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Report

Benchmark of conversion and production technologies for synthetic biofuels for aviation

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ABSTRACT
This work has identified, described and discussed the most promising and suitable technological pathways and biomass resources for the production of renewable jet-fuel in Norway by 2020-2025. The content of this study is based on data collection provided through in-depth questionnaires by the most relevant stakeholders involved currently in the product of renewable aviation fuel in conjunction with publically available literature (articles, studies, press releases and presentations).

Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT) and Alcohol-to-Jet (ATJ) technologies are identified as the three most promising technologies for the production of jet-fuel within the coming decade. In a Norwegian context, however, the large availability of lignocellulosic biomass makes FT and ATJ technologies the two main candidates for aviation biofuels. Additionally, potential alternative biofuels such as pyrolysis-to-jet fuels and fermented renewable fuels are introduced shortly.

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Preface

This work has identified, described and discussed the most promising and suitable technological pathways and biomass resources for the production of renewable jet-fuel in Norway by 2020-2025. Emphasis has been focused on the two certified routes, namely Fischer-Tropsch (FT) fuels and Hydroprocessed Esters and Fatty Acids (HEFA), and on the route currently under certification, namely Alcohol-to-Jet fuels. Two additional alternative renewable jet-fuels still in the early stage of commercialization referred to as Pyrolysis-to-Jet fuels and Fermented Renewable Jet fuels are introduced shortly.

Acronyms

HEFA-SPK – Hydroprocessed Esters and Fatty Acids-Synthetic Paraffinic Kerosene
HRJ – Hydrotreated Renewable Jet
FT-SPK – Fischer-Tropsch-Synthetic Paraffinic Kerosene
ATJ-SPK – Alcohol-to-Jet-Synthetic Paraffinic Kerosene
PTJ-SPK – Pyrolysis-to-Jet-Synthetic Paraffinic Kerosene
FRJ-SPK – Fermented-Renewable-Jet-Synthetic Paraffinic Kerosene
ASTM – American Society for Testing and Materials
GHG – GreenHouse Gas
KL – Kilolitre
HHV – Higher Heating Value
LHV – Lower Heating Value
BTX – Benzene, Toluene, Xylene
LPG – Liquefied Petroleum Gas
MTG – Methanol-to-Gasoline

1 Setting the Scene

1.1 Use of conventional Jet A-1

The current aviation fuel, kerosene (Jet A/A-1), is a blend of hydrocarbons made up of molecules with typically 8 to 16 carbon atoms per molecule [1] produced by refining of crude oil. It is a middle distillate between gasoline and diesel. Traditionally, aviation kerosene is around 10% of the crude oil cut globally, with a technical maximum of 15%, depending on the oil field. The maximum cut is seldom economical. In Europe, the high diesel demand results in kerosene shortage and thus, aviation fuels need to be imported today [1, 2].

A number of very strict technical requirements define whether a certain fuel is suitable for commercial aviation. These specifications are necessary to identify and control the properties required for satisfactory and reliable performance and thus ensure aviation industry's top priority: safety [3]. Jet-fuels need to deliver a large amount of energy content per unit of mass and volume, in order to minimize fuel carried for a given range, the size of fuel reservoirs, and the drag related to the fuel storage. In addition, jet-fuels also need to be thermally stable, to avoid freezing or gelling at low temperatures, and to meet other criteria in terms of viscosity, surface tension, volatility, lubricity, sulphur content, density, ignition properties and compatibility with the materials typically used in aviation. The aviation kerosene fuel is defined in the ASTM D1655 standard in the US and in the DEF STAN 91-91 in Europe. The standardized fuel is coordinated and practically the same throughout the world [1, 4, 5]. Figure 1.1 lists selected specifications properties of jet-fuels [3].

Fuel	Jet A	Jet A-1	TS-1	Jet B
Specification	ASTM D 1655	DEF STAN 91-91	GOST 10227	CGSB-3.22
Acidity, mg KOH/g	0.10	0.015	0.7 (mg KOH/100ml)	0.10
Aromatics, % vol, max	25	25.0	22 (% mass)	25.0
Sulfur, mass%	0.30	0.30	0.25	0.40
Sulfur, mercaptan, mass%	0.003	0.003	0.005	0.003
Distillation, °C:				
Initial boiling point	—	Report	150	Report
10% recovered, max	205	205	165	Report
50% recovered, max	Report	Report	195	min 125; max 190
90% recovered, max	Report	Report	230	Report
End point	300	300	250	270
Vapor pressure, kPa, max	—	—	—	21
Flash point, °C, min	38	38	28	—
Density, 15°C, kg/m^3	775–840	775–840	min 774@20°C	750–801
Freezing Point, °C, max	–40	–47.0	–50 (Chilling point)	–51
Viscosity, –20°C, mm^2/sec, max	8	8.0	8.0 @ –40°C	—
Net Heat of combustion, MJ/kg, min	42.8	42.8	42.9	42.8
Smoke point, mm, min	18	19.0	25	20
Naphthalenes, vol%, max	3.0	3.00	—	3.0
Copper corrosion, 2 hr @ 100°C, max rating	No. 1	No. 1	Pass (3 hr @ 100°C)	No. 1
Thermal stability				
Filter pressure drop, mm Hg, max	25	25	—	25
Visual tube rating, max	<3	<3	—	<3
Static test 4 hr @ 150°C, mg/100 ml, max	—	—	18	—
Existent gum, mg/100 ml, max	7	7	5	—

Figure 1.1. Selected specifications properties of jet-fuels [3].

The aviation industry is highly vulnerable to fuel price fluctuations; with fuel representing 33% of an airline's operating costs on average. These fluctuations are directly related to the volatility in oil prices that are strongly associated with OPEC production policies, geopolitical uncertainties, strong demand (specially in Asia), economic environment, low petroleum inventories, refinery bottlenecks and periodic problems, technical factors, speculative activities and dollar strength [6].

Airlines spent $140 billion on jet-fuel in 2010 and the cost is expected to reach $200 billion in 2012 (Figure 1.2). These high prices coupled with the significant price volatility associated with jet-fuels have become an additional factor to the already well known energy supply and reduction of GHG emissions main drivers for the emergence of sustainable alternative jet-fuels.

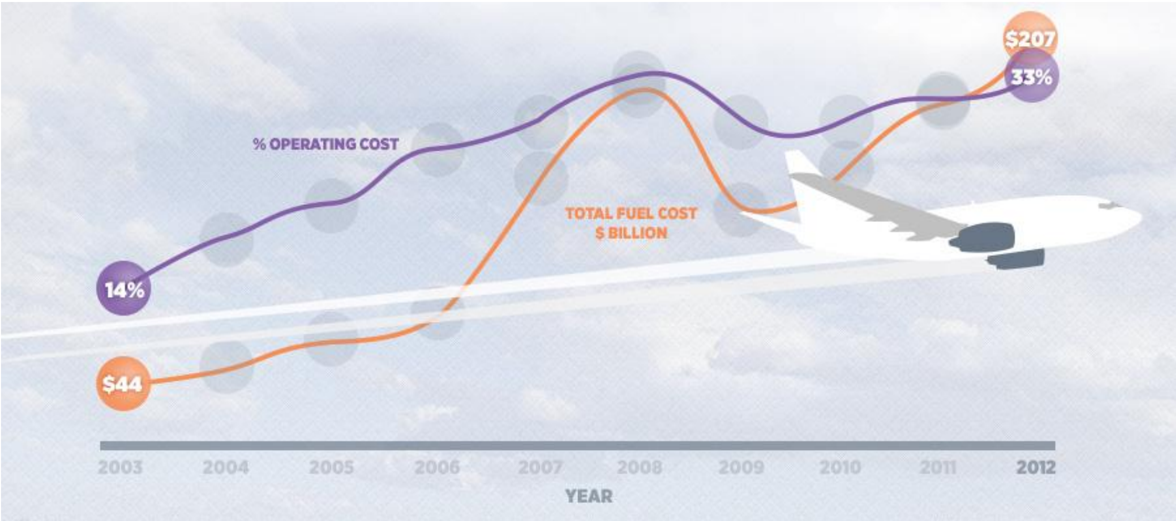


Figure 1.2. Fuel price and fuel price volatility. Adapted from http://renewablejetfuels.org [7].

A second major driver for the development of sustainable alternative jet-fuels is the environmental impact associated with the air transport sector. Although total air transport including domestic and international operations accounts for around 2% of the total man-made CO_2 emissions of more than 34 billion tons [4, 8], traffic is expected to increase at an annual average rate of 4.5% over the next 20 years, as illustrated in Figure 3 [8], which will put tremendous pressure on the sector to find ways to mitigate the impact on climate change. In Norway, in particular, the GHG emissions amounted to 2.1% (Figure 3) of Norway's total emissions which is equivalent to 1.1 million tons of CO_2 equivalent [9].

The Air Transport Action Group, ATAG, has recently modelled and evaluated the impact of several mitigating measures and concluded that technology improvement alone will not be sufficient to reduce the GHG emissions in the coming future, and therefore other means will be necessary. In this context, the development and commercialization of sustainable aviation biofuels will be essential in order to be able to meet the goal for carbon-neutral growth by 2020.

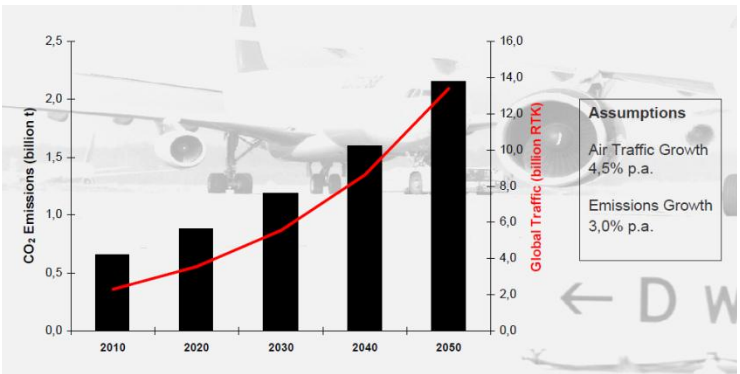


Figure 1.3. Expected CO2 emissions associated with aviation [8].

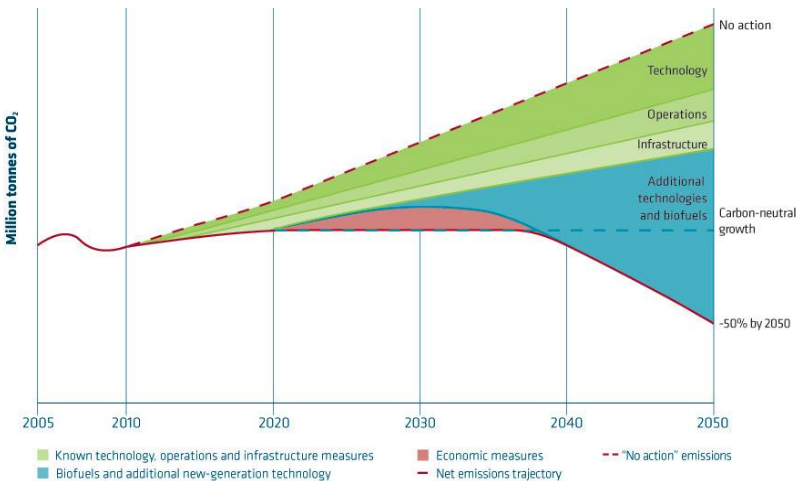


Figure 1.4. CO2 reducing measures and the expected impact of those for aviation [4].

The most likely alternative fuels for aviation over the near-medium term are biofuels that meet or exceed the oil-derived kerosene specifications and do not require any modifications to either equipment or infrastructure, known as “drop-in” fuels. If the fuel is sustainable it could be a viable solution for the challenges stated above.

Non-drop-in fuels and drivetrains (solar, hydrogen, FC, etc.), on the contrary, require new aircrafts and ground infrastructure, and considering (i) the slow rate of aircraft fleet renewal, (ii) investment costs and (iii) tailoring the technology to a specific drivetrain, these fuels can be considered as long-term solutions and will not be considered in this study.

1.2 Flight tests

The alternative fuels for aviation have been already tested extensively. The two major alternatives, Fischer Tropsch (FT) fuels and Hydroprocessed Esters and Fatty Acids (HEFA), have been through several engine and flight tests in civil and military aircrafts as well as a supersonic flight. These tests are essential prior to certification of these fuels. Some of these flight tests with and without passengers are summarized in Figures 4 and 5, respectively. After certification, further tests on scheduled passenger flights are conducted.

1.2.1 Testing (demo) flights

Table 1.1. Testing (demo) flights conducted since 2008 [10].

Carrier	Aircraft	Partners	Date	Biofuel	Blend
virgin atlantic	B747-400	Boeing, GE Aviation	23 Feb 2008	Coconut & Babassu	20% one engine
AIRBUS AN EADS COMPANY	A380	Airbus, Rolls-Royce, Shell	1 Feb 2008	Gas to Liquid (not biofuel)	50% one engine
AIR NEW ZEALAND	B747-400	Boeing, Rolls-Royce	30 Dec 2008	Jatropha	50% one engine
Continental Airlines	B737-800	Boeing, GE Aviation, CFM, Honeywell UOP	7 Jan 2009	Algae and Jatropha	50% one engine
JAL	B747-300	Boeing, Pratt &Whitney, Honeywell UOP	30 Jan 2009	Camelina, Jatropha, Algae blend	50% one engine
QATAR AIRWAYS القطرية	A340-600	Airbus, Shell	12 Oct 2009	Gas to Liquid (not biofuel)	50% four engines

KLM	B747-400	GE, Honeywell	23 Nov 2009	Camelina	50% one engine
UNITED	A319	Rentech	30 Apr 2010	Gas to Liquid (not biofuel)	40% two engines
TAM	A320	Airbus, CFM	23 Nov 2010	Jatropha	50%
interjet	A320	CFM, Safran, EADS, Airbus, Honeywell	1 Apr 2011	Jatropha	27%
Honeywell	G450	Rolls-Royce, GulfStream	18 Jun 2011	Camelina	50% one engine
BOEING	B747-8F	GE, Honeywell	20 Jun 2011	Camelina	15% four engines
AIR CHINA 中国国际航空公司	B747-400	Boeing, PetroChina, Pratt & Whitney, Honeywell UOP	28 Oct 2011	Jatropha	50% one engine
الإتحاد ETIHAD AIRWAYS	300 ER	Boeing	24 Jan 2012	Recycled Vegetable Cooking Oil	TBC
ANA	787 Dreamliner	Boeing	17 Apr 2012	Used Cooking Oil	TBC
Azul Linhas Aéreas Brasileiras	E190	Embraer, Amyris, GE Aviation	19 Jun 2012	Sugarcane	TBC

1.2.2 *Passenger flights biofuels programme*

Table 1.2. Passenger flights conducted since 2011 [11].

