THE WORLDWIDE PRODUCTION OF BIO-JET FUELS

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The current developments regarding technologies and feedstocks, and innovative new R&D developments.

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Developed in parallel with the biojet action plan of the Aeronautical Research Centre (ARC_Sudan)

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Disclaimer and caution

This report should not be used as a sole source of information on this broad topic, and particularly not as the basis for investment decisions or for commitments in planning or for infrastructure development. Instead, it should be seen as one source of information that has endevoured to be as up-to-date as possible (in mid 2014), and as a source that may be more focused than many other reports are on real issues and economics of feedstock production and aggregation.

The authors and their organisations disclaim all liability and responsibility for any decisions or investment made on the basis of information supplied in this publication.

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Preface

This report has been written to bring together the most relevant current information available in early 2014 on production of jet biofuel, and in particular the information on the potential feedstocks and the most likely technologies for production of the increasingly large volumes of jet biofuel required by 2020 and beyond.

While there is much authoritative information available on this topic it is often difficult for a person to find or compare the most relevant information: what the most feasible available feedstocks are, what the most technically suitable or cost-effective processes are, what the capital costs and technical risks are; and which are the countries where the feedstocks, technical capability, infrastructure, and availability of investment capital seem most able to all come together.

This report is being produced particularly for government policy makers, industry investors, and other people at that level. Obviously for both governments and investors to make the necessary decisions and put in place necessary forward planning, they will need to have some analysis of the available reliably authoritative information to access to help inform their decisions. This information should be brought together by people with no commercial interest in the outcomes, but who are able to recognise what is feasible, and to assess technologies and their inherent risks. Most importantly it needs to be done by people who are 'at arms length' and have no interest in the adoption of any of the range of options.

The authors have worked to produce a report that fulfils these requirements. It has been done first and foremost for the Aeronautical Research Center of Sudan which has funded this project. Our objective was to search out realistic and practical information to help inform planners and investors around the world on biofuels production logistics, capital investment and infrastructure requirements. And, above all, on the issues of producing, aggregating and transporting the necessarily very large volumes of feedstocks, delivering them on a reliable flow to the gates of the processing plants, and then piping the very large volumes to the ports, for shipping to the countries of the end users.

Chapters of this report will explore or analyse many aspects, including: how to do all this sustainably into the distant future; what the policy drivers are; what innovative new developments are in the pipeline that may radically change the status quo in production of biofuels; what are the examples of progress in countries that are actively developing their best options; which are the relatively few countries most likely to be front runners in jet biofuel production.

Our process in developing this report was to review recent literature from leading bodies, and to combine this with input on up-to-the-moment developments in the range of countries working on this field. This last source of input is necessary, partly as the available literature often is on lab work or pilot studies done some years beforehand, or on feedstocks (like algal lipids for instance, or pongamia oil) that are not as yet produced economically or in adequate volumes.

We had developed this approach for a previous report: *Jatropha oil production for biodiesel and other products – a study of issues involved in production at large scale (2013).* The topics of biojet fuel production and of jatropha oil production share some similar aspects: the need for vary large feedstock volumes, a mass of sometimes contradictory information, and the fact that the most up-to-date information was not widely known.

So a key part of our approach is to approach people working in this field around the world, particularly in feedstock production and technology development but also in policy, and used their contributed information to verify and test the information from the literature. We tried to select people or organisations that represented the full range of feedstocks, and the principal technologies. Some people who have contributed are working in the area of innovative R&D.

Andrew Lang is an Australian agricultural scientist with farming and forestry experience. He is a Churchill and a Gottstein Fellow, and a board member and a vice president of the World Bioenergy Association. As a board member of the WBA he is informed about the range of bioenergy technologies in use around the world, including within the biofuels sector. In Australia he is the current president of Farm Forest Growers Victoria. His interests are in agronomy and low rainfall forestry, and the logistics and economics of small and larger scale biomass-to-energy. Most recently he worked for the Aeronautical Research Center in Khartoum on the potential, economics and logistics of large scale production of jatropha oil for biodiesel production. Over recent years he has attended and presented at renewable energy conferences, bioenergy conferences, pellet conferences, and forestry and farm forestry conferences, in Australia and other countries including USA, China, Sth Korea, Brazil, Austria, India, Sweden, Finland, Turkey, South Africa and North America. His reports and publications deal with small-scale and lower rainfall forestry management and bioenergy (including biofuels) development.

Hazir Farouk graduated as a mechanical engineer, did her MSc in Malaysia on Advanced Manufacturing Technology, and her PhD was on optimising the process of producing biodiesel from jatropha oil with high free fatty acid content and testing the jatropha methyl ester in IC engines and a liquid fuel burner. She is an assistant professor at the Mechanical Engineering School, Sudan University of Science and Technology. She is working on the potential for anaerobic digestion of putrescible wastes to biogas for Sudanese municipalities and industry. She is also working with the Aeronautical Research Center (ARC-Sudan) as a research consultant on the development of the Sudan's Biofuels Roadmap (including large-scale biodiesel production), and on options for jet biofuel manufacture in Sudan. Over the last 18 months she has presented on aspects of this work at major conferences in Finland, Turkey, Austria, Sudan, Sweden, Germany and Malaysia. She is a board member of the World Bioenergy Association, representing Sudan and the region's Arabic-speaking countries.

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Executive Summary

There is a strong pressure on commercial airlines firstly to cap and then to reduce their emissions of greenhouse gases due to use of petroleum-sourced jet fuel. One key way that they can do this is by beginning to blend fossil jet fuel with jet biofuels produced from one or other biomass feedstocks by one of a growing number of approved technologies. Presently these jet biofuels are able only to be blended at up to 50% of the total volume, though in most of their characteristics they are the same, or some respects even superior, to the petroleum-sourced jet fuel.

Two major obstacles are presently impeding the production of biojet fuel. Firstly, depending on feedstock and scale of production, it is presently from 3-4 times up to 10-15 times the cost per unit volume, relative to petroleum jet fuel.

Secondly, the amounts of feedstock needed to produce the target volumes of biojet from 2020 onward are very large. The amounts of feedstock needed produce the amounts forecast to be required by 2050 are 10 to 20 times greater. To produce these far larger volumes of feedstock sustainably and cost-competitively will need some significant new developments in both feedstocks supply and in processing technologies.

Major advances have been made in this whole area since about 2009, including in production and testing of the ASTM-approved biojet fuels, and most recently, in development of at least four other possible production technologies or variants on the initial technologies. These are all at some stage of assessment in the ASTM-Emerging Fuels Committee's approval process and two or possibly three (being the DSHC, ATJ and HDCJ processes) are likely to be approved before the end of 2014.

In looking forward past 2020, the only thing that is certain is that change will continue to take place quite rapidly and often unpredictably in this overall field. However, it is probable that most of the following developments and changes will take place:

- Global warming will continue, and the international pressures to reduce greenhouse gas emissions, country-by-country and worldwide, will escalate. One outcome will be a lift in targets for biofuels use (including biojet fuels), and increase in prices of fossil fuels via some form of carbon 'tax'.
- Pricing and supply of crude oil will become less predictable, and, in absence of some significant international system of carbon taxation, the traded crude oil price will trend upward (however, a strong effective carbon tax or emissions trading system could cause crude oil use, and possibly even price, to decline).
- Cost per unit volume of jet biofuels (and other transport biofuels) will fall by some significant fraction, due to innovation and to scale, to improved plant designs, and number of production plants. It is possible that some production subsidies may be developed – for instance on biojet sold into the EU.
- Demand for biomass of almost every form will develop or firm as oil price rises and as technologies become widespread for using biomass feedstocks to produce substitutes for the whole range of other petrochemicals apart from transport fuels. This includes for sheet and moulded plastics, dyes, fibres, basic industrial chemicals, and the vast number of other petroleum-based products.
- Increase in the world's population (most particularly in Africa), will intensify the use of quality well-watered land. It will be required primarily for food production, secondly for fibre production, and in a distant third place, for energy crop production (including for crops like sugar cane). Pressure on secondary quality land (from a production viewpoint) will also increase.

- Impacts of forecast global warming by 2050 could significantly alter the rainfall and river flow patterns we are used to, and increase average temperatures and summer evaporation rates. The beginnings of these long-term slow changes are already evident.

It can be seen from all these points that many countries are in a potentially quite vulnerable position. This might include exposure to the flow-on effects of global warming. These include higher temperatures, higher evaporation rates, more extreme weather events, increased desertification rate, lower and more variable rainfall, and uncertain impacts on river flows. Where there is already a strong population growth it will increase the need for water, energy, food, and housing and a whole range of services. The rate and degree of onset of increased global warming will depend on the overall world actions and so it might appear irrelevant for developing countries to independently take significant steps toward reducing already quite low greenhouse gas emissions (both on a national and per-capita basis).

But when increasing evidence and impacts of climate change are being felt strongly around the world it is certain to bring about an intensified global response, and in that case there will also be real opportunity for developing countries to benefit. This would be in a number of ways, as the world's most economically developed countries look at funding actions beyond their own borders. These opportunities might include:

- Permanent carbon sequestration – by major reforestation action
- Reduced emissions – by producing and utilising biofuels (including jet biofuel) and by reducing waste and using waste streams for energy production (including biofuels)
- Energy efficiency – particularly in industry and transport, and in residential design
- Development of renewable energy – including solar hot water, and solar electric, but also biomass to energy, including by using the residues of agriculture, jatropha plantations and thinnings of reforested areas

For most developing countries, the production of biofuels -including jet biofuels, needs to be a part of a wider strategy that is developed with these above opportunities in mind. This process of investment by richer countries to help reduce GHG emissions, or sequester atmospheric carbon, has already commenced, and many developing countries are already involved with the countries of the EU, North America, Saudi Arabia and the Gulf States, and East Asia, in long running programs within this overall energy and emissions reduction area.

It has to be said that the unsubsidised production cost of jet biofuels is not yet (in 2014) equal to production cost of petroleum jet fuel. However it is necessary to do the full studies to determine if a particular country will be less affected by some of the major limitations affecting biojet production costs elsewhere. This may be due to available water and large areas of unutilised and presently-unproductive arable land. Production of relatively low cost vegetable oil in mechanically harvested, irrigated high yielding plantations of perennial species, including jatropha, could be one option. Though this has not been a successful option in the previous decades, the advances in mechanisation, processing and in genetics mean that the economics may now be substantially improved.

Chapter 1: An overview of the current situation of jet fuels and jet biofuels

The world's commercial aviation fleet of jet aircraft presently consumes about 200 million tonnes a year (250 Mm^3) of jet fuels annually, principally in the form of aviation kerosene (Jet A1) produced as one product from the refining of crude oil. This volume is about 6% of world refinery output. In 2012 the USA consumed about 93 Mm3 or 37% of this output, 63 Mm3 or about 25% was used to fuel aircraft fuelling in the EU, Brazil used about 7 Mm3, or 3% of total jet fuel, and most of the remaining 35% was being consumed in East Asia, South East Asia and the Gulf States.

Worldwide, commercial aviation is forecast to grow at up to 5% a year and this trend is forecast to continue towards 2050. Assuming aircraft fuel efficiency development the estimate is that fuel demand will rise at up to 3% per year.

Rising fuel cost is one driver of the interest in aviation biofuel development. While in the 1990s fuel cost represented 10-15% of operating costs, by 2005/06 fuel cost represented 20% of an airline's operating cost. Now as a global average it is past 30%, and in 2013 was up to 40% for Brazilian airlines.

The other main driver is the likelihood of carbon tax imposts on airlines on the basis of petroleum-sourced jet fuel use. While aviation fuel combustion by volume technically only represents 2-3% of anthropogenic (human-caused) GHG emissions, in practice the combustion products are mostly injected directly into the upper atmosphere and so have somewhat more 'greenhouse' impact than the same volume combusted at ground level.

The aviation industry world-wide is rapidly developing solutions to comply with pressures to reduce the presently rapidly rising CO_2-e emissions. One of the solutions is the production of jet fuels from biomass, including plant oils and animal fats. From 2012 aviation was to be included in the EU Emissions Trading Scheme (ETS), and so all airlines flying in and out of the EU were to be affected. The EU Renewable Energy directive required that 10% of fuels from transport be sustainably produced biofuels.

Refuelling of planes in Europe consumed about 53 million tonnes in 2010, and annual consumption of jet fuel by the largest European airlines in 2010 (Lufthansa, AF/KLM and BA) was about 20 million tonnes. The target set by the European Commission was for the aviation sector in the EU to be sourcing and using 2 million tonnes of biojet fuel by 2020.

In 2011 the European Commission produced a White Paper for reducing EU reliance on imported fossil transport fuels and to cut transport emissions by 60% by 2050. In this a target is set that there should be a 40% use of sustainable low carbon fuels in aviation by 2050.

The members of the International Air Transport Association (IATA) have pledged the following goals:

- To improve fuel efficiency by 1.5%/year over the decade to 2020
- To make all aviation industry growth carbon neutral by 2020
- To reduce net CO_2-e emissions by 50% by 2050, against 2005 levels

The changes to be implemented by 2020 will only have a minor impact on GHG emissions from jet aviation, but they are helping to drive the development of technical processes for large-scale production. They will also drive development or production of sustainably produced non-food biojet production feedstocks. This sets the stage for achieving the 2050 goals of a far greater fraction of jet fuel consumption to be produced from biomass. However, the clear limitation is not with the technical processes but with the sourcing (and the cost) of feedstock volumes needed for production of far larger amounts of jet biofuels at competitive cost.

Chapter 2: Feedstock options, and limitations on supply of some feedstocks

Since about 2007, and particularly since 2011, airlines, commercial jet aircraft producers, and jet engine manufacturers, have been involved in trialling biojet fuels and assessing which type of renewable jet fuel to source, and working out how to adapt to the legislative pressures or IATA rules that are due to come into effect within a very short time period.

At the same time the economic margins of all airlines are very tight. The cost of fuel (up to 34% of costs in late 2013) is a major contributor to their operating costs. So they have to find a source of renewable fuel for blending that allows them to comply with regulations and binding commitments on CO2-e emissions reduction, but that is not out of step with the projected cost of Jet A1 fuel. And any airline will not want to be paying more than their competitors will be paying.

The feedstocks that have already been used to produce jet biofuel fall into only three categories

- Vegetable oils – this includes oil from seeds of camelina, jatropha, rapeseed, mustard, maize (corn), as well as palm oil, and used cooking oil. The HEFA process used can also utilise animal fats and algal lipids.
- Lignocellulosic biomass (wood and agricultural residues)
- Sugar

The range of possible feedstocks is very broad . They include:

Lipids: all vegetable oils and waxes, and animal fats including –

Lipids from microalgae

Oil from seeds of halophytes (salt-tolerant plants)

Jojoba wax

Microbial oil (such as produced by yeasts and bacteria)

oils from a wide range of flowering plants including trees

Bio-alcohols (alcohols produced from biomass) **-**

Ethanol, methanol and butanol

ligno-cellulosic feedstocks, including

Woody biomass (via pyrolysis to pyrolysis oil, or via gasification to synthesis gas)

Energy crops: including fast growing trees, and grasses, such as bamboo, miscanthus and giant reed

Agri-biomass (agricultural crop residues including straw, stalk, seed husks, etc.)

