apps/news?pid=newsarchive&sid=ahm4k5yQLEjI

9.2.2.3 Support to investment

CAPEX is particularly a barrier for BTL development.

An option to trigger its development is to set up financial mechanism to support investment. Due to the uncertainties and thus the high risk associated with the development of biofuels for aviation, it does not seem likely that the investment could occur without public actions. A feedback from the European Investment Bank during the SWAFEA final conference was that, even for an establishment like EIB, such investment would be too risky to be supported.

A way to reduce the risk and the call for capital could be to propose "Public Private Partnerships", in which investment is shared between private entities and governments, with eventually additional grants from Europe as it is currently on-going for energy infrastructure in the frame of the Recovery program[77] and as it is considered in Europe 2020 initiative for energy infrastructure priority[78].

Table 9 provides an estimate of the investment that would be required to produce the 1.25 Mt required in order to achieve a 2% target of biofuel in 2020 in the pool of aviation fuel uplifted in Europe.

In order to push BTL technology, while taking into account the higher current maturity of HRJ and their lower CAPEX requirement, the following mix can be considered to provide figures:

- 0.55 Mt produced from BTL, requiring to build 4 plants with a 500 kt capacity,
- 0.7 Mt of HRJ, requiring a 2.3 Mt production capability if a 30% jet fuel is considered[79].

The corresponding required investment would be about 10 billions €. Again, considering that 75% of the produced fuel would not be jet fuel, such an investment has to be considered in close link with the automotive sector.

Considering that the public sector would take in charge 50% of the investment, the impact on the fuel production cost can be roughly estimated, considering that CAPEX represent 43% of BTL cost and 7% of HRJ cost. BTL could be produced for 942 €/ton, and HRJ for 1158 €/ton. As expected, the incentive effect on HRJ production is negligible. It is also no sufficient to offset the premium of BTL compared to kerosene.

Support to investment thus doesn't seem to be sufficient in itself to trigger the deployment of aviation biofuels.

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[77] IP/10/231 - http://ec.europa.eu/energy/eepr/doc/i10_231_en.pdf

[78] Communication "Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network" (http://ec.europa.eu/energy/infrastructure/strategy/2020_en.htm)

[79] A 1Mt production unit can be imagined if a 70% jet production is chosen. Then fuel production cost should revisited in order to take into account the possible valuation of co-products.

9.2.2.4 An integrated plan for biofuel deployment

The previous policies combine a number of drawbacks with view to the targets of the initial deployment of biofuel in aviation:

- None of them succeed in developing the BTL pathway,
- They do not necessarily select the most efficient pathway in the longer term,
- They focus on transformation industry only, letting the biomass production be driven by this industry demand.

A more global plan could be proposed that takes into account the global value chain and favour the emergence of "end to end" projects involving partnerships between biomass producers, fuel producers and eventually end users.

Such a plan could combine support to investment and incentive to the production through support to both biomass and fuel producers.

The unique target should also not necessarily be to obtain the targeted 2% of biofuels in 2020. From a future perspective, it could be indeed more interesting to favour the emergence of a larger number of smaller initiatives than to push for set-up of the few plants required to produce the 2% of biofuels. This can be done through a limitation of the support allocated to a unique project. This second option also probably makes easier the combination of various funding coming from Europe, Nations and eventually regions. It may also better comply with European competition rules.

To develop this deployment "demonstration plan", a partnership with the automotive sector would also be required considering the amount of road transport fuel to be produced. A real synergy however exists between the proposed plan and the objectives of the European Industrial Bioenergy Initiative set in the frame of the European Biofuels Technology Platform[80]. Indeed, the implementation plan proposed in November 2010 aims at enabling the commercial availability of advanced biofuel at large scale by 2020. It proposes the funding of demonstration and flagship plants[81], for seven different pathways including processes leading to jet fuels.

Finally, such an integrated plan is not exclusive from a quota mandate policy, in a "push and pull" approach that guaranties that the deployment occurs and also offers possibilities to distribute the funding on a wider range of payers (through quota, the final end user, i.e. the passenger, may also contributes).

9.2.2.5 Possible source of funding

Different sources of funding can be imagined to support the deployment policies (European funds, taxes on passengers' tickets, etc.).

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[80] http://www.biofuelstp.eu

[81] The demonstration plants allows the further design of the first commercial scale units, the flagship plants.

However, from the analysis of ETS impact carried out in the frame of SWAFEA [19], it has been identified that the cost of ETS for airlines, corresponding to the auctioned part of the allowances, may be as high as 29.2 billions for the period running from 2012 to 2020. This budget will go to the Member States.