Carrier	Aircraft	Flight paths	Date	Feedstock (Supplier)	Notes
KLM	B737	Amsterdam-Paris	22 Jun 2011	Used cooking oil (SkyNRG)	200 city pair flights from September 2011
Lufthansa	A321	Hamburg-Frankfurt	15 Jul 2011	Mix of feedstocks (Neste Oil)	1200 flights over a six-months period
FINNAIR	A321	Amsterdam-Helsinki	18 Jul 2011	Used cooking oil (SkyNRG)	
interjet	A320	Mexico City-Tuxtla Gutierrez	21 Jul 2011	Jatropha (ASA)	

AeroMexico	B777	Mexico City-Madrid	1 Aug 2011	Jatropha (ASA)	
Iberia	A320	Madrid-Barcelona	3 Oct 2011	Camelina (ASA)	
Thomson Airways	B757	Birmingham-Arrecife	6 Oct 2011	Used cooking oil (SkyNRG)	Dayly flights in early 2012 for six weeks
AirFrance	A321	Toulose-Paris	13 Oct 2011	Used cooking oil (SkyNRG)	Flight used 50% biofuel in each engine
United	737-800	Houston-Chicago	7 Nov 2011	Algae (Solazyme)	40% biofuel domestic flight
Alaska Airlines	737s and Q400s	Seattle-Portland Seattle-Washington	9 Nov 2011	Used cooking oil (SkyNRG)	75 scheduled domestic flights powered by 20% biofuel
Thai	777-200	Bangkok-Chiang Mai	22 Dec 2011	Used cooking oil (SkyNRG)	
Lufthansa	747	Frankfurt-Washington DC	12 Jan 2012	Mix of feedstocks (Neste OilMi)	Reduced CO2 emissions by 38 tons
LAN	A320	Santiago-Concepcion, Chile	7 Mar 2012	Used cooking oil (SkyNRG)	Trial flight
Qantas Spirit of Australia	A330	Sydney-Adelaide, Australia	13 Apr 2012	Used cooking oil (Sky NRG)	Trial flight
porter	Q400	Toronto City-Ottawa	17 Apr 2012	Used cooking oil (Honey well/SkyNRG)	
Jetstar	A320	Melbourne-Hobart	19 Apr 2012	Used cooking oil (SkyNRG)	
porter	Q400	Montreal-Toronto	18 Jun 2012	Camelina	
Air Canada	A319	Toronto-Mexico City	18 Jun 2012	Used cooking oil (SkyNRG)	

AeroMexico	777	Mexico City-Sao Paulo	18 Jun 2012	Mix of feedstocks (ASA)
KLM	777	Amsterdam-Rio de Janeiro	19 Jun 2012	Used cooking oil (SkyNRG)

2 Interviews

2.1 The questionnaire

A significant number of the most relevant international biosynthetic jet A-1 producers (11) involved in various technologies and from different geographical locations were identified and contacted in order to conduct in-depth interviews for data collection through an in-house formulated template/questionnaire. The template was designed to obtain information on experiences and perceptions regarding their respective technologies. The developed template, addressing the main value chain parameters defining a technology, includes the following aspects:

- *Key information on specific bio Jet A-1 production plant*
  - Facility type
  - Plant capacities and operation
- *Feedstock*
  - Nature
  - Size
  - Cost
- *Technologies*
  - Process steps
  - Technology readiness level (TRL)
- *Jet A-1 and by-products*
  - Energy content
  - Density
  - Production costs
  - Selling price
  - Testing
  - Nature of by-products
- *Advantages and challenges associated with the technology*

The formulated as well as the received templates are enclosed in the Appendix section.

2.2 Main findings

The stakeholders that had a positive response on the provided template and shared information on their respective technologies are listed in Table 2.1. Due to the strictly confidential and non-sharable information by the stakeholders, the received templates included mainly information on general aspects such as the type of technology applied, the nature of the feedstock and/or the advantages and challenges associated with their technologies. However, one of the stakeholders, Solena, gave more detailed information. The information received from the stakeholders is summarized below.

Table 2.1. Stakeholders that provided information.

Stakeholder	Technology	Location
Neste Oil [12]	HEFA	Finland
Ineos [13]	ATJ	US/Norway
BTG [14]	Pyrolysis	The Netherlands
Solena [15]	FT	US

2.2.1 Neste Oil

Neste Oil is a refining and marketing company, and their business areas are Oil products & renewables and oil retail. The company produces a comprehensive range of major petroleum products and is the world's leading supplier of renewable diesel.

Neste Oil has four commercial HEFA facilities in operation, which means that the technology readiness level is 9. The two first ones started up in Porvoo in Finland in 2007 and 2009 respectively, a plant in Rotterdam started up in 2011 and one in Singapore started up in 2012. Total annual renewable fuel capacity is 2 million tons, and the main product renewable diesel. There is ability to produce renewable aviation fuel at all four plants; however some investment for logistics will be needed. Currently renewable aviation fuel is produced in Finland, on batch basis, some thousand tons per year. This fulfils the current demand. In the future, when the market develops and the demand is higher, production is also possible on continuous basis (both diesel and aviation fuel) in Rotterdam and/or Singapore.

The advantages summarized by Neste Oil are that the technology is feedstock flexible and can use a wide range of different vegetable oils, tallow and fish oil. All feedstocks are carefully chosen based on strict sustainability and quality criteria, and the product life cycle emissions are significantly lower compared with fossil fuels. This technology gives a very pure and high quality product, and the chemical composition similar to fossil fuel.

The major challenges addressed by Neste Oil are that the investment costs of the plant and the feedstock price are high.

Further details can be found in the questionnaire received from Neste Oil (Appendices).

2.2.2 Ineos

INEOS AS is a leading petrochemical company. The INEOS Bio technology is a hybrid system producing ethanol from biomass. The major process steps are gasification to synthesis gas, bacterial fermentation of the synthesis gas and distillation to anhydrous ethanol. A process flow sheet is shown in Figure 2 1. A pilot plant has run 40 000 hours since 2003 in Fayetteville, Ark. USA, and a commercial plant is built in Verona Beach, Florida, USA. The latter will start up in Q3 2012 and commercial delivery is planned from Q1 2013.

The ethanol production is 0.4 liter / kg biomass, and the planned production of ethanol is 30 000 000 liter per year based on 100 000 tons biomass/year. The feedstock will start up using vegetative and agricultural waste, later MSW will be used as feedstock.

One of the main advantages addressed by INEOS is the feedstock flexibility. Unlike conventional bioethanol technologies, which use food crops, or even the emerging cellulosic fermentation technologies, which can convert cellulose and hemi-cellulose but not lignin, The INEOS Bio process can convert all lingo-cellulosic materials as well as other carbon materials into ethanol. The range of organic materials that can be used includes, but is not limited to:

- The biogenic portion of municipal solid waste (MSW), which includes garden and food wastes
- Organic commercial & industrial wastes
- Wood wastes
- Forestry residues and products
- Agricultural residues
- Lignocellulose energy crops

The advantages also comprise sustainability, as the process may use all kind of waste and do not need to reduce agricultural areas for food production as well as a GHG reduction of 90% compared to gasoline in cars. Further details can be found in the questionnaire received from INEOS (Appendices).

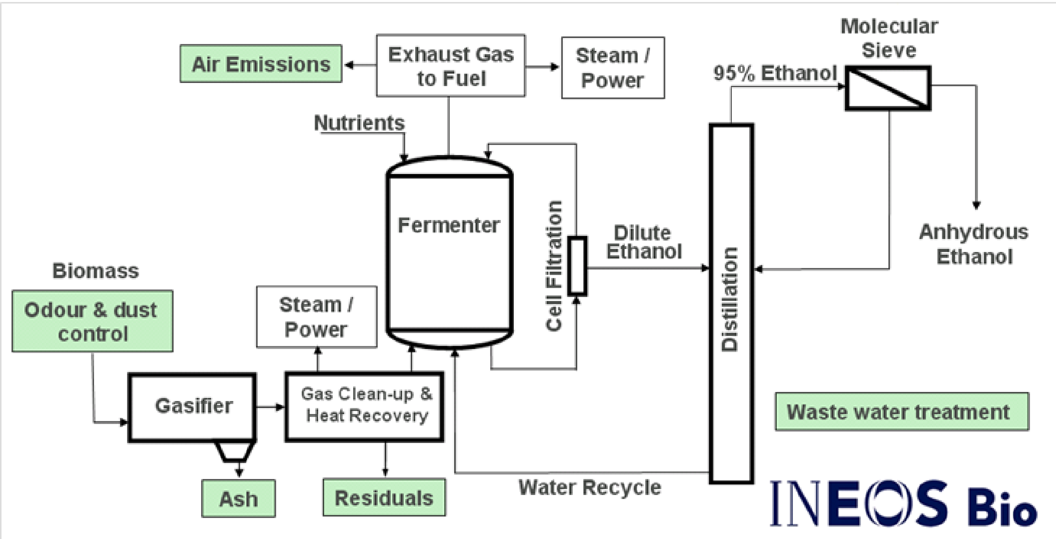


Figure 2.1. The INEOS Bioprocess

2.2.3 BTG

BTG Biomass Technology Group BV is a private SME company, which for the past 25 years has specialised in the conversion of biomass into fuels, energy, chemicals and materials. BTG consists of two business units: Consultancy and RTD. Within the RTD unit, the fast pyrolysis process has been under development since the early nineties. The fast pyrolysis process is being demonstrated through the FP7 project EMPYRO [16] (Dec 2010 – Nov 2013). The main aim is to build and demonstrate a 25 MWth polygeneration pyrolysis plant to produce electricity, process steam and fuel oil from woody biomass.

The BTG process includes a fast pyrolysis process based on mechanical mixing of biomass and hot sand. Any biomass feedstock is converted into pyrolysis oil through BTG patented technology. Further process steps are upgrading of the pyrolysis oil into refinery compatible pyrolysis oil, and co-refining of upgraded pyrolysis oil with mineral crude oil to biofuels (diesel, kerosene, gasoline).

The technology is under development, and the next stage would be prototype demonstration. The technology readiness level is 4-6.

The major advantages addressed by BTG are:

- ❖ Feedstock flexibility; basically, fast pyrolysis can use any biomass feedstock/residue,
- ❖ The resulting oil is considered as 2nd generation fuel, no competition with food or land for food. (It may even improve economics of food production).
- ❖ GHG reduction calculations have been carried out for the chain biomass-kerosene/diesel and an 82-85% emission savings is obtained.

Estimated costs of kerosene by the pyrolysis route are around 1300 euro/ton for a first plant decreasing to about 750 Euro/ton for an nth plant. Further details can be found in the questionnaire received from BTG (Appendices).

2.2.4 Solena

Solena Fuels Corporation is a global sustainable fuel company building a platform for the production of price competitive, certified, drop-in liquid jet and diesel fuels with the flexibility to use a variety of waste biomass feedstocks, including urban, agricultural, and forest waste.

Solena has provided substantial detailed information through the questionnaire about their facility planned to start up in Q4 2015 in East London, UK. The project is in the Engineering and Planning & Permitting Stages, and the construction will start in Q4 2013. The plant is based on Solena's high-temperature plasma gasification technology in combination with microchannel Fischer-Tropsch process, and the technology readiness level given by Solena is 9. The feedstock used is RDF produced from MSW, 563 136 tons/year.

Solena's Integrated Gasification BTL plant produces a total of 145.4 million liters of liquid fuels annually. This figure includes Synthetic Paraffinic Kerosene (59 million liters), clean diesel (56.9 million liters) and bionaphtha (29.5 million liters). The overall specific Liquid Fuels Production is thus 0.26 Liters per kilogram of RDF. In addition, in its standard configuration, the BTL produces renewable power (gross power output = 29.5 MW; net power output = 2.9 MW), thus making it a highly efficient, self-sustainable advanced biorefinery. The biomass to fuel energy efficiency is 57% (Energy eff, biomass, liquid). Optimizing the plant for production of steam instead of power (no power), an overall energy efficiency of 72.9% could be achieved (Energy eff, total).

Major advantages identified by Solena:

- ❖ Strong BTL plant Economics enables Solena to offer sustainable transportation fuel at competitive prices to petroleum-based fuel.
- ❖ Jet-fuel FT derived synthetic biofuel is certified for use in the Aviation Industry by the United States Air Force and by the Federal Aviation Administration and is specifically covered by a new ASTM standard for Alternatives to conventional Aviation Fuel containing Synthesized Hydrocarbons D-7665. This specification allows up to a 50 % blend of FT fuel with conventional Jet A. No testing, changes to fuel infrastructure or engine modifications are necessary.
- ❖ Ultra clean synthetic sustainable FT fuels helps reduce GHG and eliminate SO2 in transportation emissions addressing energy and environment concerns in addition to negligible particulate matter content. The industry accepted fuel meets and exceeds ETS standards based on both Roundtable

on Sustainable Biofuels (RSB) schemes and Renewable Energy Directive (RED) methodology for Life Cycle Analysis (LCA) evaluation and is not connected to food and land/ indirect land use issues.

- Feedstock Flexibility Secures Sustainable Supply Chain; Solena's technology can use a wide range of low-cost, carbon-bearing materials (like residential and industrial waste) mixed with forestry and agricultural residuals which provides long term feedstock availability.
- High Temperature Plasma Gasification can successfully gasify a mixture of feedstock including household waste because of the system tolerance to the variations in the feedstock energy values. The Solena plasma gasification/ depolymerization process has proven to be an economically viable, as well as less expensive than any other thermal process.
- The gasification process is environmentally benign, with no toxic waste by-products or emissions produced.
- Solena Fuels spent over six years integrating its patented gasification technology into a proprietary BTL design, including Velocys Inc. (Fischer-Tropsch (FT) system), Oxford Catalysts Group (FT catalysts), GE (power island), Honeywell International (controls and instrumentation), and other global technology providers.
- The project utilizes a combination of gasification, FT processing, FT upgrading, and power gen systems derived from technologies presently in commercial-scale use and successfully operating for decades.