Halophyte biomass (via fast or flash pyrolysis to bio-oil or synthesis gas)

Municipal waste feedstocks

Refuse Derived Fuel (sorted municipal wastes, via pyrolysis)

Industrial flue gas

Carbon monoxide (CO) in high concentration in the flue gas can be the base molecule for formation of long-carbon-chain molecules

Other

Putrescibles wastes, including aquatic weeds (via anaerobic digestion and upgrading of biogas to biomethane).

To this point the largest fraction of the jet biofuels reported as used in test flights of military and commercial jet-engined planes has been produced from one or other vegetable oils (including used cooking oil), or using a feedstock of algal lipid or animal fat or tallow. This fuel is produced using a hydrogenation and reforming process to convert the long chain triglyceride molecules of the feedstock oil into branched long carbon chain molecules making up a jet biofuel that conforms to the US or EU standards. This group of airlines include KLM, Air New Zealand, Qantas, TAM and GOL (in Brazil), and 20 or more other airlines.

Some flights have been made using synthesized jet fuel produced by the Fischer-Tropsch pathway (though made using natural gas or coal instead of biomass as the feedstock).

One other exception was a flight in 2012 by a TAM airliner in Brazil using a ‘drop-in’ renewable fraction for adding to jet fuel, made from cane sugar by the American company Amyris. This variant of the Direct Sugar to Hydrocarbon (DSHC) pathway was approved by ASTM in 2014 for blending with petroleum jet fuel at up to 10%.

Supply chain issues: of feedstock to production plant and of product to users.

The economic and logistical issues of feedstock production and aggregation, and issues around sustainability.

Oils, fats and algal lipids to the HEFA process. In the many studies done on production of biojet using the HEFA processing pathway two things are noted frequently. One is that while the capital cost of the plant used in the production process is relatively low (particularly by comparison with the plants for the Fischer Tropsch process), the cost of the feedstock makes up 60-75% of the final cost of the fuel. This result in current costs of biojet made from these feedstocks being from three times the price of Jet A1, and to ten times or more – depending on the source of the oil or fat feedstock.

In most cases the cost of the oil or tallow is high primarily due to a relatively high aggregation and production cost, and because supply is approximately balanced by demand. Since these are usually products that are being sold into a large market place, one type of vegetable oil, fat or tallow can often be readily substituted for a number of others, depending on bulk traded price. This trading broadly supports the price, and prevents the reduction of price for any one oil type below a certain point. This point is still too high to allow biojet to be made from this group of feedstocks at a price presently competitive with jet fuel sourced from petroleum.

The other aspect of the clean vegetable oil fraction of this large array of HEFA-process feedstocks is that in most cases the yield per hectare or per unit of labour is relatively low, at under 1 tonne oil/ha (the main exception is for palm oil, with a yield of about 4 tonnes oil/ha). So the uses of these oils for food production or for chemical, pharmaceutical or industrial uses, when added to the rising demands from the food sector, plus the relatively low yield, and the cost of fossil fuels required for the production, harvesting, etc., means that the cost will not drop.

Issues of sustainability of production play a role with some oil types. For example, expansion of area planted to oil palm in the main current supply countries (Malaysia and Indonesia) is hampered by the fact that this means either displacing production of other food products, or requires clearance of biodiverse forest or drainage of carbon-rich peat swamps.

Research is currently underway on possibilities for producing vegetable oil by means that do not require vast areas of land well-suited for other purposes. While algae are most mentioned in this respect there are other micro-organisms able to produce suitable oil, including yeasts and bacteria, which could become more important. However, as with all aspects in this research field, it is one thing to produce oil from some microorganism in a one cubic metre container in a lab, but quite another to produce millions of litres at a cost per litre significantly below that of palm oil.

So the future of production of a biojet from oils and fats is about achieving sustainability, volumes and relatively low cost. To achieve these three outcomes the only obvious options are to produce non-food grade oil feedstocks from high yielding sources in places where the very large areas (millions of hectares) of production space is available, where competition with (or displacement of) existing food production is not an issue, and where adequate water and other inputs are also available.

Three main oil sources are put forward as filling these requirements. These are jatropha, microalgae, and halophytes. Each has the potential to be produced on available unutilised land (or in fresh or salt water in the case of algae). Each can be potentially produced in significant volumes, and each is potentially able to be mechanically harvested and handled quite cost effectively. This means that the oil could potentially be produced at a cost landed in Rotterdam or Singapore at half the cost/litre of palm oil or soy oil.

Most importantly, the oil product from these sources has not got an established demand, and in the case of jatropha and the leading halophyte option the oil is not edible.

Ligno-cellulosic feedstocks to the FT process, the pyrolysis pathway, the cellulosic ethanol Alcohol to Jet (ATJ) pathway, or the DSHC pathway

World-wide there are a number of possible L-C feedstocks that appear to be available in the necessary great volumes over a long period. This includes post-mature oil palms in Malaysia and Indonesia, and some other countries/regions; woody energy crops in Brazil, Australia and sub-tropical Africa; and forestry residues in Canada, the Nordic countries and Russia. Also there are many regions where one or other species of perennial giant grasses could be produced in adequate amounts. These include miscanthus (elephant grass), clonal bamboos, high-lignin sugar cane and semi-aquatic reed species.

But in practice the economics and harvesting and transport logistics will work against some of these options or rule out some of these technologies. This might include the Fischer-Tropsch pathway, due to the very high capital cost of the plant, and where to achieve the necessary economy of scale it needs a massive supply of feedstock annually. It similarly may eliminate the cellulosic ethanol pathway for the same reason.

However the pyrolysis pathway does still appear to have real possibilities. It uses relatively lower cost plant to convert the biomass to pyrolysis oil, and the high energy density of this allows its freighting from a number of satellite pyrolysis plants to some central biojet production plant.

Bio-alcohols and the ATJ pathway

Bio-alcohols are currently being produced cost-effectively by several processes. The principal one is from sugar cane, with the bagasse and harvest trash able to be processed either into cellulosic alcohol, converted to pyrolysis oil, used in the FT pathway, used as a furnace fuel, or gasified to produce synthesis gas.

Methanol can be produced by processing of wood product or from synthesis gas or from the carbon monoxide component of industrial flue gases. And butanol can be produced by clostridium bacteria from the synthesis gas produced by gasifying cellulosic material (plant matter).

While the production of bio-jet from other feedstocks is technically practicable, it is not yet seen as either economically feasible or energy efficient. For instance the methane produced from putrescible waste in an anaerobic digestor can be upgraded to near-pure methane and then put though the Fischer-Tropsch process to eventually produce liquid biofuels, but it is more economic and energy efficient to use it directly for electricity production,.

Sugars (including 'cellulosic' sugars) and the Direct Sugar to Hydrocarbon pathway

Sugars can be converted by microorganisms into a number of intermediate organic molecular forms including farnesene and iso-butanol, and both of these can be converted into molecular forms that are suitable for blending with petroleum jet fuel.

The achievement of these impressive achievements at laboratory scale, and now at commercial scale, is an indication of what is possible when prioritisation of efforts mean that research effort and funding combine. This will prove to be only the beginning of such advances on many fronts in the area of biofuels and cost-competitive replacement of petro-chemicals with alternatives based on biomass.

Summary

The production of cost-competitive biojet by the HEFA pathway appears to require development of one of the three possible new sources of non-edible vegetable oil. One source that some developing countries could begin to explore is via production of jatropha oil. To produce a good quality of jatropha oil at a price around US$500/tonne will need much work. It will entail development of a large aggregate of planted area comprising many sites, with highly genetically improved jatropha being grown with adequate irrigation and mechanical harvesting and efficient processing.

The other two feedstocks in this non-edible vegetable oil group are oils from microalgae or halophytes. The process, economics and commercial practicality of these options is not yet really determined, but both should be monitored as possibilities for the mid-term future.

The production of biojet by the FT or pyrolysis pathway will need identification of the necessarily large volumes of biomass that are not presently utilised or that could be economically produced. This may include some aquatic or semi-aquatic plants like reeds, plants able to utilise accessible shallow (possibly brackish or saline) groundwater, or deeper-rooted non-indigenous woody plants (such as mallee eucalypt species from Australia) that can thrive in the areas of many hotter lower rainfall regions that receive the necessary minimum annual rainfall.

The development in Brazil of products such as farnesane produced from cane sugar and able to be blended with petroleum jet fuel at up to 10%, show that one option for sugar producing countries is to look at the potential for using some part of the country's sugar cane production for producing higher-value products of this sort.

Another possible feedstock for production of biojet fuel is the municipal solid waste streams (sheet plastic, PET containers, paper, cardboard, wood), which could technically be utilised as a feedstock for the FT process or for flash pyrolysis (to synthesis gas) or fast pyrolysis (to pyrolysis oil) processes.

Chapter 3: The 'short list' of feedstock processing and refining technologies, and the technical requirements for biojet fuel.

While there is a global interest in producing alternatives to petroleum-sourced jet aviation fuel, the production technologies being used in 2014 that are approved by the recognized international authority are still limited. There are currently three ASTM-approved processes for producing biojet fuel: the Fischer-Tropsch (FT) process based on use of a biomass feedstock (sometimes also called BTL -biomass to liquid), which was approved in 2009, the hydro-processed esters and fatty acids process (HEFA) which was approved in 2011, and the hydro-processed depolymerised cellulose to jet (HDCJ) process which is referred to as Synthesized Iso-Paraffinic (SIP) fuel, which was approved in June 2014. Some other pathways are well-advanced in the ASTM certification process including alcohol oligomerisation to jet fuel (ATJ).

Research also is focused on developing the process of bacterial conversion of flue gases rich in carbon monoxide (CO) to produce ethanol. This process is reportedly being scaled up by LanzaTech in China, and in 2013 two demonstration plants were said to be in development.

While the three currently ASTM-approved processes are being used to produce biojet, most volume is being produced by the HEFA pathway, since this allows use of existing plant, technically proven processes, and use of a variety of available oils from plants, algae, used cooking oil, and other feedstock such as animal fats. However, the other approved process – production of biojet from ligno-cellulosic biomass such as wood or straw via the FT process – has the potential to produce biojet more cost-competitively from plants large enough to give economy of scale. Table 1 summarizes the current biojet fuels pathway.

Table 1: The current biojet fuels pathway

Bio jet fuel pathway	Certification	Type of feedstock	Feedstock costs	Potential Scale
Fischer-Tropsch (FT)	ASTM 2009 "Max. 50% blend with fossil jet"	Woody and agricultural residues (lignocellulosic) biomass	low	Very large
Hydroprocessed Esters and Fatty Acids (HEFA)	ASTM 2011 "Max. 50% blend with fossil jet"	Plant oils, waste oils from food industry, animal fats, algal oil	High for edible oils but expected to decrease with alternative sources of oil. Medium for animal fats.	Medium
Alcohol oligomerisation to jet fuel (ATJ)	No, "Under process of ASTM certification"	Sugars, Starches	medium	Medium
Direct Sugar to Hydrocarbons (DSHC)	ASTM 2014 "max 10% blend with fossil jet"	Sugars, Cellulosic materials	medium	Large
Hydrogenated Pyrolysis Oil (HPO)	No, "Under process of ASTM certification"	Woody (lignocellulosic) biomass	medium	Very large

Fischer-Tropsch Synthesis

The Fischer-Tropsch process was pioneered in 1920 by Franz Fischer and Hans Tropsch. Their process took a synthesis gas produced from coal and this was converted to liquid fuels using a catalyst of alkalized iron chips and reactor conditions of temperature of 673K and pressure of 4100 bar. This technology is based on a catalytic process driving the reaction of carbon monoxide with hydrogen, with further steps resulting in production of liquid hydrocarbons.

The process has four main steps. The first step is creation of synthesis gas, which is a mixture of hydrogen and carbon monoxide. Whether using coal or biomass as feedstock, this step is accomplished by gasification, during which the feedstock is reacted with steam at high temperatures and moderate pressure.

The synthesis gas leaving the gasifier contains large amounts of CO2, as well as small amounts of gaseous compounds derived from impurities, such as sulfur, that are present in the feedstock. Both CO2 and impurities have a detrimental effect on FT synthesis. The second main step in the FT process removes these undesirable compounds from the synthesis gas stream. After this step the concentrated CO2 stream is released to the atmosphere.

The third step is the FT synthesis. During this step, the synthesis gas is passed over an iron- or cobalt-based catalyst under specific process conditions to form a broad mixture of hydrocarbons ranging from gases (short chain hydrocarbons such as ethane) to waxes (long chain hydrocarbons). By altering the reaction conditions (catalyst, temperature, pressure and time) the distribution of carbon length of the resulting hydrocarbons can be shifted to maximize the desired carbon chain length; so, for example, of middle kerosene distillates with a carbon chain length of C9-C15.

After leaving the FT section of the facility, the hydrocarbon product is upgraded to liquid aviation fuels using well-established methods commonly used in petroleum refineries. The outputs of the process can be narrowed to middle distillates and naphtha, both of which have a near-zero sulfur content. The middle distillates can be separated into a mix of automotive diesel and jet fuel. The process of FT is illustrated in Figure 1.

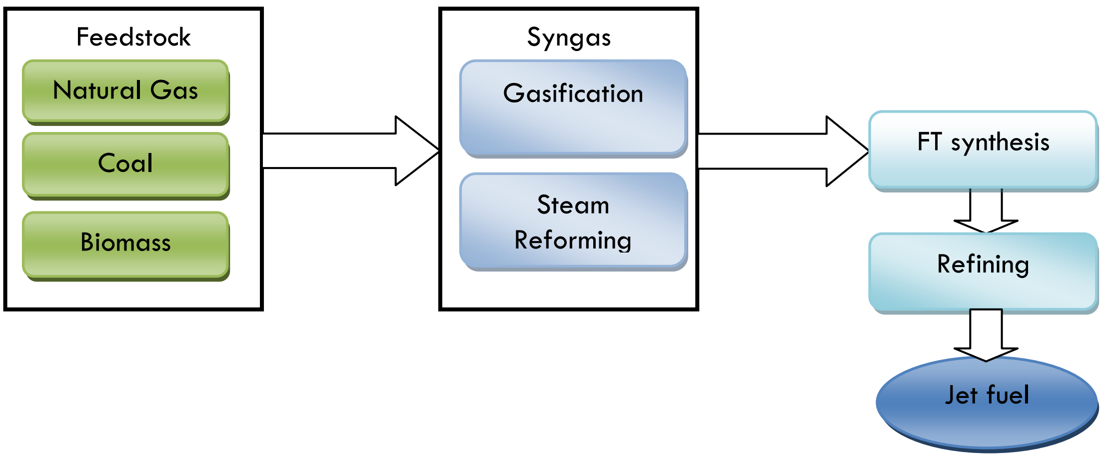

Figure 1. The Fisher-Tropsch process

When using coal as feedstock, the conversion is called coal-to-liquids or CTL. When using natural gas or biomass as feedstock, the process is called GTL (gas to liquids) and BTL (biomass to liquid) respectively. The products produced in the FT process are a mixture of hydrocarbons (HC) with carbon chains corresponding to gases (range from C1 to C4), liquids (from C5 to C20) and even waxes (>C20). FT fuels burn cleanly without sulfur dioxide (SO_2) or sulfuric acid (H_2SO_4) aerosol emissions, thus leading to increased combustion chamber and turbine life. In addition, their improved thermal stability should reduce deposits on engine components and in fuel lines. Furthermore, this aromatic-free fuel emits fewer particulates than conventional jetfuel. On the other hand, there are some disadvantages. These are in regard to the minimum density requirement obtained, and that the absence of aromatic compounds can result in leaks in the seals of certain types of seals in fuel systems. However it is possible for aromatics to be added to make up the desired percentage. The typical process steps for BTL are illustrated in Figure 2.

