

# **Review of the potential for biofuels in aviation**

**Final report**

**For CCC**

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## Glossary

<b>ASTM</b>	American Society for Testing and Materials
<b>Bio SPK</b>	Synthetic Paraffinic kerosene from vegetable oils, here called HRJ
<b>BTL</b>	Biomass-To-Liquids
<b>CAAFI</b>	Civil Aviation Alternative Fuels Initiative
<b>CCC</b>	Committee on Climate Change
<b>CO<sub>2</sub>e</b>	Greenhouse gas emissions in carbon dioxide equivalents (includes six Kyoto greenhouse gas groups)
<b>Drop in fuel</b>	A fuel that meets all the requirements of the current jet fuel specification and does not require any modification to equipment or infrastructure
<b>Energy crops</b>	Defined here as woody crops or grasses grown for energy uses
<b>EU ETS</b>	European Union Emissions Trading Scheme
<b>FT</b>	Fischer-Tropsch synthesis, a step in a process from biomass, coal or gas to fuels
<b>GHG</b>	Greenhouse gas
<b>HRJ</b>	Hydrotreated Renewable Jet – an aviation biofuel derived from vegetable oils
<b>HVO</b>	Hydrotreated Vegetable Oil – a road transport biofuel derived from vegetable oils
<b>IATA</b>	International Air Transport Association
<b>ICAO</b>	International Civil Aviation Organization
<b>ILUC</b>	Indirect Land Use Change
<b>Lignocellulosic</b>	Biomass material containing lignin and cellulose e.g. wood, straw, grasses
<b>LUC</b>	Land Use Change
<b>Mha</b>	Million hectares
<b>OEM</b>	Original Equipment Manufacturer
<b>OSR</b>	Oilseed rape
<b>SAFUG</b>	Sustainable Aviation Fuel Users group
<b>SH</b>	Synthetic Hydrocarbons – group of new routes from biomass to fuels
<b>SPK</b>	Synthetic Paraffinic Kerosene – includes fuels from FT and HRJ processes
<b>TTW</b>	Tank-to-Wake - emissions from burning fuel in aircraft
<b>ULS</b>	Unlimited Skies – highest of the Consave aviation fuel demand scenarios
<b>WTT</b>	Well-to-Tank – emissions from fuel production
<b>WTW</b>	Well-to Wake – emissions from fuel production and use in aircraft

## Executive Summary

The Committee on Climate Change (CCC) is an independent body which provides advice to Government on defining and setting carbon budgets, and on wider climate change issues. The CCC's first report, published in December 2008, recommended that the Committee report annually on UK trends in international aviation emissions, their climate impact, developments in abatement efforts and policy levers. More specifically, in January 2009 the Committee was asked by the Secretaries of State for Transport and Energy and Climate Change to report on how a new target to get aviation emissions in 2050 below 2005 levels could be met. To address this question, the Committee has commissioned a series of studies modelling projected UK demand for aviation and the associated emissions, with a project on the potential for modal shift from air to rail, and this project on the potential for biofuels to reduce emissions from UK aviation, feeding into the overall assessment<sup>1</sup>.

This project assessed the potential for biofuels in aviation globally, in terms of the potential uptake, and associated greenhouse gas (GHG) emissions savings, concluding that:

***Biofuels could supply between 35 and 100% of global jet fuel demand in 2050, with potential for high greenhouse gas savings, provided that the risk of land use change from the production of feedstocks is managed effectively***

- Biomass derived aviation fuels are a viable alternative to conventional jet fuel, with certification of blends up to 50% in place or imminent, and potential for higher blends up to 100% biofuels in the future.
- By 2020 biofuels could represent up to 1.6% of the fuel mix, if biofuel production plants and new crop types are successful, and are deployed quickly. Biofuels could then ramp up quickly from 2020 to supply between 35% and 100% of jet fuel demand in 2050, based on the high end of jet fuel demand projections.
- The variation between biofuels uptake scenarios is a result of changing assumptions on the oil and carbon price, the speed and success of development of new feedstock types and new biofuels processes, and environmental and social sustainability considerations.
- In all of the scenarios, the average GHG emissions saving from the mix of biofuels used would be around 65-70% at the early stages of deployment, increasing to over 90% in 2050 provided that land use change impacts can be avoided.

The following sections explain what is driving interest in biofuels in aviation, how their use might be limited, and how these results were derived.

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<sup>1</sup> The CCC are intending to use these scenarios to inform their analysis of the 2050 target, but scenarios and assumptions are subject to change. As such these scenarios represent 'preliminary results' in the overall CCC work. Please see the final CCC report in December for the final analysis, results and recommendations

***There are strong drivers for use of alternatives to conventional jet fuel***

Conventional jet fuel, commonly referred to as kerosene, is a blend of hydrocarbons produced by refining of crude oil. Historically, the main drivers for considering alternative fuels have been related to availability and security of supply, leading to development and use of blends containing coal-derived fuels in civil aviation in South Africa, and in military applications by the US Air Force. The current interest in alternatives, however, is driven by several other factors:

- Jet fuel price – this represents a large proportion of airlines’ operating cost, and has fluctuated significantly. This drives development of aircraft and engine technology, and also provides a strong incentive for airlines to consider alternative sources of fuel, which they hope might bring greater flexibility and improved price stability.
- Greenhouse gas emissions – there is increasing concern in the aviation industry that aircraft operations will be required to pay for their carbon emissions, for example through the European Union Emissions Trading Scheme (EU ETS) from 2012. The International Air Transport Association (IATA) estimates that this will result in €3.5 billion in additional costs for airlines in 2012, equivalent to a 5% increase in fuel expenses. By 2020, IATA estimates that this could increase to 19%.

Fuel price concerns have led to interest in a range of alternative fuels, including those derived from coal, gas, and oil shales, which have higher greenhouse gas emissions than conventional jet fuel, unless their production is coupled with carbon capture and storage. Development of biofuels is driven both by the potential for fuel cost reduction and greenhouse gas savings.

***Jet fuel specifications are being modified to include biofuel blends***

There are several constraints that limit the alternative fuel choices that the industry is considering: the very large investment in the existing fleet and jet fuel distribution system, and the typical lifetime of aircraft. These factors, coupled with stringent certification requirements for fuels, mean that airlines are not considering any fuel that is not a ‘drop-in’ replacement for petroleum-derived jet fuel. A ‘drop-in’ fuel is defined as a fuel that meets all the requirements of the current jet fuel specification and does not require any modification to equipment or infrastructure.

Jet fuel specifications are defined in terms of the required performance of the fuel, including characteristics such as the energy content, freeze point, and thermal stability. The existing specifications include some coal-derived alternative fuels, but no biofuels as yet. However, there has been considerable activity in standards development over the last two years, leading to much faster progress than previously expected, with some biofuel blends included in US specifications this year, and several more expected to be included over the next few years.

***Several routes to biofuels for aviation are likely to be commercialised in the near to mid term***

The term ‘biofuel’ can encompass any liquid or gaseous fuel derived from a biomass source. Production of biofuels involves conversion of a biomass feedstock, which can be a crop, residue, by-product or waste, through a conversion process to form one or more products. The most common types of biofuel

used in road transport today are not suitable for use as aviation fuels. In this study we consider only three main types of biofuels that could be 'drop-in' replacements for jet fuel:

- **Biomass-to-liquids (BTL)**
  - This involves gasification of biomass feedstocks, followed by Fischer-Tropsch (FT) synthesis and upgrading steps, to produce jet fuel, diesel or gasoline. A similar process is used to produce jet fuels from coal.
  - Many different feedstocks can be used, from woody energy crops and grasses to municipal solid wastes.
  - The fuel produced is very similar to jet fuel, and identical to the fuel produced using coal. Blends of up to 50% BTL were included in US standards in August 2009.
  - The technologies that make up the BTL route are proven, but the whole process is at the demonstration stage, with plans for commercial scale plants from 2012/13. Plants are expected to need to be large in order to be viable, with high capital costs, and cost reduction is needed.
- **Hydrotreated renewable jet (HRJ)**
  - Vegetable and algal oils can be converted to an aviation fuel through a process including treatment with hydrogen.
  - Conventional vegetable oils such as palm and soy can be used, but new oil crops are being considered, such as jatropha and camelina, and oil extracted from photosynthetic algae could also be used. Further research, development and demonstration of new crops and algae will be needed to achieve the potentials currently being suggested.
  - This type of fuel was used successfully in the recent tests by several airlines. Certification of blends containing up to 50% HRJ is expected by the end of 2010.
  - The technology is very similar to that currently used for producing hydrotreated vegetable oil biodiesel for road transport. Production of jet in these plants is expected from 2010, and in dedicated plants from 2011.
- **'Synthetic hydrocarbons'**
  - There are a number of proposed routes from biomass feedstocks to jet fuels based on novel biological or chemical processes, which we have considered together in this category.
  - These routes would use the same feedstocks as BTL, or sugar and starch crops.
  - These are being developed by companies, principally in the US, and several of them are at the stage of pilot scale testing, plus testing against jet specification. Demonstration of these routes may be as early as 2013, but we modeled commercial availability from 2020.

Other routes are possible, including those based on upgrading of pyrolysis oils, and routes from algal biomass. However, the three types above were those considered in more detail in this analysis in terms of greenhouse gas savings, economics, sustainability, and potential speed of uptake, leading to scenarios of overall biofuels penetration, with a combination of biofuel types.

**Greenhouse gas savings from biofuels can be high, but depend on how the feedstocks are produced**

Considering the greenhouse gas (GHG) impacts of fuels by looking at the whole production chain for each fuel type, is often known in aviation as well-to-wake analysis. This can be split into well-to-tank and tank-to-wake portions. Considering the well-to-tank GHG emissions for biofuels involves assessing the inputs to feedstock production, feedstock transport, the conversion process, fuel transport, and co-products. For petroleum derived jet, it involves extraction and refining of crude oil. In the tank-to-wake part, the CO<sub>2</sub> emissions from fossil jet are included, but those from biofuels are not, as the CO<sub>2</sub> produced when biofuels are burnt is not from a fossil source, being absorbed when the plants are grown. Note that the non-CO<sub>2</sub> tank-to-wake emissions from both jet and biofuels have not been considered, and are likely to be the same for each fuel.

The GHG savings from biofuel chains depend heavily on the type of feedstock used, and how it is produced, as shown in the summary of results below. Those chains based on using energy crops (woody crops and grasses), residues and wastes, low input oil crops, or algae, have significantly lower emissions than those based on conventional oil crops, that have much higher inputs to their production.

Table I: Greenhouse gas emissions of biofuels for aviation

Route	Feedstock	Emissions, g CO <sub>2</sub> e/MJ fuel	Savings CO <sub>2</sub> e vs jet
Fossil jet (baseline)	-	87.5	-
BTL	Energy crops	7.3	92%
	Forestry residues	4.8	95%
HRJ	Conventional oil crops (rapeseed, palm, soy etc)	40-70 (averages)	20%-54%
	Jatropha	30	66%
	Camelina	13.5	85%
	Tallow	10	89%
	Algae (Open ponds)	-21 (best case) 1.5 (realistic case)	124% (best case) 98% (realistic case)
Synthetic hydrocarbons	Not specified		70-90%

The figures above do not include **direct land use change** impacts: they assume that the risk of high GHG impacts from direct conversion of high carbon stock land to land for feedstock for aviation biofuels is low, as a result of airlines' corporate social responsibility concerns, and biofuels sustainability standards in development. They also do not include **indirect land use change** impacts. This may occur if crops for biofuels are grown on agricultural land, displacing other crops. This may cause supplies of those crops to decrease, stimulating production elsewhere. If this new production involves converting new land to agriculture, there can be large GHG and other sustainability impacts, particularly if the land previously had high carbon stocks, such as forest. The risk of indirect land use change is greatest for conventional crops, as they are grown on agricultural land, lower for energy crops and new oil crops, which can be grown on lower quality marginal land, and negligible for algae production, which does not require productive land.

Establishing the causes of indirect land use change, and the magnitude of the impact that can be attributed to production of bioenergy feedstocks, is difficult and is the subject of considerable current global research. In particular, there is no agreement on a quantitative factor that can be included in GHG calculations for individual biofuels. Indirect land use change is more difficult to control through biofuels standards and policy than direct land use change, as it is several steps removed from the feedstock production. However, the GHG and other impacts of indirect land use change could be large, enough to negate the benefits of biofuels use. As a result, we have considered indirect land use change risks throughout the report, in particular when defining scenarios for biofuels uptake.

***Each of the biofuels routes has projected costs that can be competitive with jet fuel, particularly if the cost of carbon emissions are considered, but in most cases only if feedstock costs are low***

We compared the projected costs of the three biofuels types with the projected costs of jet fuel under four jet fuel price scenarios (\$70-160/bbl in 2050), and four carbon price scenarios (£100-300/tCO<sub>2</sub> in 2050).

- **BTL** costs depend heavily on the feedstock used, with early deployment likely to rely on low cost residues and waste. Technology learning is needed to bring BTL costs down significantly in the first 15 years of deployment. With a central oil price and mid range feedstock cost, BTL would not break even with jet fuel until the 2030s, but factoring in the cost of carbon brings this back to the early 2020s.
- **HRJ** costs using **conventional oil crops** were modelled in two ways, as future price projections for vegetable oils are highly uncertain. If the recent potential link between crude oil and vegetable oil prices continues, HRJ from these feedstocks would not break even with fossil-derived jet in most scenarios. If we assume that vegetable oil prices instead drop to the low end of the range seen over the past five years, albeit a level considered unlikely to be seen in the near term, HRJ would break even with jet in the near term, even without a carbon price.
- **HRJ costs using new oil crops and algae** could be competitive with jet, assuming that they will be introduced commercially only when feedstock costs drop to the low end of the vegetable oil range.
- **Synthetic hydrocarbons** are projected to have very low costs, but little information is available on the assumptions behind the projections. Assuming that they can achieve the costs suggested, they would be competitive with jet as soon as they were commercially introduced.

***Sustainability of biofuel routes should be assessed and certified. The potential for sustainable feedstock supply is high for some routes***

Feedstocks for biofuels can have environmental and social sustainability impacts, including effects on biodiversity, soil quality, water quality, land rights and workers rights. Aviation industry interviewees emphasised the importance of sustainability, and several have made commitment to sustainable fuel use. Nevertheless, continued development of sustainability standards, and assessment of new feedstocks and impacts will be needed to ensure feedstock production is sustainable.

Table II: Summary of feedstock sustainability

Feedstock	Factors affecting sustainability and potential	Likelihood of impact
Energy crops	<ul style="list-style-type: none"> <li>High yields, low agricultural inputs, can have sustainability benefits</li> <li>Could avoid land use impacts if grown on land not needed for food production.</li> </ul>	Mid-low
Residues and wastes	<ul style="list-style-type: none"> <li>Large resource, even when limited to sustainable extraction levels</li> <li>Can have impacts if diverted from another use</li> </ul>	Low
Conventional oil crops	<ul style="list-style-type: none"> <li>Direct land use change e.g. deforestation has GHG and biodiversity impacts</li> <li>Grown on agricultural land and so risk indirect land use change in the short term</li> </ul>	High
New oil crops	<ul style="list-style-type: none"> <li>Could grow on poorer quality land than conventional crops, potentially with lower fertiliser inputs, though concerns remain over yields on this land</li> </ul>	Mid-low
Algae	<ul style="list-style-type: none"> <li>Can be grown on non-productive land, with high yields</li> <li>Potential impacts from GMOs and non-native species in open ponds</li> </ul>	Low

Estimates of the potential feedstock resource from some crops are high, even when sustainability constraints are taken in to account:

- BTL and synthetic hydrocarbons could be produced from energy crops, residues and wastes, for which the combined potential is high. This considers the potential for energy crops that could be grown without competition with food, limited by the rate at which crops can be planted. The potential for agricultural and forestry residues and wastes considers the proportion that can be collected and extracted sustainably.
- New oil crops such as jatropha and camelina are being considered as feedstocks for HRJ as they are considered to have the potential to grow on low quality land. Whilst there is poor information on land suitability for camelina, analysis has shown that areas of land suitable for jatropha production are large.

However, for any of these crops, it will be important to ensure that they are grown on the lower quality land identified, rather than being grown on better quality, higher yielding, land, leading to the risk of indirect land use change. It is also important to ensure that social and environmental impacts of growing crops on any type of land are avoided.

The potential for sustainable use of conventional crops may be limited. Despite the potential for yield increases for some crop types, there is a risk that use of vegetable oils for biofuels would lead to price increases, and increased production of the marginal oil crop – currently palm oil – with risks of indirect land use change, such as deforestation.

HRJ from algal oil could have a very large potential, as production of algae is not limited by land availability. Algae can be grown on entirely non-productive land, with the potential for very high yields.

***Considering all of these factors together with estimates of the speed of deployment of each technology gives a range of uptake scenarios***

Uptake scenarios were developed for each combination of oil price and carbon price scenario, and then varied depending on the assumptions made on the use of conventional vegetable oils, and the speed

and success of technology development in new oil crops, algae, and synthetic hydrocarbons. In all scenarios, uptake was limited by the speed with which new conversion plants could be built, and new crops and algae plants established. Uptake is given as a percentage of the highest global aviation fuel demand scenario used in the IPCC 4th Assessment report (Consave ULS).

The full set of 18 scenarios was then narrowed down to five summary scenarios:

- The summary scenarios cover the set of combinations of oil and carbon price: High for high oil price scenarios, Central for the central oil price scenario with a carbon price, Low for the central oil price scenario without a carbon price and the low oil price scenarios with a carbon price, and Very Low for the low oil price scenario with no carbon price.
- Each summary scenario includes a BTL component and an HRJ component, and some a synthetic hydrocarbon (SH) component.
- None of the summary scenarios included use of conventional oil crops for HRJ, as a result of potential sustainability impacts, and the likelihood that prices will remain above the level needed to make production competitive with conventional jet fuel.
- In all scenarios, the speed of BTL development is determined by the oil and carbon price.
- In High and Central (High) scenarios, new oil crops are introduced from 2012, and algae from 2017 and synthetic hydrocarbons from 2020. We assumed that only half of new oil crop production is available for plants producing HRJ, with the rest being used for plants only producing road transport fuels or for other uses.
- In the Central (Low), Low and Very Low scenarios, commercial introduction of new crops and algae is delayed by five years, and the development of synthetic hydrocarbons is not successful for jet fuels.

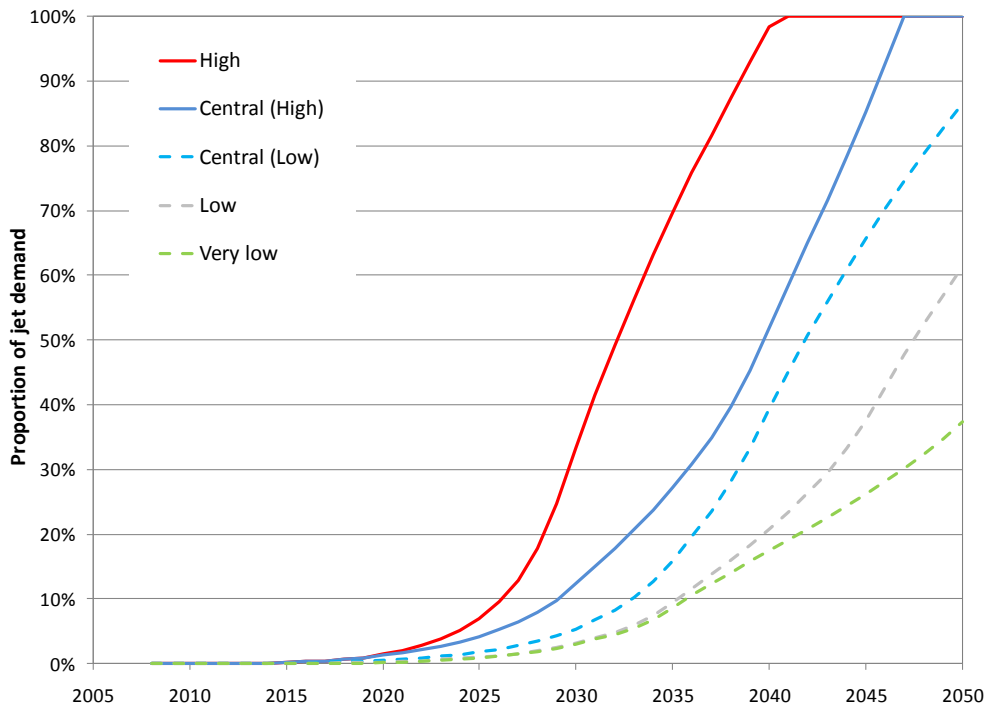


Figure I: Uptake of biofuels to 2050 under the five summary scenarios

The analysis shows that:

- **The uptake is lower in the near to mid term than some industry projections**, which suggest that 5-10% of jet could be biofuels in 2013-2015 and 10% by 2020. The uptake is limited by the build rate of BTL plants and by the availability of new oil crop feedstocks. Even if conventional oil crops were used, achieving these levels by 2020 would require a very fast ramp up of HRJ plants. For comparison, current total biofuels production for road transport is equivalent to 13% of 2020 jet demand.
- **In the longer term, fast ramp up leads to biofuels supplying 35 to 100% of 2050 demand.** This is a result of new feedstock and technology availability, and the shape of plant growth curves. These levels are comparable to some long term industry projections. The lower levels of uptake are seen where BTL and new oil crop development is slow, and synthetic hydrocarbons are not successful.
- **GHG savings from the biofuels used start at around 65-70% and increase to over 90%**, as the fuel mix shifts from new oil crop HRJ towards algae, BTL and in some cases, synthetic hydrocarbons. This relies on crops being grown with low GHG impacts, including avoiding land use change.
- **The feedstock resources required to supply this level of production are projected to be achievable, even considering sustainability constraints, and competition with food and other uses of biomass.** Many of the routes also produce co-products such as animal feed, heat and power, and so do not supply aviation alone.
  - The highest use of energy crop and residue feedstocks is in the High scenario, where supplying 100% of the 2050 jet demand using the fuel mix projected would require 200Mha of land for energy crops (equivalent to 12% of the projected energy crop resource) or 8% of the total projected energy crop and residue resource. For comparison, projected demands for these feedstocks for heat, power and road transport biofuels in other studies are around 3% of the energy crop and residue resource, partly as a result of other options available to these sectors.
  - The highest use of new oil crops is in the Central (High) scenario, where 19 Mha jatropha, 20 Mha camelina and 7 Mha algae plants would be required. The areas for jatropha and camelina can be compared with the current areas for other oil crops, of 14 Mha for palm, 30 Mha for rapeseed, and 90 Mha for soybeans, although they could be grown on lower quality land. The area for algae is much smaller, as a result of greater algal yields.
- **Biomass and biofuels are also likely to be used to some extent in heat, power, chemicals and materials, and in other transport modes.** Meeting demand in other sectors may result in competition for low cost feedstocks, in particular whilst energy crops and algae plants are more widely developed. While there may be competition in the longer term, the analysis in this report shows that there are likely to be sufficient resources to accommodate use of biomass for aviation biofuels, as well as use in other sectors.

***This level of biofuels deployment, and the associated greenhouse gas savings, will rely on feedstock availability, technology development and valuing avoided carbon emissions***

Achieving greenhouse gas emissions reduction in aviation through sustainable biofuels use to the extent seen in the summary scenarios will rely on several key factors:

- **Availability of low cost, sustainable feedstocks** – the sustainable energy crop and new oil crop potentials shown rely on ramping up planting rates, and ensuring that they are grown on land that is not converted from land with high carbon stocks, and is not needed for food production. Whilst studies have shown that this type of land is available, this does not mean that new crops will necessarily be grown on this land. In addition to this, new crops and algae require further research and development to improve their yields, and reduce costs, with wider availability of the results of this activity to allow the industry and policymakers to assess their potential and their impacts.
- **Technology development and deployment** – rapid deployment of conversion technologies close to commercialization, such as HRJ and BTL will be required to achieve the levels of biofuels uptake seen in these scenarios and projected by the industry. In addition to this, if the potential of these technologies is limited as a result of slower cost reduction than expected, low oil prices, or lack of feedstocks for HRJ, new lower cost ‘synthetic hydrocarbon’ conversion technologies would be needed if high potentials are to be achieved.
- **Valuing avoided carbon emissions** – in several of the scenarios, biofuels only break even with jet fuel when the cost of carbon is considered, particularly when oil prices are low.
- **Recognising differences between biofuels** – The EU ETS considers that biofuels have 100% GHG savings compared with fossil jet, without taking into account the emissions in biofuels production, most of which are not themselves covered by the EU ETS. Not recognising the differences in GHG performance between biofuels used in aviation in policy could lead to much lower savings than those given above. Industry members interviewed understood the differences in GHG savings and sustainability between biofuels routes, and several have pledged only to use sustainable routes with high GHG savings. However, this alone is unlikely to stop unsustainable fuels and those with lower GHG savings from entering the supply chain.

## 1 Introduction to the project

The Committee on Climate Change (CCC) is an independent body which provides advice to Government on defining and setting carbon budgets, and on wider climate change issues. The CCC's first report, published in December 2008, concluded that international aviation should not be explicitly included in the UK's carbon budget, but should be included in the UK's climate change strategy, given the growing contribution of international aviation to global greenhouse gas emissions. This is needed to ensure that GHG reduction in international aviation is achieved, as without this contribution to savings, other sectors will be required to make savings of more than 80% below 1990 levels by 2050.

The report recommended that the Committee report annually on UK trends in international aviation emissions, their climate impact, developments in abatement efforts and policy levers. More specifically, in January 2009, Geoff Hoon asked the Committee to report on how a 'new target to get aviation emissions in 2050 below 2005 levels' could be met, as part of the Government's statement on Britain's Transport Infrastructure. In order to address this question, the Committee has commissioned projects covering projected UK demand for aviation and the associated emissions, the potential for modal shift from air to rail, and this project on the potential for biofuels to reduce life-cycle emissions from UK aviation<sup>2</sup>. The results from the latter two projects feed back into the first project.

This project aims to assess the potential for biofuels in aviation globally, in terms of their technical suitability, cost, sustainable potential and likely uptake. This will show whether or not biofuels could make a substantial contribution to GHG savings in UK and global aviation, and whether this is likely given other potential uses of biomass feedstocks, oil and carbon prices, sustainability constraints, technology development, and aviation demand. The report is broken down into seven chapters, covering the questions below, plus annexes:

2. **Introduction to alternative fuels in aviation** – what has driven interest in alternative fuels in aviation? What is driving current interest in biofuels?
3. **Fuel requirements and certification** – what are the requirements of a jet fuel? How are new fuels certified? What testing has been done?
4. **Technical suitability of biofuels for aviation** – which biofuels could be used? How are they produced? When will they be commercially available?
5. **Greenhouse gas savings** – how are greenhouse gas savings from biofuels in aviation assessed? What are the savings from different biofuel chains?
6. **Economic case** – how do biofuels costs compare with fossil-derived jet? How does this change with a carbon price? How likely is it that biofuels will be used in aviation, given other potential uses of biofuels and their feedstocks?
7. **Sustainable potential** – what are the sustainability benefits and impacts of each biofuels chain? How does the potential sustainable feedstock resource compare with aviation demand? What are the competing demands for the feedstock?

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<sup>2</sup> CCC aviation reports <http://www.theccc.org.uk/reports/aviation-report>

8. ***Uptake scenarios*** – considering the time to commercialisation, costs, and sustainability constraints on biofuels, how fast could their use in aviation develop? How is this affected by changing scenarios of oil price, carbon price, feedstock prices, and technology success?

We would like to thank the following organisations and individuals interviewed during the course of this project. Note that all results and views stated are our own, and have not been reviewed or endorsed by these groups.

- ATAG
- IATA
- CAAFI
- Virgin Atlantic
- British Airways
- Rolls Royce
- Pratt and Whitney
- Boeing
- UOP
- Shell
- Rentech
- James Hileman, MIT
- David Lee, Manchester Metropolitan University and Omega
- Chris Wilson, University of Sheffield and Omega

## 2 Introduction to alternative fuels in aviation

### 2.1 The history of alternative fuels in aviation

Conventional jet fuel, commonly referred to as kerosene, is a complex blend of straight chain, cyclic and aromatic hydrocarbons made up of molecules with typically 8 to 16 carbon atoms per molecule. It is produced through the refining of petroleum crude from both the direct distillation of crude (straight-run) as well as from the hydro-cracking of heavier crude fractions such as distillation bottoms. Both the straight-run and hydro-cracked fuel streams usually need to be upgraded through hydro-treating and processed to remove acidic compounds (sweetening)<sup>3</sup>.

Experience with “alternative fuels” in aviation has centred on synthetic fuels and in particular those derived from the Fischer-Tropsch (FT) process. The drivers behind the testing of alternative fuels have been largely political in civil aviation applications and to achieve enhanced performance and increased energy security in military applications.

The most extensive experience with synthetic fuels in aviation is with the FT synthetic fuels developed by Sasol in South Africa. Since 1950 Sasol (South African Synthetic Oil) worked to develop and produce liquid fuels from coal (and more recently also from natural gas). South Africa, which has abundant coal reserves but very limited petroleum resources, was concerned about the need to import significant quantities of petroleum products. This became increasingly true as the South African apartheid policies led to the isolation of the country from European and other trading partners. Sasol’s semi-synthetic jet fuel blend (50% petroleum derived, 50% coal-derived FT jet fuel) was approved for use with aircraft in 1999 after a 7 year certification process<sup>4</sup>. Sasol’s 50% synthetic blend has been in commercial use at OR Tambo International Airport in Johannesburg since then, so there have been over ten years of experience with this blend. Starting in 1999 Sasol pursued the certification of a fully synthetic jet fuel and a specification for such a fuel was added to the British Def Stan 91-91 jet fuel standard in 2008 and is expected to be included in the equivalent ASTM standard in 2009<sup>5</sup>. However, to date, there have been no flights with 100% synthetic fuel<sup>6</sup>.

The US Air Force (USAF) has initiated an extensive program to certify the entire USAF fleet to operate on a 50/50 blend of petroleum derived and FT synthetic JP-8. The primary objective is to improve the energy security of the USAF by reducing reliance on petroleum imports. The program, which started in

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<sup>3</sup> Chevron, Aviation Fuels Technical Review, 2006, [Accessed May 6, 2009], [http://www.chevronglobalaviation.com/docs/aviation\\_tech\\_review.pdf](http://www.chevronglobalaviation.com/docs/aviation_tech_review.pdf)

<sup>4</sup> Flightglobal, Coal – Jet fuel of the future?, Feb. 2008, [Accessed 11 May, 2009], <http://www.flightglobal.com/articles/2008/02/25/221766/coal-jet-fuel-of-the-future.html>

<sup>5</sup> Aviation Today, Sasol - 100% Synthetic Fuel Wins First-Time Approval for Use Internationally in Commercial Aviation, April 2008, [Accessed 11 May, 2009], [http://www.aviationtoday.com/pressreleases/Sasol-100-percent-Synthetic-Fuel-Wins-First-Time-Approval-for-Use-Internationally-in-Commercial-Aviation\\_20968.html](http://www.aviationtoday.com/pressreleases/Sasol-100-percent-Synthetic-Fuel-Wins-First-Time-Approval-for-Use-Internationally-in-Commercial-Aviation_20968.html)

<sup>6</sup> Flightglobal, RAF ditches attempts to fly 100% synthetic fuel on TriStar, March 2009, [Accessed 11 May, 2009], <http://www.flightglobal.com/articles/2009/03/11/323656/raf-ditches-attempts-to-fly-100-synthetic-fuel-on-tristar.html>

2006 with tests on the B-52 bomber<sup>7</sup>, has so far certified three (B-52, C-17, B-1) of the USAF's more than 30 types of aircraft and started testing on a further six aircraft types (F-22, F-16, B-2, KC-135, C-5, T-38)<sup>8</sup>. The USAF plans to certify its entire fleet to use the synthetic blend by 2011, and to have a semi-synthetic fuel blend (<50%, blend not specified) replace half the jet fuel that it consumes in domestic operations by 2016<sup>8</sup>. Once the aircraft are certified, the USAF can operate them with 50/50 blends of petroleum derived and FT synthetic jet fuel regardless of the feedstock used to produce the FT synthetic fuel (e.g., coal, natural gas, biomass, shale oil). The broad range of possible feedstocks greatly enhances the value of using FT synthetic fuels since this only increases the number of potential resources on which the USAF could draw. However, the Energy Independence and Security Act (EISA) of 2007 prohibits the US Government from procuring an alternative fuel for any transport-related purposes that is more carbon intensive than the equivalent conventional fuel produced from petroleum<sup>9</sup>. At current technology levels this effectively rules out the use of FT fuels from coal, natural gas or shale oil since these all have higher life-cycle greenhouse gas emissions than equivalent conventional petroleum-derived fuels<sup>10</sup>. It is possible that with carbon capture and storage, and combining biomass feedstocks with coal<sup>11</sup> that some of these routes will become allowed under the terms of EISA.

## 2.2 Current drivers and constraints for alternative fuels in commercial aviation

The cost of fuel has been a major driver in the development of aircraft and engine technology throughout the history of jet powered flight. Historically, fuel has represented about 10-15% of an airlines operating cost (Figure 1). The recent increase in crude oil prices caused fuel to increase to about 30% of airline operating cost, a level which airlines have not seen since the early 1980's. The price of crude has dropped again relative to the peak reached in 2008, however, the large fluctuations in the cost of fuel have provided a strong incentive for airlines to consider alternative sources of fuel. The hope for the airlines is that a broader range of sources would give them greater flexibility in meeting their needs and improved price stability. Biofuels are clearly a possible alternative, but other, less

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<sup>7</sup> FlightGlobal, Fuel Renewal: The US Air Force tests synthetic fuel on a B-52 as part of foreign fuel reliance reduction drive, Oct. 2006, [Accessed 11 May, 2009], <http://www.flightglobal.com/articles/2006/10/04/209576/fuel-renewal-the-us-air-force-tests-synthetic-fuel-on-a-b-52-as-part-of-foreign-fuel-reliance.html>

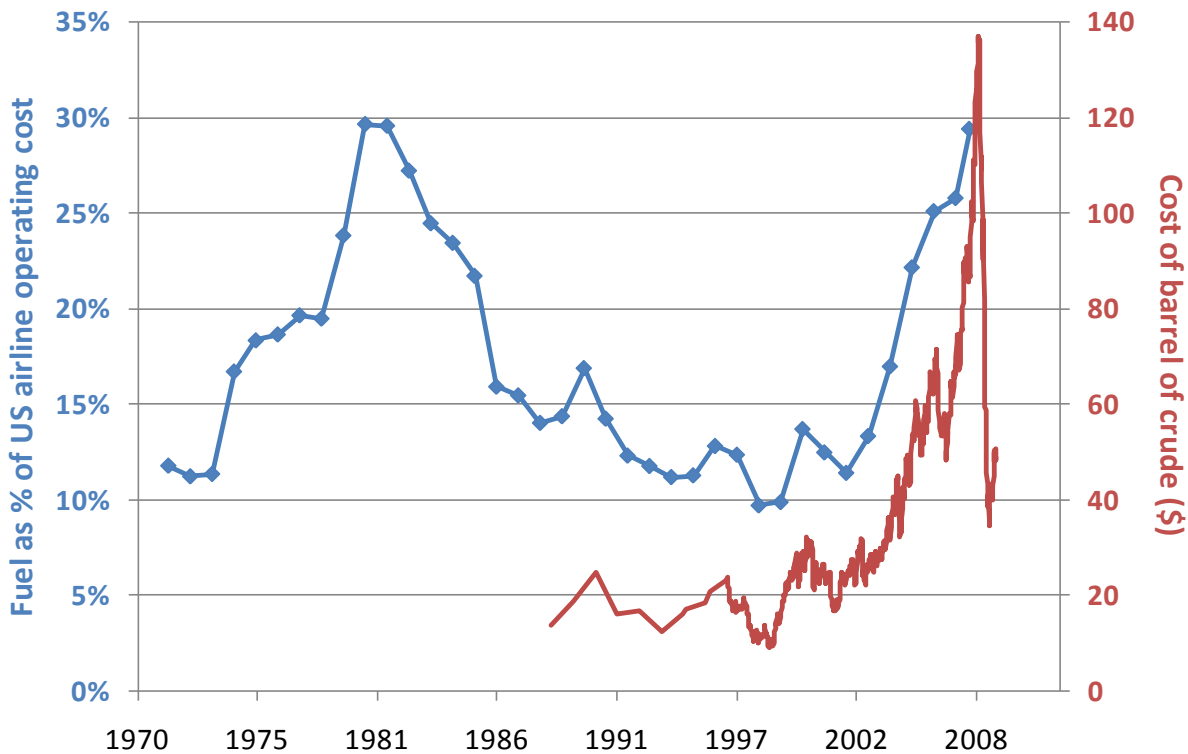
<sup>8</sup> DefenseNews, Synthetic Future, March 2009, [Accessed 11 May, 2009], <http://www.defensenews.com/story.php?i=3969089&c=FEA&s=TEC>

<sup>9</sup> Energy Independence and Security Act of 2007, Sec. 526: Procurement and Acquisition of Alternative Fuels, Jan. 2007, [Accessed 17 June, 2009], [http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110\\_cong\\_bills&docid=f:h6enr.txt.pdf](http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf)

<sup>10</sup> Wong, H.M., Life-cycle assessment of greenhouse gas emissions from alternative jet fuels, MS Thesis, MIT, Sept. 2008.