Major challenges identified by Solena:

- Still limited governmental support and incentives for sustainable aviation fuel in many countries in spite of IATA's commitment to support biofuels by all its members. The preferred choice is incineration of urban waste as the primary waste handling method in spite of the many problems connected to incineration such as toxic emissions. The structural preference for incineration restricts the availability of residential and industrial waste.

Further details can be found in the questionnaire received from Solena (Appendices).

3 Conversion technologies for the production of renewable Jet A-1

Although biofuels can be produced from a wide variety of technologies, only those producing sustainable “drop-in” fuels that meet the rigorous approval specifications for safe in existing aircrafts and fueling infrastructure and allow a direct replacement of the conventional jetfuel are assessed in this report. Qualitative assessments that highlight the most promising value chains for the production of bio jet-fuel by 2020-2025 in Norway are conducted on the basis of a detailed systematization and comparison of publically available data of the selected technologies and most suitable biomass resources in terms of economics, sustainability, greenhouse gas savings, and potential speed of up-take based. Figure 3.1 shows an overview of the most promising pathways for the production of biojet fuels, including HEFA, FT, ATJ, PTJ and FRJ as technologies. Some of these technologies are already approved by the ASTM D7566 standard, which addresses aviation fuels with synthesized hydrocarbons. This standard was developed by Subcommittee D02.J0.06 on Emerging Turbine Fuels [17].

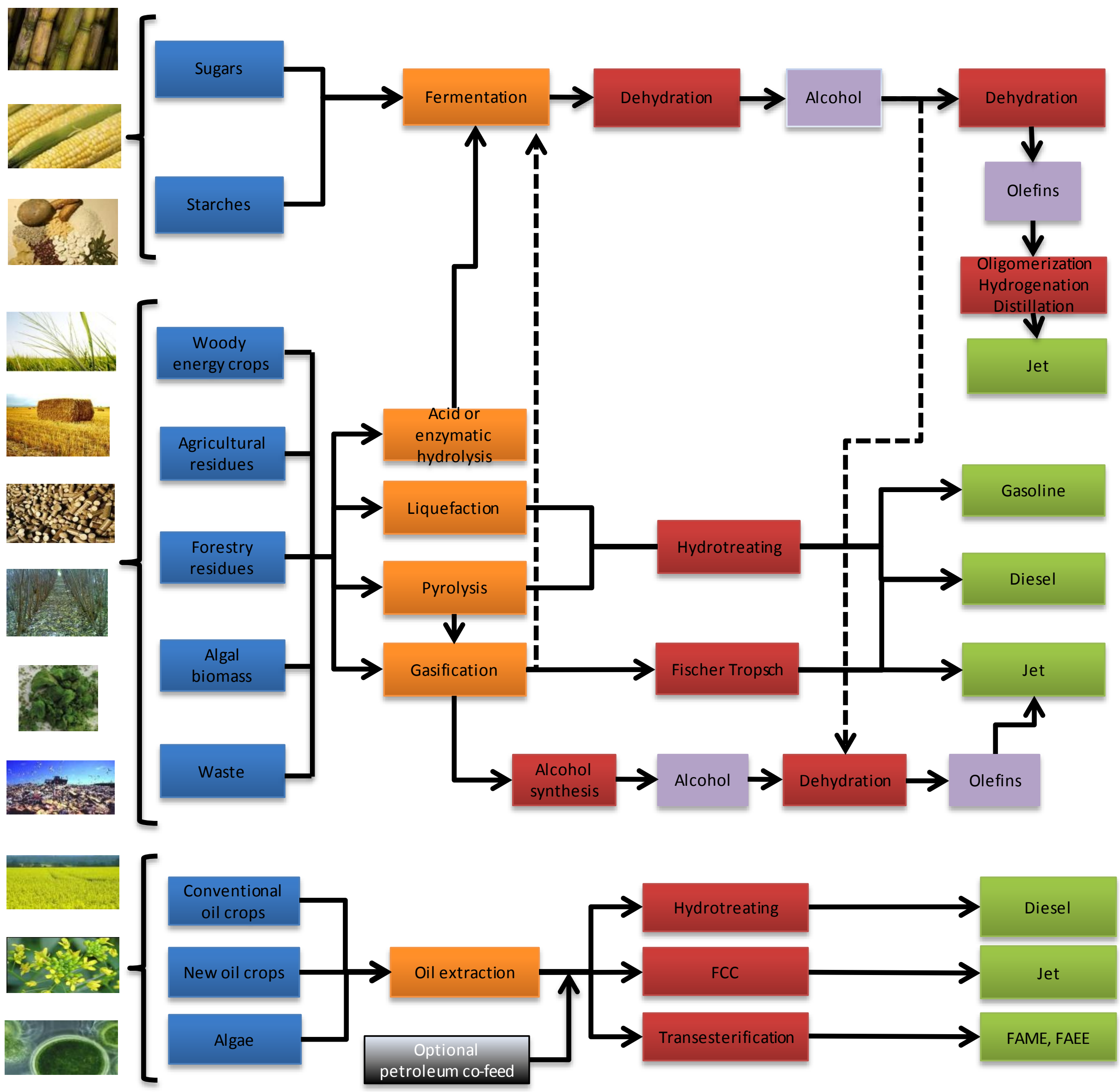


Figure 3.1. Overview of the main technological pathways for the production of renewable jet-fuels.

3.1 Hydroprocessed Esters and Fatty Acids

3.1.1 Technology

Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) was approved for certification as jet-fuel in July 2011 by the ASTM D7655 standard, allowing up to 50% blending of renewable HEFA fuels with conventional petroleum-based jet kerosene. HEFA-SPK also referred to as Hydrotreated Renewable Jet (HRJ), can be directly produced from natural oils and fats, namely triacylglycerol and free fatty acid rich feedstocks by catalytic hydrotreating, as shown in Figure 3.4 (framed-dotted area). This process involves the deoxygenation, desulfurization and denitrogenation of the original oils and fats through hydrogenation reactions and the presence of a catalyst, resulting in hydrogen-saturated straight-chain paraffin-rich hydrocarbon liquids, in the diesel range (nC_{15}-nC_{22}), that can either be used neat or blended in any proportions with existing petroleum fuels [5, 18]. The amount of renewable feedstock that can be co-processed with petroleum-derived oils and fats is limited by several parameters such as availability of hydrogen supply, reaction characteristics and the desired product spectrum [5]. For jet-fuel, the complete deoxygenation of the fats and oils is critical to ensuring production of jet-fuel that is chemically similar to conventional petroleum-derived aviation fuel, with good storage stability and maximum specific energy. The paraffin-rich hydrocarbon liquids in the diesel range are too heavy for jet-fuel and therefore there is the need for catalytic hydroisomerization and cracking reactions in order to (i) shorten down the hydrocarbon chains and (ii) obtain highly branched molecules, thus obtaining a fuel in the jet range (nC_9-nC_{15}). The extent to which the paraffin-rich hydrocarbon liquids will be isomerized and cracked depends on the characteristics of the desired jet-fuel, in terms of viscosity, freezing point, cloud point and cetane number. The hydrotreating process allows the production of 50-70 % jet-fuel and the remaining products are mainly renewable diesel, with fractions of propane, naphtha and LPG [19-21]. Figure 3.2 illustrates one of the most well-known processes for the production of HEFA-SPK, the UOP's Renewable Jet Process [18, 21].

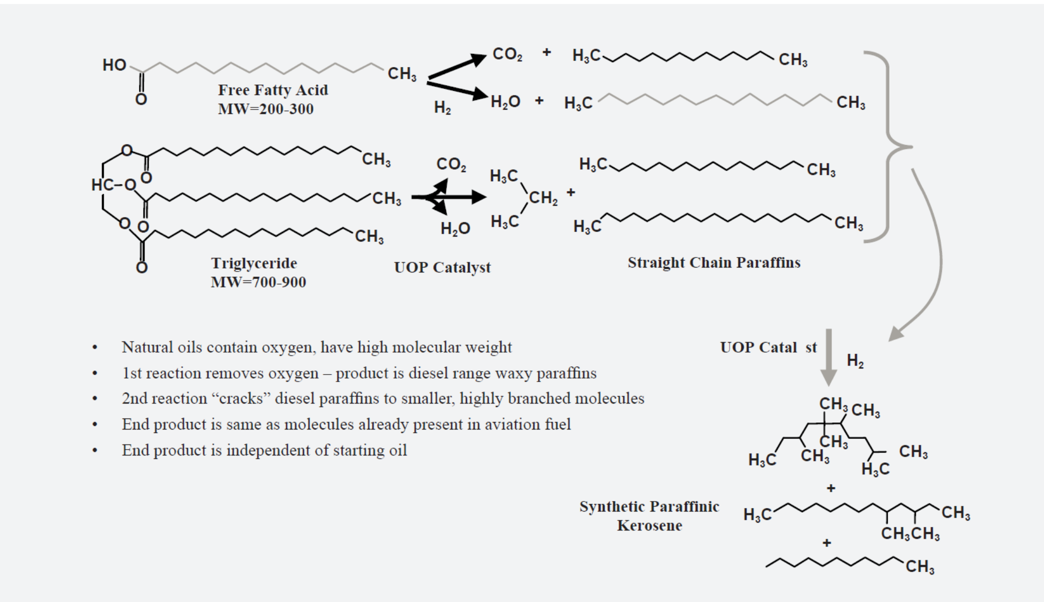


Figure 3.2. Hydrotreated vegetable oil production by UOP [18].

As observed in Tables 1.1 and 1.2, most of the biojet fuels tested to-date are HEFA-SPK produced through hydrotreating, currently being the only commercial technology in the market for the production of renewable aviation fuels.

3.1.2 Feedstock

The oils and fats converted to synthetic paraffinic kerosene can originate from different sources. On the one hand there are ready-available oils such as used cooking oils or tallow and on the other hand the oils can be produced from oil crops or microalgae, involving cultivation, drying, storage and oil extraction steps, as shown in Figure 3.3. No single feedstock will have the capacity to replace petroleum-derived fuels due to limitations in land area, water supplies, sustainability concerns and costs. A large diversity of oil crops can be processed for this purpose. Although the main focus had initially been on the conversion of first generation feedstocks currently consumed as food or animal feed such as soybean, palm oil, rapeseed, coconut, corn, etc., this focus is shifting towards the use of non-food sources which are not being constrained by feedstock availability and adverse sustainable impacts of fuel use on food/feed supply associated with first generation feedstocks. Non-food oil crops, also referred to as new oil-crops, can be grown on marginal land and that makes them promising feedstocks for future expansion. Jatropha, camelina and halophytes are three of the most investigated new-oil crops, but none of these crops have been established at scale and suffer from little understood agronomies. Microalgae have also drawn tremendous attention for the production of sustainable aviation fuels due to a number of advantages compared to any terrestrial crop: larger oil content, CO_2 recycling due to their CO_2 uptake from the atmosphere (required for their growth) and the minimal impact on land-use change and biodiversity. However, all the efforts are concentrated in producing quantities of algal oil that are appropriate for various stages of research and development.

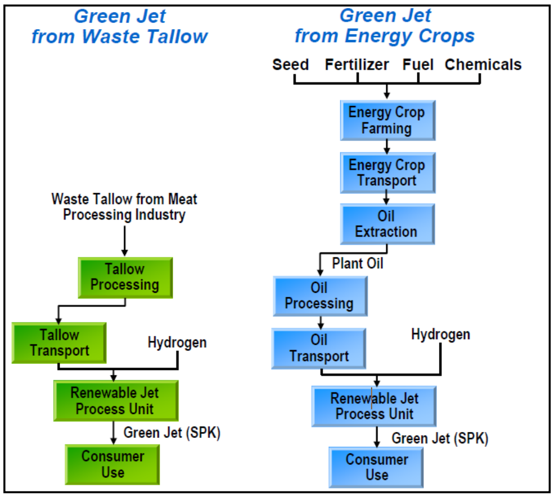


Figure. 3.3. Honeywell UOP Process [20].

Figure 3.4 shows an overview of the main oil-containing feedstocks and the main steps involved in the production of HEFA-SPK.

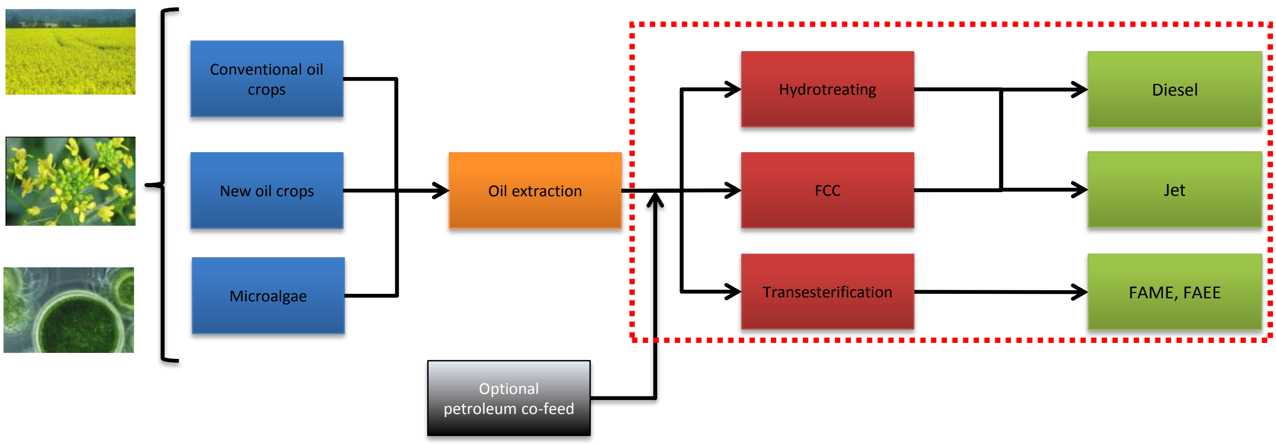


Figure 3.4. Overview of the main oil-containing feedstocks and their conversion to HEFA-SPK.

3.1.3 By-products

In addition to the aforementioned co-products obtained during the hydrotreatment process for jet-fuel production, namely renewable diesel, fractions of propane, naphtha and LPG, a wide range of other by-products are also generated (see Figure 3.5) such as natural pesticides, plastics, nutriceuticals, animal feed, heat and chemicals (alkanolamides, fatty alcohols, isopropyl esters, glycerol), that improve the market economics. These products can be further processed to different market applications [22]: emulsifying and plastifying agents, pharmaceutical and cosmetics additives, lubricants, etc.