As a suitable quality syngas can be produced from any uncontaminated organic source, the four FT process steps are not affected by the feedstock used. Therefore, fuel produced by this process is similar to that obtained from non-renewable feeds such as natural gas or coal. Feedstocks that could be used for gasification include any plant biomass containing sugar, starch, cellulose or other complex carbohydrates. Feedstocks being considered for use include sorted municipal wastes, agricultural and forestry wastes, switchgrass, sorghum, miscanthus, short rotation woody crops including willow and poplar, or even macroalgae.

The FT process is commercially proven for the conversion of coal and natural gas into non-renewable liquid fuels as CTL and GTL processes. Synthetic jet fuel produced by the South African company Sasol using CTL technology was the first synthetic jet fuel to gain ASTM approval for use in commercial jet airliners.

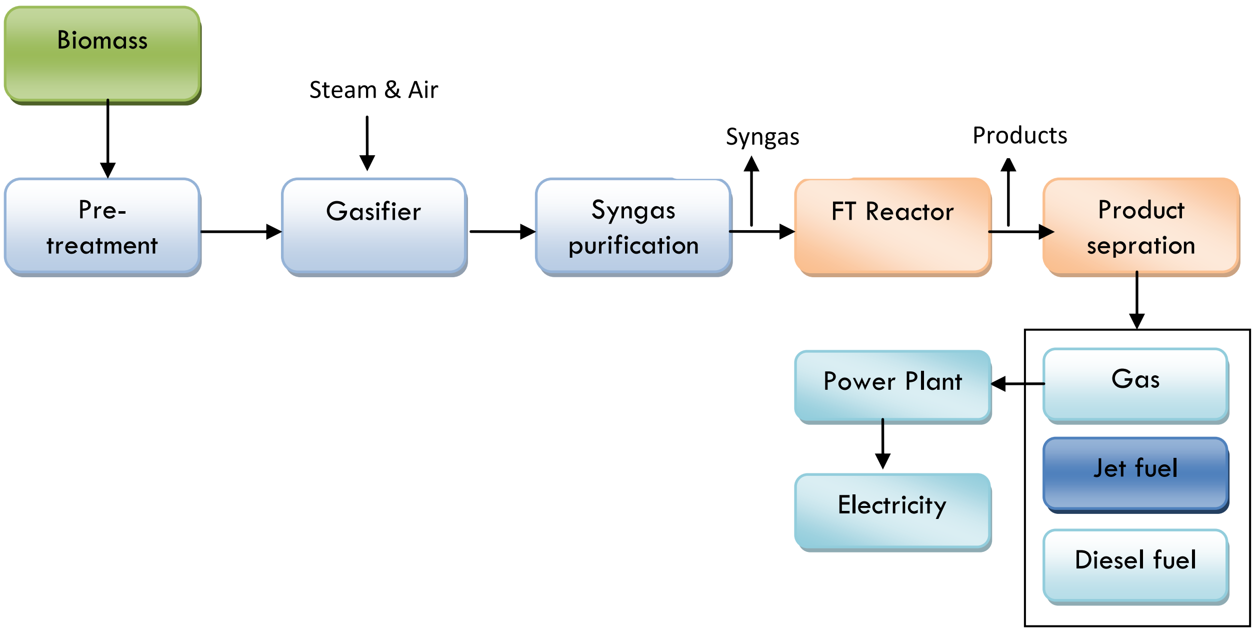

Figure 2. Fischer-Tropsch synthesis of liquid hydrocarbons

Hydrogenated Esters and Fatty Acids (HEFA)

HEFA technology is based on the hydro-processing of natural oils and fats. In this process, oxygen is first removed from triglycerides by hydro-deoxygenation/decarboxylation, and double bonds are saturated by the addition of hydrogen to produce long straight-chain hydrocarbons. Vegetable oils and fats are triglycerides, which mostly contain fatty acids with carbon numbers in the range C14 to C20, but jet fuel contains hydrocarbons in the range C8 to C16. These straight hydrocarbons mostly fall into the diesel range and are converted into jet fuel by selective cracking and isomerisation which consumes more hydrogen. The process steps are illustrated in Figure 3.

Chemically hydrotreated vegetable oil-based biojet fuels (i.e., the product of the HEFA processing) are a mixture of paraffinic hydrocarbons and are free of sulfur and aromatics. The low-temperature properties of HEFA can be adjusted to meet the local requirements by adjusting the severity of the process or by additional catalytic processing. HEFA fuel is of very high quality and its properties are very similar to the GTL and BTL jet fuels produced by FT-synthesis.

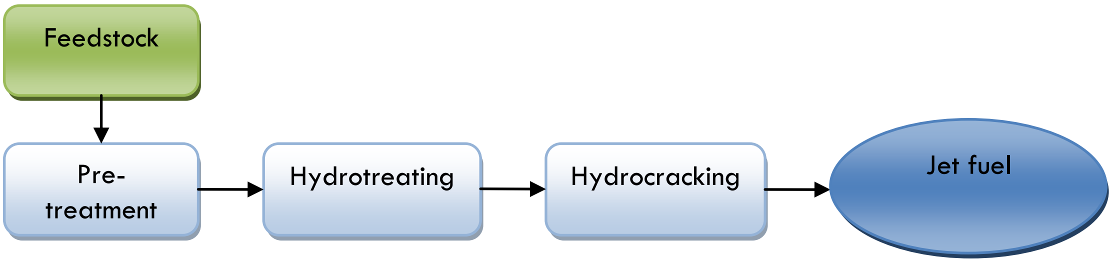

Figure 3. Hydrogenated Esters and Fatty Acids process steps

The ASTM-approved HEFA process uses vegetable oils, animal fats or used cooking oil as the feedstock. This has been developed to a commercial output scale by the companies Neste Oil (Neste Oil's version of the HEFA process, called NEXBTL, has been developed and patented by the company itself), Honeywell UOP (the UOP variant of the HEFA process is patented as Green Diesel) and Solena, among others. Over 2013 and 2014 the capacity of plants able to produce biofuels by the HEFA pathway has increased to over 1 million tonnes, and other plants are in development or construction that should soon increase this to at least 2 million tonnes. However most of this capacity is used for production of the substitute for fossil diesel fuel and only a small fraction of this capacity is dedicated to biojet production.

The current HEFA plants include those operated by the Neste Oil Company. This include at least one 190,000 tonne/year plant in Finland, an 800,000 tonne/year plant in Singapore and another 800,000 tonne/year plant in Rotterdam (Figure 4 shows a pilot HEFA plant in Finland).

The capital cost of these plants is reportedly of the same order as for a conventional oil refinery of this capacity. The initial focus on using the HEFA process for production of biojet is because the cost of plant for the HEFA process can be about a quarter the capital cost of a FT plant of the same capacity. However, the catch is in the cost of the feedstock oils, which presently means that cost of biojet even at full commercial production scale produced by the HEFA pathway (at an estimated US$1700/tonne) is still up to double the cost of fossil-sourced biojet (at about US$990/tonne). The rise in cost of fossil aviation fuel will not necessarily help make biojet made by the HEFA process more competitive as the price of bulk vegetable oils has tracked the crude oil price very closely to date.

Figure 4. A pilot HEFA plant in Finland

Alcohol oligomerisation to jet fuel (ATJ)

In this route, jet fuel range hydrocarbons are prepared from alcohols such as ethanol or butanol by oligomerisation. The alcohols used as a starting material can be produced from sugars or lignocellulosic biomass, and thus have greater potential to produce jet fuel in very large volumes, compared to use of vegetable oils/fats via the HEFA process. There are several chemical processes that can be employed to oligomerise alcohols. In each of these processes, water and/or oxygen are removed from the alcohol molecules and hydrogen is added. Jet fuel obtained by ATJ is fundamentally similar to petroleum-sourced jet fuel and ASTM approval of the ATJ process was expected to be completed by the end of 2014.

Many companies have reported development of processes to produce jet fuel from alcohols, but its economics depend upon the source from which alcohols are produced. Gevo, an American renewable chemicals and biofuels company, has claimed to have successfully produced isobutanol from fermentable sugars derived from cellulosic biomass, and converted this into isobutylene and paraffinic kerosene (jet fuel). Another company, Lanzatech, is also planning to produce alcohol from industrial waste gases containing 'clean' carbon monoxide and converting this alcohol into jet fuel. Summary of steps in this process are illustrated in Figure 5.

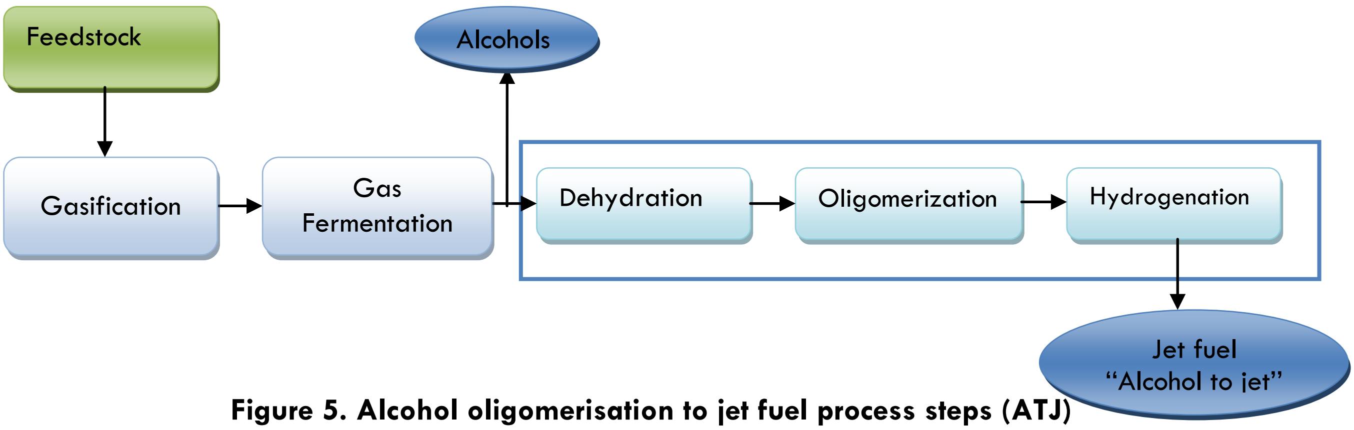

Figure 5. Alcohol oligomerisation to jet fuel process steps (ATJ)

Direct Sugar to Hydrocarbons (DSHC)

The Direct Sugar to Hydrocarbons (DSHC) process converts sugar to a pure paraffin molecule that can be blended with conventional jet fuel. The process utilizes an advanced fermentation process to accomplish the conversion. This biological conversion is carried out under aerobic conditions, unlike 'traditional' fermentation of sugars to ethanol. The feedstock in this process can be any cellulosic material. The feedstock is pre-treated using enzymatic hydrolysis. After hydrolysis the resulting juice of simple sugars is filtered in order to remove lignin-rich solids and to purify it.

Subsequent to solids removal the sugar stream may be sent directly to the biological conversion or further processed to concentrate the sugars by evaporation or other means. After the biological conversion the end-product must be separated from the water phase. Here the paraffin production has an advantage over ethanol fermentation, as the solubility of long hydrocarbon chains in water is low and the two phases separate relatively easily. The process steps are illustrated in Figure 6.

This pathway is recently approved for commercial aviation use by the ASTM. The details of fuel properties and specifications of this new fuel (referred to as Synthesized Iso-Paraffinic (SIP) have been added as Annex 3 to the alternative jet fuel specification D7566. The process in this pathway involves a yeast fermentation process fed by sugarcane (or any other plant sugars including from sugar beet, sweet sorghum or cellulosic sugars) to produce the unsaturated fermentation product farnesene. This then undergoes another conversion process that results in the hydrogenated and saturated hydrocarbon farnesane. This approved pathway is developed by collaboration between French petroleum refining and distribution company Total and California-based industrial bioscience company Amyris. However, for its use in commercial aviation this new biojet product is presently only to be used in blends of up to 10 per cent with conventional jet kerosene.

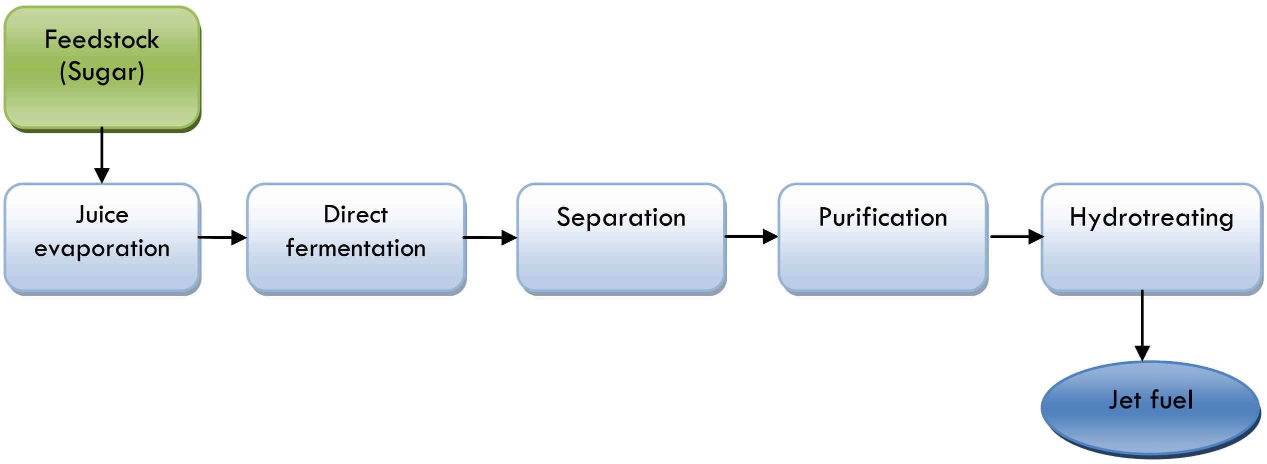

Figure 6. Direct Sugar to Hydrocarbons (DSHC)

Hydrotreated Depolymerized Cellulosic Jet (HDCJ)

This process (also known initially as HPO) is based on pyrolysis oil produced from lignocellulosic biomass by fast pyrolysis. This then can be hydrotreated either in dedicated facilities or co-processed with petroleum oils in refineries. Pyrolysis is the process of direct thermal decomposition of the feedstock organic matrix in the absence of oxygen. The feedstock for the pyrolysis process could be any dried and granulated carbon-rich feedstock including biomass. The outputs are CO2, flammable gases (mainly CO, CH4, H2, C2H6, and C2H4), bio-oil (modeled as CH1.9O), char (carbon) and ash. The pyrolysis process conditions that favour liquid pyrolysis oil product (which is a complex mixture of water and organic chemicals) are determined by the temperature, residence time, heating rate and other reaction parameters.

In producing biojet fuel by this pathway the products from the pyrolysis process are gasified in the presence of an oxidizing agent (typically steam) to produce hydrogen gas and carbon monoxide (that together make syngas), volatiles (represented as methane) and carbon dioxide. Once the gasification process has been completed, the syngas can be further processed into hydrocarbon chains of varying length, which are then refined to isolate the desired fuel (i.e. jet fuel) using the existed techniques commonly implemented in petroleum refineries. The biojet produced from pyrolysis oil contains a certain amount of aromatic compounds which are currently needed in jetfuel to avoid fuel system and engine sealing problems. The summary of the process steps are illustrated in Figure 7.