<sup>11</sup> Sigma: Energy Security, From coal and biomass to synthetic fuel, David Gray et al, Noblis, Dec. 2007, [Accessed 28 July 2009], <http://www.noblis.org/MissionAreas/ees/Services/Documents/SigmaCoalBiomass.pdf>

environmentally beneficial sources such as coal-to-liquid (CTL), gas-to-liquid (GTL), shale oils and tar sands are being considered as well<sup>12</sup>.



**Figure 1: Historical values of fuel related operating cost for US airlines compared to the cost of a barrel of crude<sup>13,14</sup>.**

In addition to the direct cost of fuel, there is increasing concern in the aviation industry that aircraft operations will be required to pay for their carbon emissions. The Kyoto Protocol instructed Annex 1 countries (industrialised nations) to pursue emissions reductions or limitations through the International Civil Aviation Organization (ICAO). There is wide expectation that aviation emissions will be included in any agreement that comes out of the upcoming UN Framework Convention on Climate Change (UNFCCC) meeting in Copenhagen in December 2009. More immediately, the European Commission has issued a directive to include aviation activities of aircraft operators that operate flights arriving or departing from the European Union (EU) in the EU Emissions Trading Scheme (ETS) effective from

<sup>12</sup> Qatar Fuel, Gas-to-Liquids Jet Fuel Development, Feb. 2009, [Accessed 12 May 2009], [http://www.icao.int/WAAF2009/Presentations/8\\_Alsobai.pdf](http://www.icao.int/WAAF2009/Presentations/8_Alsobai.pdf)

<sup>13</sup> Air Transport Association, Quarterly Cost Index, U.S. Passenger Airlines, 2009, [Accessed 12 May 2009], <http://www.airlines.org/economics/finance/Cost+Index.htm>

<sup>14</sup> Energy Information Administration, World Crude Oil Prices, 2009, [Accessed 12 May 2009], [http://tonto.eia.doe.gov/dnav/pet/pet\\_pri\\_wco\\_k\\_w.htm](http://tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm)

January 2012<sup>15</sup>. The International Air Transport Association (IATA) estimates that the EU ETS will result in €3.5 billion (\$4.0bn) in additional costs for airlines in 2012 equivalent to a 5% increase in fuel expenses (shown in Table 1). By 2020, IATA estimates that this could increase to 19% if airlines have to buy all of their EUETS allowances and the allowance cost increases<sup>16</sup>. During interviews, airline representatives indicated that they expected compliance with the EU ETS to increase their fuel expenses by about 10%. The use of biofuels could help airlines minimize this additional expense as all biomass-derived fuels will be counted as zero i.e. emitting no CO<sub>2</sub><sup>17</sup>.

**Table 1: Estimated global commercial aviation revenues and fuel expenses<sup>18</sup>**

Year	Revenue US\$ (billion)	Fuel expenses US\$ (billion)
2008	528	165
2009	448	106

Industry players cite a range of motives for their interest in alternative fuels. For instance, the Air Transport Action Group (ATAG), an industry coalition that represents more than 70 players in all areas of the global aviation industry, states:

“... concerns about rising fuel costs, energy supply, energy security and aviation emissions have called for a fresh look at the use of alternative fuels.”<sup>19</sup>

Similarly, Boeing recognizes both the environmental and economic motives behind its interest in biofuels:

“sustainable biofuels represent a major opportunity for reducing global aviations greenhouse gas emissions. And fuel is one of the largest costs for airlines and their passengers.”<sup>20</sup>

<sup>15</sup> European Commission, Aviation and Climate Change, [Accessed 12 May 2009], [http://ec.europa.eu/environment/climat/aviation\\_en.htm](http://ec.europa.eu/environment/climat/aviation_en.htm)

<sup>16</sup> IATA 2008 Report on Alternative Fuels <http://www.iata.org/NR/ronlyres/03FE754C-D30A-4E77-8C92-5A05AF75C614/0/IATA2008ReportonAlternativeFuels.pdf>

<sup>17</sup> Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community, Nov. 2008, [Accessed 17 June, 2009] <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0101:EN:NOT>

<sup>18</sup> IATA Financial Forecast, June 2009, [Accessed 17 June, 2009], [http://www.iata.org/NR/ronlyres/DA8ACB38-676F-4DB1-A2AC-5BCEF74CB2C/0/Industry\\_Outlook\\_Jun09.pdf](http://www.iata.org/NR/ronlyres/DA8ACB38-676F-4DB1-A2AC-5BCEF74CB2C/0/Industry_Outlook_Jun09.pdf)

<sup>19</sup> Air Transport Action Group, Fuel consumption & alternative fuels, [Accessed 29 Apr. 2009], <http://www.atag.org/content/showissue.asp?pageid=1084&level1=3&level2=472&level3=1084>

<sup>20</sup> Boeing, Biofuel Resource Center, 2008, [Accessed 29 Apr. 2009], <http://www.newairplane.com/environment/sustainablebiofuels/>

The Commercial Aviation Alternative Fuels Initiative (CAAFI), an industry association with a United States focus, also highlights the issues of fuel cost, energy security, environmental impact and sustainability.<sup>21</sup>

While there are several pressures that are pushing the aviation industry to consider alternative fuels, there are also constraints that limit the range of choices that the industry is willing to consider. The most significant constraint is the very large investment in the existing fleet. The Air Transport Action Group (ATAG) estimates that globally, airlines currently have a fleet of nearly 23,000 aircraft<sup>22</sup>. For reference, the list price of a Boeing 737, the jet airliner with the largest production, is \$50-90 million, while larger aircraft such as the Boeing 787 cost around \$150-200 million<sup>23</sup>. These numbers suggest that the existing fleet represents a past investment of hundreds of billions or even trillions of dollars (without even considering the investment in related infrastructure such as the jet fuel distribution system). Furthermore, aircraft have a typical life of 25 to 30 years, meaning that a significant fraction of the current fleet will be operational to 2020 or even 2030 and beyond. This long life cycle and high cost, coupled with stringent certification requirements for fuels, mean that airlines are not willing to consider any fuel that is not a 'drop-in' replacement for current, petroleum-derived jet fuel<sup>24</sup>. A drop-in replacement fuel is defined as an alternative fuel that meets all the requirements of the current jet fuel specification and does not require any equipment modification.

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<sup>21</sup> Commercial Aviation Alternative Fuels Initiative, 2009, [Accessed 29 Apr. 2009],  
<http://www.caafi.org/about/caafi.html>

<sup>22</sup> Air Transport Action Group, Facts and Figures: Aviation in General, 2009, [Accessed 12 May 2009],  
<http://www.enviro.aero/aviationenvironmentfactsfigures.aspx>

<sup>23</sup> Boeing, Commercial Airplanes: Jet Prices, 2008, [Accessed 12 May 2009],  
<http://www.boeing.com/commercial/prices/>

<sup>24</sup> Sustainable Aviation Fuel Users Group, Commitment to Sustainable Options, 2008, [Accessed 12 May 2009],  
[http://www.boeing.com/commercial/environment/pdf/sustainable\\_aviation\\_fuel\\_users\\_group.pdf](http://www.boeing.com/commercial/environment/pdf/sustainable_aviation_fuel_users_group.pdf)

### 3 Fuel requirements and certification

#### 3.1 Jet fuel requirements

The property requirements for jet fuel developed somewhat organically with the development of the jet engine and the development of catalytic cracking processes in the refining industry starting in the 1920's and 30's. From its origins, the source of jet fuel has been the refining of petroleum crude. As with most outputs of the refining process, jet fuel is a mixture of a large number—as many as a thousand or more— of different hydrocarbons. Indeed, modern analytical techniques are still not powerful enough to fully identify all the individual species that make up the mixture<sup>25</sup>. Because of this, jet fuel specifications and requirements are largely defined in terms of required performance rather than, say, a target composition (although limits on amounts of certain classes of compounds such as aromatics are part of the specification). Several of the key performance characteristics most relevant to the introduction of biofuels, are listed and described below.

#### Energy content

The primary function of the fuel on an aircraft is to act as a store of chemical energy that can be converted into the work required to fly the aircraft. Since the volume available to store fuel on the aircraft and the mass of fuel that the aircraft can carry are both constrained, the energy content of the fuel will have a significant impact on the aircraft performance. Specifically, for commercial aircraft, this means that the maximum range of the aircraft is set, in part, by the energy content of the fuel. The energy content of different hydrocarbon species is different and so, as the exact composition of a given batch of jet fuel is variable, so is the actual energy content. The standards define a minimum net heat of combustion, which is the gravimetric energy density (or energy per unit mass) of the fuel usually defined in MJ/kg. However, the volumetric energy density (or energy per unit volume) is also important, since, for a full load of fuel in a fixed volume tank, the higher the volumetric energy density of the fuel, the greater the total energy that the aircraft can carry.

#### Freeze point

Modern aircraft operate for extensive periods of time at high altitudes where air temperatures can be as low as -50°C or lower. The main fuel tanks in modern commercial jets are in the wings, thus on long flights, the fuel in the tanks will cool to very low temperatures. It is clearly important that the fuel remain pumpable even at these low temperatures. The fuel standards therefore define a maximum allowable freezing point. Since jet fuel is a blend of many different hydrocarbon species it does not freeze solid at a single temperature the way water does, for instance. Rather, the hydrocarbons with the highest freezing temperatures will solidify first, creating small waxy crystals suspended in the remaining liquid. As the temperature continues to drop, more and more of the species will begin to solidify and the fuel will change first to a slushy mixture and eventually to an almost solid wax block.

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<sup>25</sup> Chevron, Aviation Fuels Technical Review, 2006, [Accessed May 6, 2009], [http://www.chevronglobalaviation.com/docs/aviation\\_tech\\_review.pdf](http://www.chevronglobalaviation.com/docs/aviation_tech_review.pdf)

### **Thermal stability**

On the way to being burned in the aircraft engine, the fuel is used for a variety of other functions. One of these is to cool the engine lubrication oil and other engine components. At elevated temperatures, some of the more reactive species in the fuel can begin to undergo chemical reactions that can result in the formation of gums and insoluble coke particulates in a process typically referred to as coking. These gums and particulates can deposit on fuel system components such as filters and reduce or disrupt the fuel flow. In addition, they can also clog fuel injection nozzles or small cooling holes in the combustor or in the turbine resulting in the need for increased maintenance. The chemistry of the coking reactions is extremely complex, involving interactions between many components and trace chemicals, and so the thermal stability of the fuel cannot be predicted. Thus the standards define a performance test where fuel is flowed through a heated tube at a specified flow rate and tube temperature for a fixed amount of time and any deposits are evaluated.

### **Viscosity**

Inside the engine, the liquid fuel is injected at high pressure through nozzles that break the fuel up into a fine spray of droplets. The viscosity of the fuel impacts both the spray pattern coming out of the fuel nozzle as well as the size of the resulting droplets. An increase in the droplet size can result in incomplete combustion of the fuel and can also make the engine harder to relight at altitude (should that prove necessary). A change in the spray pattern can also result in sub-optimal combustion of the fuel as well as creating uneven temperature distributions that can damage the combustor or the turbine downstream. The fuel standards include a maximum allowable fuel viscosity to avoid these problems.

### **Combustion characteristics**

Certain classes of hydrocarbons typically present in petroleum-derived jet fuel, such as aromatic<sup>26</sup> compounds, are more likely to form small carbonaceous particles during combustion. These particles can have several detrimental effects on engine performance. Firstly, the particles become incandescent in the combustor and emit additional infrared radiation that can increase the wall temperatures in the combustor, potentially damaging the combustor. Secondly, the particles can be deposited on engine internal surfaces, potentially disrupting the air flow or clogging cooling holes or other features. Thirdly, the particles can erode downstream engine components. And finally, some of the particles can be emitted as visible smoke from the engine. In addition, the presence of sulphur in the fuel can result in the emission of fine particulates with detrimental air quality effects due to the formation of sulphur oxides. The fuel standards define maximum allowable concentrations of aromatic compounds and sulphur to minimize these problems<sup>27</sup>.

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<sup>26</sup> Aromatic hydrocarbons are compounds such as benzene that include one or more rings of carbon atoms that are joined by alternating single and double covalent bonds.

<sup>27</sup> Chevron, Aviation Fuels Technical Review, 2006, [Accessed May 6, 2009], [http://www.chevronglobalaviation.com/docs/aviation\\_tech\\_review.pdf](http://www.chevronglobalaviation.com/docs/aviation_tech_review.pdf)

### **Lubricity**

Another of the functions served by the fuel is to provide lubrication to various moving parts in the fuel system and engine controls. These include the fuel pumps, as well as fuel controls and hydraulic engine controls. There are two separate mechanisms that help the fuel provide lubrication. The first is hydrodynamic lubrication whereby a thin layer of fuel separates two mechanical surfaces. The higher the fuel viscosity, the greater the hydrodynamic lubrication will be. The second mechanism is boundary lubrication which occurs in regions of very high pressure or where clearances are too tight to allow a hydrodynamic fuel layer to exist. Boundary lubrication occurs when fuel molecules adhere to the metal surfaces and form a protective layer. The ability of a fuel to be a good boundary lubricant is attributed to the presence of trace amounts of sulphur, oxygen and nitrogen containing compounds as well as aromatics. Unfortunately, the lubricity of a given batch of fuel cannot be predicted based on bulk chemical properties such as the average sulphur or aromatic content and again, the standards define a performance based requirement that the fuel must meet<sup>27</sup>.

### **Material compatibility**

During distribution and use, jet fuels come into contact with a wide variety of metals, coatings and elastomers. Some of the compounds present in petroleum derived fuels such as organic acids and mercaptans can cause corrosion of metal parts. To mitigate these problems the specifications include limits on the total acidity of the fuel as well as the maximum allowable concentrations of mercaptans. An overall corrosivity test is also specified.

The presence of certain aromatic compounds in the fuel can cause the elastomers present in the aircraft fuel systems to swell. There is concern in the industry that alternative fuels that do not have these aromatic compounds could result in fuel system leaks if the seals do not swell as much<sup>28</sup>.

### **Safety properties**

The two most important fuel properties that relate to safety are the fuel's flash point and its electrical conductivity. The flash point is the lowest temperature at which fuel vapours above a flammable liquid will ignite if an ignition source is applied.

Pumping of fuel through handling equipment can generate static electric charge in the fuel. The conductivity of jet fuel is extremely low meaning that this static charge dissipates slowly and can potentially build up. If a high enough static charge builds up, it can result in a spark which in turn could initiate an explosion if the mixture of air and fuel vapour above the fuel is in the flammable range.

The standards include requirements for minimum flash point and electrical conductivity to minimize the risks of explosions in fuel handling systems and aircraft fuel tanks.

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<sup>28</sup> Chevron, Alternative Jet Fuels, 2006, [Accessed May 7, 2009],  
[http://www.chevronglobalaviation.com/docs/5719\\_Aviation\\_Addendum.\\_webpdf.pdf](http://www.chevronglobalaviation.com/docs/5719_Aviation_Addendum._webpdf.pdf)

## Summary

Table 2 gives a summary of the discussion above. It should be emphasized that both the discussion above and, in particular, the table below cover only a subset of the characteristics that are listed in the current specifications.

**Table 2: Summary of jet fuel requirements**

Requirement	Reason	Specification
Energy content	Affects aircraft range	Minimum energy density by mass
Freeze point	Impacts upon ability to pump fuel at low temperature	Maximum allowable freeze point temperature
Thermal stability	Coke and gum deposits can clog or foul fuel system and nozzles	Maximum allowable deposits in standardized heating test
Viscosity	Viscosity impacts ability of fuel nozzles to spray fuel and of engine to relight at altitude	Maximum allowable viscosity
Combustion characteristics	Creation of particulates in combustor and in exhaust	Maximum allowable sulphur and aromatics content
Lubricity	Impacts upon ability of fuel to lubricate fuel system and engine controls	Maximum allowable amount of wear in standardized test
Material compatibility	Fuel comes in to contact with large range of metals, polymers and elastomers	Maximum acidity, maximum mercaptan concentration, minimum aromatics concentration (new)
Safety	To avoid explosions in fuel handling and tanks	Minimum fuel electrical conductivity and minimum allowable flash point.

## 3.2 Certification

Certification of aviation turbine fuel in Europe and the US is governed by two standards: ASTM 1655 of the American Society for Testing and Materials<sup>29</sup> and Def Stan 91-91 of the UK Ministry of Defence<sup>30</sup>. The two standards are largely equivalent except for a few minor areas where Def Stan 91-91 is more stringent (e.g., maximum allowable freezing point is -47°C in Def Stan 91-91 and -40°C in ASTM 1655).

Certification of new fuels is a collaborative consensus process between the sponsor of the new fuel, the original equipment manufacturers (OEMs)—in this case primarily the aircraft engine manufacturers and

<sup>29</sup> American Society for Testing and Materials, ASTM 1655-08a: Standard Specification for Aviation Turbine Fuels, 2008, [Accessed May 7, 2009], <http://www.astm.org/Standards/D1655.htm>

<sup>30</sup> UK Ministry of Defence, Defence Standard 91-91, Turbine Fuel, Aviation Kerosine Type, Jet A-1, April 2008, [Accessed May 7, 2009], <http://www.dstan.mod.uk/data/91/091/00000600.pdf>

airframers—and the standard issuing body such as the ASTM. Figure 2 shows an overview of the ASTM approval process for new fuels or additives<sup>31</sup>. The three main parts of the process are:

- **Test program:** With guidance from the OEMs, the sponsor of the new fuel or additive conducts a test program and prepares a research report that is submitted to the OEMs.
- **OEM Internal Review:** The OEMs review the research report and can either request additional testing or information or, approve the fuel. If they approve the fuel, OEMs forward the research report and an OEM review report to ASTM for balloting.
- **Specification change:** The relevant committee of ASTM reviews the research report and OEM review reports and puts the proposed specification changes to ballot by all its members. Any negative votes are reviewed for merit and additional testing or information may be requested. The process is repeated until all issues have been addressed at which point the committee approves the specification changes.

The process typically goes through several iterations. Once the specification changes are approved, ASTM publishes the revised specification and the OEMs issue updated service bulletins or engine manuals that indicate their approval of the new fuel.

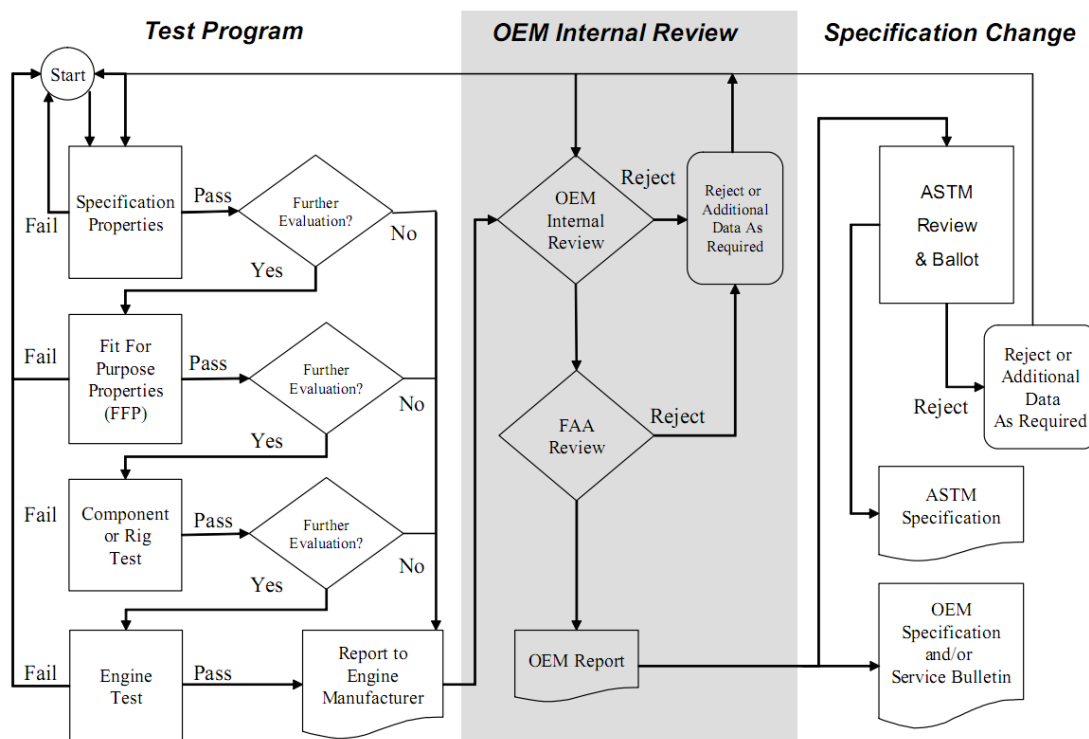


Figure 2: Overview of the ASTM fuel and additive approval process

<sup>31</sup> ASTM Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives, D4054, in press, <http://www.astm.org/Standards/D4054.htm>

The existing specifications do already include some alternative fuels. Annex D of Def Stan 91-91 lays out the requirements for fuels containing synthetic compounds and includes approval of two specific alternative fuels produced by Sasol: Sasol Semi-Synthetic Blends ( $\leq 50\%$  Sasol iso-paraffinic synthetic kerosene, with no synthetic aromatic compounds) and Sasol Fully Synthetic Jet Fuel (8-25% aromatic content).

ASTM D1655 includes specific approval for Sasol Semi-Synthetic Blends but does not yet include approval for the Sasol Fully Synthetic Jet Fuel.

In December of 2008, the ASTM International Aviation Fuels Subcommittee approved the following change proposals:

- Acceptance of generic semi-synthetic aviation fuels from the FT process (i.e. not just from Sasol plants, and from any feedstock).
- Acceptance of Sasol Fully Synthetic Jet Fuel.
- A new specification (previously referred to as DXXXX in the industry, and since August 2009 called D7566) that constructs a framework for the use of multiple alternative fuels. D7566 enables use of FT fuels now, with hydrotreated renewable fuels and other alternatives to be included in future annexes as data from technical evaluations is obtained.

These change proposals were approved by the ASTM International Aviation Fuels subcommittee at their meeting on 24 June 2009,<sup>32</sup> and D7566 was formally adopted in August 2009<sup>33</sup>. In their press release the Civil Aviation Alternative Fuels Initiative (CAAFI) also indicated that the research report needed to support the approval of hydrotreated renewable jet (HRJ) is expected by the end of 2009 which should lead to incorporation of HRJ fuel blends into the new specification by the end of 2010.<sup>32</sup>

### 3.3 Testing

The aviation industry has been conducting a series of tests with a range of different biofuels in order to collect the data required for the research report needed to support certification of alternative fuels (Table 3). The main players in these tests have been the large airframe manufacturers (Boeing, Airbus), aircraft engine manufacturers (GE Aviation, Rolls-Royce, Pratt & Whitney and their respective joint ventures CFM and IAE) and the petroleum, petrochemical and gas process technology supplier, UOP. The public face of this testing is the flight tests that have been conducted over the last few months (Table 3), however, prior to the flight tests, a broad range of laboratory and ground testing on components and full engines was conducted.

The five flight tests conducted to date have all been of blends of fossil fuel with up to 50% of an alternative fuel. Four of the tests have used fuel derived from a range of biomass feedstocks, while one has used a Fischer-Tropsch (FT) fuel derived from natural gas. While this last fuel from a gas-to-liquid (GTL) process is not a biofuel, the functional similarity of the derived fuel means that data from this

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<sup>32</sup> CAAFI, Landmark synthetic jet fuel specification passes critical hurdle, June 2009, [Accessed 26 July, 2009], <http://www.caafi.org/files/altfuelstandard-rls6-09.pdf>

<sup>33</sup> Green Air Online 'Synthetic jet fuel blends receive final stamp of approval and pave the way for jet biofuel certification' <http://www.greenaironline.com/news.php?viewStory=565>

flight test is being used to support certification of other alternative fuels made from biomass feedstocks by the FT process.

The flight tests ranged from 1.5 to 3 hours duration and included a range of “normal” and “non-normal” manoeuvres such as:

- Rapid throttle excursions (acceleration, deceleration),
- Engine shutdown and relight (in flight),
- Gravity or suction feed (one of the fuel pumps turned off, test of lubricity/viscosity),
- Simulated touch and go (simulated aborted landing done at altitude),

“Non-normal” manoeuvres are included as part of all testing of aircraft since aircraft must be certified to operate under a much wider range of operating conditions than are normally encountered during a routine commercial flight.

To date, the companies involved in the flight tests have only made a limited amount of information about the test flights available publicly. Principally this consists of announcing the success of the flight test and issuing general statements from the test pilots such as the following from the JAL test flight:

“Everything went smoothly. There was no difference at all in the performance of the engine powered by the biofuel blend, and the other three engines containing regular jet fuel.”<sup>34</sup>

And these comments from the Air New Zealand test flight:

“We undertook a range of tests on the ground and in-flight with the jatropha biofuel performing well through both the fuel system and engine, just as laboratory tests indicated it would.”<sup>35</sup>

Boeing information on the Air New Zealand, Japan Air Lines and Continental Airlines test flights<sup>36</sup>, indicates that fuel consumption when using biofuels was reduced by 1.07% (by mass), as a result of a 1.08% increased energy density, relative to the specification value. Note that in interviews, industry fuels experts have pointed out that the energy density of the biofuel, while higher than the specification, is well within the range of actual energy densities that aircraft see due to the natural variability of petroleum products.

Four additional planned flight tests have been announced by JetBlue, British Airways, Qatar Airways and Interjet respectively. British Airways has indicated that it had difficulty sourcing the 60,000 litres of biofuel that it required to conduct the test<sup>37</sup> since biofuels producers could not supply them with the required volumes of fuel. Qatar Airways has announced that it expects to fly a biofuel test flight from

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<sup>34</sup> Boeing, Biofuel Press Release, Jan. 2009, [Accessed 28 Apr. 2009]  
[http://www.newairplane.com/assets/environment/downloads/Jan\\_30\\_Biofuel\\_Press\\_Release.pdf](http://www.newairplane.com/assets/environment/downloads/Jan_30_Biofuel_Press_Release.pdf)

<sup>35</sup> Air New Zealand, World-First Biofuel Test Flight, Dec. 2008. [Accessed 28 Apr. 2009]  
<http://www.airnewzealand.co.nz/aboutus/biofuel-test/default.htm>

<sup>36</sup> Boeing, Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK), [Accessed 26 July 2009],  
[http://www.boeing.com/commercial/environment/pdf/PAS\\_biofuel\\_Exec\\_Summary.pdf](http://www.boeing.com/commercial/environment/pdf/PAS_biofuel_Exec_Summary.pdf)

<sup>37</sup> Aimée Turner, BA's search for biofuel candidates continues, Flightglobal.com, [Accessed 29 Apr. 2009],  
<http://www.flightglobal.com/articles/2009/04/06/324794/bas-search-for-biofuel-candidates-continues.html>

London Gatwick to Doha in October 2009<sup>38</sup>, Airbus and JetBlue have confirmed that their planned test flight will take place in 2010<sup>39</sup>, and Interjet has announced that it expects to fly an Airbus A320 using a biofuel blend derived from halophytes in 2010.<sup>40</sup>

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<sup>38</sup> Flightglobal, Qatar Airways to have biofuel trial in October, June 2009, [Accessed 27 July 2009], <http://www.flightglobal.com/articles/2009/06/10/327668/qatar-airways-to-have-biofuel-trial-in-october.html>

<sup>39</sup> GreenAirOnline, Airbus confirms that its first biofuel commercial aircraft test flight will not take place until 2010, Feb. 2009, [Accessed 27 July 2009], <http://www.greenaironline.com/news.php?viewStory=376>

<sup>40</sup> Flightglobal, Mexico's Interjet plans alternative fuels trial in early 2010, March 2009, [Accessed 27 July 2009], <http://www.flightglobal.com/articles/2009/03/19/324119/mexicos-interjet-plans-alternative-fuels-trial-in-early.html>

**Table 3: Summary of civil aviation test flights to date**

Date	Airline	Fuel supplier	Blend	Airframe manufacturer	Engine manufacturer	No of engines	Flight duration
24 Feb. 2008 <sup>41</sup>	Virgin Atlantic	UOP, Imperium Renewables	20% coconut and babassu methyl ester	Boeing 747-400	GE CF6-80C2	1 of 4	3 hours
1 Feb. 2008 <sup>42,43</sup>	Qatar Airways	Shell International Petroleum, Qatar Fuel	40% GTL	Airbus A380	Rolls-Royce Trent 900	1 of 4	3 hours
30 Dec. 2008 <sup>44,45</sup>	Air New Zealand	UOP, Terasol	50% jatropha	Boeing 747-400	Rolls-Royce RB211-524G	1 of 4	2 hours
7 Jan. 2009 <sup>46</sup>	Continental Airlines	UOP, Terasol, Sapphire Energy	47.5% jatropha, 2.5% algae	Boeing 737-800	CFM56-7B	1 of 2	2 hours
30 Jan. 2009 <sup>34,47</sup>	Japan Air Lines	UOP, Sustainable Oils	42% camelina, 7.5% jatropha, 0.5% algae	Boeing 747-300	Pratt & Whitney JT9D	1 of 4	1.5 hours
Oct 2009 <sup>38</sup>	Qatar Airways						
2010	Jet Blue	UOP		Airbus A320-200	IAE v2500		
2010 <sup>40</sup>	Interjet		Halophyte derived	Airbus A320	CFM56		
TBA	British Airways						

<sup>41</sup> Virgin Atlantic, Biofuel flight demonstration, Feb. 2008. [Accessed 28 Apr. 2009] <http://www.virgin-atlantic.com/en/gb/allaboutus/environment/biofuel.jsp>

<sup>42</sup> Qatar Airways, Alternative Fuels, Feb. 2008. [Accessed 28 Apr. 2009] <http://www.qatarairways.com/global/en/csr-fuel.html>

<sup>43</sup> Fonta, Philippe, Gas to Liquid (GTL) – A viable precursor to biofuels, Airbus, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009. [Accessed 28 Apr. 2009] [http://www.icao.int/WAAF2009/Presentations/10\\_Fonta.pdf](http://www.icao.int/WAAF2009/Presentations/10_Fonta.pdf)

<sup>44</sup> Air New Zealand Public Affairs, Biofuel test flight completed, Dec. 2008. [Accessed 28 Apr. 2009] [http://www.newairplane.com/assets/environment/downloads/30.12.08\\_Biofuel\\_test\\_flight\\_completed.pdf](http://www.newairplane.com/assets/environment/downloads/30.12.08_Biofuel_test_flight_completed.pdf)

<sup>45</sup> Air New Zealand, World-First Biofuel Test Flight, Dec. 2008. [Accessed 28 Apr. 2009] <http://www.airnewzealand.co.nz/aboutus/biofuel-test/default.htm>

<sup>46</sup> Continental Airlines, Jan. 2009, [Accessed 28 April 2009], <https://www.continental.com/web/en-US/content/company/globalcitizenship/environment.aspx>

<sup>47</sup> Abe, Yasunori, JAL Biofuel Flight Demonstration, JAL, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009, [Accessed 28 Apr. 2009] [http://www.icao.int/WAAF2009/Presentations/15\\_Abe.pdf](http://www.icao.int/WAAF2009/Presentations/15_Abe.pdf)

### 3.4 Outlook for future development and testing

As discussed above, Sasol semi-synthetic blends of FT fuels derived from coal are already certified. The Sasol fully synthetic fuel is already included in the Def Stan 91-91 specification and is expected to be added to ASTM D1655 by the end of 2009. Jet fuel blends with up to 50% biofuel from an FT process were certified in August 2009 and 50% blends of hydrotreated vegetable oil biofuels are expected to be certified by the end of 2010,<sup>48</sup> with several interviewees having confidence in meeting this timescale.

More novel fuels will likely require more extensive testing. Indeed the recently updated ASTM approval protocol for jet fuels states:

“The OEMs should be consulted and will provide guidance on which tests are applicable. Applicability will be based on chemical composition of the new fuel or additive, *similarity to approved fuels* and additives, and engine manufacturer experience. *Departure from engine manufacturer experience requires more rigorous testing.*”<sup>49</sup> [Emphasis added]

Indeed, industry experts have indicated that one of the reasons that certification of 50% FT biofuel is likely to happen this year—within 3 years of beginning the approval process—is that these fuels benefitted from the experience gained in the 7 year process of approving the Sasol semi-synthetic FT blend.

To facilitate a common understanding and discussion of the maturity of different fuel types the Civil Aviation Alternative Fuels Initiative (CAAFI) has proposed the use of a Fuel Readiness Level (FRL) system (Figure 3) that is modelled on the Technology Readiness Level system originally developed by NASA and used widely in the United States at both NASA and the Department of Defense. The proposed system seems to provide a good framework for assessing the maturity of fuel production and testing. However, it is important to note that all of the biofuels routes have a number of potential feedstocks, some of which are not yet commercially available, and are at varying stages of development.

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<sup>48</sup> CAAFI, Landmark synthetic jet fuel specification passes critical hurdle, June 2009, [Accessed 26 July, 2009], <http://www.caafi.org/files/altfuelstandard-rls6-09.pdf>

<sup>49</sup> ASTM Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives, D4054, in press, <http://www.astm.org/Standards/D4054.htm>

FRL	Description	CAAFI Toll Gate	FRL	Description	CAAFI Toll Gate	Fuel Qty	MRL	USAF TRL
1	Basic Principles Observed and Reported	Feedstock and process basic principles identified					1	
2	Technology Concept Formulated	Feedstock and complete process concept identified					2	
3	Proof of Concept	Small Fuel Sample Available from Lab Basic Fuel Properties Validated (Thermal Stability/Freezing Point)				500 ml	3	1. Basic Fuel Properties Observed and Reported
4.1 4.2	Preliminary Technical Evaluation	System Perf. & Integration Studies Entry Criteria/Specification Properties Evaluated (MSDS/D1655/MIL 83133)				10 gal	4	2. Fuel Specification Properties
5.1 5.2 5.3 5.4	Process Validation	Laboratory Production Development Subscale Production Demonstrated Scalability of Production Demonstrated Pilot Plant Capability Enabled	6.1 6.2 6.3 6.4	Full-Scale Technical Evaluation	Fit-For-Purpose Prop's Evaluated Turbine Hot Section Component/Rig Emissions Testing Engine/APU Testing	80 gal 4K gal 20K gal 225K gal	5 6 7 8	3. Fit for Purpose 4. Extended Lab Fuel Property Test 5. Component Rig Testing 6. Small Engine Testing
								7. Pathfinder
			7	Fuel Approval	Fuel Class/Type Listed in Int'l Fuel Standards			8. Validation/Certification 9. Field Service Evaluations
8	Commercialization Validated	Business Model Validated for Production Go-Ahead Airline/Military Purchase Agreements						
9	Production Capability Established	Full Scale Plant Operational					9-10	

Legend: R & D Certification/Qualification Business & Economics

**Figure 3: Fuel readiness levels proposed by CAAFI. The table shows the various stages in the maturation of a new fuel technology from identification of a new alternative fuel (FRL1) to full scale production (FRL9). It indicates what development stage and product**

## 4 Technical suitability of biofuels for aviation

In this section we provide a technical assessment of biofuels likely to be suitable for aviation now or in the future. For each biofuel route, we:

- Introduce the fuel chains – what feedstocks are used, and how they are converted to an aviation fuel
- Describe challenges for use in aviation, including:
  - Technical challenges. This is primarily challenges for aircraft engines – such as energy density, low temperature operability, thermal stability, flash point, lubricity, materials compatibility, viscosity, density, need for added components to meet fuel specifications. We also consider here whether there are other technical challenges for use in aviation – fuel distribution and storage at airports, supply chain challenges.
  - Certification status and outlook,
  - Potential breakthroughs in meeting these technical challenges, and the likelihood of these being achieved,
- Likely time scale for development and commercialisation, including whether the same, or a similar technologies will be used in other sectors, such as in biofuels for road transport,

### 4.1 Introduction to biofuels

The term ‘biofuel’ can encompass any liquid or gaseous fuel derived from a biomass source. Production of biofuels involves conversion of a biomass feedstock, which can be a crop, agricultural or forestry residue, or other by-product or waste, through a conversion process, which can be biological, thermal, chemical, or a combination of these, to form one or more products.

The most common biofuels types in use in road transport today are not suitable for use as aviation fuels: bioethanol, biodiesel from transesterification of vegetable oils and fats (FAME)<sup>50</sup>, and biogas from anaerobic digestion. Here we consider only biofuels that could be ‘drop-in’ replacements for jet fuel, summarised in Figure 4 below.

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<sup>50</sup> Biodiesel (fatty acid methyl ester or FAME) was used in Virgin Atlantic’s test flight, but is not a drop in fuel, and so is not considered to have potential for widespread use.