For comparison, a strategic plan associating both the subsidising of biofuel for a five years period (about 3.6 billions €) and half of the aviation share of the 10 billions € investment required to build 2 HRJ plants and 4 BTL ones, would cost about 5 billion € (assuming an automotive industry contribution to the plan).

ETS charges thus represent a significant potential source of funding and it could be proposed to European Member States to allocate part of this revenue to the development of alternative fuels.

9.3 An aviation demonstration initiative

In the course of the SWAFEA study, beyond the need for research and development, demonstration needs have been identified at the various steps of the aviation fuel value chain in order, either to consolidate the knowledge and choice for future development, or to accelerate the deployment of alternative fuels in aviation [23].

In particular:

- Looking at the critical importance of biomass production for a sustainable development of aviation biofuels, demonstration of the actual impact of a large scale production and of the achievable yields and emissions with sustainable practices is an important corner stone to consolidate the possible biomass production capability and the sustainability of biofuel production;
- The demonstration of algae at a significant scale is an important step to confirm their promising yields in large scale production and their economic viability;
- Long duration use of alternative fuels on regular flights would provide experience on long term possible effects of changing fuel average properties on engines and would bring confidence about the possible consequences on engines maintenance and life duration;
- A deployment demonstration on an airport would be a helpful initiative to identify and assess in real situation all the practical issues of the new fuels supply, to propose solutions and bring learning to pave the way for a future large deployment in European airports.

For the specific purpose of biofuels deployment in aviation, this last demonstration was considered as the most relevant. Indeed, significant developments on biofuels are going on in other sectors and particularly for road transport. Obvious synergies exist with these sectors for biomass production, and aviation should rather combines its efforts with road transport than initiates separate projects. On the other hand, aviation needs to make its own efforts to address its specific problems.

A proposal and description for such demonstration has therefore been elaborated in the frame of SWAFEA [23].

The leading idea is to demonstrate solutions for the different issues that separate the fuel approval from its regular use by airlines, apart from the obvious problem of fuel commercial availability.

Issues requiring demonstration cover regulatory, administrative and logistic aspects:

- What are all the regulatory steps between fuel approval and routine use by airlines?
- What are the required conditions for the introduction of a new fuel in an airport fuel supply infrastructure knowing that all fuels are commingled in a unique distribution system and thus that the fuel bought by one airlines is not necessarily delivered to this airlines? Responsibility issue may thus arise between the users of the airport.
- How to manage legal responsibilities related to fuel supply with the introduction of additional new possibly small suppliers?
- How to manage biofuel traceability with view to the RED and ETS application?
- How and where managing the biofuel introduction and blending in the airport fuel supply system?
- How to organize the quality control required to ensure the preservation of the mandatory high level of safety?

The proposed demonstration would consist of organising the regular biofuel supply of one chosen airport with a focus on logistics, fuel supply operations, quality assurance and the relations between the involved stakeholders. It should aim at being as representative as possible (in the current situation of early biofuel production) of an integrated biofuel supply in the global airport fuel supply.

The demonstration would involve at least one airport. A 1-2%-supply of a medium size airport would amount to approximately 3000 to 12000 t/a, therefore 5 to 15 kt/y should be targeted for procurement. In order to be representative of the more scattered fuel production that can be anticipated for biofuels, the demonstration should procure, whenever possible, its fuel from more than one provider. In practice, considering the aviation biofuel production that can be anticipated in 3 or 4 years from now[82], the initiative could require collection of biofuels from a number of small production units. A key question for the demonstration initiative will be where to introduce and blend the biofuel with the conventional jet fuel, close to the production site, at the refinery or at the airport. In the frame of the demonstration, considering the limited expectable number of fuel producers, the supply of the fuel up the blending point will probably not be representative of a large scale deployment. But the choice of the blending point with view to the supply of Jet A-1 and further supply of the fuel to the airport will have to be representative of a viable future solution.

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[82] This is the expected start of the operational phase of the demonstration

By achieving the first supply of biofuel blend to an entire an airport, the demonstration would identify all the practical problems, define and demonstrate solutions and bring the background for a later larger deployment at European scale.

The demonstration could be implemented in two phases, a first one over typically 18 to 24 months for a complete definition and organisation of the operations, a second one in two years for practical implementation. Results would be directly available for the integrated deployment plan suggested in chapter 9.2.2.4.