While there are several R&D initiatives developing fast pyrolysis processes, the pyrolysis oil to jet processing is still in demonstration phase. A few of the technology leaders (e.g. Ensyn/Envergent, a joint venture between UOP Honeywell and Ensyn Corp from Canada and BTG in the Netherlands) are implementing the pyrolysis process on a commercial scale to produce crude pyrolysis oil. Envergent/UOP, for example, is conducting a demonstration project for pyrolysis and an upgrading technology to transport fuels at the Tesoro refinery in Hawaii.

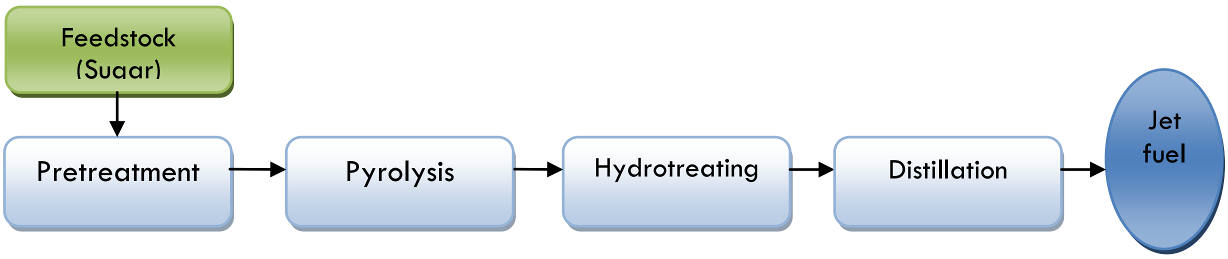

Figure 7. Hydrotreated Depolymerized Cellulosic Jet (HDCJ)

Technical specifications and certification of jet fuel

The aviation turbine fuel (Jet fuel, mostly in the form of Jet A1 for commercial jet airlines) is produced from conventional hydrocarbons. The range of their sizes (molecular weights or carbon numbers) is restricted by the requirements for the product: for example, freezing point or flash point. Jet fuels are sometimes classified as either kerosene or naphtha-type. Kerosene-type fuels include Jet A, Jet A-1, JP-5 and JP-8. Naphtha-type jet fuels, sometimes referred to as "wide-cut" jet fuels, include Jet B and JP-4.

The technical certification of commercial aviation jet fuels (Jet A and Jet A-1) is defined in US by the American Society for Testing and Materials International (ASTM) and specified in the ASTM D1655 standard. The other standard defined in Europe is the UK Defence Standard and specified in DefStan 91-91. There are some other standards, including:

- Joint Inspection Group (JIG) Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS, or “joint checklist” – international).
- GOST 10227 TS-1 (Russia and CIS)
- Number 3 Jet Fuel (China)
- Others, produced by organizations (engine manufacturers, pipeline operators, etc.) wishing to define fuel to their own requirements.

While the ASTM D1655 and DefStan 91-91 have nearly identical requirements for Jet A-1, the other specifications are all very similar. Table 2 lists the key physical and chemical specifications defining Jet A-1 according to ASTM D1655.

Table 2. Physical and chemical specifications defining Jet A-1 (ASTM D1655)

Properties	Explanation	Jet A-1
Acid no. mg, KOH/g	The number of milligram of KOH required to neutralize one gram of oil or fat	0.1 (max)
Flash point, ˚C	The temperature at which the fuel ignites in the engine and combustion occurs	38 (min)
Density @ 15°C, kg/m3	How heavy the fuel is per liter	775-840
Freezing point, ˚C	The temperature at which the fuel would freeze	- 47 (max)
Viscosity @ 20°C, mm2/s	The thickness of the fluid or ability to flow	8.0 (max)
Net heat of combustion, MJ/kg	The amount of energy that is released during combustion, per kg of fuel	42.8 (min)
Additive-Antioxidants, (mg/L)	A substance that inhibits oxidation	24.0 (max)
Aromatics, vol %	molecule with a carbon ring of unsaturated bonds	25 (max)
Sulphur content, ppm	The amount of sulphur in the fuel (parts per million)	0.30 (max)

Technical requirements for biojet fuel

To date, the Civil Aviation Authority only allows use of blends of up to 50% biojet fuel produced by either the Fischer-Tropsch (FT) process or the hydroprocessed esters and fatty acids (HEFA) process. A recently-approved pathway referred to as Synthesized Iso-Paraffinic (SIP) produces a fuel allowed to be blended at up to 10 per cent with conventional jet kerosene. However, the produced biojet fuel with either these processes must first meet the standard ASTM D7566 "Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons" Once it is blended and complies with the relevant fuel specifications (ASTM D1655 or DefStan 91-91), it is regarded as identical to conventional jet fuel. Moreover, no special handling will be required and the existing infrastructure of the supply chain could be used. This includes refineries, transfer pipelines, intermediate fuel storage and the airfield fuel transfer system. Table 3 summarizes the basic requirements of aviation turbine fuels containing synthesized hydrocarbons, based on ASTM D7566.

Table 3. Basic Fuel Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons (ASTM D7566)

Properties	FT–SPK and HEFA–SPK	SIP
Acid no. mg, KOH/g	0.015 (max)	0.015 (max)
Flash point ˚C	38 (min)	100 (min)
Freezing point, ˚C	- 40 (max)	- 60 (max)
Density @ 15°C,, kg/m3	730-770	765-780
Net heat of combustion, MJ/kg	42.8 (min)	43.5(min)
Additive-Antioxidants, (mg/L)	17 min 24 max	17 min 24 max
Aromatics %	0.5 (max)	0.5 (max)
Sulphur content, ppm	15 (max)	2 (max)

The ASTM certification and approval process

Any new aviation fuel should go first under an approval process by the American Society for Testing and Materials (ASTM) International Committee, and some other Subcommittees from Petroleum and Lubricants, and developers of aviation biofuels. Some other members must also engage to acquire and evaluate data, and address questions and concerns raised by subcommittee members. Upon approval, the new fuel will be added as an annex to the ASTM D7566 standard. The existed annexes are 1, 2and 3, which approved the alternative aviation fuels produced by Fischer-Tropsch process, HEFA process and DSHC process (referred as Synthesized Iso-Paraffinic (SIP)), in 2009, 2011and 2014 respectively.

However, some other ASTM task forces with research reports are currently under review. Of the Alcohol to Jet (AtJ-SPK and AtJ-SKA) pathways, the first one is focused on synthetic paraffinic kerosene (SPK) and expects to have completed certification in 2014, while the second one focused on synthetic paraffinic kerosene with aromatics (SKA) and expects to have completed certification in 2015.

Moreover, the research report for FT Synthetic Paraffinic Kerosene with Aromatics (FT-SKA2) - which is similar to the approved FT process, but also produces synthetic aromatics along with paraffins - is currently under preliminary review by the OEMs. Hydrotreated Depolymerized Cellulosic Jet (HDCJ), is at an early stage in the process of approval with a number of other task forces.

The Airbus A380 is a prime example of the drive for greater fuel efficiency. Airbus claims the A380 'uses 22% less fuel per seat than its nearest competitor among wide-bodied jets, and that this means about 150 kg less fuel used per seat on a flight between Paris and Tokyo.'

Chapter 4: Studies of Activity and Development in Selected Countries

These national examples have been chosen for a number of reasons.

- They cover the range of options of feedstock, including some occasionally overlooked
- They cover the options of technical production processes
- They demonstrate the way each country identifies its best options
- Some areas of potential R&D breakthrough are included
- Between them they show the range of costs and give detail or insights into logistical or sustainability issues
- Several of them deal with the critical practical aspects of blending, transfer and handling of bio jet fuels
- Among them are examples of how policy and R&D have got out of step, or where aspirational goals, policy and investment are disconnected

Australia – is an example of a country which would clearly be able to produce the necessary large volumes of feedstocks of several different types, suiting possibly four different biojet production processes – FT, HEFA, DSHC, and HDCJ. It could readily bring together the essential logistical and technical skills, it has existing port and bulk handling infrastructure, and it has the stability of government necessary for attracting long term investment.

Australia has had a history of refining all its fuels, including aviation jet fuel, from domestically produced and imported crude oil. However, due to progressive closure of its refineries the country is beginning to import an increasing amount of its jet fuel needs (of approximately 5.5 million m3/year). There would appear to be real benefit from domestic manufacture of biojet fuel, both in respect to import replacement, and with respect to improving national resource security. A number of recent high-level studies have examined and detailed Australia's various options for doing this.

Australia's most obvious feedstock is ligno-cellulosic material (wood and straw) produced in either or both the higher rainfall fast growth rate timber producing regions and the lower rainfall agricultural regions. Working groups of aviation industry and research organisations have completed several studies on the possible economics and processes. One CSIRO study has been done on production of biojet fuel via the yet-to-be-ASTM-approved HDCJ (pyrolysis oil to jet) pathway. Another CSIRO study compares the costings of the Fischer-Tropsch pathway with the HEFA or HDCJ (HPO) pathway. Some scoping work has been done by Qantas, Virgin, GE and Airbus in partnership with the Cooperative Research Centre for Future Farm Industries on utilising biomass from the oil mallee species of eucalyptus.

A report and feasibility study done by an industry group, including Qantas and Shell, with partners of Solena, Altair, Sinclair Knight Merz, the Cooperative Research Centre for plant cell walls, and SkyNRG, focussed on the use of the HEFA pathway utilising plant oils and animal fats. One plant oil source being investigated by the University of Queensland is the pongamia tree.

However it is also possible for Australia to develop biojet fuel production via the ATJ pathway using ethanol produced from sugar cane or other perennial plant alcohol production sources including sweet sorghum. The Direct Sugar to Hydrocarbons pathway, as demonstrated by Amyris in Brazil, is clearly also a possibility. Work is reasonably advanced in Australia on microalgae production using outdoor raceways and photobioreactors. A further possible source of biojet fuel is via the technology being developed by Licella. Its CAT-HTR process is claimed to produce a biocrude oil from woody biomass in a one-step process. This bio-crude could be transformed into biojet via the HDCJ process.

While the reports indicate the scope and feasibility, and generally conclude biojet production of 5% of jet fuel demand by Australia and New Zealand is possible by 2020, there is a lack of political commitment, and of investment by industry or government. For the moment it appears unlikely that there will be any development of bio jetfuel production in Australia at a commercial scale.

Brazil – is forecast by 2014 to have the 4th largest national amount of domestic air traffic. In 2011 it consumed about 7 million m3 of aviation jet fuel in 2011 (about 2.8% of global demand) and the projection is that this will rise to 11-12 million m3 a year by 2020.

Brazil's two main international airports are the main entry and departure points for South America, and more than 62,000 international flights depart Brazil annually, destined for 58 airports across 33 countries. Domestically more than 1 million scheduled flights annually provide connections between 108 airports.

In 2010 the Brazilian aviation sector carried over 71 million passengers and 870,000 tonnes of freight, to, from and within the country. Brazil's relatively high cost of jet fuel means that while for most countries the cost of fuel has risen to be about 34% of operating costs, for Brazil it is 40% or more. It is higher mainly due to a number of points of taxation. Brazil's jet fuel price at the 'producer gate' in 2012 was about 17% higher than the global average.

Brazil is already a significant user of jet fuel, both for domestic flights within the nation's very large area, and for fuelling of international airlines. It presently uses over 7 million m3 of jet fuel or about 3% of the world's jet fuel production. About 75% of this is produced domestically and the balance imported.

Brazil is one of the more advanced countries in both production and trialling of biojet fuel production. The report *Biofuels in Brazil: Action Plan* identifies 13 possible combinations of feedstock and production technology. This report drew on a broad range of stakeholders including airlines, original equipment manufacturers, biofuel producers, government agencies, and forestry and agriculture organisations.

It proposes that two main options for Brazil are Alcohol to Jet (utilising ethanol produced from sugar cane and also possibly cellulosic ethanol), and the thermochemical option - the FT pathway (possibly with a fast pyrolysis intermediate step producing economically transportable bio-oil) utilising woody biomass from fast growing eucalyptus plantations, and possibly the bagasse and trash from sugar cane production and processing. It identifies that this thermochemical option has significant issues to resolve. Principally these are of scale, logistics of supply, high capital cost, and technical complexity of the process.

The report also explores alternative feedstocks of plant oils including from jatropha, camelina (work is progressing on improving yields and economics of both these) and oil palm to biojet via the HEFA pathway, as well as the sources of flue gases and municipal solid wastes, and the option of the Direct Sugars to Hydrocarbons (DSHC) pathway.

The difficulties of cost-effective aggregation and transport of low density feedstocks are seen as one major problem by the authors of the Brazilian Biofuel report. Brazil is similar in land area to the USA but presently has limitations in road and rail infrastructure. On the other hand there is adequate productive land available for producing large volumes of different types of feedstock within the radius of any well-sited biojet production facility.

The report suggests that the feedstock of cane ethanol is one serious candidate for production of biojet for Brazil. Already production of over 35% of Brazil's light vehicle fuel comes from this source, and this is produced from only 0.5% of Brazil's land area. The report's authors estimate that a further 0.3% of Brazil's area could produce enough cane ethanol to substitute for all of Brazil's current jet fuel needs. Another source estimates that 10% of the jet fuel consumed in Brazil could be produced using sugar from about 156,000 ha or 2% of the total area under sugar cane, using the variant of the DSHC process already developed by the American company Amyris.

Canada – is a leader in the technology for conversion of ligno-cellulosic material into pyrolysis oil. Despite issues of lower conversion efficiency from this feedstock into biojet fuel this feedstock has some real positives. These include that the plant for the production of pyrolysis oil is of relatively low capital cost. Secondly, the pyrolysis oil has a number of different end uses or markets, and thirdly, that the pyrolysis oil is an energy-dense feedstock, allowing it to be produced in a number of feeder plants that supply one central final processing plant.

Canada has a number of further advantages for aiding developments in this field: its vast amounts of hog fuel residues from sawmilling; its tens of millions of hectares of softwood forests killed or damaged by the mountain pine beetle; and its effective national and provincial government support of technical development.

Again, as with Australia, Canada has stable government, good infrastructure including rail and ports, and excellent technical capability. While Canada does not have a very large domestic consumption for jet fuel it has the largest potential market for bio jet fuel of the USA, and has a well-established shipping industry for bulk products.

Denmark – is an example of a developed country with relatively few conventional options for developing commercial biojet production. However, it already uses up to 2 million tonnes a year of straw for energy production, or about 25% of the 6-8 million tonnes of straw that is an annual by-product of its cereal grain production. While most of this goes to produce heat and electricity, Denmark is also a leader in the technology for cellulosic ethanol production.

About 860,000 tonnes of Jet A1 was used in Denmark by all consumers in 2012, with about 87% supplied through Copenhagen's Kastrup airport. Since Kastrup is a major international airport much of the refueling is of foreign-owned airlines. The Danish Energy Agency estimates that Denmark's own useage of jet fuel will be about 0.6 million tonnes in 2035 and 1 million tonnes by 2050. Greenhouse gas emissions from aircraft refuelling in Denmark and flying on domestic and international routes in 2012 was about 6% of Denmark's entire GHG emissions (domestic aviation only represented 0.2%).