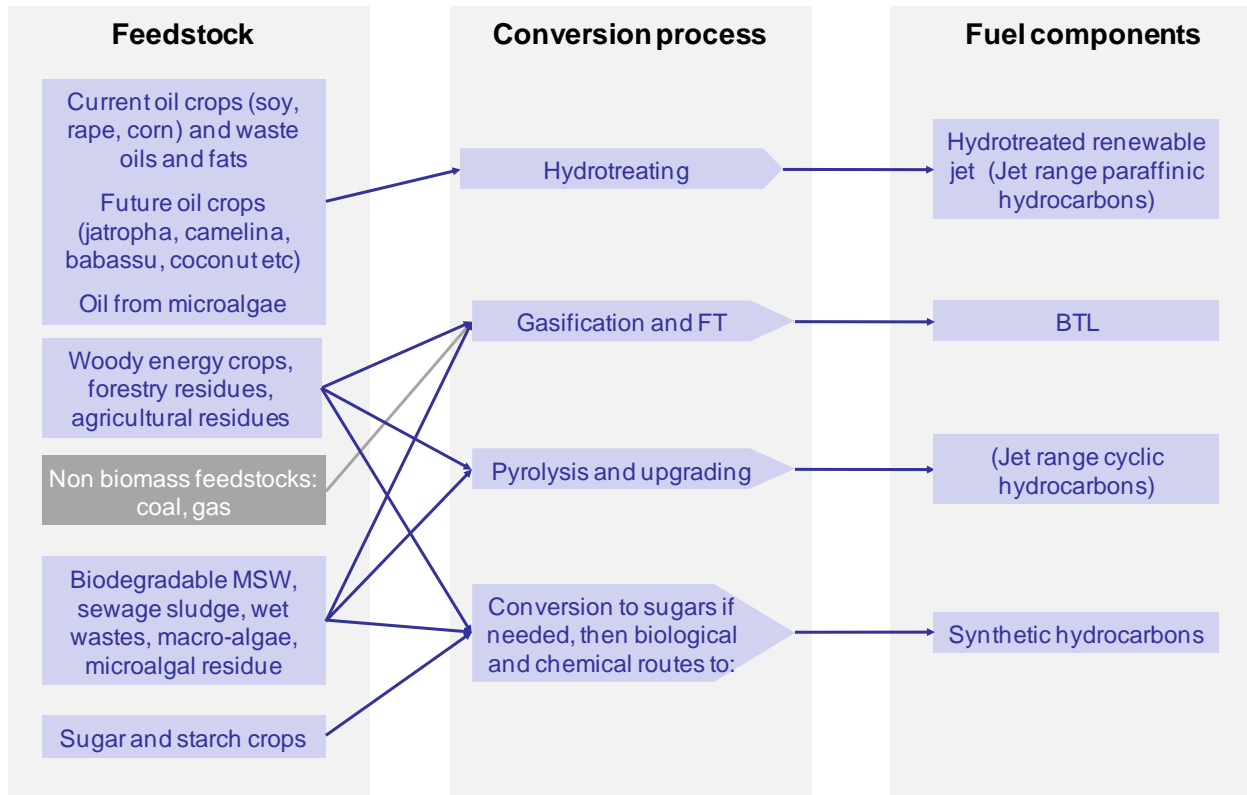


Figure 4: Overview of biofuels routes considered

## 4.2 Biomass-to-liquids (BTL)

### Introduction

Biomass to liquids (BTL) involves gasification of biomass feedstocks, followed by Fischer-Tropsch synthesis of the gas produced, to form a range of products. Jet fuel, diesel and gasoline replacements can all be produced through variations of this process. Jet fuel produced by this route is often referred to as synthetic paraffinic kerosene (SPK) or sometimes FT-SPK.

Many different biomass feedstocks can be gasified, from woody energy crops to municipal solid wastes. Problems can arise with some feedstocks, such as agricultural residues, and so use of these may be limited with some gasifier types. Most current projects focus on wood, although other feedstocks have been tested. Some projects use pretreatment steps before gasification, which densify the biomass feedstock. This could be of interest as BTL plants may need to be large in order to be economically viable, requiring large volumes of feedstock, which may need to be transported from further away. Densification could improve the economics and GHG impacts of feedstock transport.

After gasification, the gas composition is adjusted through a series of reactions, and various gas cleaning steps are used to remove tars and impurities. The syngas is then converted into liquid hydrocarbons such as gasoline, diesel and jet using Fischer-Tropsch synthesis. The yield of each fraction can be

modified either by changing process parameters or by adding additional steps such as selective hydrocracking and fractionation.

### **Use in aviation**

Figure 5 below compares representative compositions for typical petroleum-derived jet fuel (Jet A-1) and a synthetic jet fuel derived from the FT process (although using natural gas as the feedstock). Although the feedstock for the FT fuel is different, the resulting composition is still representative of what would be obtained from an FT fuel synthesized from gasified biomass.

As can be seen in the figure, the synthetic fuel has a similar distribution of normal and iso-paraffins to the petroleum-derived jet fuel, although the range of carbon numbers present in the FT fuel is slightly narrower. The biggest difference between the two fuels, however, is the absence of naphthenes and aromatics from the synthetic fuel. The performance characteristics of jet fuel, however, rely on a balance between the properties of the compounds in the various classes of hydrocarbon as no single class of hydrocarbon has entirely favourable characteristics. Table 4 below gives a high level summary of the impact of each hydrocarbon class on some overall fuel performance characteristics.

This table suggests that a synthetic fuel consisting solely of straight-chain paraffins would have a significantly worse low temperature performance than a petroleum derived fuel (due to the absence of naphthenes and isoparaffins). Thus the upgrading process for producing jet fuel from FT proposed by UOP, for instance, includes an isomerisation process step to ensure that the low temperature performance requirement is satisfied. In addition, the absence of aromatics will likely reduce the volumetric energy content of the fuel. Another issue caused by the absence of aromatics is that the seals in the fuel system have been designed accounting for the presence of aromatics which cause the seal elastomers to swell. These issues combined mean that the SPK produced by the FT process will need to be blended with petroleum derived jet fuel to ensure that all the jet fuel performance specifications are met. Indeed, the alternative fuel that is most likely to receive near term certification is a 50% blend of synthetic FT jet fuel with 50% petroleum-derived jet fuel. At blending levels above 50-60% SPK, compounds such as naphthenes and aromatics derived from another process may need to be added.

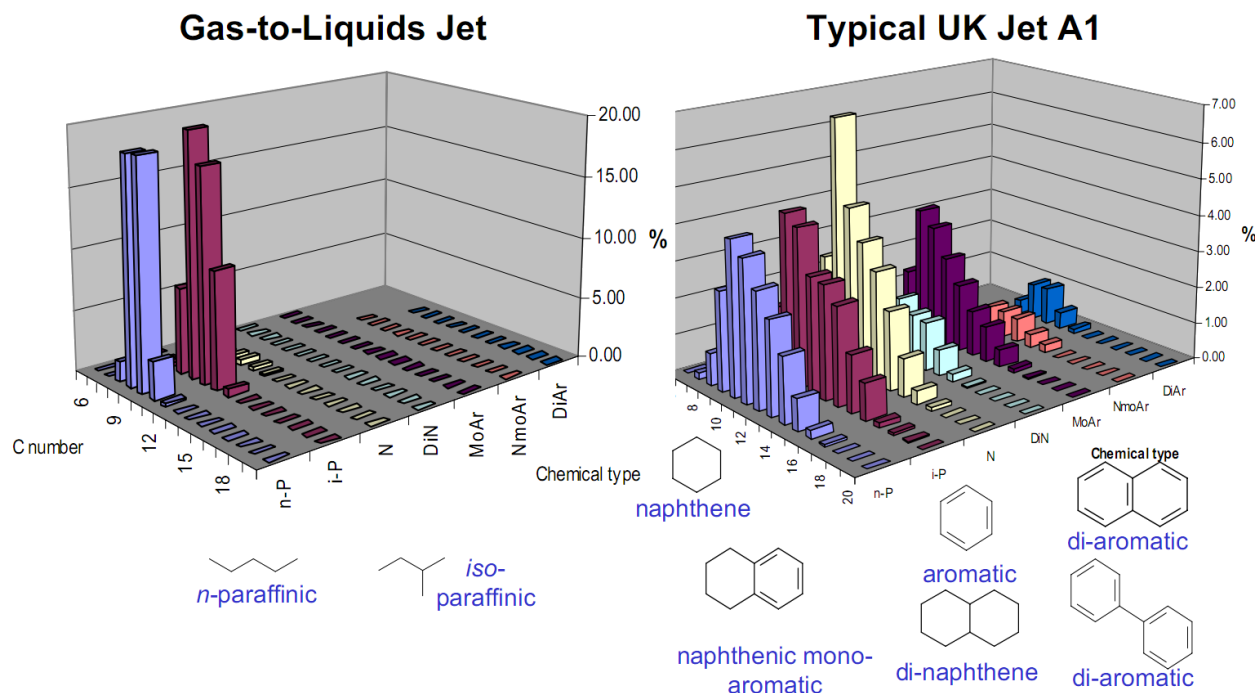


Figure 5: Composition of synthetic GTL jet fuel (left) and typical Jet A-1 fuel (right) by carbon number and hydrocarbon class, with structures of each hydrocarbon class<sup>51</sup>.

Table 4: Impact of hydrocarbon class on jet fuel properties<sup>52</sup>

Jet fuel property	Hydrocarbon class			
	n-paraffin	iso-paraffin	naphthene	aromatic
Energy density				
Gravimetric	+	+	0	-
Volumetric	-	-	0	+
Combustion quality	+	+	+	-
Freeze point	--	0/+	+	0/-

+: favourable effect, 0: neutral or minimal effect, -: negative effect

### Timescale for development and commercialisation

Many of the individual technologies used in the production of FT liquids are commercially available, such as feedstock production/collection, pre-treatment technologies and FT processes. Biomass gasification is used for heat and power production, although generally at smaller scales than envisaged for BTL plants.

<sup>51</sup> Bogers, Alternative Fuels for Aviation – Industry Options and Challenges, Shell Aviation, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009, [Accessed 28 Apr. 2009]  
[http://www.icao.int/WAAF2009/Presentations/11\\_Bogers.pdf](http://www.icao.int/WAAF2009/Presentations/11_Bogers.pdf)

<sup>52</sup> Chevron, Aviation Fuels Technical Review, 2006, [Accessed May 6, 2009],  
[http://www.chevronglobalaviation.com/docs/aviation\\_tech\\_review.pdf](http://www.chevronglobalaviation.com/docs/aviation_tech_review.pdf)

However, the integration of these components into a coherent process for BTL is only at a demonstration stage, with optimisation of the heat integration between gasification, gas clean up and the FT process, FT process optimisation for biomass derived syngas, and optimisation of feedstock logistics, densification options and plant scale still needed.

Although there are many players in some of the component technologies, relatively few are looking at the whole process from biomass to fuels. The key groups working in BTL are in strong industrial partnerships, such as CHOREN (with Shell, Daimler and Volkswagen), Rentech/UOP and NSE Biofuels (VTT/Foster Wheeler/Stora Enso/Neste Oil). Other players with BTL plans include TRI, Carbona/GTI/UPM, and CUTEC.

CHOREN are currently commissioning their 'Beta' BTL demonstration plant in Germany, with plans for a commercial 'Sigma' plant producing 200,000 t/yr FT diesel from 2012, with other plants in Germany to follow. VTT plan to have a 100,000 t/yr FT wax commercial plant built by 2013, following from their demonstration this year, and Carbona/GTI and UPM have carried out BTL testing, with plans for a commercial scale project in the near term. Rentech announced in May 2009 that they plan to build an FT diesel plant in the US, producing 24,000 t/yr FT diesel by 2012, and TRI plan to upgrade their Flambeau River site to make 135,000t/yr FT diesel soon after a demonstration next year.

In summary, there are currently no commercial BTL plants, however, with the developments above, plant scales are set to increase rapidly. FT diesel for road transport is likely to start production in 2012/2013.

## **4.3 Hydrotreated oils**

### **4.3.1 Introduction**

Vegetable and algal oils can be converted to an aviation fuel generally called hydrotreated renewable jet (HRJ), although also sometimes referred to as bio-SPK (synthetic paraffinic kerosene) . An introduction to each feedstock and the process of producing the oil is given in the following sections.

The first stage of the route involves the production of vegetable oils from crops (cultivation, drying and storage, oil extraction) or the collection of used cooking oil or tallow, followed by the transport of these oils to the hydrotreatment facility. At the facility, impurities are removed from the oils (degumming), and then they are heated and hydrotreated.

Most oil crops produce triacylglycerides containing fatty acids with carbon numbers in the range of C14 to C20<sup>53</sup>, which is higher than the C8 to C16 molecules needed for jet fuel. If this triacylglyceride blend is hydrotreated, the main product will be diesel and the yield of kerosene type compounds suitable for jet fuel will only be about 10%. To increase the yield of kerosene compounds suitable for jet fuel, an

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<sup>53</sup> Bogers, Alternative Fuels for Aviation – Industry Options and Challenges, Shell Aviation, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009, [Accessed 28 Apr. 2009]  
[http://www.icao.int/WAAF2009/Presentations/11\\_Bogers.pdf](http://www.icao.int/WAAF2009/Presentations/11_Bogers.pdf)

additional selective cracking step must be included. The yield of paraffinic kerosenes from this process is increased to 50 to 70%<sup>54</sup>. Slightly more hydrogen is needed for conversion to jet fuel than for conversion to biodiesel for road transport.

This process could be integrated within an oil refinery to avoid having to construct a dedicated production unit. HRJ could either be made in a process in which the vegetable oil is blended with crude oil and they are both hydrotreated together, or the vegetable oil hydrotreatment takes place in a separate unit. It is likely in the longer term that there will be a greater degree of co-processing of vegetable oils with crude oils.

#### **4.3.2 Use in aviation**

Much like the upgrading of FT hydrocarbons, the upgrading of vegetable oils produces a range of paraffinic hydrocarbons in the kerosene range. In order for the resulting kerosene to have cold temperature characteristics suitable for use in aviation the paraffins must be isomerised as straight chain kerosene paraffins alone do not meet the freeze point specification for jet fuel. As for the FT process, HRJ does not include aromatic compounds or naphthenes. Thus the isomerisation of the HRJ must be sufficient to ensure that the freeze point specification is met. The minimum aromatic compound content required to achieve seal swell can be achieved by blending the HRJ either with fossil-derived jet fuel or with aromatics from another process.

Certification of semi-synthetic jet fuel containing HRJ is expected by the end of 2010. This certification will cover up to a 50% blend of HRJ derived by hydrotreating vegetable or animal oils regardless of the feedstock. The balance of the blend would be fossil-derived jet fuel.

#### **4.3.3 Timescale for development and commercialisation of the HRJ process**

Hydrotreated vegetable oil (HVO) biodiesel, (often called “renewable diesel”), is currently produced commercially for road transport by Neste and Conoco Phillips; ConocoPhillips from soybean oil and tallow, and Neste from palm oil. None of these companies yet produce HRJ that is commercially added to jet kerosene, although HRJ from some of these feedstocks has been tested in recent flight demonstrations.

As the process for making HRJ is similar to the process for making HVO for road vehicles, current HVO plants could be used to produce both diesel and jet fuel. However, it is only economically viable for 10-15% of the fuel to be for jet in these plants, as a higher proportion would reduce the overall plant efficiency. “Dedicated” HRJ plants would be more likely to be built if demand were higher, producing

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<sup>54</sup> Jennifer Holmgren, Creating Alternative Fuel for the Aviation Industry, UOP, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009. [Accessed 29 Apr. 2009], [http://www.icao.int/WAAF2009/Presentations/14\\_Holmgren.pdf](http://www.icao.int/WAAF2009/Presentations/14_Holmgren.pdf)

much higher volumes of jet fuel (about 50-70% jet). UOP plans to have a dedicated HRJ plant up and running by Q4 2011 and to commercially produce jet HVO from a diesel plant in 2010<sup>55</sup>.

#### 4.3.4 Vegetable oil feedstocks

Feedstocks for the HRJ route include:

- Palm oil: Produced largely in Malaysia and Indonesia and used in a wide variety of products, including processed foods, soaps, cosmetics, etc.
- Soybean oil: Soy is mainly grown in Brazil, Argentina and the USA. The oil is commonly used in food, and the meal (left over from oil extraction) is an important source of protein for livestock.
- Coconut oil: Coconut is produced in the most significant quantities in Indonesia, India and the Philippines. Again, it has many applications – in cooking, the food industry, in cosmetics etc.
- Rapeseed oil: Produced in large quantities in the EU for food.
- Corn oil: Corn oil can be extracted from DDGS (Dried Distillers Grains with Solubles). DDGS is co-produced with ethanol during the fermentation of sugars from corn.
- Sunflower oil: The largest producers of sunflower seeds are Russia, Argentina, Ukraine, China, France and USA. It is commonly used in cooking.
- Tallow: Tallow is a by-product from the meat rendering industry.
- Used cooking oil (UCO): UCO is collected from premises where commercial food preparation is carried out.
- Jatropha oil: Jatropha is a non-food crop, the seeds of which can be crushed to produce a toxic, inedible vegetable oil. It can be grown on semi-arid lands in warm and humid climates.
- Camelina oil: Camelina is native to Northern Europe and Central Asia and currently has an oil yield similar to rapeseed but with low requirements for tillage and weed control.
- Babassu oil: Babassu is a palm tree that grows in Brazil. The oils from the babassu nuts have similar properties to coconut oils and they are currently used for similar purposes.
- Halophyte oil: Halophytes are plants that can be grown under saline conditions, and may contain useful levels of oils e.g. *Salicornia bigelovii*, which naturally grows in coastal salt flats, marshes, estuaries and shores.

#### Timescale for feedstock commercialisation

Hydrotreated fuels based on any of the currently available feedstocks (palm oil, soybean oil, coconut oil, rapeseed oil, corn oil, sunflower oil, tallow, UCO) could be made commercially today for aviation if there was a cost or policy incentive to do so. However, in addition to concerns over the potential sustainability impacts of using these oils (described in detail in sections 5 and 7.2.3), the demand for these feedstocks

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<sup>55</sup> Jennifer Holmgren, Creating Alternative Fuel for the Aviation Industry, UOP, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009. [Accessed 29 Apr. 2009], [http://www.icao.int/WAAF2009/Presentations/14\\_Holmgren.pdf](http://www.icao.int/WAAF2009/Presentations/14_Holmgren.pdf)

for food has kept the cost of the vegetable oils high, and weakened the economic driver for producing vegetable oil based biofuels.

Waste tallow and used cooking oil could be a low cost feedstock options for oil based aviation biofuels. However, the amount of tallow and UCO available is limited and these feedstocks are therefore unlikely to become important feedstocks for aviation.

Oils from jatropha, camelina, and halophytes are not produced in large quantities today. They have significant potential for expansion given that they can be grown on lands not suitable for food crops, and that they may have significant oil yields. More specifically:

- There has been increasing interest in jatropha in recent years, for example, India has plans (currently on hold) to convert more than 11Mha of wasteland to growing jatropha. However, the volume of available feedstock may not ramp up as quickly as initially expected, as a result of a range of problems. For example, in India, where nearly one third of the world's corporate-funded jatropha biodiesel plantations are either already in place or scheduled for planting, the Government has put its national biodiesel mission on hold, apparently due to concerns over too much foreign ownership of land and the poor performance of the crop on plantations<sup>56</sup>. However, should such issues be quickly overcome, jatropha oil could still potentially start becoming commercially available for HRJ from 2012, although at low volumes, as jatropha takes several years to reach full yields.
- Camelina is native to Northern Europe and Central Asia and currently has an oil yield similar to rapeseed but with low requirements for tillage and weed control. However, it has not been grown commercially for at least 50 years and consequently there has been little focus on improving yields. There is now increased interest in growth in several US states, commonly in rotation with wheat, as a biofuel feedstock. Even if countries with suitable climates and soil types were to choose to invest in growing camelina soon, it is likely to be several years before it is grown in commercial quantities; perhaps in the 2013-2014 timeframe.
- Oil producing halophytes could potentially be a very significant biofuel feedstock as they can grow in places where conventional crops cannot usually be grown (e.g. saline semi-deserts, seashores etc), using salt water as irrigation. Species such as *Salicornia bigelovii* produce oil bearing seeds in their stalks which can contain up to 30% oil. Further R&D is required to improve the yields of these plants and develop an economic agricultural system. Halophytes are unlikely to be produced commercially as biofuel feedstocks before jatropha and camelina as very little is recorded about their commercial agriculture. An example of halophyte projects are the integrated saltwater farming pilot projects of Global Seawater Inc. (GSI). GSI launched a 100 ha integrated shrimp, halophyte and mangrove farm in 1999 in Eritrea, which was abandoned due to political turmoil in the region. In the last few years, GSI has started a similar project in Sonora, Mexico, combining shrimp and halophyte farming and inter-cropped mangroves. This project had about 400 ha planted in 2008 that is expected to be

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<sup>56</sup> Biofuels Digest, India's biodiesel mission on hold due to a problem-laden Greenrush, May 2009, [Accessed 28 July 2009] <http://biofuelsdigest.com/blog2/2009/05/12/india%E2%80%99s-biodiesel-mission-on-hold-due-to-a-problem-laden-greenrush-a-biofuels-digest-special-report/>

expanded to 5,000 ha in 2009.<sup>57,58</sup> Given the fairly low level of R&D into these crops, we expect that halophytes would not be available until at least the midterm.

- Babassu is not currently extensively cultivated for biofuel production but cultivation could be ramped up if there was sufficient demand. However, unlike camelina, jatropha and halophytes, babassu does not grow on marginal land and therefore there would be land use issues with using it. Other advantages of expanding the use of this oil crop for biofuels over other oil crops already currently commercially cultivated are not obvious and so it is unlikely that it will become commercially available in large volumes in the near to mid future.

#### 4.3.5 Algal oil feedstock

Oil from algae can also be used to produce HRJ. Microalgae comprise a large group of photosynthetic, unicellular organisms and depending on the species, live in fresh, brackish or saltwater. Like plants, microalgae produce organic compounds, such as carbohydrates and lipids using CO<sub>2</sub> taken up from the atmosphere.

It is generally assumed that ultimately, microalgae for biofuels will be cultivated using one of two kinds of technology, as shown in Figure 6. Although neither of these technologies has yet produced algal biofuel economically at scale, they both have their proponents and detractors. The different technologies involved and plant configurations means that the costs and associated GHG emissions from production are likely to be quite different.



**Figure 6: Algae production: open ponds (left), photobioreactors (right)**

Another algal oil route being developed involves dark fermentation of sugars to oil by algae. In this route, being developed by Solazyme, algae are kept in the dark in large steel containers, where they are fed sugars, which the algae convert to different types of oil.

<sup>57</sup> Los Angeles Times, The old man who farms with the sea, July 2008, [Accessed 27 July 2009], <http://articles.latimes.com/2008/jul/10/business/fi-seafarm10>

<sup>58</sup> Atlantic Greenfuels, Seawater Farms Bahia Kino in Sonora, Mexico, 2008, [Accessed 27 July 2009], [http://atlanticgreenfuels.com/html/body\\_mexico.html](http://atlanticgreenfuels.com/html/body_mexico.html)

### **Timescale for feedstock commercialisation**

Algal oils are not produced on a commercial scale, and so algal HRJ is not commercially available at present; only a small amount of this fuel was produced for the test flight by Continental Airlines. Although microalgae are not currently cultured at scale for oil for biofuels, they are cultured for high value products such as nutraceuticals (e.g. beta carotene food supplements). The difference in using microalgae to produce oil for biofuel and for food supplements is that the cost of the oil needs to be at least an order of magnitude lower than the cost at which food supplements are currently produced in order for it to be competitive with oil prices or even other biofuels. There is likely to be demand for algal biofuels for both road and aviation transport.

Algal culture for oil production for biofuels is still very much at the R&D stage. The massive cost reduction required could come from an improvement in algal productivity and oil yield, a reduction in culture failure rates, simplification of culture and harvesting technology, removing the need for drying etc.

Although these methods for cost reduction are currently the focus of extensive R&D efforts, it is likely to be some time before target production costs can be reached. The target for those participating in the Carbon Trust's Algae Biofuel Challenge is to have commercial algal oil production by 2018. However, some of the (largely US based) companies working towards algae biofuel commercialisation are much more optimistic about the timeframes for commercialisation. For example, the US algae company Sapphire Energy, has said that it will reach the commercial scale by 2011 producing 1m gallons/yr, 100m gallons/yr by 2018 and 1bn gallons/yr by 2025<sup>59</sup>. It is impossible to know at this stage whether this kind of ramp up is actually feasible, without detailed knowledge of the technical progress they have made to date. However, the reality is likely to be that algae biofuels are a mid-term technology option, e.g. 2020 onwards, and unlikely to be produced in significant volumes in the near term.

For the dark fermentation route, Solazyme has so far produced algal FAME biodiesel and hydrotreated diesel. The actual volume produced of these two fuels is not clear, but the company is not commercially producing this fuel yet. There is the possibility that this route could be available before the others, however, it is dependent on sugary feedstocks which may be limited and could be used in many biofuel chains.

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<sup>59</sup> Biofuels Digest, Sapphire Energy says algae commercialization accelerating, April 2009, [Accessed 27 July 2009], <http://www.biofuelsdigest.com/blog2/2009/04/17/sapphire-energy-says-algae-commercialization-accelerating-expects-to-double-commercial-outut-in-2011-to-1-million-gallons-of-jet-fuel-and-green-diesel/>



considered promising in economic and environmental terms as a result of avoiding the use of hydrogen needed for oil based routes.

### **Timescale for development and commercialisation**

Amyris intend to:

- Make a renewable diesel fuel commercially available as early as 2010, based on sugar cane as a feedstock. This is expected to have improved performance compared with current biodiesel, have low CO<sub>2</sub> emissions, and be low cost.
- commercialize a renewable jet fuel as early as 2012, which performs well at low temperatures, can be produced in the US with competitive economics using sugar cane as a feedstock, and meets initial certification criteria. We have heard an aviation industry view that the timescale for full certification of this type of fuel would be around 2013, as a result of the availability of volumes of fuel for testing.

Amyris' development is at the pilot stage, with a pilot plant constructed in late 2008, of 9m litres/year renewable diesel output capacity<sup>67</sup>. The pilot will demonstrate the full production process and provide learning for design of a full scale plant. Amyris also has a second pilot plant in Campinas, Brazil, to enable the technology to be adapted to use of sugarcane juice and molasses as feedstocks. In 2010, Amyris aim to install the technology at a Santelisa Vale sugar cane mill (scale not stated), with Amyris and Crystalsev (Brazil), marketing the fuel produced initially in the US and Brazil.

In 2008, Amyris also announced plans to demonstrate their technology for renewable jet fuel production in southern Alabama, US<sup>68</sup>. Amyris aims to produce about 800m litres/yr of fuel commercially by 2011, at a cost of less than \$2/gallon, not including distribution<sup>69</sup>.

## **4.5 Butanol derived fuels**

### **Introduction**

Iso-butanol can be used in road transport fuel directly, and can be processed into hydrocarbon fuels including renewable jet and diesel, and into precursors for plastics and other chemicals. Gevo (US) is working on making butanol, iso-butanol, fuel components, and hydrocarbon fuels. This is based on a proprietary fermentation-based process technology, which could be retrofitted to ethanol plants, and has currently been tested on corn and sugar feedstocks. In April 2009, Gevo also licensed

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<sup>67</sup> Time, Biofuels: The New Alchemy, [Accessed 27 July 2009],  
[http://www.time.com/time/specials/packages/article/0,28804,1872110\\_1872133\\_1872143-2,00.html](http://www.time.com/time/specials/packages/article/0,28804,1872110_1872133_1872143-2,00.html)

<sup>68</sup> Amyris, State Evaluating Sugar Cane for Jet Fuel Production, Oct. 2008, [Accessed 27 July 2009],  
[http://www.amyris.com/index.php?option=com\\_content&task=view&id=84&Itemid=307](http://www.amyris.com/index.php?option=com_content&task=view&id=84&Itemid=307)

<sup>69</sup> CleanTech Group, Microbes drive new Amyris biodiesel plant , Nov. 2008, [Accessed 27 July 2009],  
<http://cleantech.com/news/3858/microbes-drive-new-amyris-biodiesel-plant>

microorganisms from Cargill, which when integrated in Gevo's process will allow use of lignocellulosic feedstocks<sup>70</sup>.

Note that there is also research in California on the conversion of butanol via 1-butene (C<sub>4</sub>H<sub>8</sub>) to new synthetic jet fuel blends, with a specific focus on the requirements for the Navy's JP-5. JP-5 has a higher flash point (60°C) compared with Air Force JP-8 and commercial jet fuel (~38°C). The product is 100% iso-paraffinic, meets flash point and cold-flow requirements, and has a volumetric power density higher than that of similar fuels made by an FT process<sup>71</sup>.

### **Use in aviation**

Gevo state that they have produced renewable jet fuel meeting ASTM standards<sup>70</sup>. No details are available for the hydrocarbon fuel produced from Gevo's process, in terms of suitability for use in aviation. However, Gevo is looking at the jet fuel market, with Virgin Fuels as an investor, and an agreement with Bye Energy, an integrator of renewable fuels for aviation to jointly explore opportunities for marketing and distribution of renewable aviation fuels to small and medium-sized airports<sup>72</sup>.

### **Timescale for development and commercialisation**

Gevo and their technology and engineering partner ICM are planning to build a plant producing approximately 4 m litres/yr, which will allow the companies to collect engineering data and produce quantities of isobutanol for research. They expect to have the first commercial plant running in early 2011.<sup>73</sup> Like Amyris' technology, one aviation industry interviewee considered that certification would be possible by around 2013 for this route.

Butanol routes are also being developed by several other companies, including a BP/DuPont joint venture, and the UK company Green Biologics. Although none of these appear to be focussing on routes to jet from butanol, successful commercialisation of these routes might lead to further development in this area.

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<sup>70</sup> Gevo, Gevo, Inc. Secures Cellulosic Technology to Make Advanced Biofuel, Feb. 2009, [Accessed 27 July 2009], [http://www.gevo.com/news\\_Cargill-pr\\_022609.php](http://www.gevo.com/news_Cargill-pr_022609.php)

<sup>71</sup> Green Car Congress, China Lake Researchers Develop Potential Biobutanol Pathway for Synthetic Jet Fuel, July 2008, [Accessed 27 July 2009], <http://www.greencarcongress.com/2008/07/china-lake-rese.html#more>

<sup>72</sup> Bye Energy, Bye Energy and Gevo, Inc. Announce Agreement for Renewable Aviation Fuels, Jan. 2009, [Accessed 27 July 2009], <http://www.byeenergy.com/pages/GEVO-MOU.html>

<sup>73</sup> Gevo, Major Oil and Gas Company, Total Invests in Advanced Biofuels Leader Gevo, April 2009, [Accessed 27 July 2009], [http://www.gevo.com/news\\_Total-pr\\_042709.php](http://www.gevo.com/news_Total-pr_042709.php)

## 4.6 Alkanes from aqueous phase reforming

### Introduction

Alkanes can also be produced from sugars by chemical processes including a step called aqueous phase reforming (APR). This involves catalytic dehydration, hydrogenation and aldol-condensation reactions. The route was developed for hydrogen production by James Dumesic and Randy Cortwright at the University of Wisconsin, and work continues in James Dumesic's research group at the university, and also through the company Virent, which was founded in 2002 to commercialise the technology. Virent combined the APR technology with other conventional catalytic processes, and in 2006, adapted the process to convert sugars into hydrocarbon molecules. The Virent 'BioForming' process is an integrated process, with hydrogen needed for the reactions provided from the biomass itself, and a range of products formed. Virent has produced gasoline, diesel and jet by this route<sup>74</sup>.

### Use in aviation

Virent literature describes how the BioForming process can produce jet fuel via a number of different pathways. In particular, jet range products of a base condensation process with boiling points in the 150-250 °C range were submitted for ASTM D1655 aviation turbine fuel analysis<sup>75</sup>. Virent state that all specification were met except the flash point, due to inadequate removal of light components in the laboratory, and the density, due to low aromatic content. They note that the fuel's freeze point was below -70 °C, which is the limit of the testing method, as a result of the very high proportion of single-branched alkanes in their product and contrast this with FT-derived fuels, which may not meet this criterion as a result of high normal alkane content. Virent state that combining moderately branched alkanes from this route can be combined with C9+ aromatics from a catalytic condensation process to produce a complete biomass-derived aviation fuel that meets current fuel specifications. Virent are working with Shell on development of jet fuels, in parallel with their work on road transport fuels.

### Timescale for development and commercialisation

Virent have demonstrated gasoline production from their processes at pilot scale, and are scaling up to a demonstration plant at 38,000 litres/year capacity in autumn 2009. However, no timescale for commercialisation has yet been given. They expect scale up to be easier than for biological routes, as the types of reactors used have proven scalability in the past<sup>76</sup>. In addition to this, once the core aqueous phase reforming technology is proven for gasoline production, jet production should follow soon after, as the catalytic condensation technology required is a commercial process.

Once commercialised, Virent expect the BioForming platform to take a refinery type approach, producing a slate of products.

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<sup>74</sup> Virent website, [Accessed 28 July 2009], <http://www.virent.com/BioForming/technology.html>

<sup>75</sup> Virent, Production of Liquid Fuels from Sugars, Aug. 2008, [Accessed 28 July 2009], [http://www.virent.com/BioForming/Virent\\_Technology\\_Whitepaper.pdf](http://www.virent.com/BioForming/Virent_Technology_Whitepaper.pdf)

<sup>76</sup> Virent presentation at World Biofuels Markets, Brussels, 2009

## 4.7 Pyrolysis derived fuels routes

### Introduction

Fuels and fuel components can be produced via a route involving pyrolysis of biomass, followed by upgrading of the pyrolysis oil produced. Pyrolysis involves heating the biomass feedstock in the absence of oxygen, to produce a liquid (pyrolysis oil), gas, and solid product (char). Most lignocellulosic feedstocks can be pyrolysed including dedicated energy crops, agricultural residues and wood residues, and wastes, although the composition of the feedstock is important as this affects the composition of the pyrolysis oil. The oil can then be upgraded to produce fuels either at a dedicated plant, or at an oil refinery.

Different fractions of the pyrolysis oil could be converted to different products, with UOP and Dynamotive presenting pyrolysis as a route to gasoline, diesel, jet fuels and chemicals<sup>77</sup>. Upgrading steps such as catalytic stabilisation and deoxygenation would be used to convert pyrolysis oil, with high acidity, water and oxygen content, to fuels. However, the specifications of jet fuel mean that converting pyrolysis oil to jet fuel through hydrotreating would require significantly more hydrogen than for production of a low blend road transport fuel, leading to prohibitively high costs and emissions. Producing road transport fuels, together with small proportions of jet fuel components, such as aromatics, may, however, be viable. There is also ongoing RD&D on new processes for upgrading pyrolysis oils with lower hydrogen requirements, and on developing new catalytic processes to produce better quality oils directly.

### Timescale for development and commercialisation

Pyrolysis technology itself is at the early commercial stage, with several companies, such as Dynamotive, Ensyn, and BTG having constructed their first plants in the 1990s. The pyrolysis oil is used to generate heat and power, and extracts from the oil have non energy uses e.g. in food flavourings. Therefore, pyrolysis technology is approaching technical maturity, with small-scale commercial specialty chemicals applications already available, at around 200 tonnes per day output (Dynamotive, Ensyn).

There has been relatively little work on pyrolysis oil upgrading and on integration of pyrolysis oils into (commercial) refinery processes, compared with other biofuel technologies. However, there has been increasing interest over the last few years, with the most advanced of this work now moving into the pilot scale demonstration phase. UoP and Ensyn launched a joint venture, Envergent Technologies, in March 2009 to produce bio-oil for heat, power and transport fuel applications. This collaboration will accelerate R&D efforts into refining bio-oil into transport fuels. Dynamotive announced in April 2009 that they have achieved scalable production of renewable diesel and gasoline, via a secondary upgrading

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<sup>77</sup> See, for example: Jennifer Holmgren, Creating Alternative Fuel for the Aviation Industry, UOP, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009, [http://www.icao.int/WAAF2009/Presentations/14\\_Holmgren.pdf](http://www.icao.int/WAAF2009/Presentations/14_Holmgren.pdf) and Dynamotive's website <http://www.dynamotive.com/mobile-fuels/>

step from bio-oil, and that early testing of bench scale products shows that the upgraded products have a jet fraction of around 30%<sup>78</sup>.

The main industries involved are pyrolysis reactor developers, catalyst developers and petrochemical companies. UOP, Shell, Arkema, Albermarle, Sasol and Sabic are all involved in US DoE and EU funded pyrolysis projects. ConocoPhillips is also working with ADM and the University of Iowa on pyrolysis and oil upgrading.

UOP expect renewable gasoline and aromatics production, including jet range cyclic hydrocarbons to be in commercial operation by Q4 2013<sup>79</sup>.

#### 4.8 Algal biomass derived fuels

Fuels could also be produced from whole microalgae, or the residue remaining after oil extraction, rather than from the oil itself. This could be done through routes including:

- Hydrothermal upgrading – a liquefaction process which takes place in the presence of water, and possibly additional solvents (e.g. methanol) at high pressure (120-180 bar) and mild temperatures (300-400 °C) for 5-20 minutes. The process yields a mixture of biocrude, gas (mainly CO<sub>2</sub>) and water. The biocrude would then need to be upgraded for use in aviation.<sup>80</sup> This is still at the R&D stage.
- Gasification – algal biomass could be dried, and used as a feedstock for the BTL route described above. Supercritical gasification is also in development, which would be more suitable for a wet waste.
  - BTL jet is not yet produced commercially from any feedstock. Because it will be some years before algae will be grown at scale at low cost, it is likely that in the early years BTL jet will be made from biomass feedstocks other than algae, e.g. waste wood and energy crops. When algae is grown commercially at scale, conversion of the residues to BTL jet is only likely to take place at those sites where the algae plants are co-located with the BTL plants, to minimise costs and inefficiencies associated with biomass transport.
- Pyrolysis fuels from algal residues.
  - Algal residues could be pyrolysed to produce a bio-oil that could be upgraded to a jet fuel.
  - Whilst the pyrolysis process itself is well understood and has been used for many years for the pyrolysis of wastes, the upgrading to a transport fuel is a process which requires further R&D and is currently an active area of research.