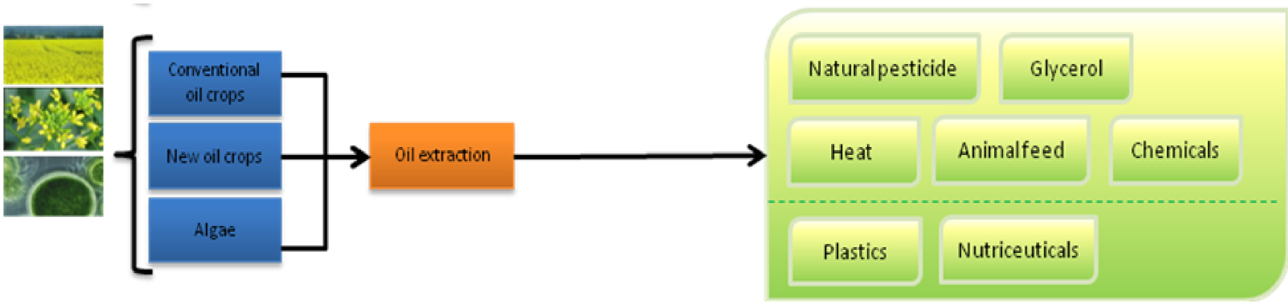


Figure 3.5. Overview of the main by-products obtained in the production of HEFA-SPK.

3.1.4 Products yields and energy efficiencies

Due to the scarcity of publicly available data on product yields and energy efficiencies regarding the HEFA-SPK technology, it is of high difficulty to draw conclusions on it. Therefore, our attempts in getting a better insight in these key process parameters will be based on a recent study conducted by Massachusetts Institute of Technology [23] that addressed the conversion of various vegetable oils into diesel, jet-fuel, naphtha and C4-C5 products via the HEFA route. This process considered in this study involved an initial hydrotreatment step in order to deoxygenate the oils followed by a hydroisomerization step to create normal and isoparaffinic hydrocarbons that fill the distillation range of Jet A. Because they are paraffinic, these fuels have properties similar to those of FT fuels.

Regarding product yields, the major product was diesel, with a production rate of 281423 KL, and other co-products were jet-fuel (53622 KL/year), naphtha (8344 KL/year) and C4-C5 products (9456 KL /year) (see Table 3.1).

Energy balances, on the other hand, were calculated based on a typical HHV for vegetable oils of 32.5 MJ/L. The efficiency of converting jet-fuel from vegetable oil was about 6 % (Energy eff, biomass, Jet A-1) and the overall efficiency by accounting all the liquid products was about 38 % (Energy eff, biomass, liquid) (Table 3.1).

Table 3.1. Typical product yields and energy efficiencies associated with the HEFA-SPK process.

	Study/Case	**Mathew et al 2007 [23]**	
	Study case description	Converts vegetable oils into Butane, Pentane, Naptha, Jet and Diesel through hydroprocessing process	
	Boundary conditions	Vegetable oils input 999882 (tonnes/year) and	
	Sub processes	The sub process steps are hydrotreatment or hydrodeoxygenation, Isomerizer &catalytic cracking and sepration process	
	Feedstock (nature)	**Vegetable oils**	
		Mass flow	**Energy**
Feedstock	Vegetable oil feedstock input (tons/year)	999882 (tonne/year)	1000 MWth
	Jet A1 production (liter/year)	53622 kL/year	
Jet A1	Jet A1 density (kg/l)	0,804 kg/l	
	Operating hours per year	8000	
Other products	Component	**C4-C5**	
	Production	9456 kL /year	8 MW *
	Component	**Naphtha**	
	Production	8344 kL/year	9.77 MW *
	Component	**Jet**	
	Production	53622 k-L/year	54.77 MW *
	Component	**Diesel**	
	Production	281423 kL year	310 MW *
	Total Production of other products	**352846 kL per year**	382 MW *
Energy	Req input of external electricity		
	Power production		
	Electricity export		
	Heat export (excess heat)		
	Yield of Jet A1 produced (liters/vegetable oil)		
Energy Efficiencies	Energy efficiency, Biomass, jet A1		**6 %**
	Energy efficiency, Biomass, Liquid		**38 %**

3.1.5 Costs

Although a significant number of economic analyses have been conducted by several stakeholders, only a few appear in the open literature [19, 23-25] making cost estimates a challenge. The capital and production costs associated with HEFA-SPK fuels vary quite significantly depending on the information source. According to [23], the major process equipment's considered in the HEFA technology are the deoxygenating process or hydrotreater, the catalytic cracking & isomerizer and other standard petrochemical support equipment's such as storage, cooling and hydrogen gas production. The costing for the HEFA process defined by the authors was estimated for a total plant capacity of about 1000 MW_{th}. Figure 3.6 discusses the incremental cost (increase or decrease in costs as a result of the addition or subtraction of output units) of HEFA process equipment's which resulted in a total equipment cost of about $200 million US. The cost quoted here is very conservative and plant cost equipment installation will vary with location. It is worth noting that the factor associated with location factor is not accounted and that the cost could decrease based on the hydrogen production on site. This total equipment costs is within the range of other information sources. The most positive scenario [25] provides for a plant of approximately 100 mill gallons/year (~379 mill litres/year) diesel or jet production capacity facility erected capital cost estimates between $60 and $80 million US, whereas other studies [19] give for similar plant capacities cost estimates around $250 US.

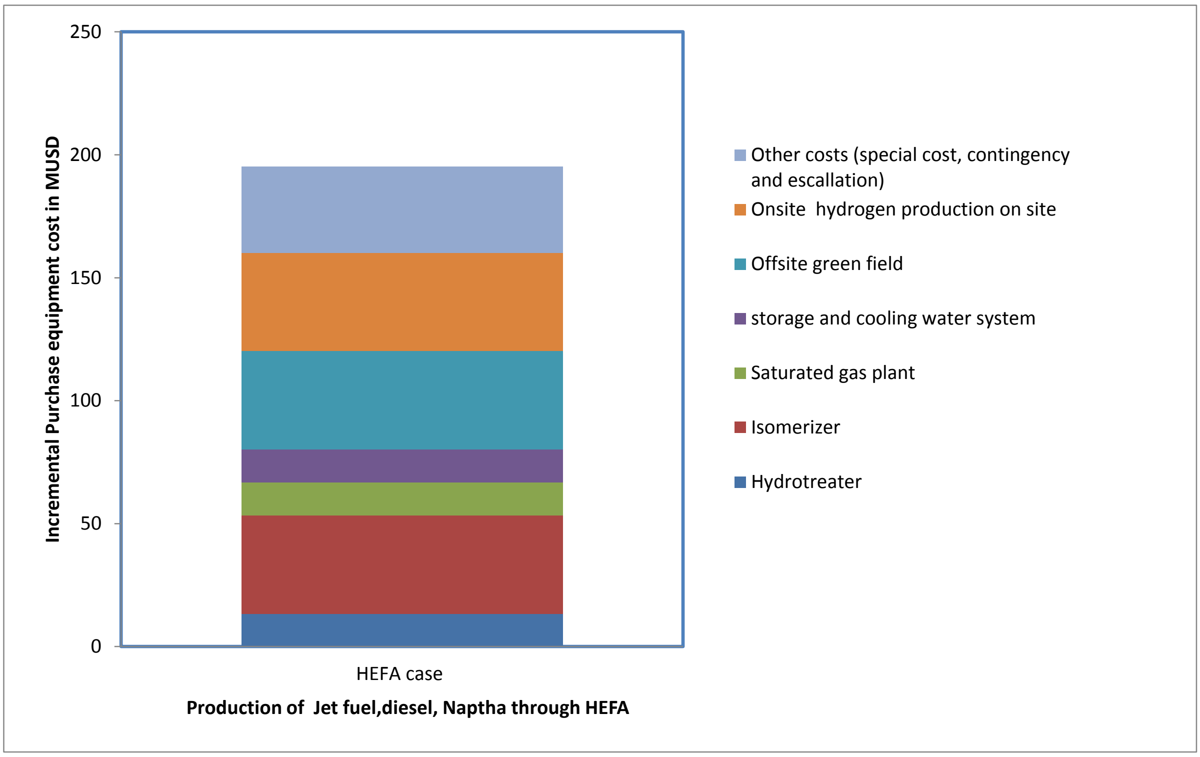


Figure 3.6. Typical product yields and energy efficiencies associated with the HEFA-SPK process.

3.1.6 Commercialization – Stakeholders

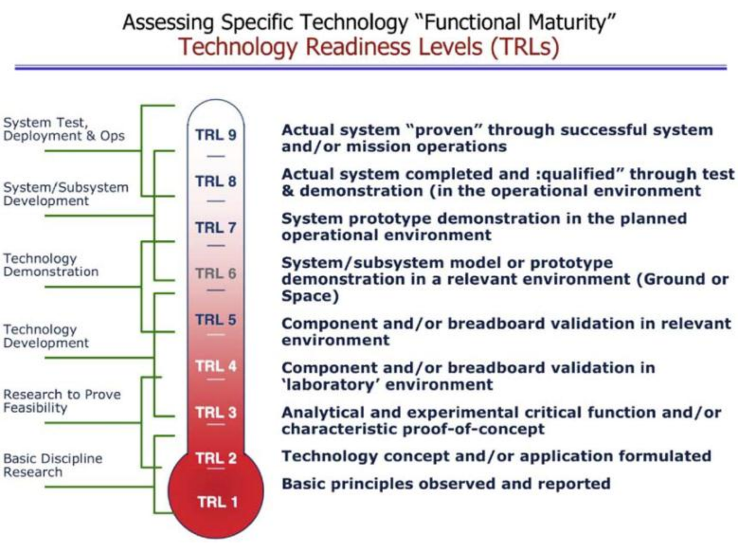


Figure. 3.7. Definition of the technology readiness level scale [26].

Several companies, as listed in Table 3.2 are currently involved in the development of the hydroprocessing technology to produce both renewable diesel and renewable jet-fuel that can substitute the conventional petroleum-derived kerosene [27]. Biodiesel is the only biofuel produced at commercial scales from renewable oil and therefore this technology is already proven and commercially available, with the maximum level (9) at the technology readiness level scale [26]. The production of hydrotreated renewable jet, on the other hand, is being developed and pilot plants are under construction, suggesting a technology readiness level scale around 5-6.

Table 3.2. Stakeholders involved in the production of HEFA fuels.

Stakeholder	Location	Fuel products/status
Neste Oil [12]	Finland	Production of renewable diesel (NExBTL) from vegetable oils, tallow and fish oils.
Syntroleum [28]		Construction of a facility for production of renewable jet-fuel and renewable diesel from low grade fats and greases.
UOP [29]	USA	Licencing technologies for the production of renewable jet-fuel and renewable diesel.
ConocoPhillips [30]	Ireland/US	Production of renewable diesel from forestry, agricultural and waste materials.

3.1.7 Strengths and challenges

Strengths:

- Wide range of feedstocks can be processed
- Product life cycle emissions significantly lower compared with fossil fuels (80-85%)
- Very pure and high quality product with a chemical composition similar to conventional jet-fuel.

Challenges:

- High investment cost of the plants
- High feedstock prices
- Feedstock availability (competing with biodiesel producers for the same feedstock)
- Large amounts of external hydrogen required
- Hydrogen used is currently from fossil fuels
- Sustainability concerns
- Low oil yields

3.2 Fischer-Tropsch – Synthetic Paraffinic Kerosene (FT-SPK)

3.2.1 Technology

Fischer-Tropsch-Synthetic Paraffinic Kerosene (FT-SPK) was approved for certification as jet-fuel in September 2009 under the designation D-7566, allowing up to 50% blending of renewable FT-SPK fuels with conventional petroleum-based jet kerosene [31].

Synthetic Fischer-Tropsch kerosene is the result of biomass gasification, perceived as one of the most attractive thermo-chemical processes for the production of liquid fuels, as it converts biomass efficiently to a high-density gas product that will be further processed to jet-fuel [32]. The production of biomass-derived FT-SPK consists of a series of consecutive steps, as illustrated (Figure 3.8) and described below.

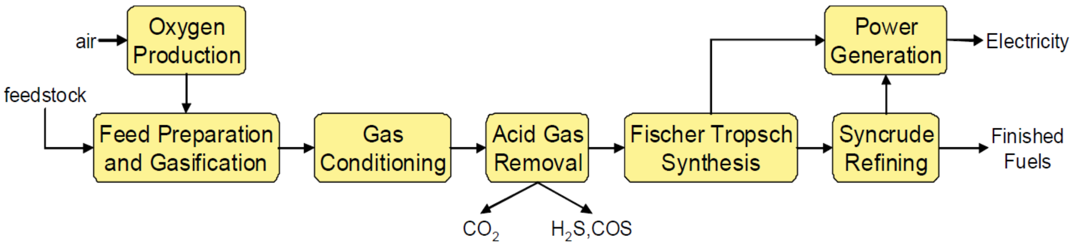


Figure 3.8. General Fischer-Tropsch fuel production diagram. Adapted from [33].

3.2.1.1 Feed preparation and gasification

The initial key step involves the feed preparation and gasification processes. Biomass thermal pre-treatment plays an important role in several aspects. In many occasions, biomass undergoes a densification process in order to produce a higher energy-density fuel that allows reduction costs associated with transport which is of particular interest when considering large production plants. Furthermore, pre-treatment processes are conducted to ensure a reliable and continuous feeding which is challenging due, among others, to the heterogeneous nature of the biomass (moisture content, density, size and energy content, etc). Torrefaction and pyrolysis are two main pre-treatment processes which may contribute to improve the aforementioned challenges. During torrefaction, biomass is pre-treated to upgrade biomass to a higher quality solid biofuel by submitting the biomass to moderate process conditions (200-300 °C) under inert atmosphere for a period of time in the order of minutes. This process allows on the one hand the destruction of the fibrous structure of biomass and with that a better grindability and entrainment properties of biomass particles, leading to better feeding and on the other hand an increase of the calorific value [34]. Flash pyrolysis is another interesting thermal pre-treatment where biomass undergoes thermal decomposition in the absence of oxygen at around 500 °C and very short residence times (typically less than 2 seconds). This process allows the production of a high energy density liquid intermediate product, known as pyrolysis oil, with yields up to 75 wt. % on a dry-feed basis, with byproduct char and gas which can be used within the process to provide the process heat requirements and in this way minimize the waste streams [35]. The Karlsruhe Institute of Technology and Future Energy Company have tested entrained flow gasification of biomass by using pyrolysis oil as feedstock in the Bioliq process [36, 37].