The consulting company NIRAS was commissioned by Danish Aviation to produce the report *Sustainable Fuels for Aviation*. This drew on input from the Nordic Initiative for Sustainable Aviation (NISA) and Sustainable Biofuels Network. The report notes that about 50% of Denmark's land area is used for agriculture – for growing food, including for livestock. Currently much of the residues from this production (about 4 million tonnes/yr) are used for energy production. The report estimates that if this biomass was to be used for biojet production in appropriately designed biorefinery systems, the output of Denmark's biojet needs would be also accompanied by production of high value chemicals, other transport fuels (including marine bunker fuel), and energy. The report also identifies the considerable expertise already in the country's research and development corporations that can assist in propelling this general approach.

One example of this is the DONG Energy subsidiary Inbicon, which has developed an enzyme hydrolysis process (with one enzyme supplier being the Danish company Novozyme) to break down straw to produce lignin and fermentable sugars. The ethanol produced from the straw is presently blended by the petroleum company Statoil with gasoline to give E5. However, a new agreement means it also will be used by the Finnish refiner Neste Oil to produce a microbial oil, with this to be used as a feedstock for production of biojet using the HEFA pathway.

Of the straw currently removed from fields in Denmark about 50% goes to animal bedding and 50% is used for energy production. However it is estimated up to 37% (over 2 million tonnes) of all straw produced remains in the fields. Possible uses of straw as a biojet feedstock include via the alcohol to jet pathway or via the direct sugars to hydrocarbon pathway. A number of Danish companies and research centres are working on these and other options.

Within the report a range of feedstocks for biojet production are noted, including used cooking oil (potentially about 17,500 t/yr but apparently not collected for biofuel production), and lipid production from microalgae. Denmark has a very strong policy of reforestation and the forestry and timber industry wastes and residues are almost all used for energy (including via pellet production). Similarly, almost all non-recyclable municipal flammable wastes are used for energy production.

While Denmark is only a relatively small user of jet fuel, it has very strong policies relating to renewable energy, and a strong commitment to play its role within the EU. Denmark is committed to conversion by 2050 to 100% biofuels, or other non-fossil options, for its transport needs.

Denmark has a considerable number of government and corporate institutions involved in R&D, strong links with clean tech research across the other Nordic countries and across Europe. It is likely that its small land area, limited supplies of cheap biomass, or other apparent limitations by comparison to countries like Australia, Canada or Brazil, will only stimulate its work on innovative solutions that can negate these.

Finland – is the home of Neste Oil, which has leadership in the development of the HEFA process for producing a drop-in synthetic diesel from plant oils. The total of its capacity in its production facilities in Singapore, Rotterdam and Porvoo (Finland) is about 1700 million tonnes a year. Presently only a small fraction of this is dedicated to producing biojet (in the Porvoo plant). This biojet production is done in a production partnership between Neste Oil and Honeywell UOP. As noted previously (section on Denmark), Neste Oil has entered a contractual relationship with Inbicon for taking cellulosic ethanol and using this to produce microbial oil which can then be converted to biofuels via the HEFA process.

Finland is also a leader in technology for producing pyrolysis oil, and companies involved in this include Valmet (which now incorporates Metso) and UPM-Kymmene.

The large amounts of woody residues generated by the forestry industry and timber industry processing in Finland are largely already utilised for energy production. However, as in the examples of Denmark and Norway, Finland has the option to intensify its forestry management to generate more biomass volume from earlier and more widespread forestry thinning, and to use this biomass as feedstock in biorefineries to produce energy and biofuels.

Germany – has some similarities to Denmark and other densely populated European countries, in that the biomass or vegetable oil it produces is mostly already utilised to the full, and there appears to be little scope for finding the feedstocks necessary for large scale production of jet biofuel.

However, as with Denmark, the Netherlands and other more industrialised countries, there are some other possibilities that have been demonstrated at pilot plant scale that would appear relevant to Germany. One, demonstrated by LanzaTech of USA, is the production of longer carbon-chain molecules from carbon monoxide captured from the industry flu gases produced in vast amounts by such processes as iron and steel manufacture. While not itself a biomass-to-liquids process, similar innovative processes are already using at a commercial scale other biomass-to-liquid pathways as, for example, synthesis gas from biomass to produce butanol using clostridium bacteria.

Germany is very active in the development and support of biojet production options and studies. Germany, with its geographical and political position in Central Europe and its large population, has Frankfurt as one of Europe's busiest airports and is the home to Lufthansa and a number of other airlines serving the EU and beyond. In addition Germany has a history of technical and manufacturing excellence, including of very large-scale production of synthetic transport fuels during the Second World War by the Fischer-Tropsh process. While this used black coal as the feedstock, essentially the same process can use biomass or sorted dry municipal waste.

Germany is exploring the other options available to it, including via investing outside the country to produce the feedstock and the biojet fuel. One reported trial is looking at the feasibility of jatropha planting in Cameroon for production of jatropha oil to be a feedstock for the HEFA pathway.

Holland (The Netherlands) – is included in this list for a number of reasons. Holland is the only European state to have committed to including its aviation fuels within the general commitment for EU member states to have 10% of all transport fuels being from renewable sources. Holland is well placed to take this step for the following reasons.

It is through Holland's major port of Rotterdam that most of Europe's current supply of bio jetfuel presently enters Europe. Rotterdam is also the site of Neste-Oil's 800,000 tonne/year capacity biofuels plant that converts vegetable oils to a drop-in diesel using essentially the same HEFA process that is used to make biojet fuel.

The ports of Rotterdam and Amsterdam send jet fuel directly by pipeline to Holland's main airport of Schiphol (Europe's fourth largest airport, using about 4 Mt of jet fuel in 2011) and supply jet fuel to many of Europe's other airports via the Central European Pipeline System. About 20% of the jet fuel used in Europe is imported through Holland or produced in refineries there. [Ecofys]

And Holland is the home for KLM, the airline that reportedly has made the most flights using biojet fuel, including a regular weekly flight to USA. Through its large use of biojet fuel, KLM has developed a high understanding of the costs and logistical issues involved with modifying or duplicating handling and storage systems at fuel terminals and airports, and how best biojet/fossil jet blends might be piped, stored, metered and costed. The summary of this can be found in the report by Ecofys (see Reference section).

KLM has signed a take-off deal to buy 4,000 tonnes a year of biojet fuel produced by Neste Oil in a HEFA process plant constructed under the EU ITAKA project. This Initiative Towards sustAinable Kerosene for Aviation project is supposed to link an entire supply chain within the consortium establishing a large-scale European sustainable biojet supply. The main feedstock for this HEFA process is intended to be camelina oil.

The world's present major biojet supplier SkyNRG is based in Holland and supplies biojet to KLM among others. By late 2013 SkyNRG had supplied biojet to over 20 airlines worldwide [Ecofys]. The biojet sourced and traded by SkyNRG is mainly produced from used cooking oil via the HEFA pathway [Denmark NIRAS report]. The main source of SkyNRG's biojet to date has been the US company Dynamic Fuels, which produces biojet principally from used cooking oil [Ecofys].

Indonesia – has led the way for South East Asia in setting a biojet use target for 2016. This is for a 2% blend of biojet with petroleum jet and the amount will be approximately 2 million litres. This will notionally result in a 17% reduction of GHG emissions from the aviation sector. To fulfil the government target of 2% blending the petroleum company Pertamina plans to build a hydrotreatment plant taking in crude palm oil. The plant capacity is to be 1500 tonnes per day, to produce 257 million litres per year by 2017. [Current Status and Sustainability Study on Alternative Fuels for Aviation Industry]

Indonesia recognises two pathways for producing its own biojet fuel. One is the most obvious one already in development - to use palm oil as the feedstock for the HEFA process. The downside of this option is the high cost of palm oil and the fact that production of a significant excess of palm oil over what is presently supplied to existing markets raises real sustainability issues.

The alternative option is to use the biomass from the overmature oil palms removed annually from Indonesia's more than 6 million hectares of oil palm plantings. This can be converted into biojet fuel by either the Hydro-treated Depolymerised Cellulose Jet (HPO) pathway or the FT pathway. A possible downside of this (certainly of the use of FT) may be the dispersed nature of these plantings and the vast tonnages of low density biomass that would need to be economically freighted by road and water to any processing plants.

It is clear that Indonesia has the necessary technically skilled workforce, a refinery and manufacturing sector that can develop the modifications or new processing plant, and the available feedstock. It may be that this development could be as a joint venture with Malaysian capital and expertise, and possibly also of pyrolysis oil sourcing.

Mexico – in 2011 took a lead among the Latin American countries in setting targets to be using a significant blend percentage of biojet in its jet fuel of 1% by 2015 (40 million litres) and 4% by 2020 (700 Ml/yr). The main identified biojet feedstocks identified then included castor, salicornia, jatropha, agave and algae.

Mexico is among the world's top ten producers and exporters of crude oil, but this petroleum supply is clearly declining. Studies commenced in 2006 to identify the best options for production of bioethanol and biodiesel. Based on the results and recommendations of these feasibility studies, federal policies were formulated and these were adopted in about 2008 as 'The Law of Development and Promotion of Bioenergy' and 'The Law for the Sustainable Use of Energy'.

These two pieces of legislation set underway a series of major initiatives to produce feedstocks for biofuels production. Incentives were devised to stimulate the production of biofuel feedstocks principally on privately-owned farm land.

One identified source of plant oil was the perennial bush or small tree *Jatropha curcas*. This is a species native to Mexico but which had been spread from the early 1800s into Africa, and more recently into South and South East Asia. However the development of large-scale plantings of jatropha commenced well ahead of the availability of seed from Mexico's own indigenous genetically improved lines of jatropha. To try and start with higher yielding jatropha genotypes, supposedly improved seed was imported from India and Thailand. However, most of this proved to have the unfortunate combination of low germination and low yield. Also some previously unknown diseases apparently came in with these seed imports, further reducing production from the affected plantings.

The outcome has been that most plantings have not produced to expectations and many have been abandoned or removed. The two biodiesel production facilities built in two states did not receive enough oil to be viable, and these too have closed.

However there has been production of jatropha oil from some well-managed plantings in southern Mexico, and new plantings of far better quality jatropha have recently begun again. Research has continued at state and federal level as well as by private research companies. Mexico has to be seen as a potential source of superior jatropha genetics, including of genotypes of jatropha that are non-toxic, and which have real potential to improve the economics of jatropha production by providing a seedcake of high nutrient value.

Norway – Norway's domestic flights emitted about 1.2 million tonnes of CO_2 in 2011, or about 2.3% of its overall emissions. International flights from Norway were estimated to generate another 1.3 Mt CO_2-e). Norway has levied a CO_2 tax on domestic flights since 1999.

Norway has a target of producing 190-250 million litres of a biojet substitute for Jet A1 by 2020-25. While not a member of the EU it is a country with significant aviation fuel requirements and a member of IATA. Along with Denmark and Sweden it is a shareholder of the international airline SAS. In addition it has a number of smaller domestic airlines. While Norway is a significant supplier of European crude oil and natural gas supplies, it also has a strong philosophy that it should play its proper role in development of options for helping to reduce the world's greenhouse gas emissions, and it invests heavily into R&D for furthering this.

A report produced in 2013 by Rambøll for Norway *Sustainable Aviation Biofuels*, identifies the FT and the ATJ pathways as being the most feasible options for the country. The annual logging residues of Norwegian forestry total about 3.6 million m3 of wood, and so about 7 terrawatt-hours (TWh) expressed as energy content. That report's writers estimate that this amount processed though the FT pathway would provide about 230 million litres of biojet. 8-10 production plants with an output each of 50 million litres a year would be needed. The output of each would be about 50% as paraffinic petroleum – the precourser for Jet A1 - with the other 50% made up of diesel, naptha (precourser of gasoline) and other byproducts. At present the production cost in Norway of FT biojet after sales of other products is presently estimated at about double the cost of fossil Jet A1. The report estimates that the cost per litre of FT-biojet would be equivalent to fossil Jet A1 by 2025, assuming sale of the other fuels produced.

The option of an ATJ pathway based on wood as a feedstock is also seen as practicable for Norway. Norwegian spruce is a suitable feedstock for second generation ethanol production and the Norwegian company Borregaard is already producing about 20 million litres a year from this. However, the cost of the final biojet from the AtJ pathway depends on the cost of the bioethanol, as this makes up about 90% of the biojet production cost. It takes about 4 litres of ethanol to produce a litre of biojet, and currently this makes the estimated production cost of ATJ biojet over four times the cost of fossil Jet A1.

Spain – is a large country in area with good infrastructure, a stable government and an educated population. It has the potential to aggregate large volumes of biomass from both agriculture and forestry, and also to further develop the use of large volumes of sorted dry municipal wastes for energy. Spain already has a number of combined heat and power plants fuelled by straw and has invested strongly into renewable energy. Spain also has competent heavy engineering, manufacturing and refining sectors and is the home for an international airline (Iberian).

As importantly, Spain has a very advanced research and development sector, within which there is ongoing work into a wide range of aspects of biofuels production. One of these is the production of oil from yeasts, where a cubic metre of yeast solution selected by the R&D company, Neol Solutions, is reported to be able to produce as much oil per year as a hectare of oil palms. It is the commercialisation of work such as this that could open up the possibilities for the sustainable production of a lower cost oil feedstock for the HEFA process.

United Arab Emirates – is the home of the Masdar Institute, which is working on halophytes (salt-tolerant plants) as a source of vegetable oil. At a pilot scale some species of these salt-tolerant plants produce enough oil-bearing seed that it is reportedly possible to produce up to 600 kg of oil per ha. Since halophytes are evolved to grow on soils and in waters that are of significantly higher salinity levels than where 'normal' agricultural production can exist, this is seen as one way that that oil and biomass production can be done without affecting land areas used for existing agricultural production of food and fibre.

While the suitable coastal area available for halophyte production in the UAE is not large, through the temperate and tropical parts of the world there are many tens of millions of hectares of coastal flats, salinity-affected land, or land that could be irrigated with sea water, or saline or brackish water. The hope is that if the economics of planting, managing and harvesting halophytes can be developed and commercialised at scale, halophytes could produce enough relatively low cost, sustainably-produced oil to be a feedstock for the HEFA process.

Most recently UOP Honeywell has announced that its 'Green Jet' production technology has been selected by the UAE company, Petrixo Oil and Gas, to be used in a major new plant. This plant for production of biojet will cost about $800 million and have the capacity to convert 500,000 tonnes of renewable oil feedstocks into biojet and renewable diesel. To be built at the port of Fujairah, the plant will be able to take a flexible mix of feedstocks and produce a flexible mix of biofuels. Feedstocks will be able to include oils from algae and halophytes as these become commercially available. [UOP Honeywell news release July 9 2014].

UOP Honeywell as a founding member of the Sustainable Bioenergy Research Consortium (SBRC), other members of which are Masdar Institute, Etihad and Boeing. The SBRC 'focuses on testing the use of desert plants grown with seawater to support biofuel crop production in arid countries, such as the UAE' [UOP Honeywell press release].

The USA – has been playing a leading role in the development of biojet fuel production, including through its activity as a major buyer of biojet fuel for its army and navy, with some programs starting in 2007. Presently much of Europe's biojet fuel is coming from manufacturers in the USA. It is produced from a range of feedstocks and mostly via the HEFA process. The feedstocks include animal fats and tallow, algal lipids, and vegetable oils (including from camelina). Other fuels bought by the US military have included a significant amount produced by the Fischer Tropsch pathway from the fossil feedstocks of coal and natural gas. This has been to test the quality of fuel produced by this pathway. The military has also tested biojet fuel produced via the ATJ, DSHC, and HDCJ pathways.