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<sup>78</sup> Dynamotive press release July 2009 <http://www.dynamotive.com/2009/06/29/analysis-of-dynamotive-upgraded-biooil%C2%AE-confirms-gasoline-jet-diesel-and-vacuum-gasoil-fractions-proprietary-two-stage-upgrading-process-provides-path-to-mobile-fuels-from-biomass/>

<sup>79</sup> Jennifer Holmgren, Creating Alternative Fuel for the Aviation Industry, UOP, ICAO Workshop on Aviation and Alternative Fuels, Feb. 2009. [Accessed 29 Apr. 2009], [http://www.icao.int/WAAF2009/Presentations/14\\_Holmgren.pdf](http://www.icao.int/WAAF2009/Presentations/14_Holmgren.pdf)

<sup>80</sup> Biomass Energy Centre, Other thermal conversion processes, 2008, [Accessed 28 July 2009], [http://www.biomassenergycentre.org.uk/portal/page?\\_pageid=75,17508&\\_dad=portal&\\_schema=PORTAL](http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17508&_dad=portal&_schema=PORTAL)

These routes are unlikely to be commercial before algae can be cultivated economically at a large scale. As discussed for the algal oil routes, this is unlikely to happen before 2018, as there are still several significant R&D challenges that still need to be overcome.

We do not consider these routes individually, as:

- The jet fuels produced from these routes are the same as the BTL and HRJ routes, and so will not have different characteristics in use.
- As both the feedstock and the conversion technologies are not yet commercially developed for most of the routes, there is little information available on potential GHG savings and costs.

However, the presence of these options means that the potential resource for other fuels could be increased compared with use of non-algal feedstocks and algal oils alone, unless the algal residues are used to produce energy on-site.

#### 4.9 Other routes

**LS9** is developing hydrocarbon fuels 'closely resembling petroleum derived ones', with a similar energy content, from sugars via a biological route using modified microorganisms. Possible products include alkanes and esters, including biodiesel precursor (8-20 carbons) and a biocrude (18-30 carbons) which could be integrated into a refinery.

**Dumesic's** research group at the University of Wisconsin have worked on several routes to furan derivatives from sugars via the chemical intermediate HMF (hydroxymethylfurfural). These compounds can then be reacted further through hydrogenation and dehydration reactions to produce alkanes with targeted molecular weights, such as C8-C15 for jet-fuel applications.<sup>81,82</sup> This is considered to have potential advantages compared with FT synthesis, through being able to produce specific *n*-alkanes with high selectivities, forming liquid-alkane fuels with targeted molecular-weight distributions. This is at the research stage.

**Avantium** (Netherlands) are working on commercialisation of furanics, principally EMF (ethoxymethylfurfural, C<sub>8</sub>H<sub>10</sub>O<sub>3</sub>) as a road transport fuel, but also including a number of molecules that they claim may have similar properties to jet fuels.<sup>83</sup> Furan-based biofuels, or 'furanics' can be derived from sugars through chemical routes. Research and development has been carried out on several pathways to different related compounds.

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<sup>81</sup> Liquid Alkanes with Targeted Molecular Weights from Biomass-Derived Carbohydrates, ChemSusChem, Volume 1, Issue 5, Date: May 23, 2008, Pages: 417-424, Ryan M. West, Zhen Y. Liu, Maximilian Peter, James A. Dumesic

<sup>82</sup> Patent WO/2008/151178 Production of liquid alkanes in the jet fuel range (C8-C15) from biomass-derived carbohydrates

<sup>83</sup> Furanics: Versatile molecules applicable for biofuels and bulk chemicals applications Ed de Jong, Avantium, RRB4 (Fourth International Conference on Renewable Resources and Biorefineries in Rotterdam) 2008 <http://www.rrbconference.org/bestanden/downloads/121.pdf>

#### 4.10 Summary

The table below gives a summary of the routes covered in this chapter. The first three routes (shown in bold) are those considered further in terms of their greenhouse gas savings, economics, and sustainability, to feed into the uptake scenarios.

The ‘synthetic hydrocarbons’ category represents any route from lignocellulosic material to a biofuel for aviation, introduced after 2020, with low costs and GHG emissions. Data for this route is based on that given for isoprenoid fuels, butanol derived fuels, and alkanes from aqueous phase reforming. Note that other routes are possible, and are likely to be developed in the timescale considered (to 2050), however, there is insufficient information to consider these in the same level of detail at this point.

**Table 5: Summary of biofuels routes reviewed**

<b>Name</b>	<b>Feedstock(s)</b>	<b>Conversion process</b>	<b>Development needed</b>
<b>Biomass to liquids (BTL)</b>	Lignocellulosic materials (energy crops, forestry residues, wastes)	Gasification and FT synthesis	Demonstration of plants at commercial scale
<b>HRJ (Hydrotreated renewable jet)</b>	Conventional oil crops (soy, palm, rapeseed)	Oil extraction and hydrotreating	Deployment of conversion plants
	New oil crops (algae, camelina, jatropha, halophytes)		RD&D on yield improvements, agronomy, and algal systems
<b>‘Synthetic hydrocarbons’</b>	Lignocellulosic materials, or sugars	Range of biological and chemical routes (data based on isoprenoid fuels, butanol derived fuels, and alkanes from aqueous phase reforming)	RD&D to prove routes at the pilot stage
Pyrolysis derived fuels	Lignocellulosic materials (energy crops, forestry residues, wastes)	Pyrolysis and upgrading	RD&D on upgrading processes
Algal biomass derived fuels	Whole algae, or the residues remaining after algal oil extraction	Routes above e.g. gasification, pyrolysis	As above

## 5 Greenhouse gas savings

### 5.1 Life cycle emissions assessment

To consider the greenhouse gas (GHG) benefits of displacing fossil fuels with biofuels, it is necessary to consider the emissions from the whole of the production chain for each fuel type. This is often known as well-to-wheels analysis, or in aviation, well-to-wake. This can be split into well-to-tank and tank-to-wake.

For both biofuels and jet fuels, we consider the well-to-tank GHG emissions. Then in the tank-to-wake part, fossil jet and biofuels have the same CO<sub>2</sub> emissions when burnt, as they have a similar composition. However, as the CO<sub>2</sub> produced when biofuels are burnt is not from a fossil source, being absorbed when the plants are grown, these emissions are not included in the analysis. Note that the non-CO<sub>2</sub> tank-to-wake GHG emissions from both jet and biofuels have not been considered here, and are likely to be the same.

Assessing lifecycle GHG emissions involves assessing the inputs, outputs and efficiency of each step in the fuel chain.

- A significant contributor to the GHG intensity of a biofuel using crops as a feedstock is the emissions associated with feedstock production. These are the emissions associated with fertiliser production, the N<sub>2</sub>O emissions from soils, emissions from machinery used for harvesting, etc. There may also be emissions resulting from loss of carbon when land is converted from one use to another, either directly or indirectly
- Those processes which do not use crops but instead agricultural or forestry residues or the organic fraction of municipal solid waste as feedstocks have a much lower GHG intensity associated with them, because there are no emissions associated with the production of the feedstock. Additionally, there are no direct or indirect land use change emissions, although other GHG impacts are possible if the feedstock have other uses.
- Energy required for conversion of the feedstock to the biofuels can often be provided by part of the biomass feedstock, and so emissions associated with energy use in conversion are generally low, with some processes exporting excess power. The GHG impacts of chemicals used in the process is also taken into account, which can often be a significant contributor for processes using hydrogen.
- Other emissions are from feedstock and fuel transport, and from pretreatment e.g. chipping, or oil extraction.
- Life cycle GHG emissions are expressed in terms of tonnes of GHG emissions in CO<sub>2</sub>-equivalent per MJ of fuel. It is important to note that well-to-tank GHG emissions, rather than CO<sub>2</sub> alone, are important for biofuels, as N<sub>2</sub>O and methane emissions can be significant for many biofuel chains.

## 5.2 Land use change

Feedstocks that are grown on land can have direct and indirect impacts from this land use, if new land is converted to agricultural uses. These include GHG emissions, described here, and other sustainability impacts described in section 7. The GHG impacts of assumptions on direct and indirect land use change (LUC) related to using crops can be large. This impact depends on the type of land on which they are grown.

- If crops bring new land into production, they will have a **direct land use change** impact, but no indirect impact. The direct impact is large if the previous land had high carbon stocks, such as forest. The impact would be smaller if the previous use was grassland. If the land was degraded (virtually no carbon stock) there could be a carbon benefit. For example, the direct emissions could be:
  - 20 tCO<sub>2</sub>e/ha from grassland in South Africa - representative of marginal grassland.
  - 180 tCO<sub>2</sub>e/ha from grassland in Brazil.
  - 520 tCO<sub>2</sub>e/ha from tropical rain forest e.g. in Brazil or Malaysia.
- If crops are grown on existing agricultural land they may have an **indirect land use change (ILUC)** impact. This is because displacing other crops from the land may cause supplies of those crops to decrease, leading to rise in price of those crops and their substitutes. This would also happen if supplies of existing crops are used to produce biofuels. In both cases, this may stimulate production elsewhere, for which new land may be brought into production. There is considerable uncertainty over the magnitude of the indirect impact. This will depend on the area and type of land brought into agricultural production globally as an indirect result of the use of land for energy crops. This in turn depends on the potential for improved crop yields on existing and new land. There are studies that show that existing agricultural land may be able to meet our needs for food, feed and other uses including bioenergy (as discussed in section 6 and in the Gallagher Review), based on global demands and potential, and a long term view. However, this does not mean that agricultural expansion will happen on the available areas identified, as a result of a large number of factors including agricultural markets and policies of all countries worldwide, in particular in the short to medium term. As a result, whether or not there is existing available agricultural land, indirect LUC is likely to happen to some extent, and new high carbon stock land is being brought into agricultural production now.

The aviation sector is highly aware of the potential sustainability impacts of biofuels production, including the GHG and other impacts of direct land use change. For example, members of the Sustainable Aviation Fuel Users group (SAFUG) have signed up to a sustainability pledge<sup>84</sup> which involves avoiding biofuels produced from feedstocks with high biodiversity impacts, low GHG savings, or where high conservation value or native eco-system lands are converted. As a result, we have assumed that it is unlikely that biofuels for aviation will be produced on land directly converted from high carbon stock or high biodiversity land, and no impact of direct land use change has been included in our GHG figures.

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<sup>84</sup> SAFUG sustainability pledge, <http://www.safug.org/docs/sustainability-pledge.pdf>

Indirect land use change is less clear; establishing the causes of land use change, and the magnitude of the impact that can be indirectly attributed to production of bioenergy feedstocks, is the subject of considerable current global research. Although some approaches have been developed, there is as yet no agreement on the results, or on the means of incorporating this into biofuels policy. In particular, there is no agreement on a quantitative factor that can be included in GHG calculations for individual biofuels. As a result, we do not include an indirect land use change factor in the GHG data given here. However, ILUC has been considered qualitatively throughout the report:

- The likely risks of ILUC from each feedstock type are stated and explained in this section and in section 7.2.
- We mention estimates of the magnitude of the impact given by the analysis done to support the Californian Low Carbon Fuel Standard, where available, expressed as an added 'ILUC factor'.
- The risk of indirect land use change, and the likely response to this risk from the industry are taken into account in section 8 when considering which biofuels uptake scenarios are more likely.

### 5.3 Initiatives on WTW for aviation

There are several studies and initiatives focusing on fuel life cycle emissions for aviation, often termed 'well-to-wake' studies. These include:

- Projects undertaken as part of the PARTNER programme<sup>85</sup>, a consortium of 9 universities and 53 partner members, sponsored by FAA/NASA/Transport Canada. Several projects being done by the Department of Aeronautics and Astronautics at MIT are working on greenhouse gas and pollutant emissions from alternative fuels, both well-to-tank and tank-to-wake. The work being done uses a modified version of the Argonne National Laboratory GREET model, a widely used tool for studying emissions of road transport fuel chains, to look at a range of fossil and biofuels chains. The analyses are based on literature data.
- A USAF/ DOE Interagency Working Group, which has a subgroup on environmental life cycle analysis. The assessment process includes university partners from MIT (PARTNER), University of Texas, University of Washington and Boeing. The process is at the stage of agreeing 'rules and tools' for assessment, and will then go on to develop baseline LCA studies covering coal/biomass to liquid production (Jun 09-Feb 10) and soybean oil to biojet fuel production, and case studies on algae, camelina/jatropha and cellulose as feedstocks for fuel production (June 09-July 10).<sup>86</sup> This will include more case-specific data about each route.

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<sup>85</sup> Partnership for Air Transportation Noise and Emissions Reduction  
<http://web.mit.edu/aeroastro/partner/index.html>

<sup>86</sup> CAAFI Defines Approach to Alt Fuel Greenhouse Gas Well to Wake Assessments, Oct. 2008  
[http://www.caafi.org/information/pdf/CAAFI\\_factsheet\\_21oct08.pdf](http://www.caafi.org/information/pdf/CAAFI_factsheet_21oct08.pdf) and 'BioFuels...Commercial Aviation (CAAFI) Emerging on the "Cutting Edge".....Aligned with USAF/DOD' CAAFI presentation to Environment and Energy Study Institute, Washington, D.C. May 2009

- The EU FP7-funded project ALFA-BIRD (2008-2012) aims to develop the use of alternative fuels in aeronautics, through assessing technical requirements, based on a series of tests and experiments, evaluating their environmental and economic performance, and mapping a path towards industrial use of the “best” alternative fuels<sup>87</sup>. This includes a task on life cycle analysis of the alternative fuels.

In addition to this, biofuels developers such as UOP have conducted and commissioned LCA studies on their fuel chains, and other aviation sector players are supporting work on new fuel chains such as algae and jatropha from university groups. The Roundtable on Sustainable Biofuels<sup>88</sup> also now includes stakeholders from the aviation sector, and is working on GHG methodologies.

#### 5.4 Baseline: emissions from jet

Emissions information on alternative fuels given by studies and company presentations is sometimes given as the absolute level of emissions, for example in gCO<sub>2</sub>equivalent/MJ fuel, and sometimes as a percentage saving compared with fossil-derived fuels. In order to make a comparison between fuels, the same baseline needs to be used for all.

We have used 2 approaches here: a WTW GHG comparison, and the EU ETS approach. For the WTW comparison, the well-to-wake emissions for fossil-derived kerosene of 87.5 gCO<sub>2</sub>e/MJ used here are the same as those used by Hileman (2009)<sup>89</sup>, which take well-to-tank GHG emissions from a report by the US National Energy Technology Laboratory published in 2008, for fuels used in the US<sup>90</sup>. Tank-to-wake emissions considered, from the same source, are CO<sub>2</sub> only, as we have assumed that jet and biofuels have the same non-CO<sub>2</sub> tank to wake emissions. For the EU ETS approach we use the stated IPCC 2006 value for TTW CO<sub>2</sub>, as required by the EUETS monitoring and reporting guidelines<sup>91</sup>.

**Table 6: Baseline emissions from fossil jet**

<b>Full WTW approach</b>	
<b>WTW GHG emissions (gCO<sub>2</sub>e/MJ)</b>	<b>87.5</b>
WTT GHG emissions (gCO <sub>2</sub> e/MJ)	14.3
TTW CO <sub>2</sub> emissions (gCO <sub>2</sub> e/MJ)	73.2
<b>EU ETS approach</b>	
<b>TTW CO<sub>2</sub> emissions (gCO<sub>2</sub>e/MJ)</b>	<b>71.5</b>

<sup>87</sup> ALFA-BIRD, Alternative Fuels and Biofuels for Aircraft Development, <http://www.alfa-bird.eu-vri.eu/>

<sup>88</sup> Roundtable on Sustainable Biofuels (RSB), <http://cgse.epfl.ch/page65660.html>

<sup>89</sup> Hileman, J. Input to GIACC 4<sup>th</sup> Meeting: US Fuel Trends Analysis and comparison to GIACC/4- IP/1. Appendix B. <http://web.mit.edu/aeroastro/partner/reports/proj28/fueltrend-analy.pdf>

<sup>90</sup> Hileman does not use tank-to-wake emissions from NETL, as these include methane emissions. NETL “Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels” November 26, 2008 DOE/NETL-2009/1346 <http://www.netl.doe.gov/energy-analyses/pubs/NETL%20LCA%20Petroleum-Based%20Fuels%20Nov%202008.pdf>

<sup>91</sup> Monitoring and reporting guidelines for emissions and tonne-kilometre data from aviation activities, April 2009, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:103:0010:0029:EN:PDF>

It is important to note that the emissions of the baseline could change over time; from small changes, such as a small increase in GHG emissions as a result of production of lower sulphur jet fuel, to much larger changes once unconventional sources of oil (oil sands and shales) are used in greater volumes, or if gas and coal to liquids became a greater part of the global fuel supply<sup>89,92</sup>. In addition to this, studies to date divide the emissions from oil extraction and the refinery between the products produced using an allocation approach, often based on their energy content<sup>93</sup>. An alternative approach used for gasoline and diesel in the EU<sup>94</sup> looked at the marginal impact of displacing these fuels with biofuels, in terms of changes to EU refinery operations. This type of analysis would be useful in showing the GHG impacts of how refinery operations worldwide would change if demand for jet is displaced by biofuels.

## 5.5 BTL

No studies were found showing the potential GHG emissions of the FT to jet process using a bottom-up approach. However, given the similarity of the process for production of FT jet fuel to that for production of FT diesel, previous studies<sup>95, 96</sup> have used GHG data for the FT diesel process as a proxy for FT jet. This was confirmed with interviewees from the fuels industry as being a reasonable approximation.

Here we consider the GHG emissions from two feedstocks: woody energy crops, and forestry residues, based on data from a well-to-wheels analysis by JEC, 2007<sup>97</sup>. The emissions of the chain are very low, giving savings compared with jet of over 90% (Table 7). This is because there is a low contribution from the feedstocks, as these require few inputs to their production, and because the gasification and FT synthesis process uses energy from the biomass itself for the process energy required. The conversion process from biomass to all liquids produced from FT synthesis is 48% by energy content, with emissions allocated between these products on the basis of their energy content.

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<sup>92</sup> Wong, H.M., Life-cycle assessment of greenhouse gas emissions from alternative jet fuels, MS Thesis, MIT, Sept. 2008. NETL "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels" November 26, 2008 DOE/NETL-2009/1346, <http://www.netl.doe.gov/energy-analyses/pubs/NETL%20LCA%20Petroleum-Based%20Fuels%20Nov%202008.pdf>

<sup>93</sup> Michael Wang, Hanjie Lee and John Molburg, "Allocation of Energy Use in Petroleum Refineries to Petroleum Products" Int J LCA 9 (1) 34 – 44 (2004) and Michael Wang Estimation of Energy Efficiencies of U.S. Petroleum Refineries [http://www.transportation.anl.gov/modeling\\_simulation/GREET/pdfs/energy\\_eff\\_petroleum\\_refineries-03-08.pdf](http://www.transportation.anl.gov/modeling_simulation/GREET/pdfs/energy_eff_petroleum_refineries-03-08.pdf)

<sup>94</sup> JEC Well-to-Wheels study, 2007 <http://ies.jrc.ec.europa.eu/WTW.html>

<sup>95</sup> Wong, H.M., Life-cycle assessment of greenhouse gas emissions from alternative jet fuels, MS Thesis, MIT, Sept. 2008.

<sup>96</sup> Hileman, J. Input to GIACC 4<sup>th</sup> Meeting: US Fuel Trends Analysis and comparison to GIACC/4- IP/1. Appendix B. <http://web.mit.edu/aeroastro/partner/reports/proj28/fueltrend-analy.pdf>

<sup>97</sup> JEC Well-to-Wheels study, 2007 <http://ies.jrc.ec.europa.eu/WTW.html>

**Table 7: WTW GHG emissions from BTL**

Feedstock	Emissions, gCO <sub>2</sub> e/MJ	Savings CO <sub>2</sub> e %, relative to jet fuel	Reference/ comments
Energy crops	7.3	92%	JEC, 2007
Forestry residues	4.8	95%	JEC, 2007

In our interviews with the aviation sector, and in several reports and presentations, many stakeholders commented that they were less interested in BTL than other routes, principally as a result of the ‘high energy use’ of the conversion process. This appears to be a statement often made in aviation biofuels discussions, and taken to imply poor environmental benefits. It is important to note that while energy is used in the BTL process to convert lignocellulosic feedstocks to liquid fuels, this is provided by the biomass itself. As a result of this, and low GHG emissions from feedstock production, overall GHG emissions are very low. This can be contrasted with HRJ production, which has low energy use in conversion to HRJ, but can have higher lifecycle GHG emissions as a result of fertiliser and energy use in growing the feedstock and extracting the oil. This shows the importance of considering GHG emissions, rather than energy alone, when comparing fuel chains.

Energy crops, like most other crops, have potential for land use change impacts. However, these are may be lower than for many other crops, as a result of the type of land that can be used to grow them. The direct land use change impact could be very low, if the land converted were low carbon stock grassland, for example. Work done for the Californian Low Carbon Fuel Standard estimated this impact at 27.5tCO<sub>2</sub>e/ha for US grassland (which had relatively low carbon stocks)<sup>98</sup>, which would be equivalent to an addition of around 10 gCO<sub>2</sub>e/MJ to the WTW GHG emissions – a significant addition to the figures above, but still resulting in considerable GHG savings versus fossil jet.

If energy crops are grown on existing agricultural land they will have an indirect impact, depending on what they are displacing. However, it is possible that policy will encourage energy crops to be grown on lower quality land less suitable for food production, which could reduce this impact, or on new or abandoned land, as above.

Other feedstocks for BTL, such as forestry residues, agricultural residues, and wastes, have no land use change emissions; although other GHG impacts are possible if the feedstock have other existing uses.

<sup>98</sup> California Environmental Protection Agency, Air Resources Board ‘Proposed Regulation to Implement the Low Carbon Fuel Standard’, Volume I, March 2009, [http://www.arb.ca.gov/fuels/lcfs/030409lcfs\\_isor\\_vol1.pdf](http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf)

## 5.6 HRJ from vegetable oils

GHG emissions for hydrotreated vegetable oil routes vary depending on the vegetable oil that is used and on the country of origin of the feedstock, due to the potential for indirect land use change impacts, and different cultivation practices in different countries. The emissions are also heavily dependent on how the hydrogen for the hydrotreatment process is made. The amount of hydrogen and electricity required for the hydrotreatment process will vary between the different vegetable oils but this should not have a significant impact on the overall GHG emissions of the route.

Table 8 shows the GHG emissions estimated for HRJ from different feedstocks, using a combination of data from UOP, and our estimates based on HVO chains analysed using the UK's RTFO carbon reporting methodology for road transport fuels. As noted above, the main difference between the process for transforming vegetable oils into diesel and for transforming vegetable oils into jet is the selective cracking process that is used to make jet fuel. The selective cracking process requires some additional hydrogen but this amount is much lower than that required in the hydrotreatment step. In most cases, the emissions assumed by UOP are similar to the default values used in the RTFO methodology for GHG emissions from HVO, with a correction to add the extra hydrogen needed for HRJ production.

As halophytes are some way from being produced commercially, let alone for biofuel feedstock, it is unsurprising that there is very little information about the GHG emissions from the fuel chain. As such the halophyte fuel chain has not been included in the table below. However, initial research indicates that nitrogen requirements for halophytes may be similar to that for rapeseed, and that halophytes require large volumes of seawater for their agriculture which will require pumping, although this is also true for conventional crops reliant on freshwater irrigation. Given that the harvesting and processing of halophyte oil is unlikely to be very different from other vegetable oils, it seems reasonable to assume that halophyte biofuel could be produced with a carbon intensity adequate to meet the requirements of the RED, i.e. 50% carbon savings relative to jet fuel.

**Table 8: WTW GHG emissions from HRJ from vegetable oils and tallow**

Feedstock	Emissions, gCO <sub>2</sub> e/MJ	Savings CO <sub>2</sub> e %, relative to jet fuel	Reference/ comments
Oilseed rape	54-108 (average 70)	20%	Based on RTFO default values <sup>99</sup> with the additional H <sub>2</sub> required for processing to jet as outlined in GIACC (2009) <sup>100</sup> . Large range depends on country of origin. Some feedstock will be available with higher savings, meeting the RED thresholds of 35% by 2013/15 and 50% by 2017.
Palm oil	57	35%	RTFO default values plus jet conversion. Some feedstocks will be available with higher savings.
Soybean oil	40	54%	Total emissions based on UOP <sup>101</sup> . For comparison, the RTFO default values for this route with jet conversion range from 56-92gCO <sub>2</sub> e/MJ. Some feedstocks will be available with higher savings.
Sunflower oil	27-81 (average 61)	30%	RTFO default values plus jet conversion. Large range depends on country of origin. Some feedstock will be available with higher savings.
Coconut oil	45-50 (average 47)	46%	RTFO default values plus jet conversion. Some feedstocks will be available with higher savings.
Jatropha	30	66%	UOP <sup>101</sup> . For comparison, the RTFO default value for this route with jet conversion is 32gCO <sub>2</sub> e/MJ.
Babassu	47	46%	Assume the same as coconut – similar trees and product, although country different.
Camelina	13.5	85%	UOP <sup>101</sup>
Tallow	10	89%	UOP <sup>101</sup> . For comparison, the RTFO default value with jet conversion for this route would be ~21gCO <sub>2</sub> e/MJ

Table 8 shows that GHG savings are largest for jatropha, camelina and tallow. For the conventional crops, the GHG savings shown above are unlikely to improve significantly over time; the majority of the emissions for these fuel routes are associated with crop production and for these crops, crop production is unlikely to get *significantly* more efficient in the future. For crops like jatropha, the GHG emissions associated with their production may change, as yields increase, but potentially also with increased inputs. UOP's high GHG savings from camelina reflect the yield improvements expected for the crop

<sup>99</sup> RFA (2009) Carbon and sustainability reporting within the Renewable Transport Fuel Obligation  
[http://www.renewablefuelsagency.org/\\_db/\\_documents/Carbon\\_and\\_Sustainability\\_Guidance\\_Part\\_2.pdf](http://www.renewablefuelsagency.org/_db/_documents/Carbon_and_Sustainability_Guidance_Part_2.pdf)

<sup>100</sup> GIACC 4<sup>th</sup> Meeting: US Fuel Trends Analysis and comparison to GIACC/4- IP/1. Appendix B. Available at:  
<http://web.mit.edu/aeroastro/partner/reports/proj28/fueltrend-analy.pdf>

<sup>101</sup> UOP, J. Holmgren's presentation at the Aviation and Environment Summit, 31 March 2009  
[http://www.envirosummit.aero/images/Downloads/speeches/speeches\\_downloads/blue\\_room\\_morning\\_jennifer\\_holmgren.pdf](http://www.envirosummit.aero/images/Downloads/speeches/speeches_downloads/blue_room_morning_jennifer_holmgren.pdf)

(which has received little attention in recent years) and also due to the expectation that low inputs of fertiliser will be required<sup>102</sup>.

Indirect land use change is likely to occur to some extent as a consequence of using palm, soy, coconut, rapeseed, corn oil and sunflower oil for biofuels. Jatropha, camelina and tallow are not included in that list because the first two are expected to be grown on marginal land (land that would not be used for food production) and the latter is not a land based crop but a by-product of the meat rendering industry. However, if jatropha and camelina are in demand for biofuels, it is likely that farmers will switch to growing these crops on better land where higher yields can be obtained, and so land displacement effects could still result. Similarly, indirect impacts could also result from the use of tallow. If the tallow already has a use in other industries, its diversion to biofuel production will mean that its initial use could get substituted for something with higher GHG emissions than jet fuel (e.g. heavy fuel oil)<sup>103</sup>.

ILUC factors are one proposed method to quantify the emissions from ILUC. When added to the overall GHG emissions savings from the different routes, they would show that waste feedstocks will have the greatest overall emissions savings followed by crop feedstocks grown on marginal land that cannot be used for food production. For example, the Californian EPA Air Resources Board has recently developed carbon intensity values for three biofuels, taking into consideration the indirect land use change impacts<sup>104</sup>. One of the biofuels they have developed an ILUC factor for is soybean biodiesel; the additional indirect land use change impact is 42gCO<sub>2</sub>e/MJ. If these indirect emissions are added to UOPs direct emissions, a total of 82gCO<sub>2</sub>e would be associated with each MJ of soybean biodiesel produced, resulting in a saving of only 5.5gCO<sub>2</sub>e/MJ relative to using fossil jet fuel.

## 5.7 HRJ from algal oils

As stated above, algal biofuels are not yet produced commercially as there are still fundamental R&D challenges to be overcome. As such, the GHG emissions associated with algal biofuel production are uncertain, and there is very little information in the public domain about expected GHG emissions from these routes. However, the GHG balance of algal biofuels is expected to be positive because, like plants, they take up CO<sub>2</sub> from the atmosphere in order to photosynthesise, and energy can be obtained by anaerobically digesting the algal residues and using the methane to produce electricity for processing the algae (and exporting any additional electricity). It should be noted that because algae oil production requires a CO<sub>2</sub> stream, which may most economically come from a fossil power plant, the use of algae is sometimes inaccurately referred to as “carbon sequestration”. This is not the case; although the algae

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<sup>102</sup> “Life cycle study shows camelina-derived biojet fuel can reduce GHG emissions by up to 84 percent” May 2009  
<http://www.greenaironline.com/news.php?viewStory=432>

<sup>103</sup> Advice on the Economic and Environmental Impacts of Government Support for Biodiesel Production from Tallow. AEA, E4tech, Metroeconomica and Miller-Klein Associates for DfT. April 2008  
<http://www.dft.gov.uk/pgr/roads/environment/rtfo/tallow/tallowfinalresport.pdf>

<sup>104</sup> California EPA Air Resources Board: Proposed regulation to implement the low carbon fuel standard. Volume I. Staff Report: Initial statement of reasons, [http://www.arb.ca.gov/fuels/lcfs/030409lcfs\\_isor\\_vol1.pdf](http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf)

do take up CO<sub>2</sub>, this CO<sub>2</sub> is released again when the algal oil or biomass is burned and thus the CO<sub>2</sub> is recycled and not sequestered.

As mentioned before the GHG emissions associated with the production of algal biofuels are likely to be very different, depending on the technology used (open ponds or PBRs).

- For open ponds, the main GHG emissions for oil production are likely to be associated with the inputs such as fertilisers, chemical flocculants, operation and maintenance (e.g. vehicles on site), amortized energy inputs for the capital items etc. For conversion to jet fuel, there are the additional emissions associated with electricity and hydrogen production for the hydrotreatment step (as with the hydrotreated vegetable oils). The emissions shown in Table 9 assume that the algal residues are anaerobically digested to produce methane, which can be used to generate electricity. This electricity is used to meet the needs of the oil extraction plant, and some is also exported from the plant.
- Due to the complexity of PBRs, it is likely that there will be higher GHG emissions associated with PBR plant operational activities, such as electricity for pumping and cleaning, as well as the higher GHG emissions associated with building the plant itself (e.g. the manufacture of thousands of hectares of glass/plastic tubing). However, proponents of this type of technology expect higher biomass productivities that can be achieved in the PBRs will counteract this, and the overall emissions per MJ will be low. As there have been no published studies of the GHG emissions associated with PBRs, they are not considered further here.

**Table 9: WTW GHG emissions from HRJ from algal oils**

Feedstock	Emissions, gCO <sub>2</sub> e/MJ	Savings CO <sub>2</sub> e, relative to jet fuel <sup>105</sup>	Reference/ comments
Algae (Open ponds)	-21 (best case) 1.5 (realistic case)	124% (best case) 98% (realistic case)	Best case based on CSIRO's estimate <sup>106</sup> of GHG emissions associated with producing algal oil, and UOP's number for conversion of vegetable oil to HRJ.

<sup>105</sup> Emissions from jet fuel assumed to be 86gCO<sub>2</sub>e/MJ (UOP, J. Holmgren's presentation at the Aviation and Environment Summit, 31 March 2009, [http://www.envirosummit.aero/images/Downloads/speeches/speeches\\_downloads/blue\\_room\\_morning\\_jennifer\\_holmgren.pdf](http://www.envirosummit.aero/images/Downloads/speeches/speeches_downloads/blue_room_morning_jennifer_holmgren.pdf))

<sup>106</sup> CSIRO, Campbell et al. (2009) Greenhouse gas sequestration by algae – energy and greenhouse gas lifecycle studies. CSIRO do not provide the breakdown of emissions for producing algal *oil* for the realistic case, so we have factored back from the estimate they give for algal *biodiesel* in the Realistic case (using the flue gas scenario and the “realistic” assumptions) to the emissions for algal oil only, based on the relationship between the two for the best case scenario (which is reasonable given that the emissions for the biodiesel production step do not change between the two scenarios). We have added to this UOP's estimate for conversion of vegetable oil to HRJ and included a typical transport step to where the fuel is sold.

The GHG intensity of algal fuels, as shown above, is likely to improve further as more useful co-products can be obtained from the algal residues. Also, one of the major benefits of algal biofuels is that they do not need to be grown on agricultural land because they are grown in ponds, or in photobioreactors. In this way, algae culture can use unproductive land, and should not, cause indirect land use change.

The emissions for the dark fermentation route based on sugars will vary considerably depending on the source of sugars used. A recent study found that the life cycle GHG emissions for Solazyme's route are 85-93% lower than ultra-low sulphur diesel<sup>107</sup>, which would give comparable savings relative to jet.

## 5.8 Synthetic hydrocarbons

As these routes are also at an early stage of development, there is little published data on their emissions, using comparable calculation methodologies (Table 10). In addition to this, the emissions of these routes, including potential ILUC impacts, will depend heavily on the source of the sugars used, with higher emissions from feedstocks such as corn, lower emissions from sugar cane and lignocellulosic crops, and potentially very low emissions from wastes.

**Table 10: WTW GHG emissions from some synthetic hydrocarbon routes**

Route	GHG data
Isoprenoids	Amyris state that the fuel will have 90% savings compared with jet fuel, or 80% compared with diesel <sup>108</sup> . This appears feasible, given that the process is based on the use of sugar cane, which can have similarly high GHG savings when converted to ethanol, and that isoprenoids can be easily separated from water, compared with the energy intensive separation seen for ethanol.
Butanol derived fuels	No information was found on this route. In general, fermentation routes from low carbon feedstocks to butanol can have very low greenhouse gas emissions, and so high savings <sup>109</sup> . However, if retrofitted to US corn ethanol plants, as has been proposed, emissions could be much higher (agricultural impacts, and fossil fuel use at the plant)
Alkanes from APR	Virent give a GHG reduction of around 72% for their technology compared with gasoline, compared with stated values of 55% for sugar cane ethanol or cellulosic ethanol <sup>110</sup> . These figures are very low for sugar cane and cellulosic ethanol compared with those generally quoted, however, and no details are given.

<sup>107</sup> Solazyme website <http://www.solazyme.com/news090421.shtml>

<sup>108</sup> Greentechmedia article, Nov. 2008, <http://www.greentechmedia.com/articles/read/amyris-were-better-than-biodiesel-ethanol-or-gas-5157/>

<sup>109</sup> Wu, M.; Wang, M.; Liu, J.; Huo, H.; 'Life-cycle assessment of corn-based butanol as a potential transportation fuel.' 2007 <http://www.ipd.anl.gov/anlpubs/2007/12/60614.pdf>

<sup>110</sup> Virent presentation at Midwestern Governors Association Energy Summit November 2007 [http://www.midwesterngovernors.org/MGA%20Energy%20Initiative/2007%20Summit/Virent%20Energy\\_MGA.pdf](http://www.midwesterngovernors.org/MGA%20Energy%20Initiative/2007%20Summit/Virent%20Energy_MGA.pdf)

## 5.9 Summary

Table 11 below gives a summary of the data from this section, including comments on the key input data. Note that the figures given do not include the impacts of direct or indirect land use change, which could occur where indicated, reducing the estimated savings.

**Table 11: Summary of WTW GHG emissions from biofuels for aviation**

Route	Feedstock	Emissions, g CO <sub>2</sub> e/MJ	Savings CO <sub>2</sub> e %	Comments
Fossil jet (baseline)	-	87.5	-	Could change over time if unconventional sources of oil are used
BTL	Energy crops	7.3	92%	Low input to feedstock production Biomass is used to provide energy for conversion For energy crops, potential for direct LUC, and risk of indirect LUC unless grown on marginal land
	Forestry residues	4.8	95%	
HRJ	Oilseed rape	54-108 (average 70)	20%	Large ranges depend on country of origin. Some feedstock will be available with higher savings, meeting RED thresholds of 35% by 2013/15 and 50% by 2017 Potential for direct and indirect LUC
	Palm oil	57	35%	
	Soybean oil	40	54%	
	Sunflower oil	27-81 (average 61)	30%	
	Coconut oil	45-50 (average 47)	46%	
	Babassu	47	46%	
	Jatropha	30	66%	Potential for direct LUC, and risk of indirect LUC unless grown on marginal land
	Camelina	13.5	85%	Yield improvements and low fertiliser inputs expected Potential for direct LUC, and risk of indirect LUC unless grown on marginal land
	Tallow	10	89%	High savings for waste tallow i.e. no other use
Algae (Open ponds)	-21 (best case) 1.5 (realistic case)	124% (best case) 98% (realistic case)	Very low number as electricity is also produced Best case based on CSIRO's estimate of GHG emissions associated with producing algal oil, and UOP's number for conversion of vegetable oil to HRJ.	
Synthetic hydrocarbons	Not specified		70-90%	Quoted in press releases for the 3 technologies considered Achievable with low carbon feedstocks e.g. sugar cane, lignocellulosic materials

## 6 Economic case

In this section, we compare the projected costs of the main options for biofuels in aviation with the projected costs of jet fuel, with and without a carbon price. We then consider whether cost, or cost of carbon alone will determine whether biofuels are used in aviation.