During gasification, biomass undergoes partial oxidation at relatively high temperatures (900-1300 °C [38]), resulting in a combustible gas mixture, referred to as syngas, containing mainly hydrogen and carbon monoxide and smaller amounts of undesired products and contaminants such as carbon dioxide, methane, tars and particles that need to be either removed or further converted to acceptable chemicals species through a syngas clean up stage. Various types of gasification reactor designs have been developed up to now.

Fluidized bed and entrained flow gasifiers are currently the two main categories of gasification technologies for biofuels production [7]. Fluid bed gasifiers operate below the biomass ash melting point in order to avoid fluid bed agglomeration and eventual collapse. This technology is attractive for its relatively low cost, ease of operation and good scale-up potential (up to 250-300 MW^{th}). However, it has associated relatively low energy efficiencies and poorer gas qualities; it requires intensive additional gas cleaning after the gasifier, namely tars handling and hydrocarbon reforming and is limited to small scale operations. On the other hand, entrained flow gasifiers operate above the melting point of the biomass ashes and produce a product gas that is essentially fully converted to synthesis gas with very low contents of residual tar components, resulting in high efficiencies and higher gas quality. However, the feeding is a challenge, it has higher investment and operating costs than fluidized beds and therefore it is only suitable for larger capacities (> 250-300 MW^{th}).

Although not as common as the two aforementioned technologies, it is relevant to highlight a third type of technology, called plasma gasification, that is only economically viable when processing non-valuable solid wastes due to the high capital and operational costs associated with this technology. It is a non-incineration thermal process that uses extremely high temperatures in an oxygen starved environment to decompose input waste material completely into syngas. Because of the high temperatures involved in the process, all the undesired products, i.e. tars, char and dioxins, are broken down, leading to a very clean syngas [39].

A substantial amount of efforts are also being concentrated in the conversion of highly wet biomass (> 50 wt.% moisture) residues that are non-food and/or non-land competing resources such as macroalgae and remaining lignin-based residues from unconverted lignocellulsic materials in fermentation processes, through hydrothermal gasification. This technology allows the direct conversion of wet biomass, without the need of a previous drying step, which is one of the most costly subprocesses in conventional gasification systems. However, the harsh reaction conditions applied, relatively high temperatures and very high pressures, lead to operational challenges that make the commercialization of this technology a challenge itself.

3.2.1.2 Gas cleaning and conditioning

The undesired tar and particulate components of the product stream need to be removed in order to improve the energy efficiency of the overall value chain and produce a tar-free clean syngas, which is a requirement for the Fischer-Tropsch unit where biofuels are generated. Gas cleaning systems may be used to reduce drastically these contaminants. The tars representing significant energy and carbon content (depending on the gasification technology used) can be removed/cracked through mainly three ways of tar removing/cracking: thermal cracking, catalytic cracking or scrubbing and most of the times, combinations of these are used. Other impurities in the produced gas are the organic BTX (benzene, toluene, and xylenes), and inorganic impurities as volatile metals, NH3, HCN, H2S, COS and HCl, which are often removed by scrubbers as well as dust, soot, ash and trace elements, which are removed by filters and cyclones [40].

3.2.1.3 Fischer-Tropsch

Once the syngas is free of undesired species, the clean syngas is converted into a wide variety of paraffinic and olefinic hydrocarbons products via elongation of the hydrocarbon chain [41, 42] through the hydrogenation of carbon monoxide (Equation 3.1). If jet-fuel is desired, hydro-cracking of longer hydrocarbon chains into smaller ones is necessary.

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH2O \qquad \textit{Equation 3.1}$$

The process is generally operated at fairly high temperatures (150-300 °C) and pressures (10-40 bars) in the presence of a catalyst which is commonly iron- or cobalt-based [43]. The choice of catalyst depends on several key aspects which are: syngas composition, content of impurities such as sulphur and ashes, and water content. Based on these premises, iron and cobalt catalysts should both be considered for gasification-FT processes [42].

The technology is mature and synthetic jet-fuels from coal, natural gas or other hydrocarbon feedstock are chemically similar to conventional kerosene jet-fuels –and ideally suited to supplement or replace them. Although the feedstock would be non-fossil when processing biomass, the resulting syngas composition is similar to what is produced when converting fossil-fuel resources. As such, any technological advancement here would be to handle biomass in the gasification stage of the process, rather than the FT operation.

3.2.2 Feedstock

Figure 3.9 shows an overview of the main feedstocks and the process steps involved in the production of FT-SPK jet-fuel. Lignocellulosic biomass such as woody energy crops, agricultural residues, forestry residues are particularly suitable for the production of jet-fuels via gasification and Fischer-Tropsch. Woody energy

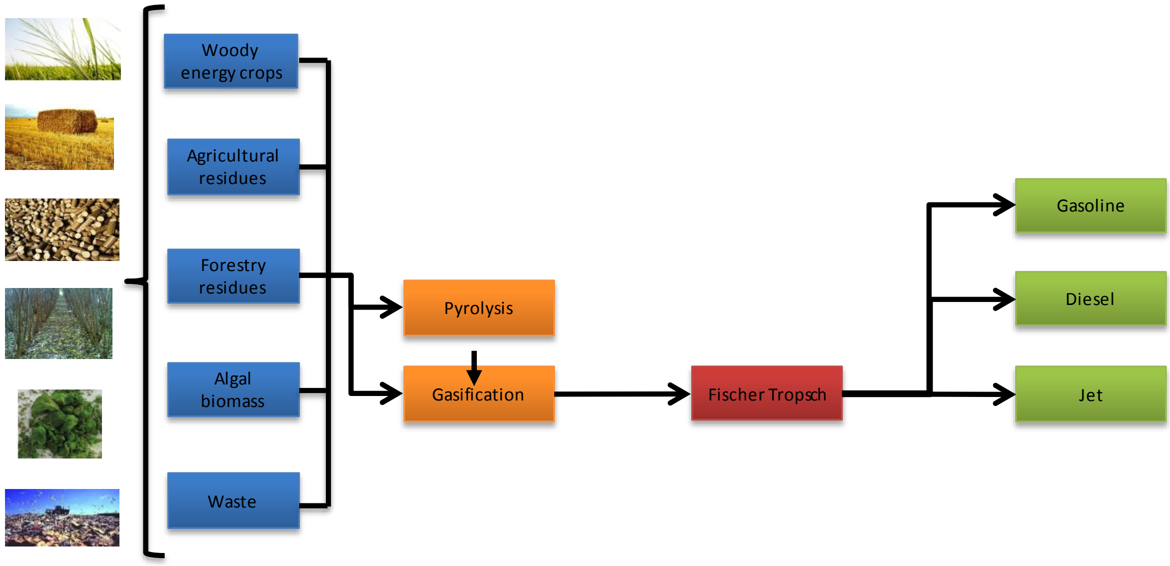


Figure 3.9. Overview of the main lignocellulosic feedstocks and their conversion to FT-SPK.

crops are another source of woody biomass for energy. Short-rotation (3-15 years) techniques for growing poplar (Populus), willow (Salix), Eucalyptus, or even non-woody perennial grasses (e.g., Miscanthus) have been developed over the past 2-3 decades [31]. A significant amount of the forest products have strong markets so the production of fuels should come from low-value materials such as forest residues that do not have any market per today. Forest residuals constitute mainly tree limbs, tops, small or broken logs, and other wood that remains after the harvesting process. It is one of the biomass resources with the highest potential in Norway (~65% of the harvested wood) due to the large forestry extensions in this country. Agricultural residues, on the other hand, are of a wide variety of types. The most significant distinction is between those residues that are predominantly dry, such as arable crop residues and those that are wet such as animal slurry.

3.2.3 By-products

The main co-products associated with the production of FT-SPK are diesel and gasoline. In addition, gasification and Fischer-Tropsch allows the production of heat, electricity and chemicals such as hydrogen and methanol, as shown in Figure 3.10. Potential chemicals include naptha, paraffins and lubricants. Production of these co-products has potential to substantially increase the overall process efficiency. The choice of co-products will depend on the price at which electricity and heat can be sold, on whether the system configurations allow enough production of the co-products in order to make an impact on the production costs of FT-SPK and on whether the location of the production plant allows district heating.

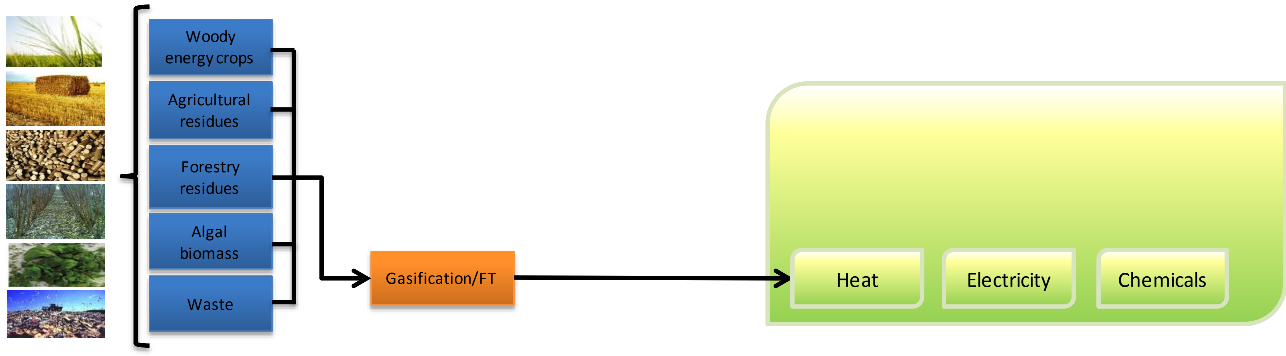


Figure 3.10. Overview of the main by-products obtained in the production of FT-SPK.

3.2.4 Products yields and energy efficiencies

A state of the art review has been conducted with the intention of collecting data on the various product yields and energy efficiencies associated with the gasification/FT process for jet-fuel production. Although a significant number of works address this technology, very few limited studies projects jet-fuel as a product commodity. Table 3.3 compiles the product yields and energy efficiencies from three recent reports concerning jet-fuel production, diesel/gasoline and heavy FT and light FT crudes.

Ekbom et al. [44], as shown in Table 3.3, evaluated the production of Jet A1 by converting woody biomass and agricultural residues with a typical heating value of 14 to 15 MJ/Kg into jet-fuel for its use in Arlanda airport, Sweden. In this case, the process raw biomass residues were converted to gaseous fuels followed by gas cleaning and conditioning to achieve a H_2/CO ratio greater than 2 for FT fuel synthesis. The Biomass input was 864000 tons/year wood chips with a moisture content of about 50%. Recovery of low-grade heat for industrial and district heat use were evaluated. The subprocess steps involved in the biojet-fuel production via FT route were the following: pretreatment of biomass, gasification via entrained flow gasifier, gas cleaning and conditioning, Fischer-Tropsch synthesis, HPC and distillation, Power and steam production air air separation. The annual jet A1 fuel production from biomass was calculated as 62,2 million liters per year and the yields corresponding to the co-products, namely naphtha and diesel were 17,9 ktons/year and 21.4 ktons/year, respectively. The given energy efficiency for the production of jet A1 from biomass was about 25 % (Energy eff, biomass, Jet A-1) and the energy efficiency considering all the FT products was about 46 % (Energy eff, biomass, liquid). The overall efficiency was further improved, up to 79%, by integrating the FT production plant with district heating and power generation that would satisfy the heat required by the nearby customers in the airport (Energy eff, biomass, total).

Swanson et al [45] from the National Renewable Energy Laboratory (NREL) in the US, studied the feasibility for production of diesel and gasoline products via the FT route. This process processed corn stover (25 % moisture content) with an input capacity of 14880000 tons/year (on dry bases). The sub-process steps involved in this specific study were pretreatment, gasification, gas cleaning and conditioning, Fischer-Tropsch synthesis, hydroprocessing, power generation and air separation. The obtained yield of diesel was 62 % whereas that of the co-products, i.e. gasoline and LPG were about 26 % and 9 %. The remaining gas product was methane (~3%). The energy efficiency to produce FT products was about 46 % (Energy eff, biomass, liquid) whereas the overall efficiency by accounting net electricity export (no heat export produced) was about 52 % (Energy eff, biomass, total), which is significantly lower than the overall energy efficiency reported by Ekbom et.al (79%). This large difference is mainly attributed to the inclusion of district heating integration in the Arlanda case. This option was not considered in the NREL case due to the lack of customers for using the excess of heat. Additionally and to a minor extent, the selection of gasification system and the yield of syngas and/or the heat losses in the plant design could also effect energy efficiencies. This study clearly shows that the efficiency of a FT plant can be improved through process integration, type of gasifier, gas separation and FT plant selection as well as feed processing.

On the other hand, Kei Yamashita et al. [43] studied the production of heavy FT crude and light FT with three different gasification and post reforming scenarios. Table 3.3 includes data from three basic cases addressing three different types of gasifiers. The first configuration is referred to as BCL's, considering a circulating fluidized bed Indirect air gasification, the second one is referred to as IGT's , considering a bubbling fluidized bed direct oxygen process and the last one is referred to as TPS's and it considers a bubbling fluidized bed direct air gasification. Typical biomass wood was considered as a feedstock. The annual biomass input (wood residues) was 623049 tons/year. The energy efficiencies (biomass, liquid) associated with the three scenarios are 16 %, 18 % and 18 % for BCL, IGT and TPS, respectively. Besides, the overall efficiencies, including the energy export (Energy eff, biomass, total), were 39.02%, 38.32% and 23.45 % for BCL, IGT and TPS, respectively. The energy efficiency of product FT crude (biomass, liquid) is very low compared to other literature surveys (Arlanda case). This is due to the fact that the BCL, IGT and TPS gasifiers are low temperature gasification systems, resulting in a poor LHV quality syngas production, with large amounts of undesired methane that requires further upgrading in order to increase the product energy efficiency (biomass, liquid). In contrast, the Arlanda case considered high temperature gasifiers leading to high quality synthetic gas (higher H_2/CO ratio). Another important difference between the studies conducted by Yamashita et al and the Arlanda case is that fact the gas conditioning step. In the former studies and In contrast to the Arlanda case, the gas is not conditioned to enhance the FT conversion yield. The syngas quality that is H_2/CO ratio produced from the BCL gasifier is in the range of 0.32 to 0.49, for IGT in the range of 0.73 to 2.09 whereas for TPS is in the range of 0.73 to 1.03. Usually, for FT synthesis the H_2/CO ratio must be above 2 to increase the yield of FT products. This makes the Energy eff, biomass, liquid for these type gasifiers low.