Due to this stimulus of purchasing of significant volumes by the US military, production facilities have been put in place that now supply much of Europe's initial demand for jet biofuel. USA companies that are prominent in biojet production include:

AltAir (licensed to use UOP Green Diesel/Biojet)

Amyris (Direct Sugar to HydroCarbons biojet pre-commercial production),

Dynamic Fuels (HEFA using feedstock of UCO)

Solena (waste gasification using plasma torch), UOP Honeywell (variant (?) of the HEFA process)

Lanza Tech (flue gas to hydrocarbons),

Gevo (isobutanol to biofuels),

Syntroleum (FT of fats and oils to biofuels),

Kior (Hydrotreated Depolymerised Cellulosic Jet - wood to jet via fast pyrolysis)

Summary

Many other countries will share common features with one or more of these countries just listed. For example it may have some similarity with Australia in having large areas of lower rainfall land which could be used to produce woody biomass or, if water is made available, large volumes of plant oil from perennial species including jatropha.

In common with Germany, Brazil and Holland it could have one or more major rivers as both a source of irrigation water and available to be the basis for an economical transport system for large volumes of unrefined fuel or other feedstocks.

In common with the UAE it might have a hot climate, along with saline areas and brackish or saline water supply suitable for production of halophytes.

If a tropical or sub-tropical country like Brazil it may have a production of sugar cane but relatively constrained road and rail infrastructure.

In practice many countries may have some strong points as a producer of biojet fuel, or interim products or feedstocks for some of its trading partners. This is based on access to water, land and to a workforce with capability in managing refining of crude oil, possibly some idle refinery capacity that could be refitted to process plant oil by the HEFA process, or to produce pyrolysis oil and refine this to biojet.

However policy makers, legislators and research organisations should take good notice of the experience in Mexico (this chapter), where some serious errors were made leading up to the decision to produce plant oil from jatropha. These included accepting over-optimistic estimates of yield, purchase of 'improved' seed that turned out to have low germination and yield, and in rushing into a major project of this nature without the vital foundations of adequate R&D processes being in place.

Similarly costly but far less well-reported failures were made in the period of enthusiasm for biofuel development just before the GFC. During this period many countries, including Indonesia, Vietnam, Philippines and Myanmar, invested heavily in jatropha plantings and possibly in other biofuel ventures. Many sub-Saharan African states also saw poorly planned, sited and managed plantings of jatropha and other biofuel crops fail economically during this period and through to 2012. Some details and lessons from this are covered in the chapter on Policy and Action Plans.

Chapter 5: Economic and logistical issues related to biojet fuel production

While the present targets for production of biojet fuels of 2-3 million tonnes by 2020 are relatively achievable, the longer-term targets proposed or set by the EU, IATA, and other bodies, involve extremely large volumes of up to 58 Mt by 2050, and possibly more [IEA]. This target for 2050 could be seen in the context that worldwide the entire biofuel production for land transport in 2013 was about 100 million tonnes.

Some present targets include:

EU: 2 million tonnes of biojet being used by EU-based airlines by 2020. 40% of aviation fuels to be low carbon by 2050.

IATA: 50% of current GHG emissions by 2050

US military: 50% of airforce jet fuel by 2018 from 'cost-competitive' renewables,

Brazil: an aspirational target of 'carbon-neutral aviation by 2020'

Indonesia: 2% of aviation biofuels by 2016

Norway: 10% of jet biofuel by 2020 (190 Ml/yr)

Mexico (2011) – 1% (40 Ml/yr) by 2015, 45% (700 Ml/yr) by 2020

A primary obstacle in the production of these large amounts of biojet fuel is that the forecast of the produced cost of the most cost-competive biojet is 2-4 times more expensive than petroleum jet fuel [Ecofys]. This is regarded as the situation in the short-term, assuming production in economically-scaled plants.

As a reflection of this, the production of biojet fuel worldwide in 2013 was measured in millions of litres rather than millions of tonnes. While combined capacity of plant capable of making biojet is in the order of 2 million tonnes/year, almost all of this capacity is presently being used to make the far more profitable options of biodiesel or drop-in ('Green' or HEFA) diesel.

It is only where airlines or governments (usually on behalf of the military) are prepared to enter into a supply contract based on paying many multiples of the petroleum jet fuel price, that companies like Neste Oil, SASOL, KiOR, UOP Honeywell, or Diamond Green Diesel are able to produce biojet on a profitable basis.

However, some break-thoughs in one or more of the feedstock production processes may soon change the situation dramatically. There are a number of such possibilities being seen even now, including the production of oils by microalgae, or by other microorganisms such as yeasts or bacteria.

The average spot price of petroleum jet fuel in 2013 (average over Jan-Sept) was US$0.75/l [IATA]. Projections by EIA for the rise in price over the next 30 years for petroleum jet fuel, due to rise in price of crude oil, range up to US$1.59/l (price expressed in terms of 2012 US dollars) [IATA].

To the authors this projection seems unrealistically low, and does not appear to factor in the forecast changes in the demand/supply balance for the world's crude oil supplies. It seems much more likely that the increasing world population, the rise of the car-owning middle class in India, China and other developing countries, and a flattening or decline in the world's oil supply, is likely to result in a significantly larger price increase that that being forecast. And this is without any impact on oil price due to regional or more widespread conflicts over resources, water and land, due to global warming and imbalances in regional or continental population increases.

Some modeling quoted in authoritative reports suggest that that production costs will be approaching parity with petroleum jet fuel cost by 2020 [IEA, Norway]. It also appears likely that either or both of a 'carbon tax' on fossil-sourced jet fuel, or a shortage of crude oil in the mid-term, will cause a rise in the cost of petroleum jet fuel. As an early indication of this likely price trend, the cost of aviation kerosene has increased by 67% between 2007 and 2013.

Projections for demand in jet fuel are for a steady increase of about 3% a year assuming a trend of increase jet flights of in the order of 5% a year but with continual improvement in economies and design reducing fuel consumption per traveller per unit of distance flown. So with over 200 million tonnes being used in 2012, the demand is forecast to rise toward 375 to 575 Mt by 2050. If a 10% blend of biojet is assumed this would require between 38 to 58 Mt of biojet by 2050 [IEA]

With this cost of Jet A1 from fossil petroleum in 2013 being on average $0.75 a litre kept in mind, the detail on costs of biojet fuels purchased by the USA Department of Defence show that the cost of biojet supplied between 2007 to November 2012 was as follows:

	average cost US$l
HEFA process biojet - over 1 million litres –	10.11
FT (coal or gas sourced) biojet - 0.73 million litres –	3.76
ATJ process biojet - 0.325 million litres	15.59
DSH (Direct Sugar to Hydrocarbon) - 0.162 Ml	6.80
HDCJ (Hydro-treated Depolymerised Cellulosic to Jet) - 24.6 Kl	2.34

[info from IATA report]

These supply costs for early biojet production will have included large added margins because of less than good economies of scale, because of needing to construct new processing plant, and also reflecting previous and current R&D costs. It might only be the FT-process fuel produced by SASOL in South Africa that does not reflect all of these extra costs, though in this case the price may reflect the lack of competition, and some shipping cost.

It is presumed that all these prices are already beginning to fall significantly as competitive sources of commercial volumes of biojet come onto the market, partly driven by major allocations of grants and R&D funding in the EU and the USA.

As some support for this the IATA 2013 report provides 'theoretical prices' from MIT in the USA based on modelling and a range of assumptions, and this suggests that biojet produced from the nth plant at commercial volumes by the HEFA, FT biomass, and ATJ processes will (could) have baseline prices (in US$) respectively of $1.09 (HEFA from tallow), $1.97 (FT using switchgrass), and $1.37 (ATJ – using cane ethanol).

Some other influences on ability of most of these processes to be the source of very large volumes include the availability of feedstock. The HEFA process stands out in this respect, where present world availability of vegetable oils and animal fats is effectively in full demand, and there is no sign of the sort of surplus volumes that could be diverted at a competitive price to be made into biojet. The total availability of tallow and 'yellow grease' (from grease traps in restaurants, etc.) in the USA for instance could, at most, produce only 3% of the current US jet fuel requirement [IATA].

This limitation in supply also encompasses palm oil, even though the total area planted to oil palm continues to expand in many countries through the tropical belt, including Brazil, Central America, West Africa and South East Asia-Oceania. This expansion of plantings is driven by the firm demand and good prices that prevail.

Despite the fact that the world's oil palm plantations potentially could provide the necessary large available volumes of suitable oil for the HEFA process in the short term, and that it presently is marginally cheaper than other bulk edible oils, price is always going to be a key issue, along with the concerns over sustainability of palm oil production.

It appears to the authors of this report that the real scope for large volumes of supply of biojet into the future would, from the viewpoint of mid-2014, mainly come from the FT, ATJ, DSHC and HDC-D processes, where they draw on low cost lignocellulosic residues, or on purpose-grown woody crops as proposed in Brazil. A second source may be of sorted flammable municipal solid waste (also called refuse-derived fuel) as proposed by the Solena waste-to-biojet production plant being built near London. However, in most central and northern countries of Europe this feedstock is already almost entirely used for production of electricity and heat.

Projected costings of biojet from these current feedstock sources vary. Some general figures or 'rules of thumb' applying to these feedstocks and processes need to be appreciated -

- It takes about 4 litres of alcohol to produce 1 litre of biojet via the ATJ process
- It requires about 5-6 tonne of dry biomass to produce 1 tonne of the combined fuels via the FT process [Norway & IEA] (and a hectare might produce from 2 to 20 dry tonne/year depending on growth rates).
- Cost of biomass as forestry residues or straw delivered to a FT plant is assumed to be above a minimum of US$60/dry tonne (or about $12/MWh). At a cost of $100/dry tonne, this feedstock cost equates to about $0.40 per litre of FT biojet. [Ecofys]
- Yields of plant oils range from 250 kg/ha (rapeseed and camelina) up to 4-5 tonne per ha (oil palm), depending on soils, rainfall, crop and climate
- To process a tonne of biojet by the HEFA process requires about 1.2 tonne of feedstock oil, and so about 4-5 tonne of oil palm fruit [IEA].

Economies of scale -

- A FT plant will need input of 0.5 to 1 million dry tonnes of biomass to be achieving economy of scale. Depending on technical settings a F-T plant will produce about 50% paraffinic petroleum, 30% biodiesel, 15% naptha, plus some minor amounts of other saleable product, plus heat and CO2. [Norway]
- For two plants of the same order of volume of biofuels produced, a HEFA plant is reported to have capital cost of about a quarter that of a FT plant. [Norway]

- Cellulosic ethanol plants are reported to require feedstock volumes of over 200,000 dry tonnes/year to produce ethanol at or below US$0.80/l [pers.comm, Inbicon]

In light of these above points, it can be seen that production of biojet fuel of a nominal output from one plant with 50,000 tonnes a year of biojet production will require the following:

By the FT biomass to liquid process – supply of feedstock of up to 10 x 50,000 dry tonnes. So 500,000 dry tonnes, or about 750,000 tonnes at about 40% moisture content. This would require wood residues from harvesting about 15,000 ha/year of northern boreal forest (i.e., in Canada, the Nordic countries or Russia), or 1500 ha/year of semi-tropical short rotation eucalypt plantation in, for instance, Brazil.

By the HEFA process – to achieve the output of 50,000 tonnes of biojet will require supply of about 60,000 tonnes/year of good quality vegetable oil, clean filtered used cooking oil, or clean rendered tallow from animal fats. If based on palm oil this volume requires the harvest yield from about 15,000 ha a year. If based on jatropha oil it would require up to 50,000 ha/year. If based on rapeseed or soy oil it would require up to 100,000 ha/year. These traded edible oils have an international bulk price of US$900-1200/tonne delivered and this is upward trending, and to date has closely followed crude oil price.

By the ATJ process – 50,000 tonnes of biojet will require 200,000 tonnes of ethanol, or other suitable alcohol. If this is to be produced from ligno-cellulosic feedstock it will require between 900,000 and a million tonnes of feedstock to produce this volume of ethanol (assuming production of 260 litres per dry tonne of straw). Obviously not all the alcohol needs to be produced in the radius of the ATJ plant, as the alcohol is a relatively energy-dense intermediate feedstock which can be transported in bulk by rail or water relatively cost-effectively.

By the hydro-treatment of depolymerised cellulose HDCJ process (i.e., bio-oil produced from fast pyrolysis) – since this produces only about 30% of initial dry weight as refined biofuels and only about 10% as biojet fuel, it follows that to produce 50,000 tonne of biojet will require 500,000 tonnes of dry biomass (or up to a million tonne of 40% MC biomass). At a yield of 10 tonnes dry weight/ha/year this will require 50,000 ha/year to be harvested.

One potential advantage of this pathway is that the pyrolysis oil intermediate feedstock can be produced in many sites quite dispersed from each other. The combined capital cost of these multiple dispersed plants is relatively low compared to the capital cost of the central final processing plant [Hayward CSIRO].

By the Direct Sugar to HydroCarbon (DSHC) process, one presentation on behalf of the Total-Amyris venture states that about 4.5 tonne of farnesane can be produced per hectare of sugar cane. A blending of 10% of farnesane with petroleum jet is now approved by ASTM. Costs and energy required for production of farnesane are not yet available, but the proponents claim is that this pathway provides a greater distance flown on the basis of biomass produced per hectare, than for most other biojet production pathways.

Summary – Even when a country appears to be reasonably reasonably well-placed, thanks to some combination of a large and productive agricultural sector and to available land and water supplies, to provide large enough volumes of some feedstocks for production of its own biofuels, including of jet biofuel. However, there is a need for much focused research and development, for a detailed analysis of all the economic and other relevant factors, and for clear and intelligent long term planning and prioritisation, if this is to be done with positive and productive outcomes.

The initial steps are of audits of biomass supplies – including of refuse-derived fuels, and an audit of technical resources (including unutilised refinery capacity, of technically skilled work force, and of the availability of patient investment capital.

The information contained in these audits would be critical data to feed into a far more detailed feasibility study into the best technical processes that could utilise the most economically available forms of biomass and waste.

Parallel to this a focussed program would need to be put into place in order to deal with the identified gaps in R&D, skills, resources, technical capability, and training.

A pilot gasification plant in Sweden – producing synthesis gas (hydrogen and carbon monoxide) from carbon rich feedstocks including wood residues and sorted municipal solid wastes

Chapter 6: Developing biojet production projects around the world

The last few years have seen increasing production of biojet fuels in a number of countries. Some significant targets have been set for biojet use or blending percentage for the years ahead, including the US Airforce (2015), Indonesia (2016, The US Navy (2018), and IATA and the EU (2020). Accompanying the setting of targets and national policies has been the allocation of large funding grants for construction of commercial biojet production plants, and of contracts for supply to various end users.