As there are similarities between some of the fuel chains described above, and limited data availability on the costs and GHG savings of some of the routes, we have represented the options as three biofuels groups as shown in Table 12. HRJ from feedstocks available in low volumes e.g. tallow, sunflower and potential routes from pyrolysis chains, for which there is little data on routes to jet, have not been modelled. However, synthetic hydrocarbons can be considered to be representative of any new low cost route from lignocellulosic materials or sugars, commercialised after 2020.

**Table 12: Routes included in economic analysis**

Name	Feedstock(s)	Conversion process
BTL	Energy crops Forestry residues	Gasification and FT synthesis
HRJ (Hydrotreated renewable jet)	Conventional oil crops (soy, palm, rapeseed)	Oil extraction and hydrotreating
	New oil crops (algae, camelina, jatropha, halophytes)	
Synthetic hydrocarbons	Lignocellulosic materials, or sugars	Range of biological and chemical routes

The figures compared in this section are bulk prices/costs, and do not include fuel distribution.

### 6.1 Baseline costs

The wholesale price of jet fuel was estimated to 2050 based on DECC oil price assumptions to 2030, under four scenarios (Figure 8). From 2030 to 2050, prices were assumed to continue the pre-2030 trend. A product crack of \$8.25/bbl was added to the oil price, based on the average spread between US spot prices for crude and jet fuel since 1990. As Figure 5 shows, this crack spread is highly variable<sup>111</sup>; over the period since 1990 it has varied between -\$1.5/bbl and \$53.5/bbl in daily data, with a standard deviation of 7.3. The average over the last year is \$20.5/bbl, reducing to an average of \$11.9 over the last 6 months. IATA note that the crack spread is generally around 24% of the jet price<sup>112</sup>: this is the average % based on the data below, though still varies between 3 and 74% over the time period.

<sup>111</sup> Data from EIA, [Accessed May 2009], [http://tonto.eia.doe.gov/dnav/pet/pet\\_pri\\_top.asp](http://tonto.eia.doe.gov/dnav/pet/pet_pri_top.asp)

<sup>112</sup> IATA 2008 Report on Alternative Fuels, <http://www.iata.org/NR/rdonlyres/03FE754C-D30A-4E77-8C92-5A05AF75C614/0/IATA2008ReportonAlternativeFuels.pdf>

This variability is a result of the interaction between increasing demand for jet, and variation in jet production in response to gasoline demand, and refinery capacity, and is wider than the variability seen in the crack spread for gasoline. The crack spread for jet is likely to continue to vary widely, and could increase over time, if the production of jet was not favoured with use of heavier crudes, and if oil product demand decreases in some regions. However, the oil price scenarios vary considerably, and so we have not considered separate crack spread scenarios. It is important to note, however, that crack spread variability presents a higher risk for financing for biofuel plants for aviation than for road transport.

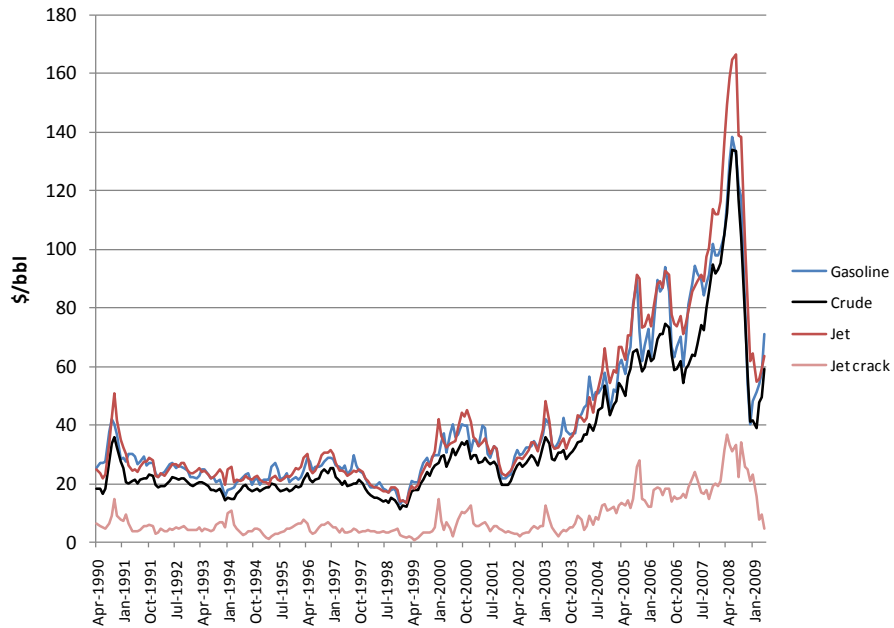


Figure 7: Monthly oil and product price data (EIA)

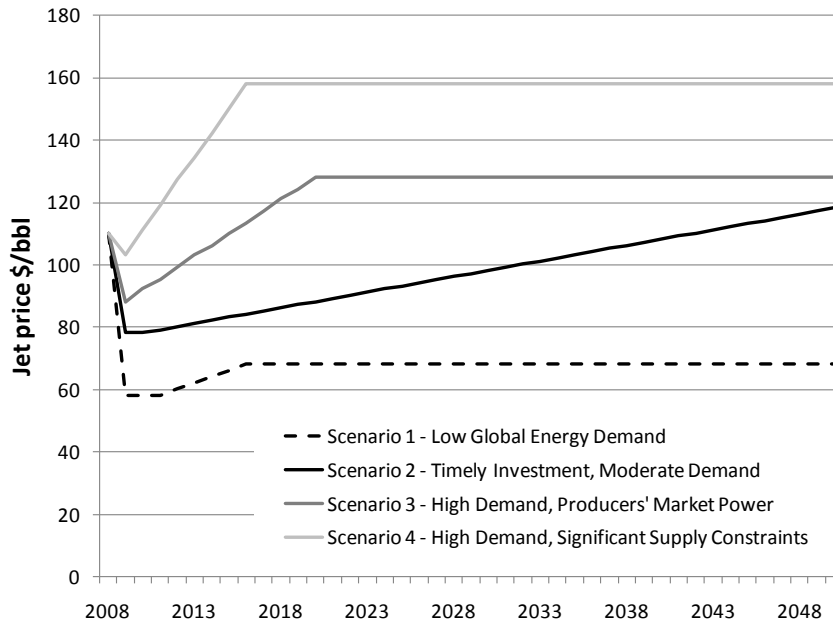


Figure 8: Jet price projections

Carbon prices used, as shown below, were provided by the CCC.

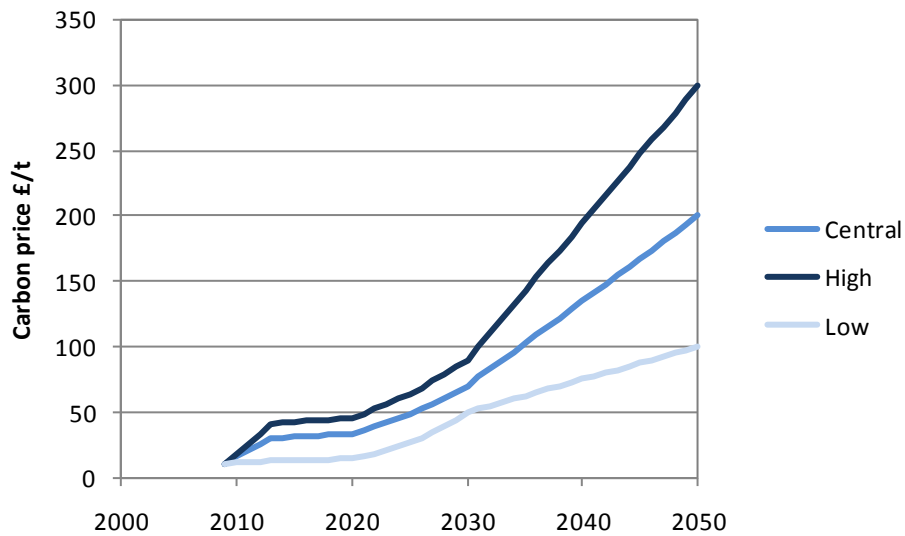


Figure 9: Carbon prices per tonne CO2

## 6.2 BTL

Input data for BTL is shown in Table 13. The costs of BTL jet fuel production are based on BTL diesel production costs, as a result of similarities in the production process. We considered two feedstocks: woody energy crops, and forestry residues/ wastes, with high and low prices used for each. Costs and

efficiency for the first plants were based on data from a European fuels study<sup>113</sup>, with future costs reduced based on industry data for commercial plants. This nth plant cost was assumed to be achieved only after 15 years, as a result of the likely slow deployment in early years, associated with the large plants and high capital costs expected for this technology. The reduction to this point was approximated with a learning curve based on potential deployment, with a 10% learning rate on capital costs<sup>114</sup>.

**Table 13: BTL input data**

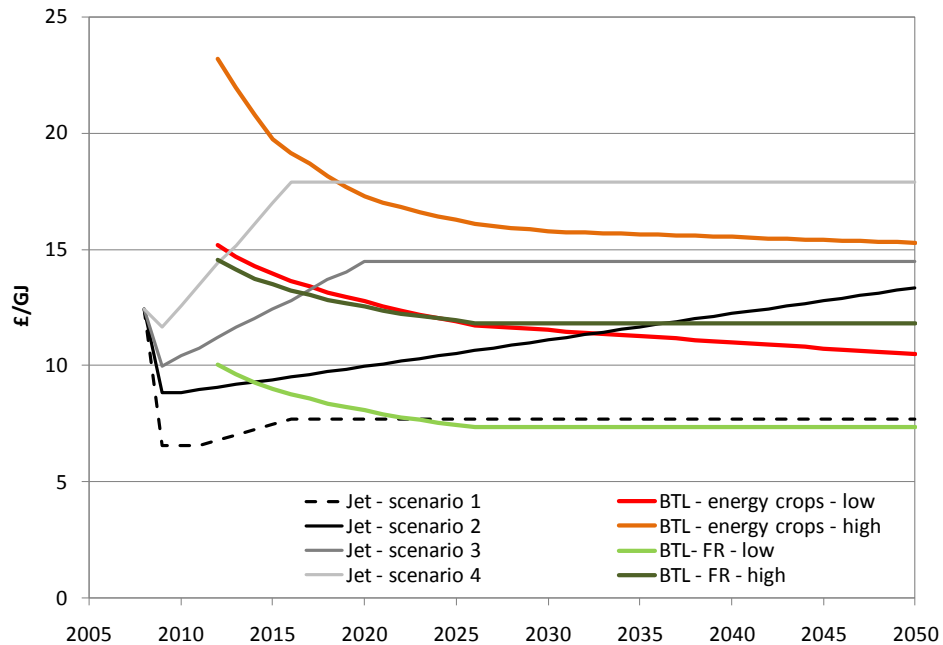
Type		Data	Reference and comments
Energy crop costs £/GJ <sub>feedstock</sub>	High	7.3 reducing to 3.8 by 2050	E4tech (2009) <sup>115</sup> : Estimated world market prices for woody biomass, extrapolated to 2050. Includes transport internationally and in the country of use
	Low	2.5 reducing to 1.5 by 2050	E4tech (2009): Energy crop production and transport in the same country
Forestry residues and wastes costs £/GJ <sub>feedstock</sub>	High	2.2	High end of cost range for forestry residues from E4tech (2009). Includes collection and chipping
	Low	0	Assumed zero. Some wastes have negative costs, as a result of avoided gate fees, but this does not apply globally.
Conversion cost £/GJ <sub>fuel</sub>		10 in 2012 reducing to 7.4 by 2026	JEC(2007) for first plants, in 2012 Industry data for 2026 value. Learning curve reduction of 10% on capex assumed
Conversion efficiency		48%	JEC(2007)
Energy crop WTW GHG emissions gCO <sub>2</sub> e/MJ		7.3	JEC(2007). Assumes no land use change impacts
Forestry residue WTW GHG emissions gCO <sub>2</sub> e/MJ		4.3	JEC(2007)

Figure 10 below shows the costs of biofuels production from these routes compared with the jet price, under the four oil price scenarios. Note that the production cost of BTL fuel is unlikely to increase significantly with oil price, as a result of low fossil fuel inputs to feedstock production and transport, and to conversion, with electricity exports from the conversion plant potentially decreasing production cost at high oil prices.

<sup>113</sup> JEC (JRC, EUCAR, Concawe) Well-to-Wheels study, 2007, <http://ies.jrc.ec.europa.eu/WTW.html>

<sup>114</sup> RENEW, a European study of BTL technologies, estimates a learning factor of 0.9, i.e. a 10% learning rate. [http://www.renew-fuel.com/download.php?dl=del\\_sp5\\_wp3\\_5-3-7\\_07-11-30\\_iee-draft.pdf&kat=18](http://www.renew-fuel.com/download.php?dl=del_sp5_wp3_5-3-7_07-11-30_iee-draft.pdf&kat=18)

<sup>115</sup> E4tech (2009) Biomass supply curves for the UK, for DECC, [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/renewable/res/res.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.aspx)



**Figure 10: Costs of BTL compared with jet price in £/GJ**

This shows that:

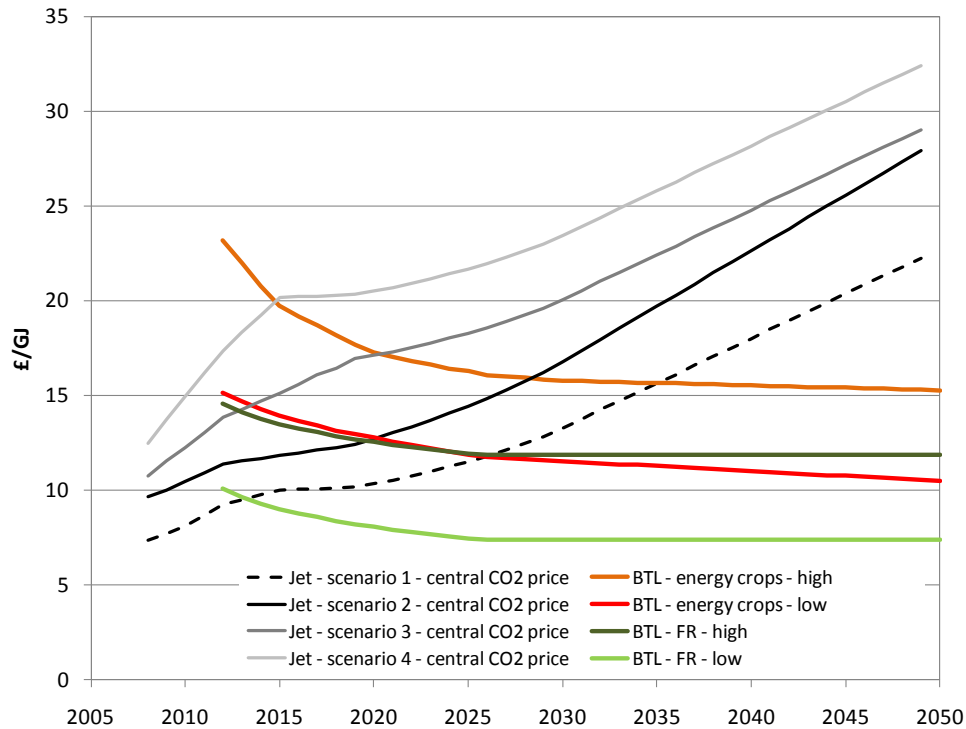
- The cost of BTL fuels decreases over time. This is principally as a result of the reduction in conversion costs with learning, which is significant particularly over the first 15 years of introduction. Continued reduction beyond this is through feedstock cost reduction with energy crop yield improvements, and cost reduction.
- The feedstock price has a large effect on the cost of the BTL fuel. With high cost energy crop feedstocks, including international transport, BTL production is only viable in the highest oil price scenario. Plants are very unlikely to be built without securing supplies of lower cost feedstocks, in the range of the low end of the energy crop costs, or high forestry residues costs, with use of lower cost residues and wastes as far as possible.
- In the central oil price scenario (scenario 2) with mid range feedstock costs (low energy crop costs or high forestry residues costs), BTL breaks even with jet fuel in 2033-2037. Depending on the proportion of low cost feedstock that can be accessed, this could be brought back to as early as 2013, i.e. the first plants being competitive. For comparison, Rentech, one of the main developers of this technology, state that their plant to be completed in 2012 will be competitive with fossil fuels, using wastes, some of which have an associated gate fee<sup>116</sup>.
- Higher oil price scenarios also bring back the point of competitiveness with mid range feedstock costs to before 2020, meaning that the first plants built using this technology would be competitive with fossil jet. In the lowest oil price scenario, only plants using zero or negative cost feedstocks

<sup>116</sup> Greentechmedia, May 2009, <http://www.greentechmedia.com/articles/read/rentech-plans-wood-waste-to-biofuel-electricity-plant-in-california-4600/>

would be viable, and only after 2022. This brings considerable uncertainty into the investment case for these high capital cost projects.

- The break even point is considerably more sensitive to oil price and feedstock price than to assumptions about technology development. Altering the learning rate for the technology only affects the break even date by a couple of years, in comparison with the differences seen above.

Figure 11 shows the impact of adding a carbon price to the emissions from jet fuel, according to the EUETS approach. This means that the tank-to-wake emissions of fossil jet are valued at the carbon price, and biofuels are assumed to have a savings of 100%, i.e. no costs of emissions.



**Figure 11: Costs of BTL compared with jet including a central carbon price – EUETS approach**

This has a significant effect on the break even point for BTL fuels. In the central oil price scenario 2, with mid range feedstock costs, the break even point is brought forward from 2033 to 2021. With low and high carbon prices, this point varies between 2019 and 2024. Even with the lowest oil price scenario, a plant using mainly low cost feedstocks could break even before 2020 with a central carbon price, as shown in the table below.

**Table 14: Break even points for BTL with mid and low feedstock prices**

Fuel	1				2				3				4			
	None	Central	High	Low	None	Central	High	Low	None	Central	High	Low	None	Central	High	Low
BTL – mid	After 2050	2027	2024	2031	2033	2021	2019	2024	2018	2015	2014	2016	2013	2012	2012	2012
BTL – low	2023	2014	2013	2017	2014	2012	2012	2013	2012	2012	2012	2012	2012	2012	2012	2012

Considering the cost of carbon emissions on a full well-to-wake GHG basis for both jet and BTL has only a small impact on these results, bringing the point of commercialisation forward by a year. This is because the GHG savings from BTL chains are very high, at 92-95%, and so adding well-to-tank jet GHG emissions has a greater effect than adding those from the BTL chains.

### 6.3 HRJ from conventional feedstocks

HRJ routes using conventional oil crop feedstocks have been modelled together, as they are available now, and can have similar GHG savings compared with jet. This has been done in two ways: using prices linked to the crude oil price, and using the low end of prices seen over the last five years.

#### Linked prices

Future price projections for vegetable oils are highly uncertain, as a result of many oils being substitute products, demands from the food, fuel and oleochemical industry, and variability in agricultural production. Two options for overcoming this are to either use a flat price, based on short term commodity price futures or historic prices, or to link to the price of another commodity.

Data from the FAO<sup>117</sup> shows that in recent years, there may be a relationship between the price of crude oil and the price of vegetable oils (Figure 12). This is likely to be related to their substitutability for several uses, rather than to inputs to vegetable oil production alone. We have used this relationship to project the price of vegetable oils depending on the oil price scenario, when the crude oil price is above \$60/bbl. Below this, we have assumed that the price of vegetable oils stays constant, as the graphs show no evident relationship. It is important to note that this relationship may change in the long term, with increasing oil scarcity, but also with changes to vegetable oil productivity and increasing demand.

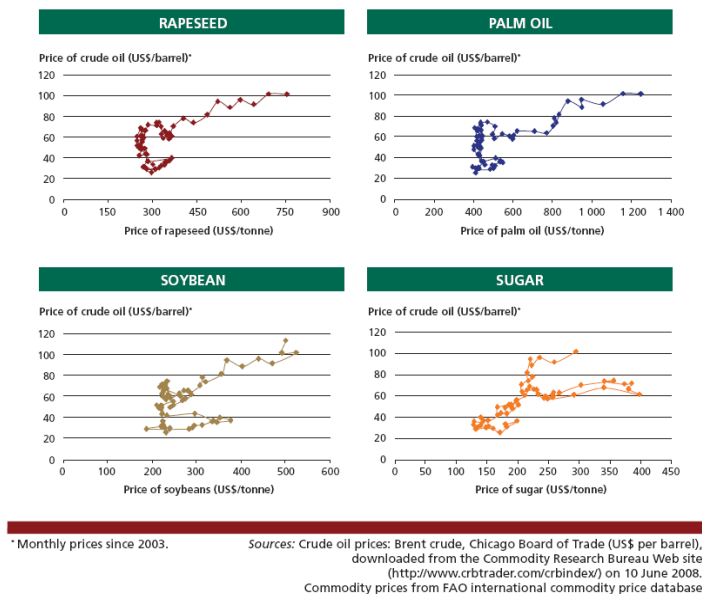


Figure 12: Price relationships between crude oil and biofuel feedstocks 2003-8, FAO

<sup>117</sup> FAO, The state of food and agriculture, 2008, <http://www.fao.org/docrep/011/i0100e/i0100e00.htm>

We then looked at the relationship between crop prices and the prices of the oils derived from them<sup>118</sup>. This showed that for rapeseed, the price of the oil is around 2.5 times the price of the feedstock. In the range of vegetable oil prices seen, palm oil is the cheapest, and rapeseed oil the most expensive, so these were taken as the high and low values, with an average used as the mid value. For example, in 2009, using the relationship above gives oil prices of \$744/t for palm oil, and \$1000/t for soy, at an oil price of \$70/bbl (Oil price scenario 2), as used in Figure 14. This is in the range of variation seen over the past year, as shown in Figure 13 below.

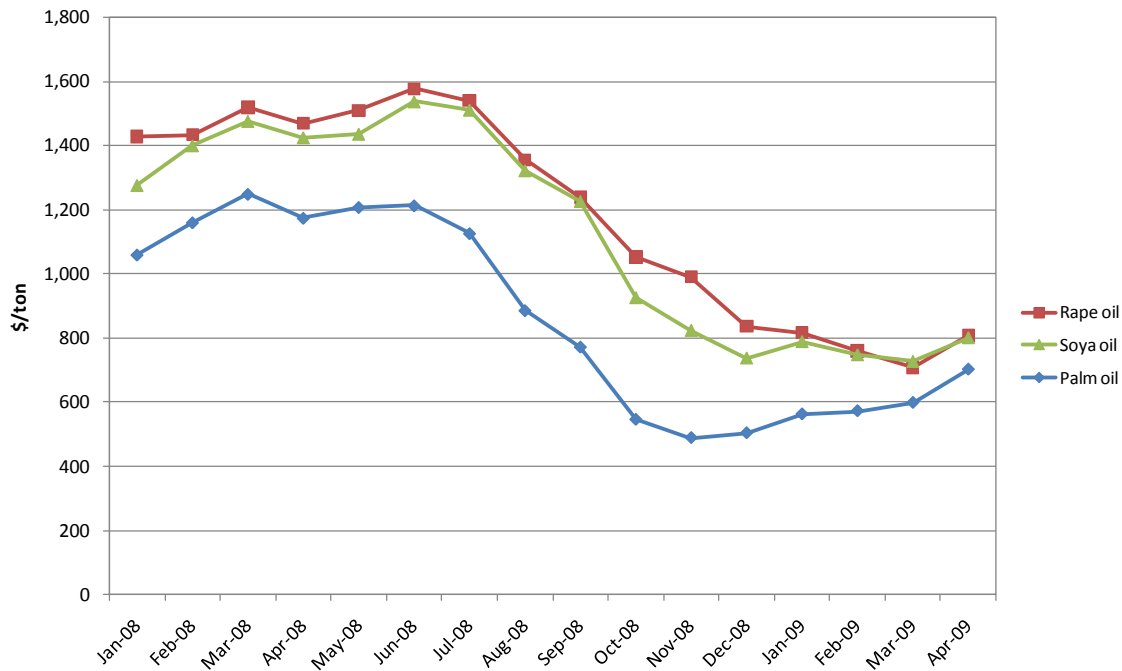


Figure 13: Vegetable oil prices 2008-9<sup>119</sup>

Whilst several analyses of the cost of hydrotreated vegetable oils for fuels have been presented, no very detailed breakdown was found. However, UOP's analysis of the cost of hydrotreating vegetable oils to green diesel for road transport<sup>120</sup> show that these fuels are profitable when the cost of the oil feedstock per barrel is the same as the crude price. This has been used as an approximation for jet fuels, by applying the spread between crude and jet of \$8.25/bbl to the vegetable oil price in \$/bbl. We have kept

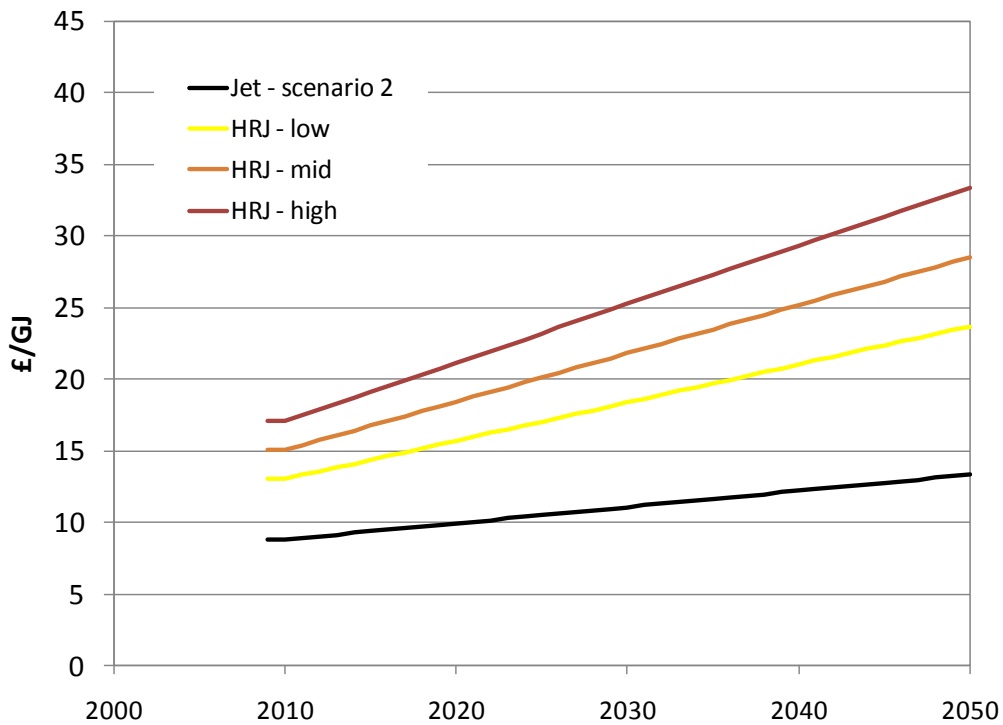
<sup>118</sup> EnAgri Bioenergy market report, June 2008, [http://www.enagri.info/market\\_data/weekly\\_reports/2008/080627oethsyeg.pdf](http://www.enagri.info/market_data/weekly_reports/2008/080627oethsyeg.pdf)

<sup>119</sup> FAO, International Commodity prices, <http://www.fao.org/es/esc/prices>

<sup>120</sup> "New developments in renewable fuels offer more choices" J. Holmgren, C. Gosling, R. Marinangeli and T. Marker, UOP LLC, Des Plaines, Illinois, and G. Faraci and C. Perego, Eni S.p.A. Refining and Marketing Division, Novara, Italy. Hydrocarbon Processing, Sept 2007 pp 67-71. <http://www.uop.com/renewables/HP0907%20New%20Development%20in%20Renewables%20Fuels.pdf>

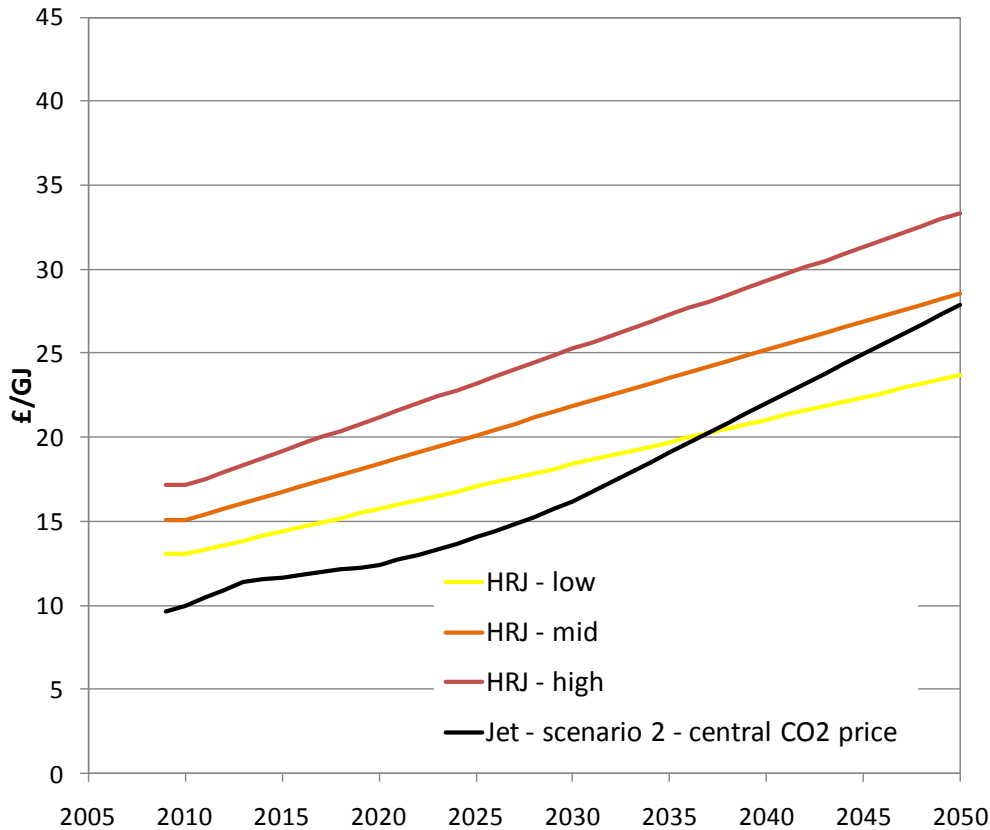
this constant over time, as although there is potential for process improvement in hydrotreating, the costs of this conversion are small compared with the feedstock price.

Figure 14 shows a comparison of HRJ prices calculated using crude oil-linked feedstock prices, and the jet price, under oil price scenario 2, to 2050. This shows that if linear relationship between crude oil and vegetable oil prices continues, then HRJ does not break even with fossil jet. In the other oil price scenarios, the results with a link between crude oil and vegetable oil prices are the same, and HRJ does not break even.



**Figure 14: Comparison of HRJ prices with jet under oil price scenario 2**

Figure 15 shows the impact of adding a carbon price to the emissions from jet fuel, according to the EUETS approach. This means that the tank-to-wake emissions of fossil jet are valued at the carbon price, and biofuels are assumed to have a savings of 100%, i.e. no costs of emissions.



**Figure 15: Comparison of HRJ price with jet+carbon under EUETS approach**

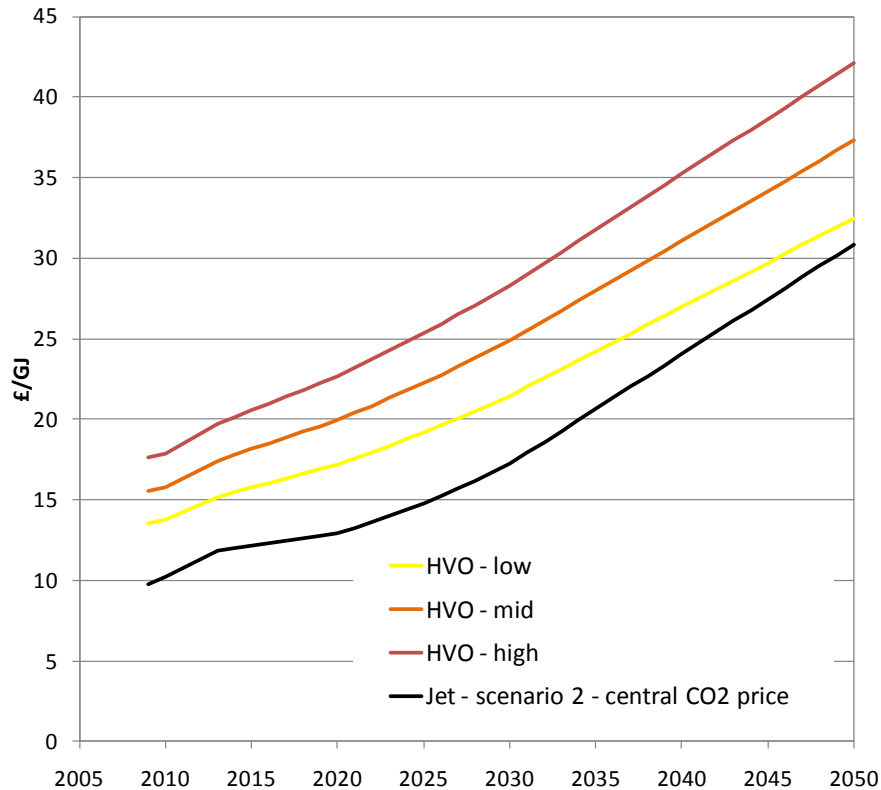
When a central cost of carbon is added to the scenario 2 jet price, HRJ with low cost feedstocks breaks even in around 2037. With a high cost of carbon this is brought forward to 2032. The results for other oil price scenarios for the low end of the feedstock cost range are shown in Table 15. This shows that with oil price 1, and a carbon price, HRJ from conventional crops breaks even in the near to mid term, but with other scenarios this happens much later, if at all.

**Table 15: Break even dates for HRJ with jet with linked prices**

	No carbon price	Central carbon price	High carbon price	Low carbon price
Oil price				
1	No break even	2022	2015	2028
2	No break even	2037	2032	After 2050
3	No break even	2045	2037	After 2050
4	No break even	After 2050	2044	After 2050

Considering the full WTW GHG emissions of each fuel type changes this result, however, as shown in Figure 16. HRJ does not break even by 2050 with crude oil-linked feedstock prices. The greenhouse gas savings from conventional oil crops are assumed to be 50% compared with jet fuel. GHG savings given in section 5.6 show that savings can be lower for HRJ derived from these feedstocks. However, these

default values represent common practice, with some data set conservatively so as to encourage companies to report on the actual data related to the fuel chain they supply. As a result, it is likely that some feedstock will be available with higher savings, where better agronomic practices have been applied. This will be reflected in considerations of the sustainable potential of these routes.



**Figure 16: Comparison of HRJ and jet prices considering the carbon price of GHG emissions from each fuel type**

### Historic prices

Given the uncertainties in vegetable oil pricing, we have also considered a case where vegetable oil prices do not follow the crude oil price according to the relationship above. Instead we assume that they are available at the low end of the range of prices seen over the last 5 years<sup>121</sup>. This would mean the lowest price oils being available at \$402/t (palm oil), and the highest at \$633/t (rapeseed oil). This is a useful case to consider as it shows the reasons for interest in this route, but we consider it unlikely to happen: contacts within the biodiesel and vegetable oil trading industry do not consider it likely that vegetable oil prices will drop in the next few years, as a result of growing demand.

<sup>121</sup> Data from FAO, International Commodity prices, <http://www.fao.org/es/esc/prices>

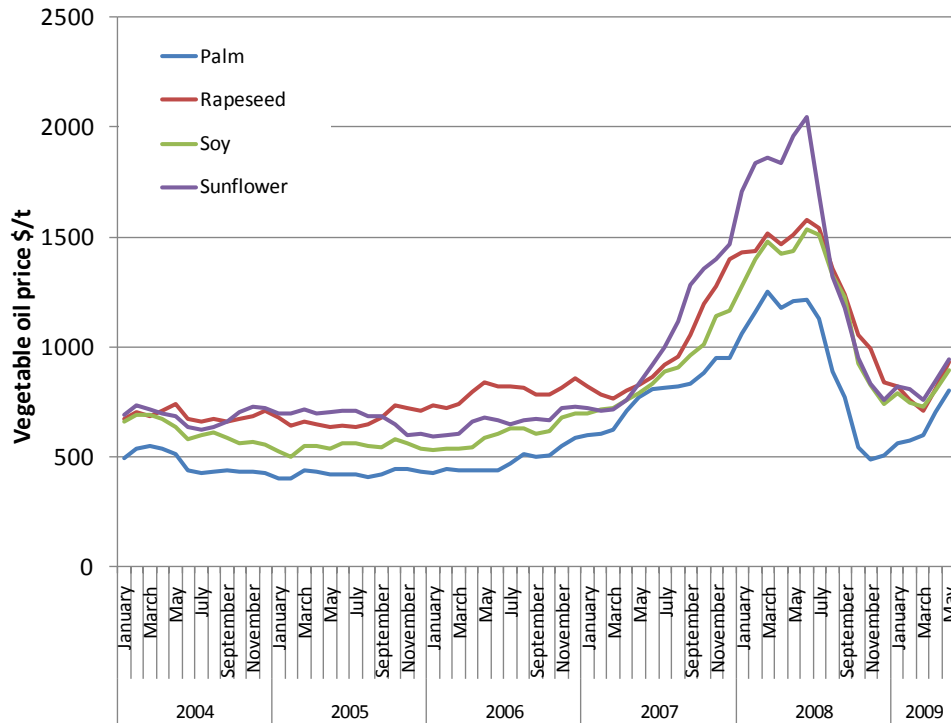


Figure 17: Prices of the principal vegetable oils 2004-2009 (FAO)

If conventional oils were available at these prices, but crude oil prices increase as in the scenarios given, widespread production of HRJ and HVO for road transport would become viable in the near term, even with no carbon price.