9.4 Recommendations

On the basis of this outlook and of the outcomes and findings from SWAFEA, a number of recommendations have been assembled in four main topics:

- Economics and policy,
- Sustainability,
- Research and development needs,
- European networking.

9.4.1 Economics and policy

Regarding the time perspective of the deployment of alternative fuels in aviation, it seems that the major recommendation to the policy maker, apart from intensifying the research effort, is to provide an initial signal for the start-up of biofuels in aviation and to build policy for the development of biomass production.

Short term (to 2016)

- Define an initial moderate aspirational target for biofuel in aviation by 2020 (defining the precise blending value, for example 2%, requires further analysis).
- Set-up an incentive policy encouraging "end to end" deployment projects, multiple actors' involvement and technology development and diversification. A public support to a number of "end to end" intermediate size demonstration projects through a combination of various financial tools (co-funding of investment through "private public partnerships", incentives to biomass and biofuel production) could be the way to promote such initial deployment. It should also be investigated whether it makes sense to possibly combine it with the introduction a limited quota mandate by 2020 in a "push and pull" approach.
- Propose to the Member States to invest part of the ETS auction revenues to support biofuels development in aviation.

- Promote harmonisation of policies, in particular for biofuel sustainability recognition, at ICAO level.
- Improve stakeholders' awareness of the possibility for aviation biofuel to contribute to the 10% target of renewable energy in transports of the RED.

Mid-term (2016-2025)

- Define a long term strategy for the use of biomass by the different end user sectors, including aviation.
- Update target for biofuel in aviation from the experience gained and the assessment of new available technologies.
- Define a strategic plan for agriculture orientation in Europe with respective long term target for food crops and energy biomass, including aviation fuel.
- Define measures to support agriculture development in developing countries in relation with the long term strategy for biomass use and also to mitigate the consequences of a new orientation of European agriculture policy.
- Support joint venture with developing countries to ramp up biomass production including food and energy crops (CDM mechanism for developing countries, specific incentive like tax reduction for investors....)

Long term (2025-2035)

- Update target for biofuel in aviation from the experience gained in the previous period and the assessment of new available technologies.

Note about ETS application

In addition to the previous recommendations, an additional issue has to be considered in the short term with view to the application of ETS in aviation.

Indeed, current regulation plans that the biofuel burnt on flights which are included in the EU ETS scope (flight from and to airports form EU-27) benefit from a zero emission factor. However current drop-in fuel such as SPK are chemically undistinguishable from conventional jet fuel, and the reality of the unique aviation fuel supply network gives airlines no control over the physical content of biofuel in the fuel supplied to a given aircraft. All the fuels delivered to the airport are co-mingled in the unique supply infrastructure. Thus the current ETS regulation is not operationally applicable. Report of biofuel use by airlines should be done on the basis of biofuel purchase rather than on the basis of the fuel burned in the aircraft.

The easiest way forward would be to use a "book-and-claim" methodology working with fuel delivery notes separate from the physical biofuel delivery: Each airline would purchase the quantity of biofuel it required for its operation based on the available bio-components at a given manufacturing site or refinery. Suppliers would surrender certificates to the airlines which in turn can be used as evidence to claim a zero emission factor under the current ETS scheme but continue to deliver into the joint supply network and "commingled" with normal jet fuel.

In order to ensure the traceability of the biofuel along the supply chain, a methodology based on certificates assigned to each batch of biofuel, similar to the RIN (Renewable Identification Number) standard used by the RFS should be evaluated in order to adapt it to aviation. Such a system would be particularly useful for showing compliance in a potential future aviation biofuel blend mandate.

In the aviation global international market, EU-ETS scope represents only a part of the global network. The introduction of a "book and claim" system should thus be done in such a way to avoid market distortion and "carbon leakage"[83].

9.4.2 Sustainability

Short term (to 2020)

- Consolidate the assessment of biomass availability for all type of resources (agriculture, forestry, waste, unexplored sources,…):
    - Link the teams involved in the field, confront approaches and hypothesis, initiate specific studies to clarify uncertainties.
    - Investigate the consequences of the targeted production:
        - Analyse availability and impact of the fertilizers;
        - Study impact of the projected use of land from both an environmental and societal point of view (in particular grazing land).
- Define European guidelines for biomass production going in a more local analysis of regional production of biomass in order to better estimate the potential and provide guidelines for agriculture development.
- Harmonise sustainability requirements between the different European regulations and policies (possible introduction of the RED sustainability criteria in the ETS for biofuel to be credited of zero emissions).
- At international level (ICAO), propose the harmonisation or the alignment of the various LCA methodologies and a harmonisation of sustainability criteria in order to facilitate a worldwide certification of aviation fuel.
- Support research on methodological approach of indirect Land Use Change and associated policy measures

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[83] Incentive to airlines to use kerosene out of the ETS scope or to increase emissions by circumventing the regulation (these aspect have detailed in [22])

Mid term (2020-2035)

- Monitor and update the evolution of biomass availability.
- Monitor environmental impact of biofuels deployment in aviation.