The net result of this has been a major stimulus to the whole area of research and development in almost all areas of feedstock supply, technologies and related aspects. A number of these are summarised below (some are mentioned elsewhere in this report):

Biojet production, or biojet feedstock production

EU ITAKA project: 4000 tpy HEFA process plant using camelina oil as primary feedstock and to be managed by Neste Oil. KLM has the take-off agreement for the output. [ecofys]

UAE, Fujairah. Petrixo announced that it is using Honeywell UOP technology at a new plant costing about $800 million to be built at Fujairah port. Projected output is initially 0.5 million tonnes a year. [Honeywell]

Australia: Lufthansa in 2012 was to invest in Algae.Tec to build a large industrial CO_2 to algae facility in Europe, with a take-off agreement for 50% of the biojet produced [ecofys]

US: Dynamic Fuels production of biojet from used cooking oil

US: Qatar Airlines has invested in Byogy Renewables along with a take-off agreement to buy biojet produced using the ATJ pathway [ecofys]

US: United Airlines have a 'letter of intent' with Solarzyme to buy 75 million litres of biojet produced from algal oil [Ecofys]

US: Los Angeles. United Airlines in 2013 signed a purchase agreement with AltAir to purchase 18.75 million litres a year for three years. The AltAir production system uses Honeywell UOP 'Green Jet' process technology. [Ecofys]

UK, London. British Airways has signed a 10 year take-off agreement to take 60 million litres a year of biojet produced from London's municipal waste by Solena. The plant cost is reportedly around US$500 million and output will be about 40% as jet fuel, 40% diesel and 20% naptha. [Australian Flightpath report].

Brazil. The Amyris plant uses modified yeasts to produce a long chain hydrocarbon, farnesene, from cane sugar. Farnesane produced from farnesene has been used in a 10% blend by the Brazilian airline GOL, and also supplied to the US Airforce.

Italy, Crescentino. The commercial cellulosic ethanol plant now produces up to 50 million litres of fuel grade ethanol a year from lignocellulosic feedstock using the enzymatic hydrolysis process.

Finland, Joensuu. Production of pyrolysis oil has commenced from a pyrolysis plant built at the Joensuu bubbling fluidised bed combined heat and power plant.

Major R&D project areas

Halophytes:Masdar Institute in collaboration with Boeing, Honeywell UOP, Safran and Etihad, developing halophyte production as source of plant oil produced from saline sites using saline or salt water

Jatropha:Multiple R&D companies working on high yielding and advanced production varieties of jatropha (Brazil, Mexico, Guatemala, India, Ghana, Australia, and elsewhere)

Lignocellulose-to-biojet pathways: Licella in Australia has developed a one-step process for producing a bio-crude from lignocellulosic feedstocks using subcritical water as reaction medium

Algae: Multiple R&D companies working algae selection and on pond and raceway systems or on photo-bioreactor systems.

Bacteria: many research and pilot projects using bacteria to convert synthesis gas to alcohols, and also into use of bacterial to produce oils

Yeasts: Research in Spain and elsewhere on production of oil by yeasts in reaction medium. Yeasts are used by Amyris in Brazil for production of farnesene from cane sugar.

Chapter 7: Research and Development: examples from around the world. Areas of breakthroughs that may lead to significant advances

Around the world research and development is underway in almost every university and in every private corporation or government research agency that is working in this space of development of alternatives to use of fossil petroleum for energy, including on biofuels and jet biofuels. The researchers actively working on the range of topics would number in the tens of thousands, if not hundreds of thousands. The combined budgets of all parties in this research field is in the tens of billions of US dollars. It is all being driven by both the quest for saleable or valuable patentable technology, microorganisms or processes, and by the urgency of the need to reduce overall world emissions of green house gases.

In the end it all means that this research and development effort is throwing up developments of promise on an almost daily basis, and that at least some of these will radically change the need for fossil sources of energy in the world of 2050.

But it has to be realised also that much of this R&D is based on processes or advanced that date back 100 years or more. Examples of these are:

- Gasification of woody biomass to produce a crude synthesis gas was in use in the late 1800s, and use of wood gas to power spark ignition engines goes back to well before very widespread use in the World War of 1939-45.
- The Fischer-Tropsh process, of producing substitute fuels for petroleum gasoline and diesel from synthesis gas produced from coal, dates back to the early 1920s, and was used by Germany in WW2 for producing almost all its land and air transport fuels. Similarly SASOL in South Africa used this process to produce transport fuels during the years of the sanctions against the South African Apartheid Regime though the 1980s. Production of synthesised transport fuels using the Fisher-Tropsh process continues in Qatar, South Africa, New Zealand and Malaysia (mostly using natural gas as the feedstock).
- The refining of crude oil, by cracking and then distilling into separate fuel fractions, has been in use since the early 1900s.
- Use of vegetable or plant oils as a fuel for diesel engines has been around as long as diesel engines themselves, with the first diesels being fuelled by walnut oil. Similarly the use of ethanol as a fuel for spark ignition engines dates to the earliest cars equipped with these motors.
- The planting of jatropha as a source of vegetable oil dates to at least the early 1800s when it was grown at a large scale in the Cape Verde Islands and then in Benin and Mauritus, for export of the seeds and oil to Europe.
- The yeasts used for producing ethanol from hydrolysed or 'broken down' cellulose are derived from bakers or brewers yeasts selected over the last few hundred years

Some areas of intensive R&D that are yielding real benefit and advances are into the following main areas:

Microalgae, yeasts and bacteria. The production of oil and alcohols from crops grown on land is subject to real limitations due to rainfall, available suitable land area, competition with food production, and concerns about GHG emissions and loss of biodiversity due to clearing of forest and drainage of peat swamps.

While it is the production of oil from microalgae that has received the most publicity and continues to be regarded with possibly overinflated enthusiasm, the production of oil, alcohols, and other hydrocarbons by yeasts and bacteria will possibly prove to be where the biggest breakthroughs come. One instance of this is by use of microorganisms to convert synthesis gas or 'pure' industrial flue gas into alcohols. Obviously the CO2 or CO emissions from industrial plants fired with coking coal making steel, or from fossil fuel-fired power plants, if utilised could prove to greatly reduce the net Greenhouse Gas emissions of these plants.

Another new development is the production of oil by yeasts. This research underway is Spain has moved from small containers to containers of one m3 volume and is soon to move to a pilot scale. Reports on this stage of the research state that a m3 of this selected yeast in solution is able in a year to produce up to 4 tonne of oil, or as much as a hectare of oil palms.

The production of microalgae can be done in a variety of ways but research focuses on developing ways around the limitations. The main microalgae development is with the autotrophic form that uses sunlight, warmth and CO2 to rapidly increase in number and bulk while producing lipids. While lipid production by microalgae in clear water circulating in a shallow raceway system can in theory be very high per ha per year, the issues include the problems of contamination, evaporation, and economics of harvesting.

The alternate photo-bioreactor production system entails keeping the microalgae within water in a sealed system with circulating CO2, warmth and high incident light. This results in relatively high costs of energy, housing and the growth containment system, but some new data indicates that algal oil could be produced at a lower cost per unit volume by such an enclosed system.

Use of saline (brackish) water. Use of and access to fresh water is something that is of increasing interest to world leaders, and to the NGOs that have increasing input into the sustainability criteria for such things as food and fibre (and now fuel) production. However saline (brackish) water is in relatively greater supply for the purpose of producing biojet feedstock. Similarly the use of grey water or primary treated sewage water is an area into which research is presently being done, particularly in countries that have a significant percentage of their area where this is the only excess of water that is available.

One area of this research focus is into production of food plants and other plants producing vegetable oils. While microalgae production is one research area covered here, another has been the irrigation of jatropha using primary treated sewage effluent. Egypt is one country where this has been done with success on a number of sites, at least for a period. It has also been modelled as a possibility in southern Morocco, investigated in Oman, and trialled in many other countries including semi-arid parts of China.

Halophytes – plant oil production using saline or salt water. World wide it is estimated that 45-60 million ha of irrigated land has been damaged by salt- representing 20-25% of all the irrigation land in the world. Clearly plants that can produce well on this land could bring it back into some sort of productivity. And around the world the plants that have evolved to survive and even thrive on such land (known as halophytes) have been attracting the attention of researchers for many years. [Salt tolerance, Crop potential of Halophytes]

While the most publicity about production and potential of oil from halophytes is presently coming from the Masdar Institute in the UAE, it is a subject that has been studied for many years in a number of countries. Researchers in the USA prior to 2007 had studied a range of halophytes including seashore mallow (Kosteletzkya virginica or KV) and Salicornia bigelovii, and found that the seed yield and oil yield and its qualities were high enough to warrant doing further development work

The perennial halophyte, seashore mallow, that normally grows on coastal marshland or around inland brackish lakes, is reported to produce a seed yield/ha of about 640 kg/ha when harvested one year after sowing into a saline site. The seed is similar in size to that of wheat and the plant can be planted with slightly modified conventional farm seeding equipment and the seeds harvested with a conventional cereal harvester. They have an oil content of 18% - about that of soybeans – and oil composition similar to that of cottonseed. Percentage of protein in the seedcake is about 30% [Alternate fuelled flights- halophytes].

The halophyte Salicornia bigelovii, is an annual plant being studied by Masdar Institute. Small-scale trials there are assessing the potential for salicornia to be grown in conjunction with mangroves on coastal sites. The interest is due to the seed of salicornia containing 27-31% oil, and the plant has been reported as producing 2 tonne/ha of seed. Protein level in the press cake is about 30%. Salt content in the seeds is acceptably low but salt levels in the leaf is relatively high, though it has potential as a component of stock feed. In one trial goats fed dry salicornia leaf and stalk at up to 50% of the diet did not suffer any significant growth setback. [Salt tolerance and crop potential of halophytes]

The use of highly saline water for flood or spray irrigation is not suitable for many sites. Though salicornia can yield well when the soil solution is up to 70 gm/litres of NaCl (or twice the salt content of seawater), this amount of salt remaining in most soil will significantly change its characteristics quite rapidly, including its permeability.

In general it appears that halophyte irrigation works either when high salt content water is used on very porous soils where it can leach away readily (such as in when high volumes of sea water are used on very porous coastal sands), or when the water used is more saline than ordinary crops will tolerate but not so saline that salt accumulates in the upper levels of the soil profile. Early research indicates that soils with a sodium absorption ratio (SAR) of greater than 15 would be precluded from being irrigated by highly saline water. A well designed drainage system may possibly allow higher salinity water to be used. [Salt tolerance, Crop potential of Halophytes]

Cost of pumping irrigation water, and cost of irrigation systems modified to cope with high salt content water, have to be factored into the economics of halophyte production. Work has been underway exploring the possibilities for some decades. A pilot plant was reported working in Saudi Arabia in 1994, where four centre pivot irrigation systems were each irrigating a 50 ha plot of salicornia with 44 gm/litre seawater. [Salt tolerance, Crop potential of Halophytes]

Enzymes and chemicals. While there are several technologies or processes that can convert alcohols to a biojet fuel, to date the cost of the alcohol feedstock has meant that the final biojet is too expensive. Up till now it was cheaper to make ethanol from sugar cane than ethanol from cellulose, yet clearly cellulose is very cheaply available in vast quantities as straw, stalk and sawdust. If the production of ethanol from cellulose could be made significantly cheaper, this may make it possible to produce cost-competitive biojet by the ATJ pathway.

To produce ethanol from cellulose, first the complex carbohydrate that is cellulose has to be broken down into simple carbohydrates. These can be then converted into ethanol by selected yeasts. Until now the breaking down of the cellulose cell wall of the plant was done quickly using an expensive enzyme, or more slowly by use of diluted acid.

A team of Iranian and Danish researchers have found out how to extract an organic acid from rice husks [Danish NIRAS] that may be able to do this dismantling of cellulose significantly more cheaply than by the use of a specially-produced enzyme.

New process developments: there are very many areas of research and development within this overall field. One example is with pyrolysis or other processes for converting agricultural residues and woody wastes into some form of biocrude oil. Licella in Australia is one company that is working on hydro-liquefaction of ligno-cellulose - the reaction medium of water being kept at a subcritical (liquid) state by the correct combination of temperature and pressure. The resulting bio-oil product is significantly different in its composition to the bio-oil produced by conventional fast pyrolysis. Any advantage of the process will lie in its ability to either produce a bio-oil that can be more readily converted to a final biojet, or that allows a cheaper and less technically complex process, or both.

Summary. Research into some areas related to feedstock production could be carried out in a country's universities and research organisations. This could include into systems of microalgae production, production of yeasts and bacteria, production and selection of jatropha and halophytes. It is likely that there are some options for biomass production where a country has a distinct advantage over many other countries, and this may be in some combination of indigenous species, growing conditions, and availability of water and land.

Chapter 8: Sustainability Assessment

Issues of the sustainability of biojet production must be considered seriously in any review of development of feedstocks and technolgies. The whole driver for the development of biojet production, and its introduction within the EU and the support of its use by IATA, is due to concern about global level of greenhouse gas emissions and the contribution of jet fuel use in adding to overall emissions.

For a jet biofuel to be sold and used internationally it is important that it passes the criteria of a recognized international system, and so is certified as sustainably produced. Without this certification the market value of the biojet is likely to be significantly lower. For the international airlines to show that they are complying with the IATA or EU requirement they must demonstrate that they are use only certified biojet for blending with petroleum jet fuel.

The criteria by which sustainability is assessed can be divided into separate environmental, social and economic groupings. These are:

- Land - its use or change, and any indirect land use change
- Water – its use, contamination/silting, access, and recharge
- Greenhouse gas emissions involved with production
- International labour laws and conditions, including employment of underage children, and payment of proper wage rates
- Laws and International Conventions
- Land Rights. Displacement of rural or indigenous populations or interference with traditional or customary practices.
- Rural and Social Development– jobs, health, education, cultural loss
- Contractors and Suppliers
- Environmental and Social impacts
- Biodiversity and Ecosystems
- Use of chemicals, crop management practices
- Soil and air pollution, and management of waste
- Employment, Wages and Labor Conditions
- Human Health and Safety
- Engagement and Communications with Stakeholders
- Food Security
- Economic Viability and Production and Processing Efficiency

Clearly not all of these sections will apply in every location, and the last point is surely a given for any supposedly commercial venture. The second last point – Food Security – is a crucial issue for many NGOs, which have been witness to gross violations of this point in particular, among many of these points, including displacement of communities and overriding of legal rights, and in some cases a sentencing of these groups to poverty and sometimes starvation.

For something to qualify as 'sustainable', in general it has to either satisfy all these criteria, or at least not fail the more critical ones among them. A significant project should get a score of positive or neutral on each item in the list. It may be possible that a minor negative score for one item can be offset by some strongly positive score for some other item. For instance some project may be sited in a way that it blocks a nomadic herding route, but the project has a positive feature that offsets some negative point – i.e., it provides better grazing or water for the herds.

In relation to larger-scale production of biojet the different stages in the production process are likely to be examined on their own merits (or demerits)

1. large-scale production of a feedstock – this may take up thousands of hectares of land and use millions of litres of water annually. It will require workers and roads. It may add a new source of surface water for wildlife and a new source of food and shelter for birds and wildlife. It may reduce sand movement and may sequester very large amounts of carbon.

2. aggregation and transport of the feedstock – this will use fossil fuels (though later it may use entirely biofuels)

3. processing of the feedstock into biojet fuel – this will require significant electricity though may generate its own heat. A modern system will have tight control on any release of noxious odours or fumes, or chemicals that will enter or accumulate in land or water.

4. transport of the biofuel – this may be by pipeline, barge or by petroleum-fuelled or biofuelled road vehicles.

Each of these steps can be done with a greater or lesser concern for the efficiency or sustainability of the step. Often it costs no more (and may cost significantly less over the longer term) to manage or design each part of the process to be more efficient or more sustainable.