Table 16: Break even dates for HRJ with jet with historic prices

Oil price	No carbon price	Central carbon price	High carbon price	Low carbon price
1	2015	2010	2010	2012
2	From 2009	From 2009	From 2009	From 2009
3	From 2009	From 2009	From 2009	From 2009
4	From 2009	From 2009	From 2009	From 2009

However, this could also increase the market price of vegetable oils to the crude price, or even higher if incentives for fuels are widely available, rather than vegetable oils remaining available as a much lower cost feedstock. This is because the feedstock is widely traded, and can be relatively easily incorporated into refinery operations. This is more likely for HRJ than for BTL, as the feedstocks used for BTL are likely to be more localised, less widely traded, and have a stronger link to the production plant. BTL producers would take some rent if BTL could be produced at lower costs than road transport and aviation fuels they substitute, but a link between crude and feedstock prices would be less likely.

#### 6.4 HRJ from new feedstocks

Given the early stage of development of jatropha, camelina, and particularly halophytes and algae, there is relatively little information available on their potential costs.

In the UK, in 2007, camelina could expect to sell for a minimum price of \$380/tonne<sup>122</sup>. This is comparable with the price of soybeans today. Camelina has approximately 35% oil<sup>123</sup>, considerably higher than for soybeans (from which approximately 17% is economically extracted<sup>124</sup>), but may have lower value co-products, as a result of limitations to animal feeding. There may also be potential for further cost reduction. We have assumed that camelina oil could be purchased at prices comparable with the low end of the vegetable oil price range.

In 2006, D1 Oils estimated that the landed cost of jatropha oil to Northern Europe would be between \$350-500/tonne (with the range depending on the oil content of 29-40%)<sup>125</sup>, equivalent to £6.1-8.7/GJ. This is slightly lower than the low end of the cost range for conventional oil crops, but relatively uncertain given the early stage of commercial development of this crop.

Algae biofuels are not currently produced commercially. At their inauguration conference in June 2009, the European Algae Biomass Association put forward their expectation that it would take another 10-15 years before algal biofuels could be produced at an industrial scale. They also noted that the *current* cost of producing algal biofuels is 10 to 30 times more than making traditional biofuels<sup>126</sup>.

Calculations of *potential achievable* algae oil production cost, based on a 1996 study done for the US Aquatic Species Programme<sup>127</sup>, result in an oil production cost of \$900/t (£15.6/GJ). When taking into consideration that the algae oil still has to be converted into HRJ, the 1996 projection of production costs is still significantly higher than costs from other oils. However, these algal oil production costs are based on the best estimate of available technology at the end of the Aquatic Species Programme in 1996. Further new technology improvements currently being considered (for example through integration of technologies that remove the need for a drying stage or low cost oil extraction technologies, etc) would result in further cost reductions, making current projections for production

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<sup>122</sup> Nix (2006) Farm management pocketbook. Imperial College London Wye Campus, 37<sup>th</sup> Edition.

<sup>123</sup> CALU (2007) Camelina - Technical Notes. Available at:  
[http://www.agmrc.org/media/cms/030201Camelinafinal\\_11FBCD0049BD3.pdf](http://www.agmrc.org/media/cms/030201Camelinafinal_11FBCD0049BD3.pdf)

<sup>124</sup> Based on Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. National Renewable Energy Laboratory.

<sup>125</sup> D1 Oils Plc. Preliminary results for year ended 31 December 2006. Available at:  
[http://www.d1plc.com/pdf/analyst\\_28\\_03\\_07.pdf](http://www.d1plc.com/pdf/analyst_28_03_07.pdf)

<sup>126</sup> 'European body sees algae fuel industry in 10-15 years,' June 2009, <http://www.reuters.com/article/GCA-GreenBusiness/idUSTRE5526HY20090603>

<sup>127</sup> J. R. Benemann and W.J. Oswald, (1996), Final report to the DoE: Systems and economic analysis of microalgae ponds for conversion of CO<sub>2</sub> to biomass,  
[http://www.osti.gov/bridge/product.biblio.jsp?query\\_id=0&page=0&osti\\_id=493389](http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=493389)

costs lower. In line with this, Raffaello Garofalo, the Executive Director of the EABA has been quoted as saying he saw a competitive price for algae biodiesel of \$500-550/tonne (around £12/GJ of biodiesel)<sup>128</sup>. This is comparable with the low end of our cost range for HRJ from conventional vegetable oils.

We have assumed that new feedstocks will be introduced commercially at the point where they can be produced at the low end of the historic vegetable oil cost range i.e. \$400/t of oil. Camelina and jatropha are considered to be available first, from 2012. Algae is assumed to be available from 2018. As a result of lack of information on halophytes, these are not included in the analysis. The prices used are not linked to oil or edible vegetable oil prices. It is likely that the price of new feedstocks will increase towards the oil price once they are widely used to replace fossil fuels. However, as they are not used for foods, and in some cases may have more limited oleochemical uses than conventional oils, they are unlikely to increase to the price of edible vegetable oils.

Results of comparing HRJ costs with jet are the same as for conventional feedstocks with historic pricing: HRJ from new feedstocks breaks even with fossil jet as soon as they are available, even with no carbon price. Note that if a full GHG savings approach were considered, new crops would be favoured over conventional ones as the GHG emissions savings of these routes are much higher.

## 6.5 Synthetic hydrocarbons

Given that the development of synthetic hydrocarbon fuels is at an early stage, and also is being undertaken by early stage companies, there is little information on their potential costs. Information given in press releases and presentations for these fuels is given below, where available. However, it is important to note that fuel production costs cannot be compared on the same basis where the feedstock type and price, plant size, and stage of development (first plant, nth plant etc) is not given.

- Isoprenoids - Amyris aiming at less than \$2/gallon in 2011, not including distribution<sup>129</sup>. Assuming that the product has the same energy density as jet, this is equivalent to £9.5/GJ.
- Virent's analyses based on a 100mgallon/yr plant show that production costs for biogasoline are \$8.69 to 16.96/mmbtu depending on feedstock costs, or £5.1 to 10.1/GJ. Around £3.8/GJ of this is capex and opex, with feedstock at £1.9-7.5/GJ<sup>130</sup>.
- Gevo estimate potential production costs for green gasoline of \$50/bbl, or £5.7/GJ<sup>131</sup> based on retrofitted ethanol plants.
- LS9 estimate potential production costs of \$45/bbl, or £5.0/GJ.

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<sup>128</sup> 'European body sees algae fuel industry in 10-15 years,' June 2009, <http://www.reuters.com/article/GCA-GreenBusiness/idUSTRE5526HY20090603>

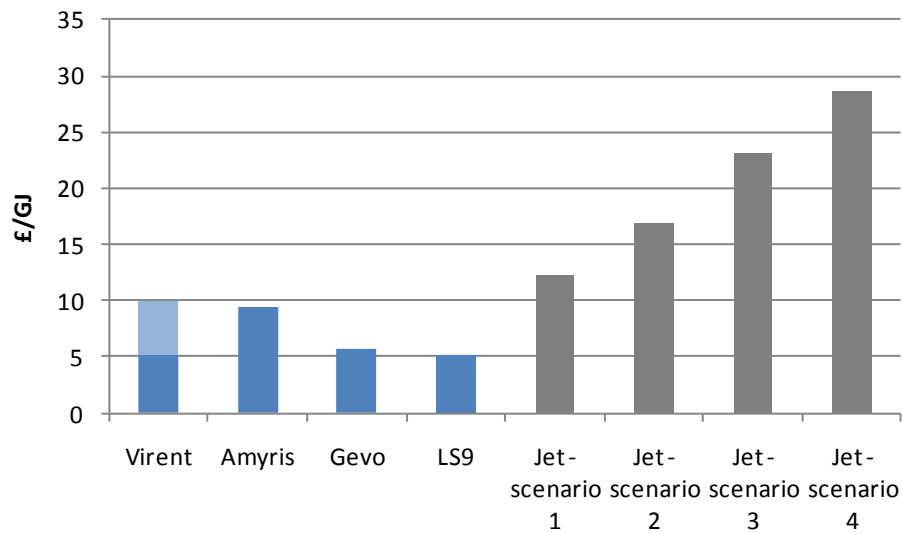
<sup>129</sup> "Microbes drive new Amyris biodiesel plant" Cleantech, November 2008. <http://cleantech.com/news/3858/microbes-drive-new-amyris-biodiesel-plant>

<sup>130</sup> Virent presentation at Midwestern Governors Energy summit, November 2007, [http://www.midwesterngovernors.org/MGA%20Energy%20Initiative/2007%20Summit/Virent%20Energy\\_MGA.pdf](http://www.midwesterngovernors.org/MGA%20Energy%20Initiative/2007%20Summit/Virent%20Energy_MGA.pdf)

<sup>131</sup> On the Road to Green Gasoline: Leveraging carbohydrate-to-hydrocarbon chemistry to give transportation fuel supplies a lift, Gevo, November 2008 [http://www.gevo.com/news\\_CE\\_111708.php](http://www.gevo.com/news_CE_111708.php)

The higher end of these estimates is in the range of low cost biofuels produced today, such as ethanol from Brazilian sugarcane, and so it appears feasible that a commercially developed process, using low cost feedstock, could achieve these costs.

These costs would mean that synthetic hydrocarbons would be cost competitive when commercialised with jet at prices of \$45-90/bbl, meaning crude prices of \$37-82/bbl. However, it is not known what the likely costs of initial production might be, and the rate of reduction of costs with deployment. As a result, it is not possible to show graphs of these costs over time, but Figure 18 shows the comparative prices with jet in 2025, by which time these routes may have reduced to the costs given. The high greenhouse gas savings cited for these routes, of 70-90%, would also increase the competitiveness significantly if these could be valued.



**Figure 18: Estimated production costs of synthetic hydrocarbon routes compared with jet prices projected for 2025. Note that all costs are highly speculative based on data from press releases and company presentations**

## 6.6 Summary

A summary of the cost results is given in Table 17 below, and a summary of the break even points in Table 18.

**Table 17: Summary of biofuel costs results**

Route	No carbon price	With carbon price
<b>BTL</b>	<ul style="list-style-type: none"> <li>Feedstock has a large impact</li> <li>Breaks even in 2033 with central oil prices and mid range feedstock prices</li> <li>Low cost feedstocks bring this back to 2014</li> </ul>	<ul style="list-style-type: none"> <li>Break even brought back to 2019-2024 with central oil prices and mid range feedstock prices</li> <li>Full WTW analysis would make little difference as GHG savings are high</li> </ul>
<b>HRJ from conventional oil crops</b>	<ul style="list-style-type: none"> <li>Uncertainty over vegetable oil prices</li> <li>If linked to crude oil price, HRJ does not break even</li> <li>If available at historic prices, HRJ breaks even in the near term. However, feedstock costs could increase to the cost of crude</li> </ul>	<ul style="list-style-type: none"> <li>With linked prices, only breaks even in the near term in oil price scenario 1</li> <li>If full WTW emissions are considered (50% savings), HRJ does not break even with linked feedstock prices</li> <li>With historic prices, a carbon price would improve the economic case further</li> </ul>
<b>HRJ from new oil crops</b>	<ul style="list-style-type: none"> <li>Assumed to be the same as the low end of the historic vegetable oil prices, and so breaks even in the near term</li> <li>Available from 2012 for jatropha and camelina, 2018 for halophytes and algae</li> </ul>	<ul style="list-style-type: none"> <li>With historic prices, a carbon price would improve the economic case further</li> <li>Under full WTW, 70-90% savings would mean these routes were favoured over conventional crops</li> </ul>
<b>Synthetic hydrocarbons</b>	<ul style="list-style-type: none"> <li>Costs are very uncertain (data is from press releases)</li> <li>Cheaper than even the lowest oil price scenario if compared in 2025</li> </ul>	<ul style="list-style-type: none"> <li>A carbon price would improve the economic case further</li> </ul>

**Table 18: Summary of break even points**

Fuel	1				2				3				4			
	None	Central	High	Low	None	Central	High	Low	None	Central	High	Low	None	Central	High	Low
BTL – mid feedstock	None	2027	2024	2031	2033	2021	2019	2024	2018	2015	2014	2016	2013	2012	2012	2012
BTL – low feedstock	2023	2014	2013	2017	2014	2012	2012	2013	2012	2012	2012	2012	2012	2012	2012	2012
HRJ – linked prices - low	None	2022	2015	2028	None	2037	2032	None	None	2045	2037	None	None	None	2044	None
HRJ – historic prices - low	2015	2010	2010	2012	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now

## 6.7 Likelihood of biofuels use in aviation

The analysis above shows that most of the biofuels routes considered become competitive with jet fuel, in terms of relative costs alone, and earlier if the cost of carbon for jet fuels is included in the comparison. However, there are other potential uses of land (which could mean that the growth of crops for bioenergy is not favoured), other uses of biomass feedstocks, such as heat, power, chemicals and materials production, and other biofuels pathways for road transport applications. An estimate of the magnitude of the demand from aviation and others sector is given in section 7.3, showing that there is likely to be a large resource, meaning that biomass could be used in all sectors to some extent. However, questions have been raised as to where they ought to be used, depending on policy priorities. As a result, in this section we consider whether biofuels are likely to be used in aviation.

Below is a summary of the factors affecting likelihood of use in aviation, based on our interviews with the aviation and fuels industry, and E4tech knowledge of the biofuels and energy sector. None of these factors is conclusive in determining to what extent biofuels will be used in aviation, but they are useful in considering how the sector might develop. Factors that favour use in aviation are marked with **+**, and those that disfavour it with a **-**.

The factors are grouped into those relating to:

- relative costs and benefits of carbon savings
- policy mandating use of bioenergy in other sectors
- the costs and availability of jet fuel
- technical specifications
- concentrated nature of fuel purchasing and distribution in the aviation sector
- corporate social responsibility

The main arguments in this area concern the **relative costs and benefits of carbon savings** in aviation compared with the road transport sector, and in other biomass-using sectors. Interviewees were split on this issue:

- +** The costs of the EUETS on airlines mean that they need to reduce emissions, and biofuels are one way to do this, as well as operational and equipment efficiency. Introduction of biofuels will be faster than fleet turnover. A global carbon trading scheme for aviation would extend this to the whole sector.
- +** There are fewer options for emissions reduction in the aviation sector, and in particular for reduction in the near term, than in road transport, as a result of technical constraints, and slow fleet turnover. In the road transport sector, there are more options such as demand reduction, efficiency, and fuel decarbonisation through electrification. In the heat and power sectors, efficiency, and a wide range of other renewables are possible.
- +** One interviewee considered that the other options for emissions reduction in aviation are more expensive than those in other sectors.

- Others note that there are options for emissions reduction with a negative cost of carbon saving, such as winglets and engine cleaning, which will be cheaper than biofuels.
- The cost of carbon saving is lower in biomass to heat and power than in biofuels, as production costs are lower, and higher GHG alternatives, such as coal-fired power generation, are displaced. This has also been shown for production of some chemicals.
- As the fuels being developed are drop in, then no change to the infrastructure and aircraft will be required. This led to the point that it would be easy to deploy biofuels in aviation later, and it is not necessary to do this now. Biomass and biofuels could be used now to displace higher GHG emissions sources such as coal use for power production, and used to produce jet fuels later.

**Policy mandating use of bioenergy in other sectors** was thought to be more certain, and therefore provide a greater driver for investment, than emissions trading in aviation. It may also be easier to implement policy for biofuels in these more localised sectors.

- The EU Fuel Quality Directive and Renewable Energy Directive support the use of renewable fuels in road transport, but not in aviation. Note, however, that biofuels used for aviation will count towards the RED renewable energy target if they meet sustainability criteria.
- National and regional mandates on biofuels use give greater policy certainty to the road transport biofuels market, than the EUETS, which would be easier to circumvent, and has more uncertainty surrounding the carbon price, and more options for reduction. Similarly, mandates for biomass use or renewables in heat and power create more certain markets for biomass feedstocks.
- To allow the use of biofuels in aviation to be valued e.g. through valuing avoided emissions in a global or EU trading scheme, a chain of custody system will need to be established. This would enable airlines to purchase biofuels in any global location, irrespective of the fuel used, in a book and claim system. Otherwise, biofuels could be shipped around the world in order to be counted (as in the road transport sector). This type of system was thought to be possible, but would take time to be established, and would need to link with emissions trading schemes.
- ✚ There is the potential for responsibility for emissions reduction in aviation will revert to UNFCCC rather than ICAO, as at present<sup>132</sup>, which could lead to binding targets on the sector. However, support for ICAO was expressed at the July 2009 G8 conference.<sup>133</sup>
- Due to the relative emissions of the aviation sector compared with other sectors, and to the potential price implications of increased regulation on the sector, the incentive for policymakers to place stronger policy on aviation may be limited.

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<sup>132</sup> 'Australia calls for UNFCCC to sidestep ICAO and set emissions reduction targets for international aviation' Greenaironline, June 2009, <http://greenaironline.com/news.php?viewStory=498>

<sup>133</sup> 'G8 supports ICAO role in emissions policy,' July 2009, <http://www.atwonline.com/channels/eco/article.html?articleID=2897>

- + The EUETS will consider that biofuels have zero emissions, regardless of their source. In the road transport sector, many countries and regions' market support policies now require calculation of each fuel's GHG savings, and will reward them accordingly. This could mean that the value of biofuels to the aviation sector is higher than in the road transport sector, as greater savings are assumed. Note that lack of policy requirements for GHG saving for aviation biofuels is unlikely to mean that biofuels used in aviation will have lower GHG and sustainability benefits, as many interviewees stated that they would expect common standards for biofuels in both sectors. All of the biofuels considered here are likely to be produced by suppliers supplying both markets.

**The costs and availability of jet fuel** generally favours use of biofuels in aviation:

- + Jet has a higher crack spread than gasoline, and there is much greater variability in this figure, making it more difficult for airlines to source fuel at consistent prices, even with a degree of hedging. This variability was cited by several interviewees as a main driver for biofuels use in aviation.
- + The cost of fuel has a significant impact on airlines' costs, and directly challenges their business model. This creates a greater driver for switching to biofuels than the effect of policy on fuel supplier (where biofuels supply into the road transport sector is obligated), or the effect of fuel price on drivers.
- + Airlines have little bargaining power with the fuel supply industry. As demand for jet fuel exceeds supply, there is no incentive for suppliers to lower prices for larger purchases, for example. It has been suggested that airlines may expect to have better control over fuel costs if purchasing from biofuels suppliers. However, given that biofuels supply may be through existing fuel suppliers in many cases, this will only be likely if biofuels suppliers and airlines become more vertically integrated.
- + As refineries use heavier crudes, production of jet fuel will become less favourable, and so supplies are likely to become more restricted, and prices go up.
- + If the demand for gasoline and diesel in road transport slows in some regions, as a result of emissions reduction policy leading to reduced road transport demand, efficiency, or alternative fuels, less of these fuels will be produced. As a result, less jet will be produced.
- + Energy security concerns lead to a stronger driver for military and commercial aviation interest in alternative fuels.
- There may be higher value in other products from biomass, such as chemicals and materials. Higher values for non-fuel products have already seen diversion of biofuels production to chemicals, for example in butanol plants in China. However, there is currently less of a policy driver for lower carbon inputs to the chemicals and materials sector.

**Technical specifications** were thought likely to push some fuels towards the road transport sector:

- Several interviewees questioned why biomass would be used to make aviation biofuels, when more processing is required than to make road transport biofuels, for example, further hydrotreating. However, it should be noted that the additional costs and emissions of producing jet fuels compared with road transport fuels was considered by several interviewees to be insignificant in comparison to total costs and emissions.
- New fuel types, such as the synthetic hydrocarbon fuels discussed above, and higher fuel blends will require additional certification to aviation fuel specifications. As testing for certification purposes can be expensive, this could be a barrier to use in aviation for some fuel types, leading to easier markets in road transport.
- ✦ In part because of the tight specifications on jet fuel, a stringent quality assurance system is already in place in the jet fuel distribution system which could alleviate any concerns about the consistency of product from new entrants such as biofuels companies.

The **concentrated nature of fuel purchasing and distribution in the aviation sector** could lead to faster uptake, but there remains a question over the value of the market overall.

- ✦ There are a much smaller number of players in the aviation sector than in road transport and other biomass-using sectors, with a greater concentration of buying power. If the industry decides to go for biofuels, this will provide a strong market signal, leading to faster uptake than would be possible in other sectors.
- It has been suggested that the aviation sector alone could not support biofuels production, as a result of the size of the market, and the need for production of fuel to particular specifications. Production for road transport to a certain level would be needed to enable production of both types of fuel, and to get to deployment volumes needed to bring down costs of some parts of the fuel chains through learning. For example, HRJ may only be produced in plants also producing hydrotreated fuels for road transport, rather than having dedicated plants.
- ✦ Distribution of jet fuel is concentrated in a few hundred airports worldwide rather than tens of thousands of fuelling stations for road transport fuels which could facilitate roll out.

There is a strong driver for airlines to reduce emissions for **corporate social responsibility** reasons:

- ✦ There are strong negative public and policymaker perceptions on the environmental impact of aviation and airlines themselves, compared with individual drivers. Airlines have a strong incentive to reduce emissions to improve this perception. This is supported by customers, for whom air travel is a large proportion of personal GHG impacts, mainly corporate customers.
- ✦ Several airlines have made commitments to GHG savings, and biofuels use.
- However, any further backlash against biofuels production could mean that airlines consider it less risky to avoid association with the industry.

## 7 Sustainable potential

### 7.1 Introduction

In this section, we consider the likely potential for production of biofuels for aviation, given sustainability constraints. The principal factors affecting the sustainability of biofuels pathways are both environmental and social. The principles underpinning the sustainability standards for biofuels under the UK Renewable Transport Fuel Obligation are shown below:

<b>Environmental principles</b>
1. Biomass production will not destroy or damage large above or below ground carbon stocks
2. Biomass production will not lead to the destruction of or damage to high biodiversity areas
3. Biomass production does not lead to soil degradation
4. Biomass production does not lead to the contamination or depletion of water sources
5. Biomass production does not lead to air pollution
<b>Social principles</b>
6. Biomass production does not adversely affect workers rights and working relationships
7. Biomass production does not adversely affect existing land rights and community relations

The sustainability of aviation biofuels is important in the near term, as this will be one of the limiting factors for deployment. All interviewees considered that any biofuels used in aviation will need to meet sustainability criteria under development for biofuels for road transport, such as those being developed by the Roundtable on Sustainable Biofuels (RSB), and feedstock-specific activities such as the Roundtable on Sustainable Palm Oil. It was felt that biofuels for aviation should meet standards as stringent as those for road transport, but not more so, as this would hinder co-production of fuels for different markets. Concerns over feedstock sustainability have strongly influenced the choice of feedstock, and fuel supplier, for tests carried out to date. Companies are keen to avoid the potential sustainability impacts, and associated negative publicity, experienced by biofuels in the road transport sector. They have learnt from this experience, and benefitted from the work that has already been done and initiatives established. There are also several aviation-specific sustainability activities, aside from aviation industry members being part of general groups, such as SAFUG, the Sustainable Aviation Fuel Users Group, including Boeing, UOP, and airlines such as Virgin Atlantic, All Nippon, SAS, KLM, Air France, Gulf Air, Cargolux, Air New Zealand, Alaska Airlines, British Airways, CathayPacific, TUIfly and Virgin Blue<sup>134</sup>.

<sup>134</sup> SAFUG press release "Boeing and Leading Airlines Announce New Members Added to Sustainable Aviation Fuel Users Group," July 2009, <http://www.safug.org/docs/press-release-01.pdf>

The EU Renewable Energy Directive requires that 20% of EU Member States' energy use be renewable, and that within transport, 10% should be renewable. Aviation fuel is counted in the overall target, but not in the transport target. However, use of biofuels in aviation would count towards meeting both targets, providing the biofuels meet the sustainability criteria set out in the RED.

In the longer term, sustainability must be considered by users and policymakers in assessing the extent to which biofuels can be used to displace jet, and the potential for GHG saving.

## **7.2 Sustainability benefits and constraints**

### **7.2.1 Energy crops**

The term '*energy crops*' is used here to mean woody crops, such as short rotation coppice willow and poplar, and grasses, such as switchgrass and miscanthus. There is interest in these crops as a result of the potential for high yields combined with low agricultural inputs, and the potential to grow on poorer land than would be required for profitable yields of other crops. Sustainability impacts of energy crops will depend heavily on the crop type and location<sup>135</sup>: benefits could include increase in soil carbon if grown on low carbon stock land, improvements in soil condition as a result of reduced tillage, potential for low fertiliser use and so low nitrate run off, reduced erosion, and treatment of contaminated land. Biodiversity can be improved compared with arable land, though there is also potential for biodiversity impacts if direct land use change occurs. Energy crops have high water demands, and therefore can have impacts on hydrology if planted in areas of low rainfall, and would have significant water use if irrigated. As a result, estimates given below are based on analyses using rain fed potentials only. As discussed above, energy crops could also have direct and indirect land use change impacts. Large direct land use change impacts are currently less likely than for some other crops, as energy crops are generally being planted with policy support, which discourages use of high carbon stock land. Indirect land use change could occur as a result of use of land for energy crops, which could push up land prices and so the price of other crops. This will be mitigated if crops are grown on lands unsuitable for production of other crops, with low carbon stocks.

In the long term, the global potential for energy crops will depend on land availability, and the potential for crop yield increases. Many estimates have been made of the global biomass potential over the last decade, e.g. Fischer and Schrattenholzer (2001)<sup>136</sup>; Hoogwijk et al. (2003)<sup>137</sup>; Smeets et al. (2004)<sup>138</sup>;

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<sup>135</sup> 'Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK' Renewable and Sustainable Energy Reviews, Volume 13, Issue 1, January 2009, Pages 271-290. Rebecca L. Rowe, Nathaniel R. Street, Gail Taylor

<sup>136</sup> Fischer and Schrattenholzer (2001) Global bioenergy potentials through 2050. *Biomass and Bioenergy* **20** 151-159

<sup>137</sup> Hoogwijk et al. (2003) Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy* **25** 119-133

<sup>138</sup> Smeets et al. (2004) A quickscan of global bioenergy potentials to 2050. Available at: <http://www.bioenergytrade.org/downloads/smeetsglobalquickscan2050.pdf>

Parikka (2004)<sup>139</sup>, including energy crop potentials. In most studies, the energy crop potential is calculated by assuming that land needed for food production is supplied first, thus avoiding indirect land use change impacts, and that areas for conservation, and forest areas, are protected. These estimates can vary greatly in magnitude (i.e. from zero to hundreds of EJ) depending on the assumptions made, and on the level of detail of the analysis. Below are the principal factors that affect this potential:

- Land needs for other uses, e.g. food production, housing, infrastructure, nature conservation, etc.
- Current agricultural land surplus – based on intensification and modernisation of farming and improvements in crop yields.
- Productivity of marginal land used for growing bioenergy crops.
- Availability of water, fertilisers and pesticides for agriculture.
- Acceptability of the use of plants that have been genetically modified to be higher yielding and able to grow in less favourable soils.

E4tech has undertaken several pieces of work that assess and compare the assumptions behind these studies, and use the results to assess bioenergy potential<sup>140</sup>. Based on this experience, we have considered the following detailed bottom-up studies, which are in the mid range of global estimates. These estimate the technical potential of energy crops in 2050 as:

- 215EJ (low scenario from Smeets et al. (2006)) - Assumes that energy crops could be grown on 729 Mha of surplus agricultural land by 2050, as a result of an increase in efficiency in food production on the 5000Mha presently used for agriculture.
- 652 EJ (the central (A1) scenario from Hoogwijk (2004)<sup>141</sup>) This results in energy crops being grown on abandoned agricultural land (409 EJ, from 1370Mha), and pasture land (243 EJ, 2500Mha). Around 68% of this (446 EJ) is available at less than \$5/GJ (£3.1/GJ).

These potentials are very large, of the same order as current global primary energy consumption.

These studies show that in the long term, there is a large energy crop potential, without competition with land for food, and without deforestation or loss of protected areas. However, this does not mean that agricultural expansion will happen on the available areas identified, as a result of a large number of factors including the agricultural markets and policies of all countries worldwide. It will be important to ensure that this expansion does happen on the areas where impacts are low (abandoned agricultural land, low carbon stock pasture) rather than on arable land, or on high carbon stock lands.

In the near term, energy crop potential may be limited by the planting rate, rather than land availability or energy crop yield increases. The current global planted area of energy crops is uncertain, but from

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<sup>139</sup> Parikka (2004) Global biomass fuel resources. *Biomass and Bioenergy* **27** 613-620

<sup>140</sup> For example, global potential analysis in E4tech (2009) Biomass Supply Curves for the UK, for DECC ([http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/renewable/res/res.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.aspx)), previous analyses for the Carbon Trust, Defra and energy companies

<sup>141</sup> M.M. Hoogwijk (2004) "On The Global and Regional Potential of Renewable energy sources" Utrecht Universiteit thesis, <http://www.library.uu.nl/digiarchief/dip/diss/2004-0309-123617/full.pdf>

our estimates, is relatively small, at around 13 Mha. This would give production of 3EJ of energy crops if yield assumptions from Hoogwijk (2004) are used. The rate at which this could increase depends on the willingness of farmers to plant a new crop, for which the market is uncertain, and which grows over several years, delaying returns, and making switching more difficult. There will also be a need for learning and new equipment to grow new crop types. To get an idea of the order of magnitude of this constraint, in previous work<sup>142</sup> we estimated the *maximum* rate of increase in UK energy crop production, and factored this up to a world scale, based on the relationship between UK and world arable areas as a proxy for the agricultural sector capacity. This gave a planting rate increasing from 0.3Mha/yr to 48Mha/yr in 2017, giving a planted area of 240Mha in 2020. For comparison, 25 Mha of land is used for production of feedstocks for the current 1.6 EJ of biofuels for road transport<sup>143</sup>. This would produce 66EJ in a BAU scenario, or 76EJ in a scenario with higher crop yields and better quality land use. Continuing this planting rate to 2050 would reduce the 657EJ given in Hoogwijk (2004) to around 460EJ<sup>144</sup>, albeit still higher than the potential given in some other studies. The steps involved in getting to the planted area in 2050, using Hoogwijk's analysis followed by this constraint are shown in the figure below.

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<sup>142</sup> E4tech (2009) Biomass supply curves for the UK, for DECC,  
[http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/renewable/res/res.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.aspx)

<sup>143</sup> Günther Fischer, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen (2009). 'Biofuels And Food Security' IIASA for the OPEC Fund for International Development (OFID).  
<http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

<sup>144</sup> Factored up from 2020 potentials and land areas in E4tech (2009) Biomass supply curves for the UK, for DECC

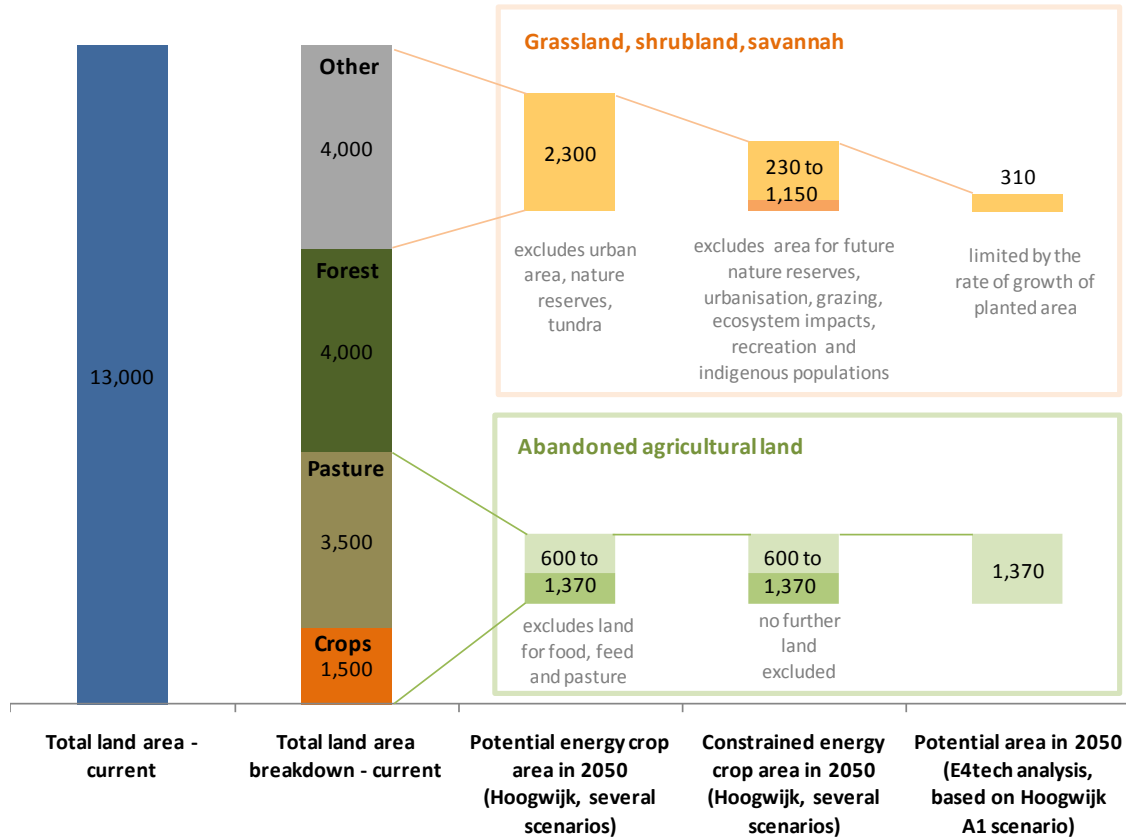


Figure 19: Steps to derive planted areas of energy crops in 2050, based on Hoogwijk’s analysis, and E4tech planting rate constraint.

### 7.2.2 Residues and wastes

There is a very wide range of residues, by-products and wastes that can be used for energy production. These include crop residues such as straw, forestry and wood processing industry residues, waste wood, the organic fraction of municipal solid waste, animal wastes and dried sewage sludge.

Some of the residues have limits associated with their extraction as a result of sustainability constraints, such as a proportion of the straw that must be left on the ground to maintain soil quality and nutrient levels, and a proportion of the forestry residue that should be left to provide nutrients for the forest. Most other wastes and by-products do not have other sustainability impacts associated with their use, and may have benefits, such as avoided impacts from landfilling or alternative disposal methods. However, it is important to consider the potential indirect impacts of using by-products that have an existing use, rather than true wastes, which are disposed of. If a by-product is being used to generate

heat and power, for example, diverting it to biofuels production may lead to fossil fuels being used instead. The GHG emissions from this can outweigh the benefits of displacing fossil fuels with biofuels<sup>145</sup>.

The potential from wastes and residues is large, as shown in the table below, even with conservative estimates for MSW.

**Table 19: Wastes and residues potential**

Resource type	Global potential (EJ)	References
Agricultural residues <sup>2</sup>	65	Smeets et al. (2007) based on low scenario (system 1)
Forestry fuel and wood residues <sup>2</sup>	130	Smeets et al. (2007) based on low scenario (system 1)
Other wastes i.e. MSW <sup>3</sup>	2	Reference: IPCC, 2007. Conservative estimate based on 2002 data.

<sup>2</sup> Three types of residues and waste are considered: harvest residues, process residues, and biomass waste (food, wood etc). The alternative use of residues for energy and materials is excluded, with the exception of the use of crop process and harvest residues as animal feed, which is subtracted from the available crop residues. Residues assume a recoverability fraction of 0.25. Process residue generation fraction of wood is set at 0.5 for all regions. The recoverability fraction of crop process residues is set at 1.0. The recoverability fraction of wood process residues is set at 0.75. For both crops and wood waste it is assumed that all waste is available in the year 2050. Biomass consumption for energy is currently estimated at about 40,000 PJ, a significant amount of which is provided by residues and wastes.

<sup>3</sup> This is a *very conservative* estimate based on 900Mt of municipal solid waste in 2002. Assumes organics recoverable for energy represent 25% of total waste. Average heating value of organic waste is assumed to be 9GJ/t.

In the near term, potential for these routes will be limited by the ramp up of residues collection, and wastes separation. These feedstocks can provide a low cost and GHG option for early stage plants. Plant developers are currently working on using and accessing this type of resource, and so resource availability is likely to increase with demand for feedstock for biofuels and other bioenergy plants.