9.4.3 Research and Development

Short term (to 2020)

Biomass production

- Carry out research program to improve yields of energy crops (plant breeding) which are still at an early stage compared to food crop.
- Demonstrate energy crops performances under controlled agricultural practices ensuring sustainability.
- Intensify research on algae to diversify sources of biomass and relax the pressure on agriculture:
    - Initiate demonstration at significant scale, to confirm yields and scalability of the production,
    - Study integrated projects in order to maximise the potential benefit and minimize the life cycle emissions and energy.

Processes

- Intensify research on novel pathways (feedstock + processes) likely to produce drop-in fuels.

  It is in particular recommended:

    - to increase or develop a research effort in bio-chemistry and thermo-chemistry with view to the development of higher efficiency processes for Synthetic Paraffinic Kerosene, whether as a standalone product or as a subset of a broader paraffinic middle distillate product mainly targeted at the automotive diesel market;
    - to improve the understanding of fundamental aviation fuel requirements and further investigate the "drop-in" envelope of aviation fuels properties, in particular with regards to processes producing a reduced number of chemical species compared to Jet A-1's wide spectrum of chemical components.
    - To monitor alternative fuels and production routes not yet included in the standard fuel mix
- Further investigate and eventually approve the possibility of relaxing blendstocks properties with view to low blending ratios.

Implementation and deployment

- Initiate a pilot project for logistics and management of supplying an airport with biofuel, demonstrating the supply chain organization including technical aspects of the supply up to blending station and to the airport, and administrative aspects (inclusion of biofuel suppliers in the local fuel supplier pool, quality insurance,...)
- Conduct project to evaluate long term impact of alternative fuel on aircraft in order to give confidence to airlines, engines manufacturers, insurances etc. in the use of alternative fuels

Environmental impacts

- Include alternative fuels in research programs on atmospheric impacts of aviation to more completely assess their impacts compared to conventional Jet A-1.
    - Build a data base for engines emissions with alternative fuels (including measure on real engines).
    - Carry out deeper analysis of alternative fuels impact on atmosphere physics.

9.4.4 European networking

In addition to these thematic recommendations, it is recommended to set in Europe a network of excellence in alternative fuel which maintains an evaluation and monitoring capability for the European Union. Such a network should gather the technical capabilities to evaluate new fuel pathways with regard to aviation requirements. In that domain, it should complement and interface with rather than compete with ASTM and Defence Standards. Some form of integration could be envisaged. This network could support initial evaluation of pathways proposed in Europe and be in a position to independently create a Research Report for submission to ASTM including all necessary fit-for-purpose testing and also contribute to some ASTM approval processes which would provide European industry with better vision of proposed fuel solutions 85[84]. In addition the network should also include capability to consider sustainability and industrial aspects. Whilst other groups deal with these issues, they are not integrated and as such an improved model could be created within European Union.

The need for coordination between the different initiatives or R&D programs engaged in Europe, and also of coordination at political level concerning regulations or policies has also appeared in the course of SWAFEA[85]. A possible form for such coordination could be the setting of a European Technology Platform that makes the synthesis of the on-going actions, offers a forum for exchanges

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[84] The experience of HRJ approval has shown the interest of being involved in the process, since one of the reasons for the negative vote in 2010 directly stems from a test performed in Onera's Mercato facility for Turbomeca in the frame of the DREAM European program.

[85] A workshop was organised under the Spanish presidency of Europe in Madrid on June 2010 to discuss the needs for a coordination in alternative fuels for aviation.

and builds a research and demonstration agenda in coordination with initiatives existing at national level. Such a platform could contribute to the elaboration and the implementation of the Strategic Transport Technology Plan (STTP) currently built by the European Commission.