3.2.5 Costs

A substantial number of economic analyses for the production of biofuels through the gasification-FT process are available in literature [43-45]. From a general point of view, these studies show that this technology has associated very high capital costs, as illustrated in Figure 3.11. The costs vary widely depending on the gasification technology applied as well as the upgrading of the crude products desired. Figure 3.11 also depicts the incremental costs breakup for each piece of equipment involved in the study cases reviewed in the section 3.2.4. The cost comparison has been done with respect to 2010 MUSD values and capacity ratio using Equation 3.2 in order to be able to compare several studies with similar equipment that are based on different plant capacities. The equipment purchasing cost depends on the size expressed as:

Table 3.3. Typical product yields and energy efficiencies associated with the FT-SPK process.

	Study/Case	Ekbom et al - 2009 [44]		NREL - Swanson et al 2010 [45]		Kei Yamashita et al., 2004 [43]		Kei Yamashita et al., 2004 [43]		Kei Yamashita et al., 2004 [43]	
	Case description	Converts biomass into bio-jet fuel through gasification of biomass, Fischer Tropsch synthesis and upgrading		Converts biomass into liquid transportation fuel through high-temperature gasification of biomass,		Convert biomass into heavy FT crude and light FT crudes		Convert biomass into heavy FT crude and light FT crudes		Convert biomass into heavy FT crude and light FT crudes	
	Boundary conditions	Biomass input: 864000 tons/year wood chips, 50% moisture. Production of 50 kton/year bio-jet fuel on site. Recovery of low-grade heat for industrial and district heat use. Export of excess heat.		Biomass input: 14880000 tons/year (dry), 25 % moisture. Production of diesel and gasoline, with methane and LPG as co-products. Export of excess electricity. **No Jet A1 production**.		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**	
	Sub processes	Pretreatment, gasification, gas cleaning and conditioning, Fischer-Tropsch synthesis, HPC and distillation, Power and steam production, air separation		Pretreatment, gasification, gas cleaning and conditioning, Fischer-Tropsch synthesis, Hydroprocessing, Power generation, air separation		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,	
	Feedstock (nature)	**chipped wood biomass and wood residues**		**Corn stover**		**wood**		**wood**		wood	
	Gasifier type	Pressurized Fluidized Bed (Andritz/Carbona)		Entrained flow gasifier		BCL (Circulating fluidized bed) Indirect gasification		IGT(Bubbling fluidized bed)Directly oxygen		TPS (Bubbling fluidized bed)Directly air	
		Mass flow	**Energy**		**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**
Feedstock	Biomass input (tons/year)	864000 tons/year (50% moisture)	289 MWth	14880000 (dry)	389 MWth	623049	430 MWth	623049	430 MWth	623049	430 MWth
	Jet A1 production (liter/year)	62,2 million liters/year	74,8 MW	0	-	-	-	-	-	-	-
Jet A1	Jet A1 density (kg/l)	0,804 kg/l		-	-	-	-	-	-	-	-
	Operating hours per year	8000		7440		7440		7440		7440	
	Component	**Heavy diesel + UCO**	754 kg/m3, 930 kg/m3	**Diesel (hexadecane)**		**heavy FT Liquids (C10-C19 chains)**		**heavy FT Liquids (C10-C19 chains)**		**heavy FT Liquids (C10-C19 chains)**	
Other	Production	21,4 kton/year	32,2 MW	61,67 wt%							
products	Component	**Naphta**	687 kg/m3	**Gasoline**		**Light FT liquids (C5-C10 chains)**		**Light FT liquids (C5-C10 chains)**		**Light FT liquids (C5-C10 chains)**	
	Production	17,9 kton/year	27,9 MW	26,1 wt%							
	Component			**LPG**							
	Production			8,77 wt%							
	Component			**Methane**							
	Production			3,46 wt%							
	Total Production of other products	39,3 kton/year	60,1 MW	100 wt%	193,2 MW		66.7 MW		78.8 MW		78.8 MW
	Req input of external electricity		21,2 MW		22,06 MW		self produced		self produced		self produced
Energy	Power production		19,4 MW		35,88 MW		40.4 MW		34.4MW		34.4MW
	Electricity export		need 1,8 MW		13,8 MW						
	Heat export (excess heat)	listrict heat, 5000 h/yea	96,9 MW		0		0		0		0
	Yield of Jet A1 produced (liters/tonne of dried biomass)		143.98	0	0		-		-		-
Efficiencies	Carbon conversion efficiency			34 %		34 %		34 %		34 %	
	Energy efficiency, Biomass, jet A1		25 %		0		-		-		-
Energy	Energy efficiency, Biomass, liquid		46 %		49 %		16 %		18 %		18 %
Efficiencies	Energy efficiency, Biomass, total		79 %		52.50 %		39.02 %		38.32 %		23.45 %

$$C_{P2} = C_{P1}\left(\frac{S_2}{S_1}\right)^m$$

Equation 3.2

with CP2 as the equipment cost for equipment size 2, CP1 as the equipment cost for equipment size 1, S2 as the equipment size 2, S1 as the equipment size 1 and m as the cost index. Guthrie et al [46, 47] correlated 59 processes and obtained an *m* within the 0.38 to 0.9 range, with an average of 0.7. The Arlanda case (289 MW_{th}) was taken as a reference and the other studies, involving other plant capacities, have been adjusted with in order to be able to make easier comparisons. The cost for gasification and FT are in general terms the largest share as compared to other process equipment. The

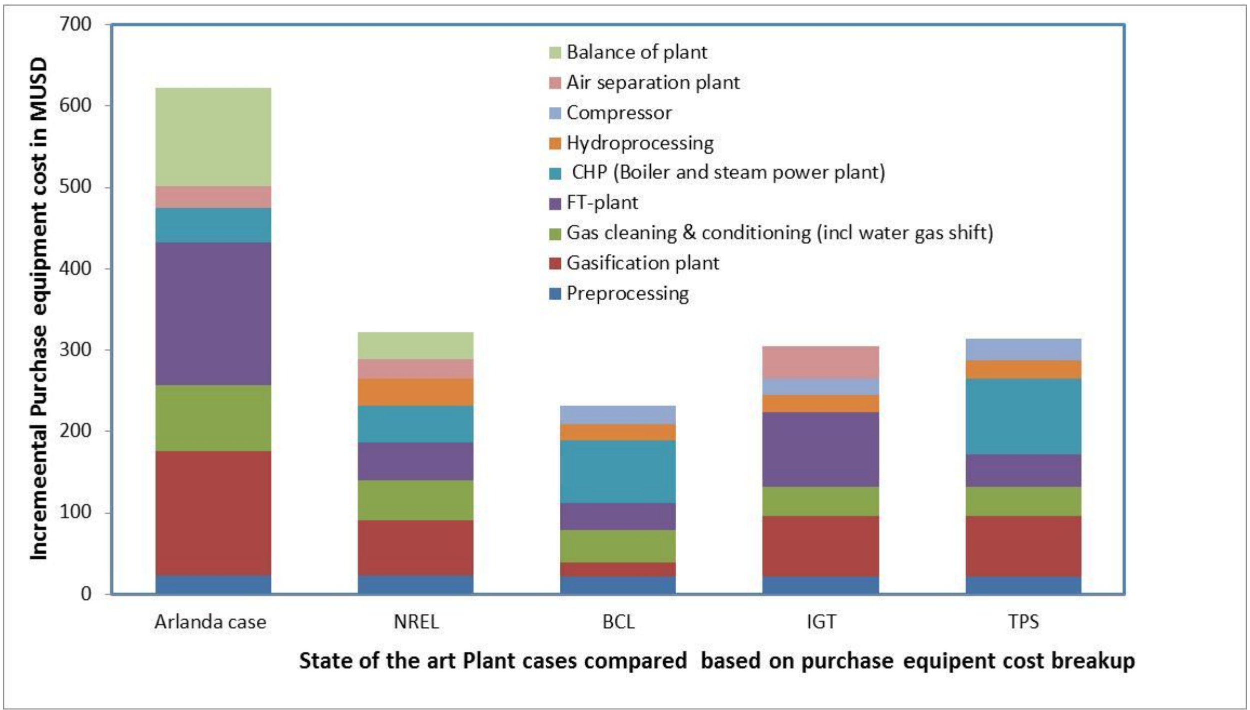


Figure 3.11. Incremental Purchase equipment costs associated with several gasification/FT configuration systems

case studies of NREL, BCL, IGT and TPS reported similar plant cost breakups whereas the incremental purchase equipment costs showed by the Arlanda case are significantly higher. This is due to the production of heat as a co-product for the district heating facility. The cost component for excess heat production with district heat facility increases the incremental cost of the plant significantly. Other attributes may be due to the location factor. This factor considers that the installation of a plant in a European region will differ from the installation in other continents. Another major reason for explaining the higher costs associated with the Arlanda case as compared to the NREL, BCL, IGT and TPS scenarios is the fact that the former is based on a first plant case whereas the lower cost scenarios are based on an nth plant. Finally, it is important to highlight that in the Arlanda case, the biomass gasification technology assumed in the plant design is not been demonstrated at large scale for synthesis gas production. This also contributes to higher incremental purchase equipment costs, as illustrated in Figure 3.11.

3.2.6 Commercialization – Stakeholders

The FT synthesis process has been known for several decades and is currently applied at a commercial sale for the production of liquid fuels from fossil fuel resources such as coal and natural gas. Sasol, as one of the main stakeholders in this field, has currently few FT plants outside South Africa in full industrial-scale operation producing fuels, lubricants and chemicals from coal and gas [42, 48] and additional production plants worldwide, as illustrated in Figure 3.12. Shell, on the other hand, operates a commercial FT plant located in Malaysia where liquid fuels are produced from natural gas [49]. Furthermore, Shell is currently involved in the development of the word's largest gas-to-liquid FT, Pearl, plant in Qatar that will produce diesel and kerosene, base oils for top-tier lubricants as well as naphtha and paraffin, these latter used to make plastics and detergents, respectively. It will produce enough fuel to fill over 160,000 cars a day and enough synthetic base oil each year to make lubricants for more than 225 million cars [50]. It is expected to start operation in 2012.

As regards to biomass-to-liquid FT plants, the majority of the developments are in the pilot or demonstration scale (TRL 7-8). Table 3.4 lists some of the most active stakeholders in this field. The BioTfuel demonstration plant in France is one of the ongoing BTL projects that includes the construction and operation of two pilot plants, expected to start operation in 2012, for the production of biodiesel and biokerosene. Also in France, CEA announced the construction of a pilot BTL plant in Bure Saudron producing disel, kerosene and naphtha from forestry and agricultural residues. In Germany, Forschungszentrum Karlsruhe GmbH in partnership with LURGI GmbH is constructing a pilot plant (due 2016) for production of BTL and ''gasoline type fuels'' and in Finland NSE Biofuels Oy (a joint venture between Neste Oil and Stora Enso) has opened a BTL demonstration plant at Stora Enso's Varkaus Mill in Finland., In partnership with Foster Wheeler and VTT, it was planned to develop a commercial production plant at one of Stora Enso's mills with a potential launch date of 2016 [42]. However, it was recently announced (August 2012) that it has been decided not to progress with their plans to build a biodiesel plant due to the high investment costs [51]. Solena has a planned a facility to produce aviation fuels from municipal solid waste to start up in Q4 2015 in East London, UK. The project is in the Engineering and Planning & Permitting Stages, and the construction will start in Q4 2013. The plant is based on Solena's high-temperature plasma gasification technology in combination with microchannel Fischer-Tropsch process, and the technology readiness level given by Solena is 9.

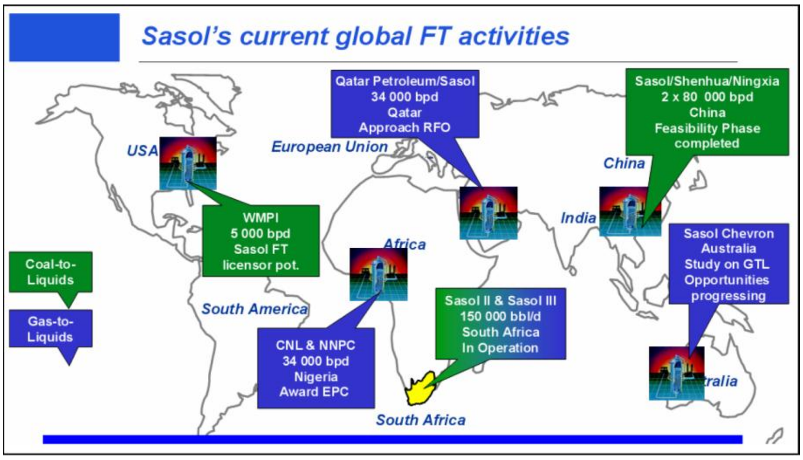


Figure 3.12. Sasol's coal to liquid and gas to liquid facilities [33]

Table 3.4. Stakeholders involved in the production of FT fuels.

Stakeholder	Location	Fuel products/status
NSE Biofuels [52]	Finland	Demonstration plant for the production of BTL fuels
Enerkem [53]	Canada	Demonstration plant for the production of syngas, biomethanol, acetates and cellulosic ethanol.
Rentech [54]	USA	Production of jet-fuel, diesel and chemicals from biomass, municipal solid waste and coal.
Solena [15]	US	Production of renewable jet-fuel from municiapal solid waste as well as agricultural and industrial waste.
Bioliq [37]	Germany	Production of BTL fuels from residual biomass (straw and wood) through a three-stage process consisting of flash pyrolysis, entrained-flow gasification, and synfuel production.

3.2.7 Strengths and challenges

Strengths:

- Wide spectra of potential products, ranging from gaseous fuels such as hydrogen or syngas to liquid fuels such as alcohols, dimethyl ether (DME), gasoline or diesel.
- Highly flexible to the feed material: all kinds of organic materials, even different wastes such as waste from agriculture, wood processing, paper production or municipality can be used. Even if the quality of the feedstock can be quite different, the contents of the synthetic gas are almost the same.
- High carbon conversions
- Low operating costs, with no need for external hydrogen addition in the indirect gasification case.

Challenges:

- Biomass gasification section of the process still requires optimization, particularly with regard to minimizing tar production.
- High capital costs due to gasification unit operations and large scale of plant required to make processing economical.
- Gasification and FT catalysts can deactivate easily in the presence of impurities.