### 7.2.3 Conventional oil crops

Conventional oil crops such as soybean, palm, oilseed rape, sunflower and coconut all grow in very different environments and have very different sustainability issues associated with them:

- Soybean meal by-product is an important source of animal feed. In South America, the destruction of the Amazon rainforest has in part been blamed upon clearing for growing soy<sup>146</sup>. Since a 2006 Greenpeace investigation uncovered a direct link between soy expansion and Amazon deforestation, the soy industry agreed to stop purchasing soy grown in newly deforested areas of the Brazilian Amazon. This moratorium has been in place since June 2006. In the US, 10% of soybean plantations

<sup>145</sup> Advice on the Economic and Environmental Impacts of Government Support for Biodiesel Production from Tallow. AEA, E4tech, Metroeconomica and Miller-Klein Associates for DfT. April 2008  
<http://www.dft.gov.uk/pgr/roads/environment/rtfo/tallow/tallowfinalresport.pdf>

<sup>146</sup> 'Amazon Soy Moratorium Holds' April 2009 <http://www.greenpeace.org/usa/press-center/releases2/amazon-soy-moratorium-holds>

are believed to be irrigated<sup>147</sup>. Not only is irrigation expensive and increases the carbon intensity of production, but it also puts pressure on available water resources. The global area technically suitable for soy production, on existing cultivated land, grassland and woodland is large<sup>148</sup>. However, that does not mean that this land could be used: using existing cultivated land could lead to indirect land use change. In the future, there is likely to be abandoned agricultural land, as shown above for energy crops, which could be used for soy production; however, no detailed analysis of suitability of this land is available, and yields are likely to be low. Using grassland or woodland would also have large impacts: the GHG emissions from converting grassland to soy production would be very unlikely to be compensated by fuel chain greenhouse gas savings, as a result of low soy yields. Oilseed rape (OSR) is grown largely on existing crop land (or on previously “set aside” land in Europe). Depending on where it is grown, the crop will either be rain-fed (e.g. in Europe) or irrigated (e.g. N. America). Where it is irrigated, as with soy, this can lead to pressure on local water resources. Effective crop rotation management can improve the biodiversity of the cropped area (in terms of desirable “weed” species, and pollinating insects etc). There is potential for yield improvement in rapeseed production in some regions<sup>149</sup>, and for expansion of the area grown, as the global area technically suitable for rapeseed production is many times the current area of production, as for soy. Indirect impacts of this expansion could again be significant, and although direct impacts of grassland conversion would be lower than for soy, as a result of higher yields, they could nevertheless be significant. Again, there may be the potential for growth on abandoned agricultural land in the future, avoiding these direct impacts, but again with relatively low yields.

- Many palm plantations are not sustainably managed; peat swamp forests have been and continue to be logged and drained to make way for palm plantations. These peat forests, as well as being a considerable carbon sink, are also extremely bio-diverse and home to rare species of e.g. orang-utan. As a result, the loss of these forests and replacement with palm oil plantations is doubly damaging from a sustainability perspective. There is potential for considerable yield increase in most regions, which could increase production, but still the risk of expansion onto new land, which could lead to deforestation. Analysis by Fischer et al. (2009)<sup>150</sup> of global land suitability for palm production shows that there is a relatively small potential for further palm production on land where impacts could be low: 83 Mha on cultivated land and 44Mha on grassland and woodland, compared with 14Mha current production. However there is a very large potential on unprotected forestland, of around 490Mha. There are organisations that are attempting to ensure that palm oil

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<sup>147</sup> FAO (2008), Water biofuel figures – Jippe. Available at:

[http://www.fao.org/nr/water/docs/wwf5/b\\_adg\\_panel\\_wfen/Water-biofuels-figures-Jippe-May-2008.ppt](http://www.fao.org/nr/water/docs/wwf5/b_adg_panel_wfen/Water-biofuels-figures-Jippe-May-2008.ppt)

<sup>148</sup> Günther Fischer, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen (2009). ‘Biofuels And Food Security’ IIASA for the OPEC Fund for International Development (OFID).

<http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

<sup>149</sup> FAO, The state of food and agriculture, 2008, <http://www.fao.org/docrep/011/i0100e/i0100e00.htm>

<sup>150</sup> Günther Fischer, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen (2009). ‘Biofuels And Food Security’ IIASA for the OPEC Fund for International Development (OFID).

<http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

plantations are sustainably managed, such as the Roundtable on Sustainable Palm Oil (RSPO). This stakeholder group is currently working towards developing and implementing global standards for sustainable palm oil, so that the destruction of such valuable tracts of land by the palm oil industry can be avoided. Palm plantations are rain-fed rather than actively irrigated.

- Coconut is not used in significant quantities for biodiesel production at present. It requires a significant amount of water, and as a result grows best in coastal areas. Coconut plantations are irrigated, using drip, flood or basin irrigation. Drip irrigation is the most sustainable practice because it saves water, is less labour intensive, maximises uptake and increases plant productivity. There are likely to be many ways in which the productivity of existing plantations can be improved to meet an increase in demand, but new land would also probably need to be converted to palm plantations.

Vegetable oils, to a large extent, are used interchangeably in food products and for cooking. Thus, when one feedstock is used for biofuel, the problem is that more of the cheapest vegetable oil that has potential to expand, (the marginal feedstock) is grown elsewhere to replace it. To illustrate this with a current example, if OSR from Europe was used to make biofuel, the cheapest oil crop that could be grown to replace it is palm oil. If this additional palm is grown on deforested land, the consequence of using the OSR for biofuel needs to take into consideration not only the type of land that the OSR is grown on but also the land that the palm is grown on. This is one of the key sustainability issues that needs to be considered in relation to using conventional oil crops. Additionally, the recent increase in use of these vegetable oils for biodiesel production has been blamed for vegetable oil price spikes in recent years, although the link between these two is difficult to prove, given the complexity of these markets, and the relatively small amount of vegetable oils currently being used for biofuels.

In the short term, the main factor limiting the supply of these conventional oil crops to the biofuel sector is the availability of feedstock at a viable price and that can be guaranteed to have been grown using sustainable practices and not resulting in indirect land use change impacts elsewhere in the world (although sustainability may only be a constraint if policy requires it). Sustainability is going to be difficult to guarantee and will depend on the development of effective policy to protect important and vulnerable forested land in developing countries from being logged and other area of high carbon and high diversity value from being exploited. It will also depend on increased investment in agriculture in developing countries such as Africa, where there is great potential to sustainably improve crop yields per hectare, as well as policies to encourage the use of large areas of previously agricultural land that is no longer in use (for example in CIS countries and in the USA).

Members of SAFUG have signed up to a sustainability pledge<sup>151</sup> which involves using feedstocks that “should be developed in a manner which is non-competitive with food”. This could limit use of any crops grown on agricultural land, but in particular would affect use of conventional vegetable oils.

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<sup>151</sup> SAFUG sustainability pledge, <http://www.safug.org/docs/sustainability-pledge.pdf>

#### 7.2.4 New oil crops (jatropha and camelina)

Jatropha grows well on rain fed<sup>152</sup> semi-arid land in warm and humid climates. The main benefits of jatropha are that it is claimed to grow well on land that has been degraded and that it has a better level of drought tolerance than other similar oil crops. Fischer et al. (2009)<sup>153</sup> assessed the suitability of land globally for jatropha production, finding that 20% of cultivated land (409Mha) and significant grassland and woodland (467Mha) would be suitable for production under rain-fed conditions. This means that there could be significant potential on grassland not currently needed for food, and some of which is likely to have lower carbon stocks, and so be suitable for conversion with low GHG impacts. However, the concern with jatropha is that because higher yields will be achieved on better quality land, it will be grown on arable land that is currently being used for food crops, thereby resulting in additional land (potentially with high carbon stocks) being converted to cropland, to replace the food cropland that has been diverted to jatropha production. Additionally, because jatropha will largely be grown in developing countries which may lack appropriate regulatory frameworks, extra care should be taken to ensure that land rights are respected in the production of this crop. In the short term, jatropha is likely to be limited by the rate of establishment of plantations.

Camelina grows in Northern Europe and Central Asia but in recent years its level of production has dwindled<sup>154</sup>. It has lower fertilizer requirements than crops with similar oil yields and growing at similar climates, e.g. OSR. The lower nitrogen requirement reduces the risk of environmental problems such as eutrophication of nearby lakes and rivers.

In the short term, the supply of camelina will be limited by the need to re-establish plantations and improved varieties of the crop. Given that it grows well in the Northern European climate, it could grow well in countries such as Russia which has 41m ha of abandoned (or idle) agricultural land<sup>155</sup> (just under twice the total area of Great Britain) that they could use to grow such biofuel crops. If such land were put back into production to grow crops such as camelina, there could well be large quantities of camelina available in the long term. Note that there would be some small land use change emissions associated with the conversion of this abandoned land to arable land (due to the above and below ground carbon stored in grasses that have been growing on the land since it was last in production).

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<sup>152</sup> Fact Foundation (2006) Jatropha Handbook, [http://www.jatropha-platform.org/documents/FACT-Foundation\\_Jatropha-Handbook\\_March-2006.pdf](http://www.jatropha-platform.org/documents/FACT-Foundation_Jatropha-Handbook_March-2006.pdf)

<sup>153</sup> Günther Fischer, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen (2009). 'Biofuels And Food Security' IIASA for the OPEC Fund for International Development (OFID). <http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

<sup>154</sup> CALU (2007) Camelina - Technical Notes. Available at: [http://www.agmrc.org/media/cms/030201Camelinafinal\\_11FBCD0049BD3.pdf](http://www.agmrc.org/media/cms/030201Camelinafinal_11FBCD0049BD3.pdf)

<sup>155</sup> Russian Biofuels Association (2008) Russia and CIS: Biofuel Resources. Available at: [http://www.biofuels.apec.org/pdfs/apec\\_200810\\_ablaev.pdf](http://www.biofuels.apec.org/pdfs/apec_200810_ablaev.pdf)

### 7.2.5 Halophytes

The major sustainability benefit of halophytes is that this group of plants does not require freshwater, but instead grows on brackish or seawater. There are indications that many halophytic species have significant economic potential for desert and coastal agriculture in the Middle East, and they have been used as forage in arid and semi-arid areas for millennia<sup>156</sup> and in more recent years for saline soil reclamation. As with conventional agriculture, large mono-cultures should be avoided and the crop should be established on marginal or set-aside land (and where saline water is readily available).

Halophytes are unlikely to be available in the short term as a biofuel feedstock because they are not grown on any significant scale at present and further work is required for their economic production at scale. In the long term, this is potentially an attractive option, particularly for desert regions such as the Middle East. There is also the potential for co-production of other products e.g. shrimps, mangroves<sup>157</sup>.

### 7.2.6 Algae

The main benefit of using algal feedstocks is that algae do not need to be grown on productive land but can be grown on entirely non-productive land, as they are grown in water, either in ponds built into the land or in bioreactors constructed on the land. Algae also has the potential to achieve significantly (e.g. 6-10 times<sup>158</sup>) higher oil yields than terrestrial plants, which means that a smaller land area will be required than for conventional crops. As with other biofuels, algae do require nitrogen fertiliser, which has significant GHG emissions associated with its production. As research continues into developing commercially viable algal biofuels, it will be crucial to focus on algal species that can grow in salt or brackish water, to reduce demands on limited fresh water supplies. If non-native or GM species are used in open ponds, there could be impacts on the biodiversity. However, generally, algae biofuels are believed to be a sustainable route to biofuels, if they can be grown economically.

Algae biofuels will not be available in significant quantities in the short term as they are still very much at the R&D stage. In the longer term, their supply is most likely to be limited by the build rate of algae biofuel production plants at suitable sites; from what we currently know about the requirements of producing algal biofuels, there are certain location criteria that will need to be met (e.g. co-location with source of CO<sub>2</sub>, seawater supply nearby, adequate light, high all round yearly temperature, low humidity, etc) and there is likely to be a limited number of locations that perfectly match these (although they may still make economic sense at less than perfect locations).

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<sup>156</sup> USDA: Jaradat, A.A. Halophytes For Sustainable Biosaline Farming Systems In The Middle East. Alsharhan, A.A. Et Al. Editors. A.A. Balkema/Swets & Zeitlinger, Rotterdam, The Netherlands. Desertification For The Third Millennium. 2003. P. 187-203. Abstract available at:  
[http://www.ars.usda.gov/research/publications/publications.htm?seq\\_no\\_115=141621](http://www.ars.usda.gov/research/publications/publications.htm?seq_no_115=141621)

<sup>157</sup> Global Seawater, <http://globalseawater.com/whatwedo.html>

<sup>158</sup> Carbon Trust (2008) Algae Biofuels Challenge Launch Event.  
<http://www.carbontrust.co.uk/NR/rdonlyres/77C2F2E5-3AA6-43A5-9F43-55C7E02162E3/0/ABCLaunchEventUpdated.pdf>

### 7.2.7 Summary

For all feedstocks, the sustainability impacts can vary depending on the practices used in producing or collecting the feedstock, and through competition with other uses. However, in the summary below, we have given an indicative likelihood of impact. In many cases, sustainability impacts will limit the potential, in the long term at least.

**Table 20: Summary of feedstock sustainability characteristics**

Feedstock	Factors affecting sustainability	Main factors limiting the sustainable potential	Likelihood of impact
<b>Energy crops</b>	<ul style="list-style-type: none"> <li>• High yields, low agricultural inputs, potential to grow on poor land</li> <li>• May have sustainability benefits, though could still have LUC impacts</li> </ul>	<ul style="list-style-type: none"> <li>• Planting rates</li> <li>• Sustainable land potential</li> </ul>	<b>Mid-low</b>
<b>Residues and wastes</b>	<ul style="list-style-type: none"> <li>• Large resource, even when limited to sustainable extraction levels</li> <li>• Can have indirect impacts if diverted from another use</li> </ul>	<ul style="list-style-type: none"> <li>• Extraction/separation rates</li> <li>• Competing demands</li> </ul>	<b>Low</b>
<b>Conventional oil crops</b>	<ul style="list-style-type: none"> <li>• Direct LUC has GHG and biodiversity impacts - soy, palm</li> <li>• Indirect LUC – using any oils leads to production of the marginal crop</li> </ul>	<ul style="list-style-type: none"> <li>• Land availability and indirect land use change concerns</li> <li>• Competing demands</li> <li>•</li> </ul>	<b>High</b>
<b>New oil crops</b>	<ul style="list-style-type: none"> <li>• Jatropha could grow on degraded, and semi-arid land – though concerns remain over arable land use and land rights</li> <li>• Camelina – low fertiliser inputs, high yields</li> <li>• Halophytes – use salt water. Very little information available</li> </ul>	<ul style="list-style-type: none"> <li>• Crop development, then planting rates</li> </ul>	<b>Mid-low</b>
<b>Algae</b>	<ul style="list-style-type: none"> <li>• Can be grown on non-productive land, with high yields</li> <li>• Require N fertiliser, and some use fresh water</li> <li>• Potential impacts from GMOs and non-native species in open ponds</li> </ul>	<ul style="list-style-type: none"> <li>• System viability: algal growth, harvesting, oil extraction, then build rate</li> </ul>	<b>Low</b>

### 7.3 Comparison with aviation demand

In this section, we compare the projected demand for fuel for aviation with the projected potential resource for biofuel feedstocks, and with other demands for these feedstocks.

#### 7.3.1 Aviation demand

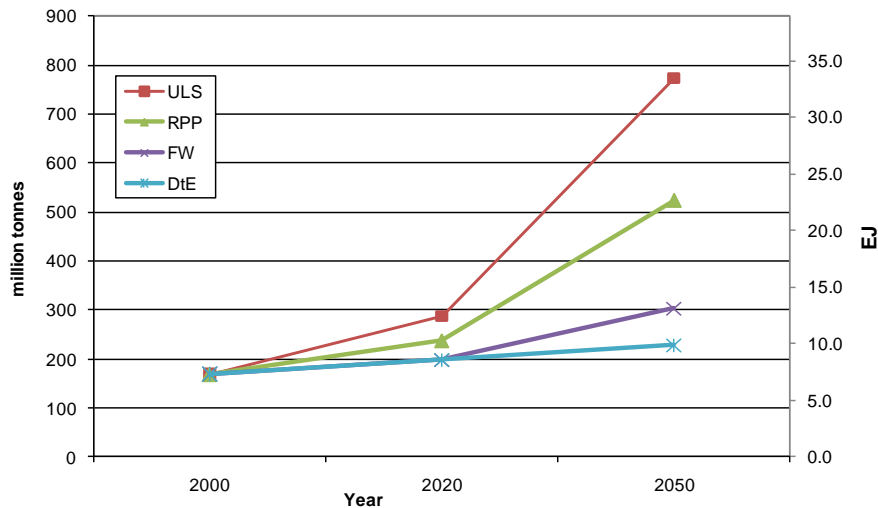
The Consave scenarios<sup>159</sup>, used in the IPCC 4th Assessment report, give four scenarios of aviation demand to 2050:

- Unlimited Skies: very high air transport demand.
- Regulatory Push & Pull: The (hypothetical) "unconstrained" demand of this scenario is the same as in Unlimited Skies above. However, a number of constraints as well as regulatory actions addressing those are likely to dampen the effect on global transport volume.
- Fractured World: This fractured world scenario assumes an absolute decline in international flights and the second lowest GDP-air transport elasticity of all scenarios considered.
- Down to Earth: This scenario of significant lifestyle changes (high environmental consciousness) postulates an entire decoupling of air transport from GDP growth.

These result in the following levels of global aviation fuel demand:

Scenario	Year	Fuel (Mt)	Fuel (EJ)
Historical	2000	168	7.3
ULS	2020	287	12.4
	2050	773	33.5
RPP	2020	237	10.3
	2050	524	22.7
FW	2020	197	8.5
	2050	303	13.1
DtE	2020	198	8.6
	2050	228	9.9

<sup>159</sup> Consave project (2005) - Results [http://www.dlr.de/consave/7\\_Results.pdf](http://www.dlr.de/consave/7_Results.pdf)



**Figure 20: Consave aviation fuel demand scenarios**

Using the highest scenario (Unlimited Skies (ULS)) as a benchmark, supplying global aviation fuel demand in 2050 would require 773mt, or 33.5 EJ of biofuels. This highest scenario is used to show the largest amount of biofuel that would be required to meet demand. UK demand, depending on how this is calculated, is around 8% of global demand currently. If this were maintained to 2050, this would be equivalent to 2.7 EJ. The feedstock implications of supplying **100% of global jet demand in 2050 using a single feedstock** are given in the following sections. The calculations consider only the feedstock needed for aviation biofuels, not other biofuels produced through the same conversion process or co-produced i.e. diesel or naphtha from HVO and BTL plants. However, from many of these routes, several other co-products would also be produced, such as straw, animal feed, and electricity from the conversion plant, and so this level of resource use does not supply aviation demand alone.

### 7.3.2 BTL

Supplying 100% of global jet demand via an FT route with a 48% process efficiency of feedstock to BTL products leads to a feedstock demand of 69.8 EJ. This would mean using:

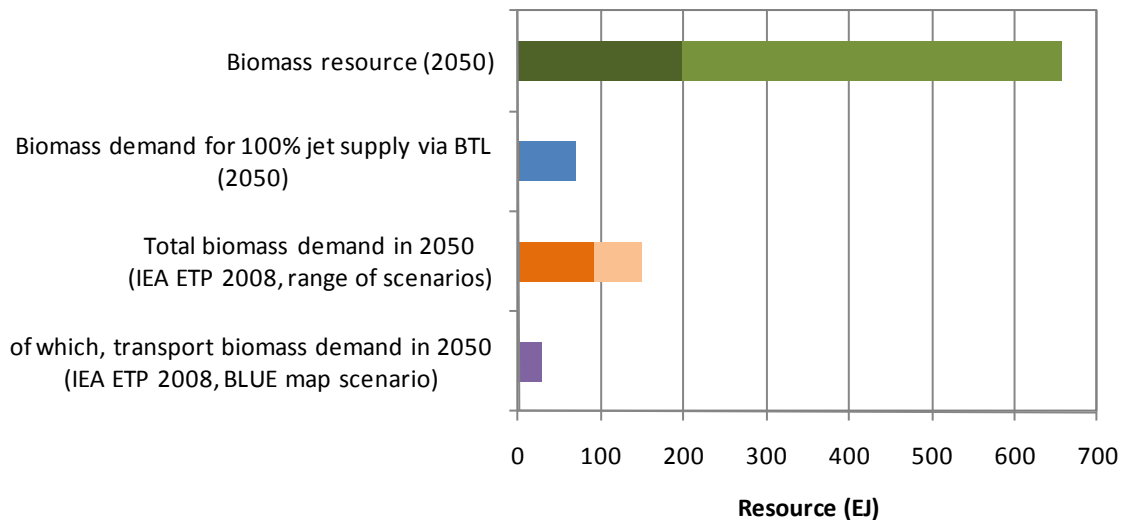
- 254mha of woody energy crops. This is 15% of the global energy crop resource calculated in section 7.2.1 above, based on use of abandoned agricultural land and grassland, OR
- 11% of the total energy crop, residue and waste resource, OR
- 35% of the residue and waste resource (using very conservative waste resource estimates)

A co-product could be electricity from the conversion plant.

There will be competition for lignocellulosic feedstocks and BTL products from other sectors, such as heat and power production, synthetic natural gas production for heating, road transport biofuels, and materials and chemicals production. The level of this competition is difficult to quantify without detailed

analysis of each sector, but for comparison, the IEA's Energy Technology Perspective report (2008)<sup>160</sup> estimates that the total biomass feedstock use in 2050 will be between 92 and 150EJ, depending on the scenario used. In the BLUE Map scenario, of the 150EJ total, 28.5EJ is estimated to be used for transport, including aviation and shipping.

In this context, a demand for 70EJ of feedstock for BTL fuels in a high aviation demand scenario is high compared with the projected demands in other sectors. However, if this were added to the total projected biomass demand, the overall total would be around 220EJ, compared with the projected lignocellulosic resource of between 200EJ (residues) and 650EJ (residues and energy crops), as shown in Figure 21, below.



**Figure 21: Comparison of projected biomass feedstock resource with projected feedstock demand for aviation, and estimates of total feedstock demand (range of scenarios) and feedstock demand for transport biofuels (including aviation) in 2050 for IEA Energy Technology Perspective 2008. Within the resource bar, the residues and wastes resource is shown in dark green, and energy crop resource is shown in light green**

### 7.3.3 HRJ

Supplying 100% of global jet demand via an HRJ route would lead to a vegetable oil demand of 27.8 EJ. The conversion process from vegetable oils to hydrogenated products is assumed to have a mass conversion efficiency of 100%. This means that 1.2EJ of HRJ are produced for every EJ of vegetable oil input, the increase being as a result of added hydrogen. 27.8EJ of vegetable oil would require growth on the following areas:

<sup>160</sup> IEA (2008) Energy Technology Perspectives. Available via <http://www.iea.org/techno/etp/index.asp>

**Table 21: Land requirements for HRJ. \*Note that for jatropha, camelina, and in particular, algae, poorer quality land may be able to be used, and as such, the proportion of global arable area is given for comparison only**

Feedstock	Area (Mha)	% of current global arable area
Soy	1934	138%
Camelina	1031	74%*
Rapeseed	773	55%
Jatropha	477	34%*
Palm	267	19%
Algae <sup>161</sup>	31	2%*

Co-products also produced using this resource would be animal feed and/or heat and power from crop residues and residues from oil extraction, and other products for some feedstocks such as palm kernel oil, palm stearin, fertiliser and nutraceuticals.

The land areas required for the oil crops are very large, as the yields of these crops per hectare are low. The suitability of land for oil crop production is generally more restricted for some oil crops than for the range of woody energy crops considered in the global potential studies discussed above<sup>162</sup>. The energy crop potential figures above are based on supplying global food demand first, and do result in abandoned agricultural land, as yields increase, some of which may be suitable for oil crop production. A technical potential of these crops could be determined using this type of approach. However, in the near term, it is likely that conventional oil crops would be grown on existing agricultural land, with the associated indirect land use change impacts. For new land-based crops, it is possible that marginal land could be used, outside the existing agricultural area. In the near term, the technical potential of new crops on this type of land is less important, as shorter term factors such as planting rate are more likely to limit uptake.

Competition for resources will affect these chains in terms of competition for land, such as the current indirect land use change concerns. Competition for the oils produced from crops will include demands for food, and demands from the oleochemical industry. Demands for vegetable oils for food are projected to increase, as a result of population increase and changing diets, but it is not known how the interaction of demand, crop yields and land availability will affect supply, and therefore prices. There is also likely to be competition for vegetable oil feedstocks for production of HVO for road transport. The degree to which these are demanded will depend on biofuels policy, vegetable oil prices, and the development of alternative biofuels routes, and of alternative emissions reduction technologies in the road transport sector.

<sup>161</sup> Using projected future yield data of 25 t oil/ha

<sup>162</sup> Günther Fischer, Eva Hitznyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuisen (2009). 'Biofuels And Food Security' IIASA for the OPEC Fund for International Development (OFID).  
<http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

Note that for algae this would mean 31,000 algae plants of 1000 ha each.

#### **7.3.4 Synthetic hydrocarbons**

The conversion efficiency of these routes is not known. The conversion efficiency of lignocellulosic ethanol production, a comparable biological route is around 35-42%, and the efficiency of the BTL process, a thermochemical route, is 48%. Assuming the conversion efficiency of the synthetic hydrocarbon processes is the same as for BTL, the feedstock requirements would be the same when produced from lignocellulosic feedstocks (70 EJ), with the same competing demands. It is not yet known what co-products would be produced from these processes. Production of 100% of jet fuel via synthetic hydrocarbon routes from sugar and starch crops would have different impacts: if produced from Brazilian sugar cane alone, with a conservative yield of 70 wet t/ha, this would lead to a land area requirement of 185 Mha, equivalent to 13% of current global arable land.

## 8 Uptake scenarios

In this section we combine the data and information from the previous sections, together with further considerations on the rate of crop and plant development, to give uptake scenarios for biofuels in aviation to 2050, and associated GHG savings. The scenarios vary according to the oil and carbon price, and also according to assumptions made about the price and sustainability of vegetable oils, and speed and success of crop and conversion technology development. Several scenarios are possible for each oil and carbon price combination, which are explained in full here. A number of summary scenarios are then chosen to represent the range of biofuels uptake outcomes, which have been fed into the overall CCC modelling work.

### 8.1 Building up full scenarios

Scenarios were developed by considering the impact of each combination of oil price (4 scenarios) and carbon price (4 scenarios) on the development and uptake of BTL, HRJ and synthetic hydrocarbon (SH). Where large uncertainties existed, about conventional vegetable oil prices, sustainability and availability, speed of development of new oil crops, and success of synthetic hydrocarbon routes, multiple scenarios were developed.

There are 18 separate scenarios in total, shown in bold in Table 22. Each scenario contains a BTL component, HRJ component from oil crops, and an SH component.

**Table 22: Full scenarios**

	Oil 1 (low)	Oil 2	Oil 3	Oil 4 (high)
<b>High carbon</b>	Low BTL, conventional and new oil crops, SH	Mid BTL, conventional and new oil crops, SH	High BTL, conventional and new oil crops, SH High BTL, new oil crops only, SH High BTL, slow new oil crops only, SH	
<b>Mid carbon</b>	Low BTL, conventional and new oil crops, SH Low BTL, new oil crops only, SH Low BTL, slow new oil crops only, SH	Mid BTL, new oil crops only, SH Mid BTL, slow new oil crops only, SH Mid BTL, new oil crops only, no SH Mid BTL, slow new oil crops only, no SH		
<b>Low carbon</b>	Low BTL, new oil crops only, no SH Low BTL, slow new oil crops only, no SH			
<b>No carbon</b>	Very low BTL, conventional and new oil crops, SH Very low BTL, new oil crops only, SH Very low BTL, slow new oil crops only, SH Very low BTL, new oil crops only, no SH Very low BTL, slow new oil crops only, no SH	Low BTL, conventional and new oil crops, SH Low BTL, new oil crops only, SH Low BTL, slow new oil crops only, SH Low BTL, new oil crops only, no SH Low BTL, slow new oil crops only, no SH		

There are several scenario components for each fuel:

- BTL – four different speeds and levels of uptake: **high, mid, low** and **very low**.
- HRJ – three different scenario components: a scenario component where both **conventional and new oil crops** can be used, one where **new oil crops only** are used, and one termed **slow new oil crops only** where only new oil crops are used, but their development is delayed.
- SH – two different scenario components: one where **SH** is successfully commercialised at the projected costs, and one where **no SH** is used, as the technology is not successfully commercialised.

A summary of the assumptions behind the scenario components is given below:

**Table 23: Scenario components summary**

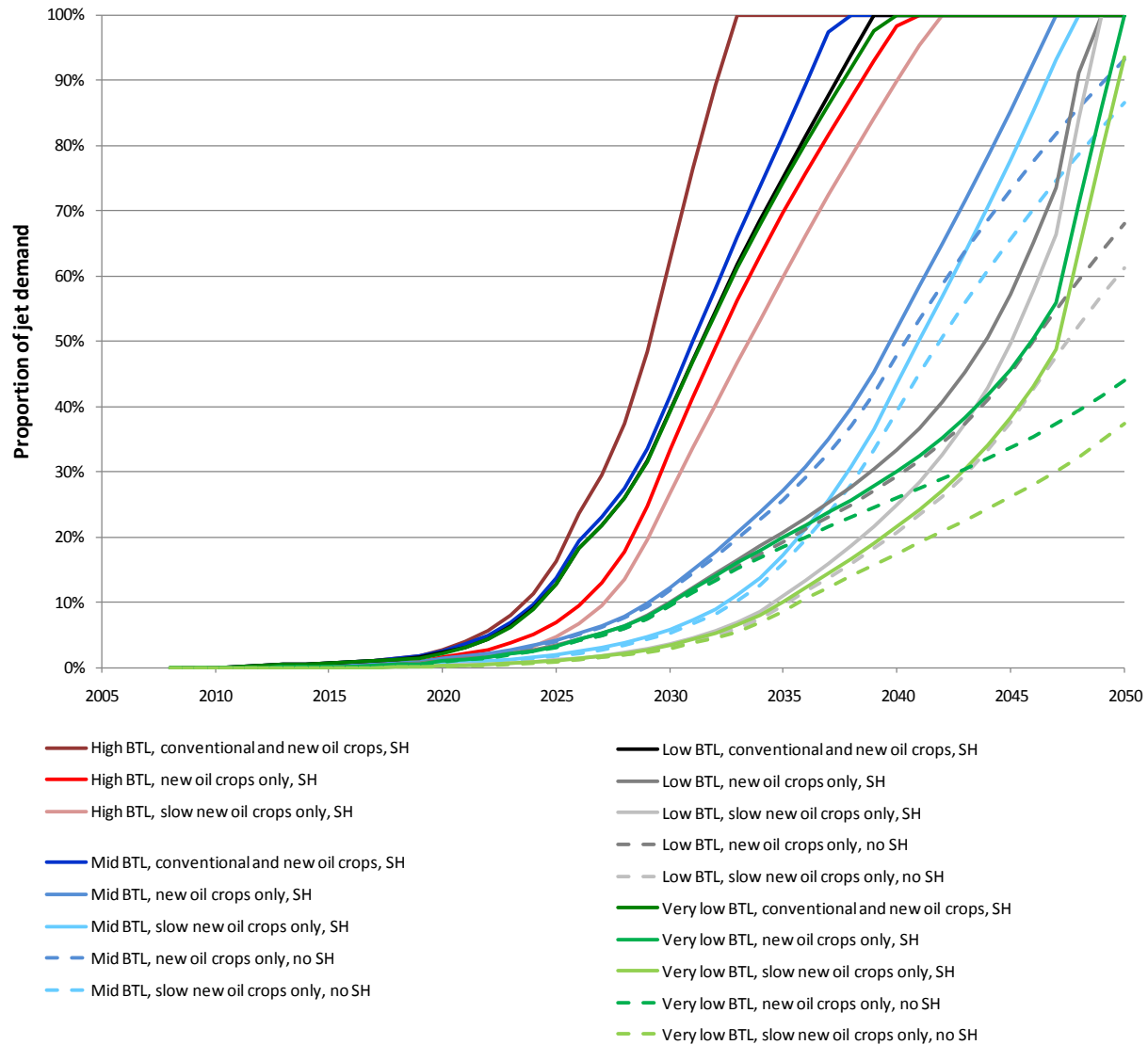
Scenario component	Description
Mid BTL	<ul style="list-style-type: none"> <li>• BTL plants are built in 2012, and ramp up exponentially. Costs reduce with learning at the rate given in section 6.2. BTL breaks even with mid cost feedstock from 2019-24 in scenarios with a carbon price, which corresponds with a steeper ramp up</li> <li>• Jet production begins from 2015: the first plants are considered unlikely to produce jet fuels. After this an increasing proportion of plants have 65% jet output.</li> <li>• The potential for feedstocks at low and mid costs is large, and so feedstock availability is assumed not to be a constraint</li> <li>• GHG savings of 93% were used for all BTL scenario components</li> </ul>
Low BTL	<ul style="list-style-type: none"> <li>• BTL ramp up is slower at the start with under half the number of plants in 2020 compared with Mid BTL. There is less interest in the sector, as only low cost feedstocks break even with a carbon price</li> <li>• The build rate increases at the same rate as Mid BTL once mid cost feedstocks break even in 2027</li> <li>• Again, the first plants do not produce jet, but the proportion producing jet increases faster than in Mid BTL, as a result of the potential increased revenue from markets with a carbon price</li> </ul>
High BTL	<ul style="list-style-type: none"> <li>• BTL plant build rate is the same as Mid BTL until 2019, as the technology is proved</li> <li>• After this, the rate of BTL plant increase is faster than for mid BTL</li> </ul>
Very low BTL	<ul style="list-style-type: none"> <li>• Viability only with low cost feedstocks, such as wastes, restricts the BTL potential</li> <li>• The first ten plants are built at the same rate as for low BTL, by 2020. No jet is produced from these plants, as BTL jet does not break even with no carbon price until 2023</li> <li>• The number of plants increases exponentially at a slower rate, to a third of the potential in 2050 as seen for Low BTL, based only on low cost feedstocks.</li> </ul>
Conventional and new oil crops	<ul style="list-style-type: none"> <li>• Conventional oil crops are available at historically low prices of around \$400/t. Production of the four main oil crops has been projected to grow at 3.4% p.a. to supply food and road transport biofuel needs (around 20% of supply). We assume that the growth rate increases by 10%, meaning it grows at 3.7% p.a., with the additional supply available for aviation biofuels.</li> <li>• Availability of feedstock certified to sustainability criteria such as RSPO increases</li> <li>• Build rate of plants producing HRJ: from 2010, a small number of HVO plants produce 15% HRJ. From 2011, dedicated HRJ plants producing 70% HRJ are built. From 2020, we assumed that co-processing of HRJ in refineries is more widespread, and plant sizes increase, modelled as a plant build rate increase.</li> <li>• 50% GHG savings were assumed for conventional crops.</li> <li>• New oil crops are also used, with assumptions as below. When the plant build rate is the limiting factor, new oil crops are assumed to be used first, as a result of higher GHG savings and lower costs</li> </ul>
New oil crops only	<ul style="list-style-type: none"> <li>• Production from jatropha begins in 2012, and increases to 2.7 Mha in 2020. From 2020, the area increases at 30% p.a. capped at of 2Mha/yr. Total land area is not limited, as jatropha is expected to be able to be grown on a wide range of degraded lands. GHG savings of 66% were assumed</li> <li>• Production from camelina also begins in 2012, with 40 kha of production. This increases to 4 Mha by 2020. From 2020, this increases at 30% p.a. capped at 2Mha/yr. GHG savings of 85% were assumed</li> <li>• Production from algal oil begins from 2017. The number of algae plants doubles every year for the first ten years, then increases by 50%p.a. capped at 1000 plants p.a.. Oil yields increase to 18t/ha by 2020 and 25 t/ha by 2030. GHG savings of 98% were assumed</li> <li>• Halophytes were not included, as there was insufficient information on cost, yield or land area suitability</li> <li>• New crops are assumed to be able to produce oil at the historic low price for vegetable oils.</li> <li>• 50% of the production of new crops is assumed to be available for plants producing jet, with the rest going to plants producing HVO with no jet, or other uses. Note that because plants producing jet also produce diesel or naphtha, this means that jet uses under half of the production.</li> </ul>
Slow new oil crops only	<ul style="list-style-type: none"> <li>• Introduction of jatropha, camelina, and algal oils is delayed by 5 years, with data as above.</li> </ul>
SH	<ul style="list-style-type: none"> <li>• Synthetic hydrocarbons are introduced for jet from 2020, and are assumed to be competitive with jet. A plant build rate equivalent to the rates used for mid BTL and HRJ was then used.</li> <li>• GHG savings of 80% were assumed.</li> </ul>
No SH	<ul style="list-style-type: none"> <li>• Synthetic hydrocarbons are not commercialised successfully</li> </ul>

It is important to note that:

- The scenarios using the *conventional and new oil crops* scenario component rely on the price of conventional vegetable oil feedstocks dropping from current prices to the lower end of the prices seen over the past few years (the 'historic' prices). This is not considered to be likely to happen, by those we have spoken to in the feedstock trading and biodiesel production sectors. However, it has been included to show the effect of being able to use conventional crops; with current vegetable oil prices or those linked to the oil price, these feedstocks do not become viable for jet production until after 2030, if at all, in most oil and carbon price combinations. Note that this use of conventional oil crops is more likely in the low oil price and high carbon price combination. Here even a vegetable oil price linked to the crude oil price would be low when compared with the jet+carbon price. As a result, no *new oil crops only* scenarios are given here.
- As a result the scenarios using *new oil crops only* are more likely to occur. Small volumes of conventional feedstocks may be used in these plants as they build up, or to secure supply, but the rate of uptake will be dependent on availability of the new feedstocks.
- The development of new types of fuel, such as synthetic hydrocarbons (SH), will require further RD&D and work on commercialisation. Whilst some individual technologies may fail, it is likely that a number of new routes will be successful. However, we have included scenarios where these are not successful, as in several scenarios their contribution has a large effect on the results after 2040. Note that for the scenarios with conventional and new oil crops, or High BTL, there is a very small contribution of SH, and so no '*no SH*' scenarios were developed.

## 8.2 Full scenario results

The results of each full scenario, in terms of the % uptake of biofuels to 2050 in the Unlimited Skies (ULS) demand scenario, are shown in Figure 22, below. This scenario is the highest global aviation demand and fuel demand profile to 2050 as per the IPCC 4th Assessment report (Consave ULS), and is used to be as conservative as possible on biofuels uptake as a proportion of jet fuel demand, and to show the resource requirement in a high aviation fuel demand scenario.