A Technology Platform for biofuels, the European Biofuel Technology Platform (EBTP) has already been created in the frame of the 7th Framework Program on automotive industry initiative. Its mission is "*to contribute to the development of cost-competitive world-class biofuels value chains and the creation of a healthy biofuels industry, and to accelerate the sustainable deployment of biofuels in the European Union, through a process of guidance, prioritisation and promotion of research, technology development and demonstration*". The platform includes five thematic working groups addressing biomass, conversion, end use, sustainability and marketing. Whilst its dominating orientation is road transport, aviation is not excluded from the considered end use. EBTP has in particular built the proposal for a European Industrial BioEnergy Initiative (EIBI) in the frame of the SET plan (Strategic Energy Technology plan) of the European Commission. The EIBI in particular promotes the demonstration of seven value chains for bioenergy up to building of the first “flagship” commercial scale units.

Considering the synergy existing for many links of the biofuel chain between aviation and car industry and the need for the two sectors to work closely together, a coordination structure for aviation should be considered in close connection with EBTP to make an optimal use of the already on-going work. Whether the optimal way is to reinforce aviation representation in the EBTP or to create a cross-connected structure should be further analysed.

In addition, the coordination structure could be opened to international cooperation and international partners.

10 Conclusion

Although the aviation sector has a good track record in reducing its environmental impact through efficiency gains, it is highly unlikely to reduce or even stabilise its emissions through this means alone.

Biofuels present a real potential for reducing GHG emissions, provided the feedstock production step is well mastered, and BTL and HRJ pathways should be available in the short term to produce biofuels compatible with aviation requirements and current aviation systems.

However the assessment of traditional biomass potential availability in 2050 shows that the most ambitious target of aviation to halve its CO_2 emission in 2050 compared to 2005 will require radically more efficient solutions, such as algae, in addition to current transformation process and traditional biomass from agriculture and forestry. A stabilisation of aviation emissions at their 2020 level is more easily feasible but will take time to be achieved, probably well beyond 2030. The development of the biomass production is a key issue for the deployment of biofuel and for its sustainability. It has to be considered along with the development of the processing industry, in particular with view to the mitigation of the possible competition between food and fuel.

From an economical point of view also, meeting emissions reduction targets would be extremely challenging considering the number of plants to deploy and the associated required investments, especially for Fischer-Tropsch plants that would nevertheless be likely to represent the major part of production plants since lignocellulose feedstocks constitute the largest part of the potential biomass production.

The major economic issue of biofuels is their lack of competitiveness with conventional fuel at least in the first decade of the deployment and the strong dependence of this competitiveness with changes in feedstock prices. Biofuel economic viability requires low feedstock price. In addition, the exemption of biofuels use from ETS is not expected to be sufficient to offset this competitiveness gap. With current technologies, deployment of biofuels in aviation will also need a deployment of similar processes in automotive industry since both Fischer-Tropsch and hydroprocessing for aviation coproduce significant amount of automotive fuels.

Both biomass availability and economics evidence the need for more efficient processing pathways, with higher transformation yields and reduced costs, and for new sources of feedstocks. In that field, algae today appear as the most promising axis of research. A higher economic efficiency is also expected from the sugar derived hydrocarbons pathways, the yields of which are nevertheless today still low. Emergence of these new solutions is likely to require about 10 years.

Contrary to other modes of transport, aviation has no other energy solution in view than liquid fuels and it is questionable for its long term development whether it would be socially accepted if aviation does not reduce its emissions. Biofuels provide a solution for aviation emissions reductions and also for the diversification of its fuel supply. Achieving significant reduction will nevertheless need time and a determined policy, meaning also that aviation will have to offset a part of its emissions beyond 2030. Initiatives have to be decided from now to start the process and generate the learning and technological progress which is required for a faster future deployment in order to achieve emissions reductions targets.

In a first step, defining a low minimum goal for biofuel introduction in aviation in 2020 is proposed as a basis for setting policy measures suitable for triggering a start-up of the production. No single measure seems adapted to achieve both the production target and a significant involvement of multiple stakeholders in biofuel production. A combination of measures is probably to be preferred. In particular a global plan pushing for the emergences of a number of "end to end" projects addressing the complete production chain from feedstock to fuel could be a way to reach a minimum production target while favouring technology development and diversity along with the development of energy biomass production. Such an integrated plan could possibly be funded using the revenues from the ETS auction. To complement it, the possible interest of a quota mandate policy could be investigated, in a "push and pull" approach that guaranties that the deployment occurs and also may offer possibilities to distribute the funding on a wider range of payers.

In any case, early deployment should definitely go with an intensification of the research on innovative processes and feedstocks, and should be considered in synergy with other sectors and in particular with the automotive industry.

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