3.3 Alcohol-to-Jet – Synthetic Paraffinic Kerosene (ATJ-SPK)

3.3.1 Technology

Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) is under ASTM certification and is expected to be approved as fully synthetic aviation fuel with 100% replacement of the conventional jet-fuel by 2014 [55]. This renewable aviation fuel is produced through the conversion of alcohols that can proceed from several feedstocks and technological pathways. All the steps involved in this process, indicated in Figure 3.13, are currently used at commercial scale in the petrochemical industry, making the main barrier to uptake of this technology the cost effective production of the alcohol itself. A detailed explanation of the different process phases is given below.

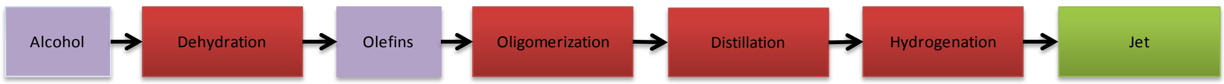


Figure 3.13. Main steps in the alcohol-to-jet process.

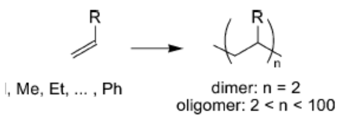
3.3.1.1 <u>Dehydration</u>

The first step in the production of jet-fuel from alcohols involves a catalytic dehydration process that results in the formation of olefins (hydrocarbons containing one or more carbon-carbon double bonds) through water removal. In order to do so, the initial alcohol is submitted in the presence of a catalyst at temperatures around 300-500 °C. The dehydration reaction also leads to the formation of ethers, which compete with the formation of the olefins and therefore it is essential to optimize the reaction conditions in order to maximize the selectivity towards olefin formation.

The catalysts that have been reported in literature for this purpose include activated clay, phosphoric acid, sulfuric acid, activated alumina, transition metal oxide, transition metal composite oxide, heteropolyacid, and zeolites [56]. In order to remove the water present in the reactor, the effluent stream is condensed by cooling the entering gas with spray water. This allows the separation of the olefin from the undesired products, consisting of water, impurities and unconverted alcohol. At this stage, the olefin contains small amounts of CO_2 that need to be removed before drying the olefin and thus obtain a gas that does not contain water. Once this step is conducted, the remaining impurities are removed in a cryogenic distillation column [57].

3.3.1.2 <u>Oligomerization, distillation and hydrogenation</u>

Once the olefins which are the building blocks for the production of jet-fuel are formed through dehydration of alcohols, these intermediates are further converted at moderate temperatures and pressures (150-250 °C, 3-4 MPa) into a middle distillate that contains diesel and kerosene via oligomerization, as expressed by Equation 3.3 [58-60].



Equation 3.3

Several oligomerization processes and technologies have been operated an industrialized. They are generally catalytically achieved either by means of heterogeneous acidic catalysts such as zeolites, supported phosphoric acids and silica-alumina-based or by homogeneous organometallic catalytic systems such as metallocenes [59-61]. Two well-established processes are The Polynaphta™ process and The AlphaSelect™ process. The former converts light olefins such as C3 and/or C4 fractions into higher value gasoline and kerosene. The reaction is operated in a series of fixed bed reactors under mild operating conditions using an acid-based catalyst. The AlphaSelect™ process, on the other hand, operates in the liquid phase in the presence of a soluble Zr-based catalytic system and an Al-based co-catalyst which leads to the generation in-situ of the active catalyst. The process, in this case, takes place in the presence of a solvent, at moderate temperatures and pressures [59]. The middle-distillates produced through these processes shall as a final step undergo hydrogenation and distillation in order to obtain the range of paraffins that meet the standard specifications for aviation purposes [62].

3.3.2 Feedstock

Although there are a wide variety of alcohols that can be used as a feedstock for the production of aviation fuels, ethanol and isobutanol are the ones receiving most attention. These alcohols can be produced from a wide variety of biomass and (off-gas) feedstocks and technological pathways, as illustrated in Figure 3.14.

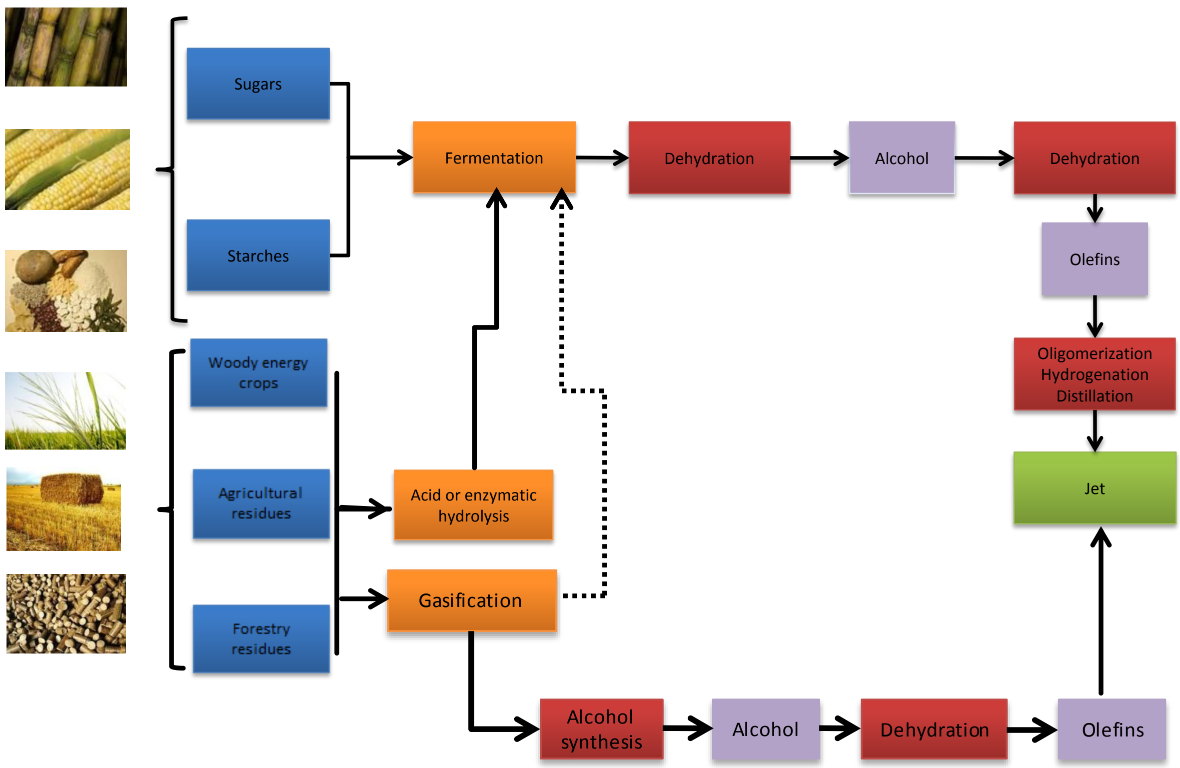


Figure 3.14. Overview of the biomass feedstocks and technological pathways for the alcohol-to-jet technology.

The biomass feedstocks can be divided into three main types of raw materials: sugars, starches and lignocellulosic biomass [63]. Sugars (from sugarcane, sugar beets, molasses, and fruits) can be converted into alcohols directly through a fermentation process using yeasts or microbes. Starches (from corn, cassava, potatoes, and root crops), on the other hand, need to be hydrolyzed by means of acid or enzymes prior to the fermentation process in order to produce fermentable sugars. The third type of biomass feedstocks, i.e., lignocellulosic biomass, (from wood, agricultural and forestry residues, energy crops, waste), needs to undergo a more difficult and harsher hydrolization step (either acid or enzymatic), as cellulose and hemicellulose, where the sugar is stored, are more resistant than starch. Once the simple sugars are formed, enzymes from microorganisms can readily ferment them to alcohols. Lignocellulosic ethanol can also be processed to alcohols via thermo-chemical conversion routes such as gasification technologies. As described in section *3.2.1*, the gasification process results in the formation of syngas ($CO+H_2$) which can be either further synthesized to alcohols through the catalytically hydrogenation of CO [64] or fermented into alcohols by microbial catalysts [65].

It is worth noting that alcohols can also be produced from waste gases rich in CO and CO_2 that are not necessarily biomass-based such as industrial flue gases from steel mills and processing plants. The advantage associated with this value chain is the fact that there is no requirement for the development of a dedicated feedstock production infrastructure [66], and the CO_2 inventory is reused before entering the environment.

3.3.3 By-products

Figure 3.15 shows a summary of the main by-products obtained from alcohol-to-jet value chains. When converting alcohols into jet-fuels as a primary product, significant amounts of diesel are also generated as by-product. Additionally, a substantial number of other by-products are obtained during the production of the alcohols. When the alcohols are produced from the fermentation of sugars and starches, only the fermentable sugars released from starches and sugars can be converted into alcohols for the further production of aviation fuels. The remaining unfermented residues (~ 15-30%) are then separated from the alcohols and can be converted into a product called distillers' dried grains with solubles that may be sold as

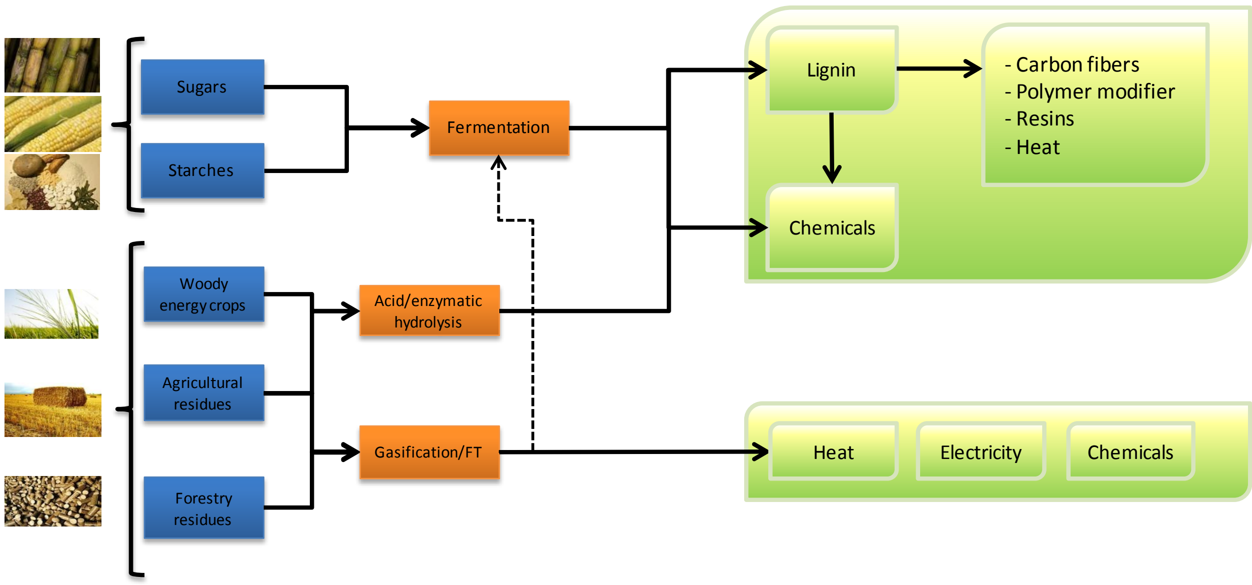


Figure 3.15. Overview of the main by-products obtained in the production of ATJ-SPK.

animal feed or converted into other bio-based products. Furthermore, the fermentation process releases gases such as CO_2 that can be captured for sale to other sectors, for instance, to the beverage industry [67]. When lignocellulosic biomass is the feedstock considered for fermentation purposes, the residual cellulose and the non-fermentable lignin (~60%) that remain from the hydrolysis pre-treatment are the main sources of by-products which can be utilized for several purposes. One common approach is the combustion of these by-products in order to produce electricity or steam that can either be integrated in the fermentation system itself or it can be delivered and distributed to nearby customer. Another approach is the conversion of these remaining residues through a variety of thermochemical processes (gasification, liquefaction, pyrolysis) producing a wide spectra of chemicals such as hydrogen and alcohols, and to fuels. Recently, significant R&D efforts have been made to develop high-value products from lignin, including: alcohols, FT liquids, BTX and higher alkylates, vanillin, acids, carbon fibres, polymers, resins, composites, pharmaceutical products, etc., in order to increase the process revenue [68].

When gasification is the selected technology for the production of alcohols, the by-products are similar to those described previously for the FT-SPK technology pathway, namely heat and electricity and therefore will not be further discussed in this chapter.

3.3.4 Products yields and energy efficiencies

The product yields and energy efficiencies discussed in this report and associated with the ATJ technological pathway are also based on four available studies addressing different biomass feedstocks and conversion processes, both biochemically and thermo-chemically based. The main results are summarized in Table 3.5. It is important to highlight that most of the studies available focus on the production of alcohols or on the single steps involved in the further conversion from the alcohol to the jet-fuel. That makes the collection and interpretation of data associated with the ATJ route a big challenge.

Humbird et al. [69] studied the feasibility evaluation for corn stover to ethanol by fermentation. The annual biomass input was about 700830 tons/year (on dry basis) corn stover. The subprocess steps involved were feed handling, diluted acid pre-treatment and conditioning, enzymatic hydrolysis and fermentation, cellulose enzyme production, product recovery, wastewater treatment, storage and steam, electricity generation and utilities. The product yields obtained through this conversion technology were 0.26 kg/kg of dry biomass for ethanol, 0.26 kg/kg of dry biomass also for diesel and 0.116 kg/kg of dry biomass for Jet A1. The energy efficiency of production of jet A1 from biomass was 29 % (Energy eff, biomass, Jet A-1) and the overall efficiency after accounting net heat export was about 32 % (Energy eff, biomass, total).

Dutta et al. [70] conducted a techno-economic feasibility study for the conversion of lignocellolosic biomass (35 wt.% moisture) to ethanol and higher alcohols (co-product) via indirect gasification, followed by gas-to-liquid synthesis. The annual biomass input was 700830 tons/year (on dry basis). Although the biomass input was the same as for Humbird et al, the plant capacity in terms of MW_{th} was not the same (364 vs. 430 MW_{th}) due to the difference in heating value of the processed biomasses. The subprocesses involved in this plant design case were feedstock handling and drying, gasification, gas cleanup, alcohol synthesis, alcohol separation, steam and power generation, cooling water and utilities. The product yields were 0.3189 kg/kg of feedstock for ethanol and 0.0415 kg/kg dry feedstock for the mixture of higher alcohols. The energy efficiency of production of biomass to ethanol was about 40 %, and energy efficiency with the inclusion of co-products was about 45 % (Energy eff, biomass, liquid).