**Figure 22: Full scenario uptake results.**

The graph shows that a significant uptake of biofuels could be achieved in all scenarios. Full descriptions of the results are given in Annex 1. The results are more dependent on some scenario components than others, and also on some key input assumptions:

- Several of the scenarios reach 100% of jet supply. Few interviewees commented on what they considered the long term potential could be, with one or two envisaging levels of 50% or 100%. The reason for this is that once technologies and feedstocks are available that can produce biofuels for aviation at lower than the jet plus carbon price, and when feedstocks are not a constraint, there is no reason to restrict their uptake. In some cases, the biofuels price would be significantly lower than the jet plus carbon price, providing a strong driver for uptake.

- Additional certification for blends above 50% would be needed, but this should not present a barrier in the time scale envisaged. The earliest scenario to exceed 50% is High BTL, conventional and new oil crops, SH, which reaches 50% in 2030. By this time, it is likely that higher blends could be certified, and that any additives needed will be developed (e.g. aromatic additives from biomass pyrolysis).
- The fastest uptake is seen when conventional oil crops can be used to produce HRJ, with 10% of jet fuel being supplied by around 2024, and 100% of jet fuel being supplied before 2040. However, the near term uptake remains slower than some projections given by industry stakeholders (see section 8.5). Until 2024, these scenarios are constrained by the plant build rate, rather than by feedstock availability. This shows that if these targets are to be met, both access to low cost conventional feedstocks with certified sustainability would be required, and a fast ramp up of HRJ plant capacity. In these scenarios, by 2040, most of the supply is from HRJ, predominantly from conventional rather than new crops. As discussed above, using conventional crops could have sustainability impacts as a result of indirect land use change. These impacts are difficult to quantify and to include in sustainability schemes.
- The rapid development seen in all High BTL scenarios leads to 100% of jet fuel being supplied by the early 2040s. When only new oil crops are used to produce HRJ, the near to mid term ramp up of aviation biofuels is much slower than when conventional crops are used, with 10% of jet fuel being supplied in 2026-7. This is limited by availability of new oil crop feedstock throughout, rather than by the plant build rate.
- Note that after the point of 100% supply, the fuel mix could change as biofuels routes develop, e.g. more BTL and SH could be used in conventional and new oil crop scenarios, even though HRJ dominates early on. In calculating the GHG emissions to 2050, we have assumed that fuels are used in proportion to their availability after the point of 100% supply, rather than assuming that the mix stays the same.
- Central oil prices (scenario 2) lead to the Mid BTL scenarios, which give much slower ramp up when only new oil crops can be used, but still reach 100% of jet by around 2045. As a result of this slower BTL development, synthetic hydrocarbons (SH) make more of a contribution to the fuel mix, meaning that scenarios where SH is not successful are useful for comparison. In the conventional oil crops or High BTL scenarios, there is very little SH penetration, and so no 'no SH' scenarios were developed.
- Scenarios where only new oil crops can be used are limited by feedstock: the rate of planting for jatropha and camelina, and the rate of building algae plants. Limits to this growth are uncertain, as there are few proxies for this type of development, and there are uncertainties over the rate at which yields can be increased, and costs reduced. Slowing development of new oil crops by five years has a large impact on the potential uptake between 2025 and 2040.
- When BTL is less successful, in the Low BTL and Very low BTL scenarios, achieving a high uptake of biofuels in aviation is much more dependent on the new routes represented by SH. In the Low BTL scenario, lack of successful SH commercialisation leads to a biofuels penetration of around 65% in 2050, and 40% in the Very low BTL scenario.

### 8.3 Selecting summary scenarios

We then selected a smaller number of ‘summary scenarios’ from the full list, to be fed into overall CCC modelling of the different options for reducing aviation emissions to 2050. At least one scenario was provided for each oil and carbon price combination. We also chose scenarios to reflect different degrees of success in technology and crop development. This success or failure, however, is *not determined by the oil and carbon price alone*: technologies and crops may still fail, or be slow to succeed even with high oil and carbon prices, if there are fundamental technology limitations. There could also be a strong driver for technology development even with some low and medium oil and carbon price combinations, such as the influence of other policies.

**Table 24: Summary scenarios mapped on to oil and carbon price combinations**

	Oil 1 (low)	Oil 2	Oil 3	Oil 4 (high)
<b>High carbon</b>	Low	Central (High) or Central (Low)	High	High
<b>Mid carbon</b>	Low	Central (High) or Central (Low)	High	High
<b>Low carbon</b>	Low	Central (High) or Central (Low)	High	High
<b>No carbon</b>	Very Low or Low	Low	High	High

Note that:

- the Central (High) scenario is more likely than the Central (Low scenario)
- the Very low scenario is more likely than the Low scenario with Oil 1 and no carbon price

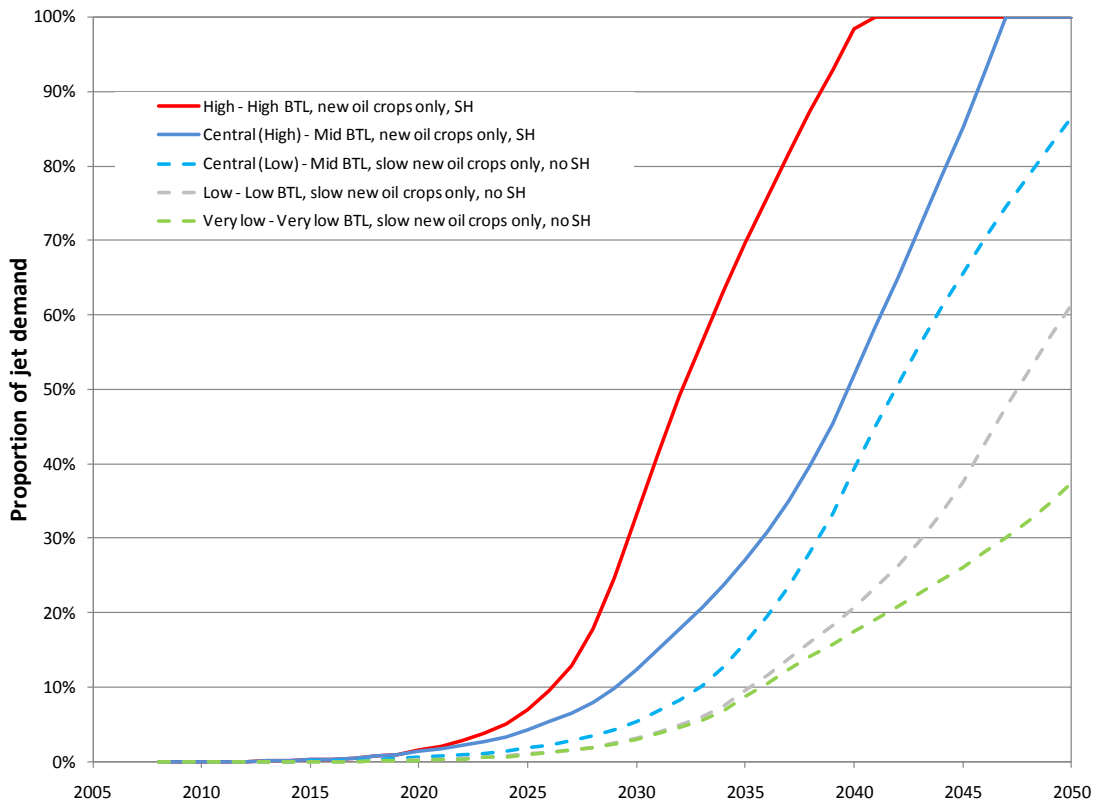
None of the summary scenarios include the use of conventional oil crops for HRJ, as we consider it unlikely that prices will drop to the levels needed to make HRJ competitive with jet, and that large volumes of crops with certified sustainability characteristics are achievable in the near term. Despite the increasing supply of crops certified to sustainability standards, these standards and other policies do not currently mitigate the risk of indirect land use change. Given that work on indirect land use change is at an early stage, and is ongoing, there is the potential for biofuels standards, or other policies on land use to mitigate this risk in the future. However, to be conservative on this issue, as well as on price projections, we have restricted HRJ to new oil crop feedstocks.

**Table 25: Reasons for the choice of full scenarios as summary scenarios**

Summary scenario	Full scenario	Reasons for choice of full scenario
High	High BTL, new oil crops only, SH	A high oil price leads to fast BTL uptake. When oil prices are high, it is likely that the price of conventional oil crops will also be high, making the <i>High BTL, conventional and new oil crops, SH</i> scenario, which assumes historically low vegetable oil prices, very unlikely. The high oil price also drives development of new oil crops and new biofuel technologies.
Central (High)	Mid BTL, new oil crops only, SH	A central oil price, together with concerns over the use of food crops for biofuels and indirect land use change, again makes use of conventional oil crops unlikely, and drives development of new oil crops. The carbon price supports development of all fuels, including synthetic hydrocarbons. This is the more likely central scenario.
Central (Low)	Mid BTL, slow new oil crops only, no SH	A central oil price, together with concerns over the use of food crops for biofuels and indirect land use change, again makes use of conventional oil crops unlikely. Despite a driver for new crops and fuels, technology for new crops develops more slowly, and synthetic hydrocarbons are not successfully commercialised. This scenario shows the effect of slow technology development compared with Central (High), but is less likely to be the case.
Low	Low BTL, slow new oil crops only, no SH	<p>Low oil prices or central oil prices with no carbon price lead to much slower development of BTL. We have also assumed here that new oil crops are developed slowly and that synthetic hydrocarbons are not commercialised successfully. It is important to note that this scenario is used to represent slow or unsuccessful technology development, rather than being a result of the oil and carbon price combination alone.</p> <p>With low oil prices and high or medium carbon prices, the other potential scenario is a Very High scenario (<i>Low BTL, conventional and new oil crops, SH</i>) which is similar to the High scenario, but has a faster uptake in the near term, as a result of the use of conventional oil crops for HRJ. This could occur as even with the vegetable oil price linked to the oil price, HRJ from conventional crops breaks even. However, we have not used this scenario for several reasons:</p> <ul style="list-style-type: none"> <li>• The oil price/vegetable oil price relationship used was assumed not to hold at below \$60/bbl, based on FAO data. The oil price scenario 1 is at \$60/bbl, and so the relationship may not hold at this point.</li> <li>• Even if the oil price dropped now to scenario 1 levels, and the oil price/vegetable oil price relationship holds we do not think that the vegetable oil price would drop to this level in the next 5 years, and so HRJ from conventional feedstocks would not have the early build up projected</li> <li>• Sustainability concerns. Airlines representing over 20% of the jet demand have joined SAFUG, which includes signing up to not using crops that compete with food. This trend may continue, reducing the demand for HRJ from these crops</li> </ul>
Very low	Very low BTL, slow new oil crops only, no SH	Low oil prices and no carbon prices lead to slow BTL development. HRJ from new oil crops is only marginally viable, leading to slow uptake, and synthetic hydrocarbons are not developed as a result of lack of commercial interest.

### 8.4 Summary scenario results

The summary scenario results are shown in Figure 23, below. Note that these are based on the detailed scenarios, and so the results are exactly the same as in the previous graphs.



**Figure 23: Uptake results for the five summary scenarios**

The results are described in the table below, together with a summary of the uptake in 2020 and 2030.

**Table 26: Summary scenario results**

Scenario	Description (all figures relate to ULS scenario)	% in 2020	% in 2030	Reaches 100% in
<b>High</b> High BTL, new oil crops only, SH	<ul style="list-style-type: none"> <li>Biofuel supply to 2023 is mostly from HRJ, produced from new feedstocks as they become available. From this point, BTL overtakes HRJ, giving 24% of jet production in 2030, and over 70% by 2041 with 25% HRJ and 5% SH.</li> <li>WTW GHG savings increase from around 68% to 90-95% as the bulk of production moves from jatropha to BTL and algae.</li> </ul>	1.6%	33%	2041
<b>Central (High)</b> Mid BTL, new oil crops only, SH	<ul style="list-style-type: none"> <li>Biofuel supply to the early 2030s is mostly from HRJ, produced from new feedstocks as they become available. From this point, BTL ramps up more quickly, reaching 24% of jet by 2040, and overtaking HRJ, with SH also growing faster from this point.</li> <li>By 2047, half of jet production could be BTL, with 30% HRJ, and 20% from SH.</li> </ul>	1.4%	12%	2047
<b>Central (Low)</b> Mid BTL, slow new oil crops only, no SH	<ul style="list-style-type: none"> <li>Feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks. Fast growth once they are introduced, and fast BTL build up in 2030s means that 87% of jet is supplied in 2050, of which over 60% is from BTL.</li> <li>GHG savings increase from around 69% with jatropha and some camelina to 90-95% as algae and BTL dominate</li> </ul>	0.6%	5%	After 2050
<b>Low</b> Low BTL, slow new oil crops only, no SH	<ul style="list-style-type: none"> <li>New oil crop availability limits HRJ potential to only 0.3% in 2020. Faster ramp up of jatropha from 2020, camelina from 2024 and algae from 2028 give HRJ supply of around 2.5% of jet in 2030, with some BTL.</li> <li>After 2040, BTL grows faster, leading to overall 61% of jet in 2050, of which 36% is from BTL.</li> <li>GHG savings increase from around 69% to 90-95% as algae and BTL dominate.</li> </ul>	0.3%	3%	After 2050
<b>Very low</b> Very low BTL, slow new oil crops only, no SH	<ul style="list-style-type: none"> <li>Biofuel supply is very low, mostly from HRJ, as feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks.</li> <li>By 2050, 37% of jet is supplied, made up of 25% HRJ and 12% BTL</li> </ul>	0.2%	3%	After 2050

The feedstock requirements for meeting the percentage of demand supplied in 2050 in each of the summary scenarios are in

Table 27 below.

**Table 27: Feedstock requirements for summary scenarios**

Scenario	Feedstock implications
<b>High</b> High BTL, new oil crops only, SH	Supplying 100% of the 2050 jet demand using the shares of fuels seen in 2041 would require: <ul style="list-style-type: none"> <li>• 194Mha of land for energy crops (12% of the energy crop resource) OR 8% of the total projected lignocellulosic material resource, for BTL and SH together, PLUS</li> <li>• 15Mha jatropha, 16Mha camelina and 6Mha algae plants</li> </ul>
<b>Central (High)</b> Mid BTL, new oil crops only, SH	Supplying 100% of the 2050 jet demand using the shares of fuels seen in 2047 would require: <ul style="list-style-type: none"> <li>• 178Mha of land for energy crops (11% of the energy crop resource) OR 7% of the total projected lignocellulosic material resource, for BTL and SH together, PLUS</li> <li>• 19Mha jatropha, 20Mha camelina and 7Mha algae plants</li> </ul>
<b>Central (Low)</b> Mid BTL, slow new oil crops only, no SH	Supplying 87% of the 2050 jet demand using the shares of fuels given would require: <ul style="list-style-type: none"> <li>• 155Mha of land for woody energy crops (9% of the energy crop resource) OR 6% of the total projected lignocellulosic material resource, for BTL, PLUS</li> <li>• 17Mha jatropha, 18Mha camelina and 6Mha algae plants</li> </ul>
<b>Low</b> Low BTL, slow new oil crops only, no SH	Supplying 61% of the 2050 jet demand using the shares of fuels given would require: <ul style="list-style-type: none"> <li>• 91Mha of land for woody energy crops (5% of the energy crop resource) OR 4% of the total projected lignocellulosic material resource, for BTL, PLUS</li> <li>• 17Mha jatropha, 18Mha camelina and 6Mha algae plants</li> </ul>
<b>Very low</b> Very low BTL, slow new oil crops only, no SH	Supplying 37% of the 2050 jet demand using the shares of fuels given would require: <ul style="list-style-type: none"> <li>• 30Mha of land for woody energy crops (2% of the energy crop resource) OR 1% of the total projected lignocellulosic material resource, for BTL, PLUS</li> <li>• 17Mha jatropha, 18Mha camelina and 6Mha algae plants</li> </ul>

Note that the feedstock requirements given are only for aviation biofuels, and not for:

- other biofuels produced through the same conversion process or co-produced i.e. diesel or naphtha from HVO and BTL plants. However, from many of these routes, several other co-products would also be produced, such as straw, animal feed, and electricity from the conversion plant, and so this level of resource use does not supply aviation demand alone.
- other plants using the same technology, that do not produce biofuels for aviation (most of the scenario components assume that plants are built for production of biofuels for road transport, as well as those for aviation).

This shows that a relatively small proportion of the identified resource for lignocellulosic materials is needed, plus a relatively small area of land for algae, and larger, but still achievable areas for jatropha and camelina. For comparison:

- The highest use of lignocellulosic materials is in the High scenario, for BTL and SH production.
  - Here, supplying 100% of the 2050 jet demand would require 200Mha of land if all supplied by energy crops. This is equivalent to 12% of the projected potential energy crop resource in 2050, taking into account only abandoned agricultural land and grassland, and restricted based on assumptions on potential planting rates.
  - Alternatively, supplying the same demand would require 8% of the total projected lignocellulosic material resource, made up of energy crops, agricultural and forestry residues, and wastes.

- As shown in section 7.3.2, there will be competing demands for lignocellulosic resources, for production of heat, power, materials and chemicals, but these are projected to be relatively small in comparison with the total projected resources, partly as a result of alternative options in other sectors. Achieving much larger proportions of the demand for biomass and biofuels in other sectors would put pressure on lignocellulosic resources, and even at the levels given, there may be competition for low cost feedstocks.
- The highest use of new oil crops is in the Central (High) scenario, where 19Mha jatropha, 20Mha camelina and 7Mha algae plants would be required.
  - The areas for jatropha and camelina can be compared with the current areas for other oil crops, of 14Mha for palm, 30Mha for rapeseed, and 90Mha for soybeans, although they would be grown on lower quality marginal land, with the potential for lower sustainability impacts.
  - The area for algae is much smaller, as a result of greater algal yields. In addition to this, the location of algae production would be limited by access to sunlight, sources of CO<sub>2</sub> and water, rather than land type.

## 8.5 Conclusions and comparisons

### Uptake

In general, the full scenarios developed have lower uptake in the near to mid term than some industry projections.

- Table 28 shows published industry projections and targets for biofuels and alternative fuels, together with one row combining estimates given confidentially in our interviews. This shows that the most optimistic projections have 5-10% of jet being reached in 2013, with others estimating this level would be reached by 2015, and several considering that the higher end of this range would be likely by 2020.
- In our scenarios, uptake is much slower, with even the highest scenario having an uptake of 0.75% in 2015. 10% of jet would be reached in 2023-24 if conventional crops were used for HRJ production, as a result of slower plant rate build up. For comparison, achieving 10% in 2020 would require 164 plants producing 70% HRJ at 250kt/yr fuels output). This would imply a steep ramp up from introduction in 2011, and from the Commercial Aviation Alternative Fuels Initiative (CAAFI)'s 'optimistic' projection for 10 HRJ plants at around this scale in 2013. In our modelling, there are 34 plants at this scale in 2020.
- In the more likely scenarios where conventional crops are not used, 10% of jet is not reached until 2026 even in the highest scenario (High BTL, new crops only, SH scenario). In the other scenarios, this is pushed out as far as 2035. This is limited by the availability of new oil crops, and the BTL plant build rate. The speed at which new oil crops will become available for HRJ production depends both on their successful development (breeding, agronomy etc), and on the rate of uptake by farmers and agro-industry, who must adapt to new practices and markets. In addition to this, there was relatively poor availability of data on new oil crop status and potential, and so this could be better assessed with further work or further information put into the public domain. Another key uncertainty is the availability of the new oils produced for HRJ production: we have assumed that only half of new crop production is available for plants producing HRJ, with the rest being used for plants only producing HVO or other uses. Considerably more detailed analysis of vegetable oil markets would be needed to assess how much production would be driven by HRJ demand alone.

For comparison, current biofuels production for road transport is around 1.6EJ<sup>163</sup>, which is equivalent to 17% of current jet demand, or 13% of 2020 jet demand.

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<sup>163</sup> IEA World Energy outlook 2008, <http://www.iea.org/w/bookshop/add.aspx?id=353>

**Table 28: Summary of industry targets and projections for the % biofuels use in global jet (except where specified), and specific technologies. Data is from published statements only, except the ‘Other’ row, which is from interviews and is non-attributable**

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2030	2050
<b>UOP</b>		Commercial HRJ production <sup>164</sup>										
<b>Boeing</b>		First commercial HRJ <sup>165</sup>										
<b>IATA</b>							10% alternative fuel <sup>166</sup> (1.2 EJ)					
<b>Airbus</b>										Algae biofuel in service <sup>167</sup>	30% (5.8 EJ) <sup>167</sup>	
<b>USAF</b>					25% of USAF domestic jet is biofuel <sup>168</sup>							
<b>CAAFI</b>			10 HRJ plants, 3 BTL plants <sup>169</sup>									
<b>Fedex</b>											30% (5.8 EJ) <sup>170</sup>	
<b>Sustainable Aviation</b>										Deployment	20% <sup>171</sup>	
<b>Policy Exchange<sup>172</sup></b>										20%-40% in EU	40%-80% in EU	80% in EU
<b>Others</b>			5% 5-10% 1.5% of US jet		1% 1% 10%					5-10% 6-10% 10%		50% 100%

<sup>164</sup> Holmgren, UOP, Creating a Sustainable Biofuels Future: A Few Thoughts on Infrastructure, [Accessed 27 July 2009], [http://www.enviros Summit.aero/images/Downloads/speeches/speeches\\_downloads/blue\\_room\\_morning\\_jennifer\\_holmgren.pdf](http://www.enviros Summit.aero/images/Downloads/speeches/speeches_downloads/blue_room_morning_jennifer_holmgren.pdf)

<sup>165</sup> ATWOnline, Experts say biofuel-powered commercial flights possible within five years, [Accessed 27 July 2009], <http://www.atwonline.com/news/story.html?storyID=16108>

<sup>166</sup> IATA, Aviation and Climate Change: Pathway to carbon-neutral growth in 2020, [Accessed 27 July 2009], [http://www.iata.org/NR/rdonlyres/2B1211C9-503B-4E29-B8E3-EA84FFA2EC59/0/AviationClimateChange\\_PathwayTo2020\\_email.pdf](http://www.iata.org/NR/rdonlyres/2B1211C9-503B-4E29-B8E3-EA84FFA2EC59/0/AviationClimateChange_PathwayTo2020_email.pdf)

<sup>167</sup> ATWOnline, Getting Closer to a Biofuel Future, [Accessed 27 July 2009], <http://www.atwonline.com/magazine/article.html?articleID=2609>

<sup>168</sup> DefenseNews, Synthetic Future, 2009, [Accessed 11 May, 2009], <http://www.defensenews.com/story.php?i=3969089&c=FEA&s=TEC>

<sup>169</sup> CAAFI, Biofuels: Commercial Aviation Emerging on the “Cutting Edge”, [Accessed 27 July 2009], [http://files.eesi.org/altman\\_051209.pdf](http://files.eesi.org/altman_051209.pdf)

<sup>170</sup> ClimateBiz, FedEx Aims for 30 Percent Biofuels by 2030, <http://www.climatebiz.com/news/2009/04/30/fedex-aims-30-percent-biofuels-2030>

<sup>171</sup> Sustainable Aviation, CO2 roadmap, Dec 2008, <http://www.sustainableaviation.co.uk/images/stories/key%20documents/sa%20road%20map%20final%20dec%202008.pdf>

<sup>172</sup> Policy Exchange “Green skies thinking” Ben Caldecott & Sean Tooze, July 2009, [http://www.policyexchange.org.uk/images/publications/pdfs/Green\\_skies\\_thinking\\_-\\_promoting\\_the\\_development\\_and\\_commercialisation\\_of\\_sustainable\\_bio-jet\\_fuels\\_-\\_strictly\\_embargoed\\_until\\_22nd\\_July.pdf](http://www.policyexchange.org.uk/images/publications/pdfs/Green_skies_thinking_-_promoting_the_development_and_commercialisation_of_sustainable_bio-jet_fuels_-_strictly_embargoed_until_22nd_July.pdf)

In the longer term, faster ramp up of our scenarios leads to uptake comparable to some of the industry projections.

- The need for technology and crop development in the near term, and the shape of the plant build rate curves leads to a faster rate of uptake in the mid-long term, compared with the slower start
- In the High scenario, 33% of jet supply is reached by 2030, comparable with the Fedex and Airbus timelines, and this is delayed by only 5 years to 2035 in our Central (High) scenario, where BTL uptake is slower.
- In all of the full scenarios, 100% is reached by 2050 or soon after if the development of the new routes represented by 'synthetic hydrocarbons' (SH) is successful. Two of the summary scenarios, High and Central (High) reach 100% of jet supply before 2050, with Central (low) likely to reach this level soon after 2050.
- If new SH routes are not successful, and BTL and new oil crop development is slow, the uptake can be lower, at 35-70% of jet in 2050. However, this is still a substantial penetration of potentially very low GHG fuel.
- Few interviewees were prepared to give a view on the potential to 2050, mostly as a result of uncertainty over biomass supply potential, being outside their area of expertise. One stated that there was no reason to limit use of biofuels, and that 100% could be biofuels, whilst another thought that only 50% could be reached, though did not give reasons for this limit.

### **GHG savings**

Greenhouse gas savings associated with biofuels use can be high, particularly for new crops and conversion technologies, providing the land use change impacts of feedstock production are avoided:

- The GHG savings are lowest in scenarios where conventional oil crops are used, starting at around 50% WTW savings, and increasing to 65-75% as small amounts of new oil crops and BTL are introduced. This also assumes that the conventional crops used for HRJ production are only those with 50% savings, as a result of industry sustainability concerns; lower savings would be possible
- In scenarios with no conventional oil crops, savings start at around 66%, and increase to over 90%, as new oil crops, BTL and in some scenarios, synthetic hydrocarbons, are used.

The EU ETS approach of considering that biofuels have 100% GHG savings is correct for the tank to wake part of the fuel chain, but does not take into account the well-to-tank emissions in biofuels production. Not recognising the differences in GHG performance between biofuels used in aviation in policy could lead to much lower greenhouse gas savings. All interviewees understood the differences in GHG savings and sustainability between different biofuels chains, and many industry members have pledged only to use the sustainable routes with high GHG savings. However, this alone is unlikely to stop unsustainable fuels and those with lower GHG savings from entering the supply chain.

As explained in section 5, the use of biofuels is unlikely to reduce tank-to-wake non-CO<sub>2</sub> emissions, aside from as a result of the potential for small reductions in fuel consumption, which were not considered in detail here.

## Resource implications

The land use required in the full scenarios using conventional crops would vary considerably depending on which conventional crops were used, but would be likely to be very large. Whilst there is potential for yield improvement from all of these crops in some regions<sup>173</sup>, it is likely that expansion of the area grown would be needed. Given that this would clearly be on land suitable for growing food, this could cause indirect sustainability impacts much greater than those for energy crops and new oil crops grown on lower productivity land. Expansion of palm, which has the highest per hectare oil yields, is likely to be limited by availability of suitable land not currently under forest. If palm expansion is limited, then crops such as soy and rapeseed would be used in these scenarios, which have much lower per hectare yields, giving extremely high land demands, and greater risk of indirect impacts. As a result, resource considerations make these scenarios very unlikely.

Scenarios where conventional crops are not used require a relatively small proportion of the identified resource for lignocellulosic materials, relatively small areas for algae, and reasonable areas for jatropha and camelina. It is important to remember that the type of land used for these crops could be lower quality land, in the case of energy crops, jatropha and camelina, and any land type in the case of algae.

- The highest use of lignocellulosic materials is in the High scenario, where supplying 100% of the 2050 jet demand would require 200Mha of land for energy crops (equivalent to 12% of the projected energy crop resource) or 8% of the total projected lignocellulosic material resource, for BTL and SH together.
- The highest use of new oil crops is in the Central (High) scenario, where 19Mha jatropha, 20Mha camelina and 7Mha algae plants would be required. The total can be compared with the current figures of 14Mha for palm, 30Mha for rapeseed, and 90Mha for soybeans.

For comparison, 25 Mha of agricultural land is used for production of feedstocks for the current 1.6 EJ of biofuels for road transport<sup>174</sup>. As stated previously, from many of these routes, several other co-products would also be produced, such as straw, animal feed, and electricity from the conversion plant, and so this level of resource use does not supply aviation demand alone.

Meeting demand for biomass and biofuels in other sectors may result in competition for low cost feedstocks, in particular whilst energy crops and algae plants are more widely developed. While there may also be competition in the longer term, there are likely to be sufficient resources to accommodate a significant use of biomass for aviation biofuels, as well as use in other sectors.

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<sup>173</sup> See, for example, FAO, The state of food and agriculture, 2008, <http://www.fao.org/docrep/011/i0100e/i0100e00.htm> and ADAS 'Anticipated and potential improvements in land productivity and increased agricultural inputs with intensification' 2008, as part of the Gallagher Review. [http://www.renewablefuelsagency.org/db/documents/ADAS\\_Improvements\\_in\\_land\\_productivity\\_and\\_increased\\_agricultural\\_inputs\\_with\\_intensification.pdf](http://www.renewablefuelsagency.org/db/documents/ADAS_Improvements_in_land_productivity_and_increased_agricultural_inputs_with_intensification.pdf)

<sup>174</sup> Günther Fischer, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah and Harrij van Velthuizen (2009). 'Biofuels And Food Security' IIASA for the OPEC Fund for International Development (OFID). <http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

## 9 Annexes

**Annex 1. Full scenario results**

Scenario	Description	% of jet in 2020	% of jet in 2030	Reaches 100% in
Low BTL, conventional and new oil crops, SH	HRJ based on conventional oil crops ramps up quickly from 2010, and uses new oil crops where possible: jatropha and camelina from 2012 and algal oil from 2017. Uptake is limited by the availability of conversion plants until 2027, as HRJ plants are built, and co-processing in refineries is adopted. BTL ramps up slowly as the technology is proven, and is not used for jet production in the first few plants. From 2027 a faster ramp up is enabled by cost reduction and the viability of mid cost feedstocks (low cost energy crops and the high end of forestry residues). However, HRJ dominates, with fast increase in uptake in 2020-2030, leading to 92% of jet being supplied by HRJ in 2039, with 5% BTL and 3% SH. WTW GHG savings increase from 50% to 60-70% with the introduction of the new oil crop feedstocks	2.3%	39%	2039
Low BTL, new oil crops only, SH	HRJ is produced using new oil crops only: jatropha and camelina from 2012 and algal oil from 2017, with production limited by feedstock availability. By 2030, HRJ has reached around 9%, with small contributions from BTL and SH, which only grow quickly after 2035. By 2049, HRJ and BTL make up around 30% of supply, with the faster growing SH providing the rest. This shows the importance of an alternative route i.e. SH if conventional oil crops cannot be used, and BTL is not very successful. GHG savings increase from around 69% with jatropha and some camelina to 85-90% as algae, BTL and SH dominate.	1.1%	10%	2049
Low BTL, slow new oil crops only, SH	New oil crop availability limits HRJ potential to only 0.3% in 2020. Faster ramp up of jatropha from 2020, camelina from 2024 and algae from 2028 give HRJ supply of around 2.5% of jet in 2030, with some BTL and SH. After 2040, faster BTL and SH growth lead to their supply overtaking that of HRJ by 2049. GHG savings increase from around 69% with jatropha and some camelina to 85-90% as algae, BTL and SH dominate.	0.3%	4%	2049
Mid BTL, conventional and new oil crops, SH	Even though mid oil prices and a carbon price lead to faster BTL ramp up than with no carbon price or low oil prices, this scenario remains dominated by HRJ using conventional feedstocks, and new feedstocks as they become available, initially limited by the HRJ plant build rate. BTL ramps up faster from the start than in Low BTL, with exponential growth limited by the plant build rate, and again is not used for jet production in the first few plants. The BTL growth rate increases as it breaks even with higher cost feedstocks, but the faster ramp up of HRJ leads to over 80% of jet being supplied by HRJ in 2038 with around 13% BTL and 2% SH.	2.6%	42%	2038
Mid BTL, new oil crops only, SH	Biofuel supply to the early 2030s is mostly from HRJ, produced from new feedstocks as they become available. From this point, BTL ramps up more quickly, reaching 24% of jet by 2040, and overtaking HRJ, with SH also growing faster from this point. By 2047, half of jet production could be BTL, with 30% HRJ, and 20% from SH.	1.4%	12%	2047
Mid BTL, slow new oil crops only, SH	Feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks. Fast growth once they are introduced means that 100% jet is reached only one year later, again with around half from BTL, 30% HRJ, and 20% from SH. WTW GHG savings are high at 80-95%, as BTL rather than conventional oil crops or jatropha dominates from the start.	0.7%	6%	2048
High BTL, conventional and new oil crops, SH	The viability of conventional oil crops, and fast ramp up of BTL production lead to 100% of jet being able to be supplied by biofuels in 2033, with HRJ providing 60% of supply. BTL builds up to 2019 as in the Mid BTL scenario, as the technology is proven, but then ramps up much faster, as mid price feedstocks are viable even without a carbon price, providing around 40% of supply in 2033. Minimal SH are produced.	2.8%	63%	2033
High BTL, new oil crops only, SH	Biofuel supply to 2023 is mostly from HRJ, produced from new feedstocks as they become available. From this point, BTL overtakes HRJ, giving 24% of jet production in 2030, and over 70% by 2041 with 25% HRJ and 5% SH. This shows the importance of BTL if conventional crops are not used. WTW GHG savings increase from around 68% to 90-95% as the bulk of production moves from jatropha to BTL and algae.	1.6%	33%	2041
High BTL, slow new oil crops only, SH	The 2020 potential remains low, as feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks, and BTL is still being proven. Fast growth from this point, principally from BTL means that 100% jet is reached only one year later, again with around 76% from BTL, 18% HRJ, and 6% from SH. WTW GHG savings are high at 80-95%, as BTL rather than conventional oil crops or jatropha dominates from the start.	0.8%	27%	2042
Very low BTL,	As in the other scenarios where conventional crops are used, HRJ based on conventional oil crops ramps up quickly from 2010, and	2.2%	39%	2040

conventional and new oil crops, SH	uses new oil crops where possible, leading to HRJ providing nearly 100% of jet in 2040, with very little BTL or SH.			
Very low BTL, new oil crops only, SH	Biofuel supply is low, mostly from HRJ, produced from new feedstocks as they become available. From the late 2040s, SHs ramp up faster, providing 56% of supply in 2050. BTL ramp up is the same as in the Low BTL scenario to 2022, as the technology is proved, but then ramps up much more slowly, as it is only ever viable with low cost feedstocks, and then only from 2023. As a result, potential feedstock availability for BTL limits the industry's growth, so it only provides 12% of jet supply in 2050. 100% jet supply is only met as a result of introduction of SH in 2020 and fast build up in the 2040s.	1.0%	10%	2050
Very low BTL, slow new oil crops only, SH	Biofuel supply is very low, mostly from HRJ, as feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks. In the 2030s, faster HRJ ramp up leads to the potential for 15% of jet supply from HRJ, but this is overtaken in 2040s, by SH. In 2050, only 94% of jet can be supplied, 56% from SH, 25% from HRJ and 12% from BTL. Again the role of another route such as SH if BTL is not viable and conventional crops are too expensive is emphasised.	0.2%	3%	After 2050
Low BTL, new oil crops only, no SH	HRJ is produced using new oil crops only: jatropha and camelina from 2012 and algal oil from 2017, with production limited by feedstock availability. By 2030, HRJ has reached around 9%, with small contributions from BTL and SH, which only grow quickly after 2035. By 2050, 68% of jet supply is split between HRJ and BTL. GHG savings increase from around 69% with jatropha and some camelina to 90-95% as algae and BTL dominate.	1.0%	10%	After 2050
Low BTL, slow new oil crops only, no SH	New oil crop availability limits HRJ potential to only 0.3% in 2020. Faster ramp up of jatropha from 2020, camelina from 2024 and algae from 2028 give HRJ supply of around 2.5% of jet in 2030, with some BTL. After 2040, BTL grows faster, leading to overall 61% of jet in 2050, of which 36% is from BTL. GHG savings increase from around 69% with jatropha and some camelina to 90-95% as algae and BTL dominate.	0.3%	3%	After 2050
Mid BTL, new oil crops only, no SH	Biofuel supply to the early 2030s is mostly from HRJ, produced from new feedstocks as they become available. From this point, BTL ramps up more quickly, reaching 24% of jet by 2040, and overtaking HRJ. By 2050, 95% of jet is supplied, of which over 60% is from BTL. GHG savings increase from around 69% with jatropha and some camelina to 90-95% as algae and BTL dominate.	1.3%	12%	After 2050
Mid BTL, slow new oil crops only, no SH	Feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks. Fast growth once they are introduced, and fast BTL build up in 2030s means that 87% of jet is supplied in 2050, of which over 60% is from BTL. GHG savings increase from around 69% with jatropha and some camelina to 90-95% as algae and BTL dominate	0.6%	5%	After 2050
Very low BTL, new oil crops only, no SH	Biofuel supply is low, mostly from HRJ, produced from new feedstocks as they become available. As BTL ramp up is also slow, and no SH is available, only 44% of jet is supplied in 2050, made up of 32% HRJ and 12% BTL.	0.9%	9%	After 2050
Very low BTL, slow new oil crops only, no SH	Biofuel supply is very low, mostly from HRJ, as feedstock availability limits HRJ production, with delayed introduction of new oil crop feedstocks. By 2050, 37% of jet is supplied, made up of 25% HRJ and 12% BTL	0.2%	3%	After 2050