Summary

The more likely options for biojet production in a developing country are

1). to produce vegetable oil (from some high yield, non-edible and low cost/tonne source such as improved properly managed jatropha) and convert it to biojet using the HEFA pathway

2) to produce pyrolysis oil from sorted dry municipal wastes and convert it to biojet by the HDCJ (pyrolysis oil) pathway

3) to produce ethanol from sugar cane and convert it to biojet using the ATJ pathway

4) to produce biojet using the DSHC pathway – as now being done by Amyris in Brazil, producing an aromatic hydrocarbon from sugar that can be blended at up to 10% with jet fuel

At first glance the sustainability of the second option seems to be the most positive – at least until the final steps. It takes an already aggregated waste that is not well handled at present, and converts it into a valuable product.

The other three options require large areas of land and a lot of water. Option 1 has the advantage that it will use land that has no other present use, and will use a relatively smaller amount of water per unit of production area.

Option 3 will be hard to make pass all the criteria for sustainability.

On the positive side options 2, 3 &4 may be shown to reduce the national greenhouse gas emissions, stimulate rural and regional development, utilise water or land that was presently not used, and generate large number of jobs. Other positives that might offset some perceived negatives would include a demonstrated significant reduction of deforestation or slowing of desertification.

Chapter 9: Policy development, Roadmaps and Action Plans in place for different countries and regions.

While many countries have developed policies to support and introduce biofuels for road transport, a much smaller number have committed to implementing policies for production and significant use of jet biofuels. In Chapter 4 – Studies of Activity and Development in Selected Countries – some mention is made of jet biofuel policy development and of targets for production and use in countries including the Netherlands, Brazil, Norway and Indonesia.

But the main activity with policy development is occurring at a regional level (i.e., the European Union), or within the number of working groups which usually include countries or groups of countries, fuel producers, NGOs, airlines and original equipment manufacturers (i.e., makers of aircraft and engines). In either case the activity must work within the existing frameworks, obligations or requirements that apply to biojet fuels. These are

- the ASTM approved processes for production,
- the IATA, ICAO and EU regulations, targets and goals for 2020 and 2050
- the criteria for sustainability of feedstock production
- regulations or requirement of international agreements relating to trade, labour and other areas, including transport
- the existing technical. logistical and economic constraints

There have been a number of examples where countries have launched into production of biofuels feedstocks, or of final biofuel product, without adequately or fully developing a comprehensive Roadmap by which the process should have been guided and assessed. Such a Roadmap would normally examine and scope all aspects of the proposed biofuels development, including identification of risks, and identification of funding and timeframes. It should also have built into the process some reliable feedback processes (which might be based on timelines, 'milestones' and assessment benchmarks) which will sound an alarm in the right quarters if the process bogs down or loses its way. It is critical that this feedback process is effective, as when a biofuels program has failed it has usually been embarrassing, costly and damaging for the sector.

Failure of a national biofuel development program, or of some critical part of a biofuel program, has generally been due to one or more of a group of factors. These have included-

- basing a program for biofuels production on unrealistic forecasts of cost or yield of production of a feedstock. Examples of this include major plantings of low yielding jatropha plantings around the world from 2000-2010
- producing the biofuel before there were adequate legislation and regulation in place for pricing, distribution or blending, or logistical frameworks or physical systems in place, or public education about the changes in supply.
- A collapse in the national or international economic situation, or loss of funding for a key stage of the process – for example, the global financial crisis impacting on the Fischer-Tropsh plant being built by Choren in Germany, and the subsequent failure of the project

- A removal of some critical part of the supportive policy framework on which the planning is based – i.e., the repeal of carbon tax legislation in Australia in 2014
- Subsidies or market-distorting funding programs interfering with normal market economics, stimulating and supporting energy-inefficient biofuels production – the corn ethanol production program in the USA is one example.
- Lack of preliminary investment in well-focused R&D. Lack of Mexican investment in assessment and selection among its indigenous forms of *Jatropha curcas* is one example. But investment in R&D is a problematic area, as R&D is costly, can go off in unproductive directions, and, even when properly focused, is often slow in producing commercially useful results. In many cases it is better to buy the proven technology developed from R&D elsewhere.
- Getting too far in front of the general trends internationally, including of the market place, in committing to a technology, or a product. Sometimes this can work- as in Brazil's development of ethanol to replace gasoline.

A well-developed National Biofuels Roadmap will identify and should avoid these and other traps, or at least provide an assessment of the risk and how to 'insure' against the risk. An essential part of any National Biofuels Roadmap will be an Action Plan. The purpose of this is to identify the timelines and all the actions that need to take place in their approximate order, and the policies that need to be put in place, so that the process proceeds as smoothly as possible.

There are an increasing number of examples of national Aviation Biofuel Action Plans. This chapter looks at those produced for Brazil and the Netherlands. In addition to those this overall publication has drawn on reports and feasibility studies done for the USA, Norway, Australia, the EU, and Denmark (see reference section for detail).

While the reports done for each country may differ in the technologies identified as being most suitable for short and longer term development, they all follow a similar logical sequence of

- defining the present national situation,
- outlining the legislative or economic requirements for taking any action,
- detailing the R&D elements for focus in shorter and longer term,
- detailing the actions that need to be taken and the policies that need to be put into place
- identifying the importance of continual interaction with stakeholders, including other countries or regional governments.

The report authors suggest that the general approach taken in the Aviation Biofuel Action Plan of Brazil and the report done by Ecofys for the Ministry of Infrastructure in The Netherlands are two (among the many reports and plans available) that provide examples which can be considered in developing the approach to follow for Sudan in developing its Biojet fuel Action Plan

Brazil: The Action Plan identified two main sources of biomass – woody biomass from short rotation high growth rate eucalyptus plantations, and sugar and harvest residues from the sugar industry. Based on this it looked at the Alcohol to Jet, the Direct Sugar to Hydrocarbons pathway and the Fischer-Tropsh pathway as being of more immediate relevance, but also saw the biomass pyrolysis oil to jet (HDCJ) pathway and HEFA pathways as having a possible place in future Brazilian biojet production.

The large group of over 43 stakeholder organizations from all levels and areas of feedstock production, transport, technologies, financing, standards and research contributed to development of the Action Plan. The project was managed by a steering committee of three and an executive committee of three (with one person from Boeing being on both committees)

The project used a facilitator team and research team totalling nine well-qualified people from different institutions. These two teams included people with expertise in all the necessary areas - from sustainability, though refining technologies, roadmap development, legislation, and engines fuels and logistics.

The combined input from all the stakeholders and individuals described out the present situation and explored the issues. All the input is brought together in a comprehensive document full of quite prescriptive information, including on most promising feedstocks, most likely technologies, and identification of the gaps in research or other aspects that need to be attended to. Page 15 of this report breaks down the Recommended Actions into

- Issues related to feedstock production: including policies required, R&D gaps, logistical infrastructure issues, monitoring sites to assess sustainability and legislation needed to enforce aspects of sustainability
- Refining Technologies:progress research on different technologies, establish pilot plants, and establish demonstration and first commercial plants
- Biofuel logistics and certification: prepare the Brazilian set of regulations, develop competence for certification, and develop a long term strategy and plan for production and distribution of biofuels.
- Policies: establish facilities to be the centre of scientific and commercialization activites, anticipate regulatory actions by ICAO, establish/regulate sustainability criteria, build up high level human capacity for biojet fuels, establish policies to include small farmers and/or local communities in biojet fuel production chain.

The Netherlands: The report by Ecofys (published in 2013) identifies opportunities and barriers for the Netherlands with regards to increasing the use of jet biofuels. The report specifies some actions the Dutch government should take and the policy options that should be implemented in order to create a Dutch market for jet biofuel. It splits its time frame into short term (2013-2015), mid-term (2015-2020), and longer term (2020-2030). It advises that through the entire period there should be a stable policy maintained by the Dutch government with regard to R&D on the jet biofuel supply chain, and on 'the (new) production technologies of biojet fuel, so that advanced production technologies can be deployed once the market reaches full commercialisation'.

On page vi in the summary section of this report, the layout of policy recommendations and short term actions for the Dutch government are added to with some short recommendations and actions for the part the Netherlands will need to play during this part of the time frame in the EU, and worldwide. So, one thing the Netherlands needs to be doing over the period 2013-2015 is to 'explore cooperation with other nations', and over the period 2015-2020 is to 'investigate support for feedstock projects in developing countries'.

In relation to feedstock production (section 4.4, P 29) the report is quite specific in saying 'currently most bio jet is produced using jatropha oil, camelina oil and used cooking oil as a feedstock. Jatropha and camelina will typically be grown outside of the Netherlands because of limited available space. However securing the availability and acceptable pricing of feedstock will be essential to the development of a successful bio jet fuel industry'.

Summary

The two sources used here provide some useful examples of a process that can be followed, of the breadth and depth of the consultation that is needed within and beyond the borders of any one country, and of the areas of particular focus over different parts of the overall time frame. Neither source went deeply into the costs or risks (though it is obviously critical for these to be identified in any more complete study). Both identify that it is a major priority that the country does not act alone, but must act in concert with regional and neighbouring governments, major organisations – including sustainability certification bodies and aviation regulatory bodies, and the general research community, as well as with the main national stakeholders.

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Glossary

Agri-biomass – material produced as a by-product or residue of agricultural or horticultural production

Agricultural residues – by-products or residues from agriculture

Algae (autotrophic) – refers to algae (and usually to microalgae) that need sunlight, CO_2 and usually warmth to grow (and for producing lipids)

Algae (heterotrophic) – algae that does not photosynthesise (i.e., require CO_2 and light) but instead use some alternate growth inputs and process

Alternative fuel – fuel from non-petroleum source

Anaerobic digestion – breakdown of 'wet' or putrescible organic waste by bacteria in absence of oxygen, and with production of methane and carbon dioxide

Aromatics – molecule with a carbon ring of unsaturated bonds

ASTM D1655 – ASTM standard specification for aviation turbine fuels

ASTM D7566 – ASTM standard specification for aviation turbine fuels containing synthesized hydrocarbons

Biochemical – chemical activity in microorganisms and/or by organic enzymes

Biodiesel – the methyl ester of vegetable oils or animal fats. Its combustion properties in a diesel engine are similar to those of petroleum diesel.

Biofuel – transport fuel produced from biomass feedstocks

Biogas – the mix of methane and CO_2 produced by anerobic decomposition of organic matter of low dry matter content (usually under 20% DM)

Biojet fuel – jet fuel produced from biomass by any one of a number of processes

Biomass – a cover-all term meaning all material that comes from plants or animals

Biomethane – methane produced from biogas by removal of CO_2, water vapour and hydrogen sulphide. Also known as 'upgraded biogas'

Blend – a mix of different compatible fuels. Here it refers to a mix of petroleum jet and biojet

Butanol – an alcohol comprising 4 carbon atoms

Carbon neutral – with zero net amount of carbon dioxide emissions attributed to a product or activity; so CO_2 emissions = CO_2 absorption

Catalyst – a material that facilitates or speeds up a chemical reaction without itself being changed. Many catalysts in fuels synthesis are metals (i.e., cobalt, iron) or alloys of several metals, processed to have very large surface area exposed to gases

Cellulose – a complex carbohyrate consisting of linked D-glucose molecules

DefStan 91-91 = UK Defense standard for turbine Fuel, aviation Kerosene type

Density – mass per unit volume

Distillation – the separation of liquids by means of their difference in boiling point

Drop-in fuel – renewable fuel substitutes for petroleum-sourced fuels. They are produced from biomass by some chemical or thermo-chemical synthesis process. Often chemically identical (so biodiesel is not a 'drop-in' fuel).

Ethanol – alcohol containing 2 carbon atoms

Feedstock – raw material entering a process. It can be solid, liquid or a gas

Fermentation – biochemical process of transforming of biomass with yeast

Flash point – the temperature at which the fuel ignites in the engine and combustion begins to occur

Freezing point – temperature at which a liquid freezes on cooling

Gasification – process transforming a feedstock principally into CO and H_2 under high temperature and almost zero oxygen

Genotype – refers to the genetic makeup of plants: genes influencing useful characteristics can be selected for and the characteristics enhanced

Halophyte – plants evolved to grow in salt water or on salinity-affected land

Heating value – a fuel's specific energy; units in MJ/kg

Hydrocarbons – molecules formed of carbon and hydrogen, frequently used as fuels

Hydrocracking – splitting or shortening of longer carbon chains by use of hydrogen

Hydrogenated – 'raw' biofuels feedstocks (i.e., vegetable oil) upgraded by hydroprocessing

Hydrotreatment – saturating and removing impurities in hydrocarbons using hydrogen

Jet A – main commercial jet fuel for North America
Jet A-1 – main commercial jet fuel outside North America

Ligno-cellulosic – cover-all term for fibrous plant material including wood

Lipids – a general term for oils, fats, waxes and tallows

Paraffin – alkane hydrocarbons with general formula CnH2n+2

Pyrolysis – thermal decomposition of biomass in the absence of oxygen. Pyrolysis can be categorised as 'slow', 'fast' or 'flash', depending on temperature involved. Fast pyrolysis of biomass produces a complex mix of volatilized material

Pyrolysis oil – the condensate of the volatilized compounds produced by fast pyrolysis

Smoke point – relative smoke-producing property of fuel

Sulphur content – the amount of sulphur in the fuel (parts per million)

Switchgrass – a perennial grass grown in North America

Synthesis gas (also called syngas) - gas containing a mix of simple molecules resulting from breakdown of complex molecules under extreme heat and absence of oxygen

Tallow – rendered-down and purified animal fat

Viscosity – measure of the flow rate of a fluid at standard temperature and pressure

Yellow Grease – mix of vegetable oils, fats and water caught in 'grease traps'

Abbreviations and acronyms (items in bold are biojet-production pathways)

ASTM American Society for Testing and Materials

ATJ Alcohol-to-Jet fuel

BtL Biomass to liquids (Fischer-tropsch process)

CAA Civil Aviation Authority

CO Carbon monoxide (a flammable and reactive gas)

CO2 Carbon dioxide (a non-flammable and relatively-unreactive gas)

CtL Coal to liquids (Fischer-Tropsch process)

DSHC Direct Sugars to Hydrocarbons (sugars to jet pathway)

EC European Commission

ETS Emissions Trading Scheme

EU European Union

FT Fischer-Tropsch

GHG Greenhouse gas (the group of atmospheric gases that act to retain incoming solar radiation: CO2, methane, water vapour, nitrous oxide…)

GtL Gas to liquids (Fischer-Tropsch process)

Ha Hectare (1 hectare ~ 2.4 feddan. I feddan is 0.42 ha or 4200 m2)

HDCJ Hydro-treatment of Depolymerised Cellulosic Jet (i.e., pyrolysis oil to jet)

HEFA Hydrogenated Esters and Fatty Acids (also HVO–hydrogenated vegetable oil)

IATA International Air Transport Association

i.e., abbreviation of the Latin 'id est', meaning 'that is', or 'for example'.

IEA International Energy Agency

MJ Megajoule

Mtoe million tones of oil-equivalent (unit for energy content of different fuels)

NGO Non-Government Organisation.

OEM Original Equipment Manufacturer

ppm Parts per million

RED Renewable Energy Directive (EU)

SIP Synthesized Iso-Paraffıns (*from hydroprocessed fermented sugars)*

SKA Synthetic Paraffinic Kerosene with Aromatics

SPK Synthetic Paraffinic Kerosene

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