Pham et al. [71] evaluated through a feasibility analysis, the conversion of energy crops and chicken (80:20 ratio, respectively) manure into liquid fuels (gasoline and jet-fuel) through fermentation, hydrogenation to mixed alcohols, and further conversion to hydrocarbon fuels. The main products were gasoline and jet-fuel. The annual biomass input was about 320 000 tons/year (on dry basis) which is approximately half the plant size of the study conducted by Humbert et al. The jet-fuel yield was about 70 litres/ton of dry biomass and the gasoline yield (co-product) was 235 litres/tone of dry biomass. The energy efficiencies are not disclosed in the open literature and therefore will not be given.

Finally, Phillips et al [72] performed a techno-economic feasibility evaluation for the hybrid poplar wood chips (50 wt.% moisture) into gasoline through biomass gasification followed by the methanol-to-gasoline synthesis. The annual biomass input was 700500 tons/year (dry), similarly to the evaluation of Humbert et al. The main product was gasoline with LPG as co-product. Although the process did not address the production of jet A1, the product yields give in this study can provide an estimation of the product yields if jet-fuel was considered. The subprocess steps considered were feedstock preparation, biomass gasification, syngas cleanup, methanol synthesis, the MTG process, gasoline separation and finishing processes and power generation. The product yields were about 230 liters/ton dry feedstock for gasoline and about 39 liters/ton dry feedstock for LPG. The energy efficiency of gasoline production was about 37.7% and the energy efficiency by accounting co-products was improved up to 42.6 % (Energy eff, biomass, liquid). These energy efficiencies were substantially higher than those obtained for a similar plant capacity when fermenting corn stover into ethanol, diesel and jet-fuel.

3.3.5 Costs

Figures 3.16-3.19 show the incremental costs associated with the original plant sizes discussed in section 3.3.4 and the corresponding costs for a hypothetical plant with a capacity of 289 MW in order to compare the costs with the plant size taken as a reference (Arlanda case) when discussing the FT route.

The NREL case, as shown in figure 3.16, depicts the incremental cost breakup for each piece of equipment associated with production of ethanol. However, no data was found on the specific costs associated with ethylene oligomerization on the one side and olefin hydrogenation and product fractionation on the other side. Both water treatment and steam generation show to be the most costly subprocesses of the fermentation process.

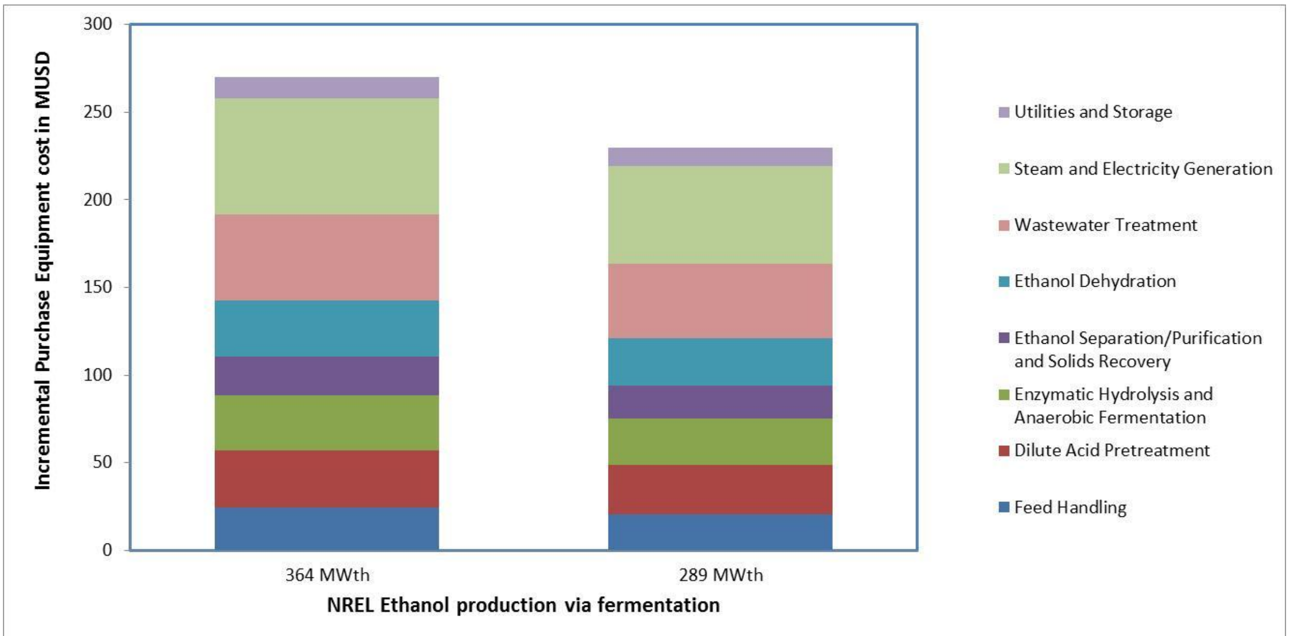


Figure 3.16. Incremental Purchase equipment costs associated with ethanol production via fermentation [69].

The incremental purchasing equipment costs for the indirect gasification of lignocellulosic biomass into alcohols followed (Dutta et al) are illustrated in Figure 3.17. The gas clean up and conditioning and the water cooling and utilities appear to be the most costly subprocesses whereas the gasification unit and alcohol synthesis processes were relatively inexpensive.

Table 3.5. Typical product yields and energy efficiencies associated with the ATJ-SPK process.

	Study/Case	Humbird et al 2011 [69]		Dutta et al 2012 [70]		Pham et al 2010 [71]		Phillips et al 2011 [72]	
	Case description	Converts corn stover to ethabol by dilute-acid pretreatment, enzymatic saccharification, and co-fermentation and modification posibilites to jet via Ethanol		Converts lignocellolosic biomass to ethanol and a higher alcohols coproduct via indirect gasification, followed by gas-to-liquid synthesis.		Converts biomass feedstock into liquid fuels (gasoline and jet fuel) through fermentation, hydrogenation to mixed alcohols, and further conversion to		Converts biomass feedstock into gasoline through biomass gasification, methanol synthesis and MTG technologies	
	Boundary conditions	Biomass input: 700 830 tons/year (dry) corn stover. Product: Ethanol.		Biomass input: 700 830 tons/year (dry), 35 wt% moisture. Production of ethanol with higher alcohols as coproduct. **No Jet A1 production.**		Biomass input: 320 000 tonnes/year (dry). Production of gasoline and jet fuel. Self sufficient in hydrogen		Biomass input: 700500 tons/year (dry), wood chips, 50 wt% moisture. Production of gasoline with LPG as co-products. **No Jet A1 production**. Self	
	Sub processes	Feed handling, pretreatment and conditioning, enzymatic hydrolysis and fermentation, cellulase enzyme production, product recovery, wastewater treatment, storage, steam		Feedstock handling and drying, gasification, gas cleanup, alcohol synthesis, alcohol separation, steam and power generation, cooling water and utilities		Pretreatment with lime, fermentation, dewatering, thermal conversion, hydrogenation of ketones to mixed alcohols, oligomerization of alcohols to hydrocarbons		Feedstock preparation, Biomass gasification, syngas cleanup, methanol synthesis, MTG process, gasoline separation and finishing processes, power generation.	
	Feedstock (nature)	**Corn stover**		**Southern pine wood**		**Sorgum (energy crops)+ chicken manure (80:20)**		**Hybrid poplar wood chips**	
		Mass flow	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**
Feedstock	Biomass input (tons/year)	700 830 (dry)	364 MWth	700 830 (dry)	430 MWth	320000 (dry)	200 MWth	700500 (dry)	433 MWth
	Jet A1 production (liter/year)	0		0	-	19 gallons/tonne biomass (daf)	Jet fuel	0	-
Jet A1	Jet A1 density (kg/l)			-	-	-		-	-
	Operating hours per year	8410		8410		8000		8406	
Other products	Component	**Ethanol**		**Ethanol**		**Gasoline**		**Gasoline**	
	Production	0.2601 kg/kg feedstock		0,3189 kg/kg dry feedstock		62 gallons/tonne biomass (daf)		229.9 l/tonne dry feedstock	
	Component	**Heavy diesel**		**Higher alcohol products**				**LPG**	
	Production	0.26 kg/kg feedstock		0,0415 kg/kg dry feedstock				38.8 l/tonne dry feedstock	
	Component	**Jet A1 yield**							
	Production	0.116 kg/kg feedstock							
	Total Production of other products								
Energy	Req input of external electricity		0		self sufficient				self sufficient
	Power production		0						self sufficient
	Electricity export		0.923 kWh/liter		0				0
	Heat export (excess heat)								0
Efficiencies									
	Carbon conversion efficiency							Ceff to liquid	31 %
Energy Efficiencies	Energy efficiency, Biomass, jet A-1		29 %		0				0
	Energy Efficiency (Biomass to desired product)			Ethanol	40 %			Gasoline	37.70 %
	Energy Efficiency, Biomass, liquid				45 %			Gasoline + LPG	42.60 %
	Energy efficiency, biomass, total		32 %						

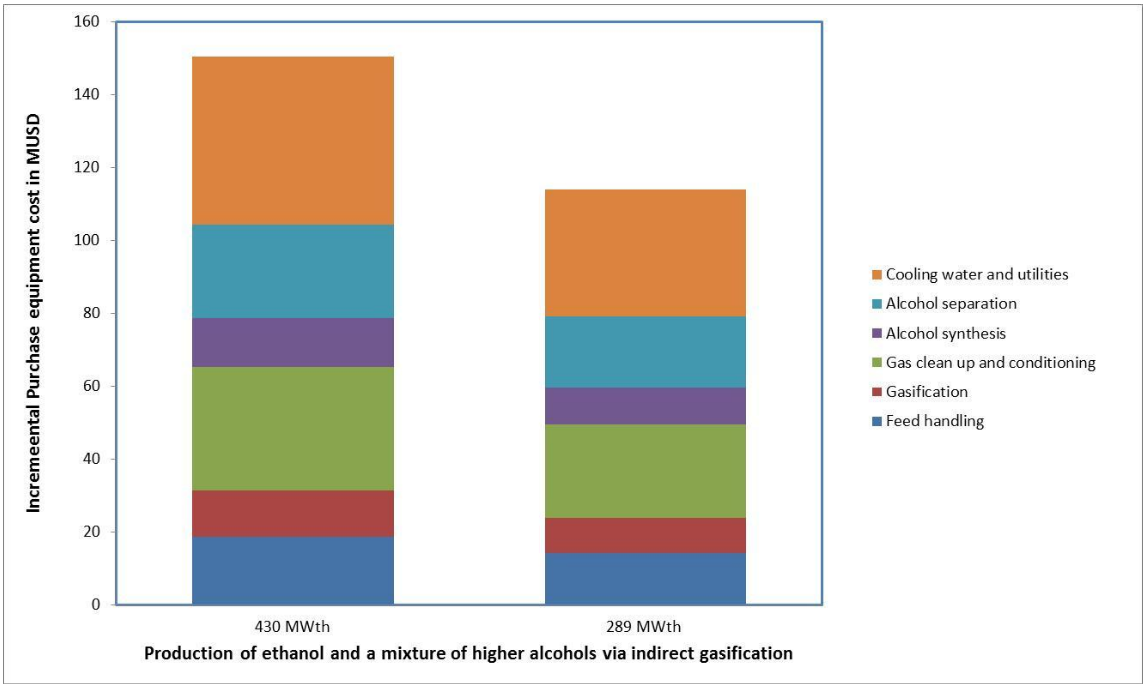


Figure 3.17. Incremental Purchase equipment costs associated with the production of ethanol and higher alcohols via indirect gasification [70].

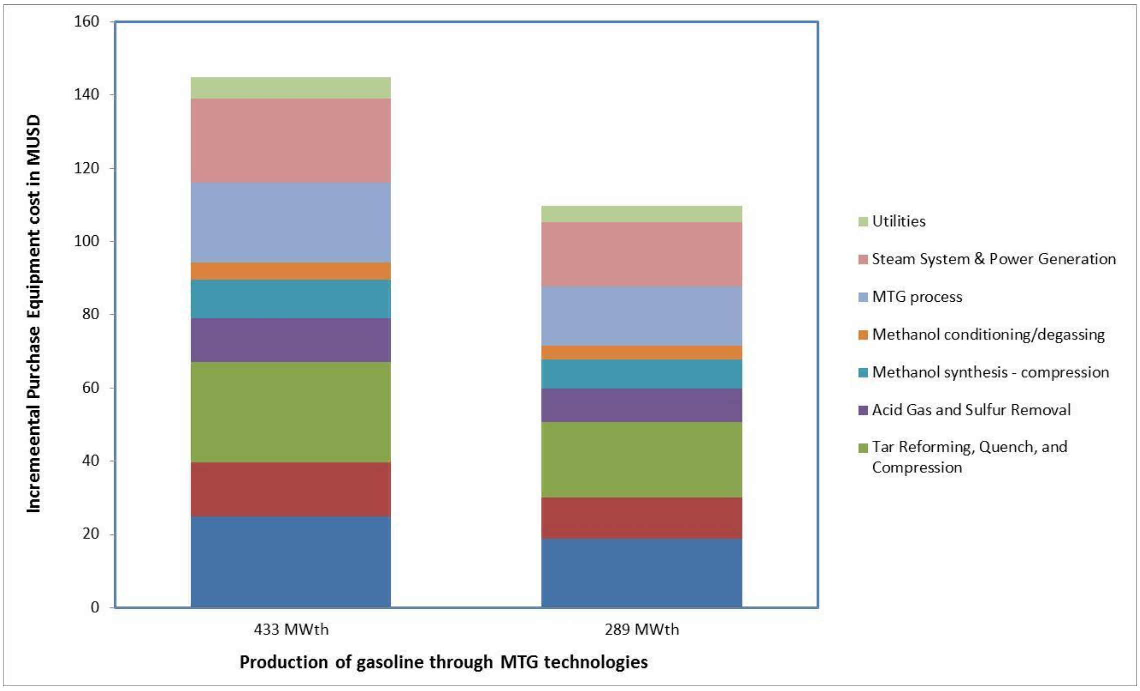


Figure 3.18. Incremental Purchase equipment costs associated with gasoline production via MTG technologies [72].

Figure 3.18 shows the conversion of biomass feedstock into gasoline through biomass gasification, methanol synthesis and the MTG technologies. Similarly to the previous study on gasification from Dutta et al., gas cleaning and conditioning was in their study one of the most costly steps in the overall process. However, in contrast to that same study, the cost associated with gasification was relatively high.

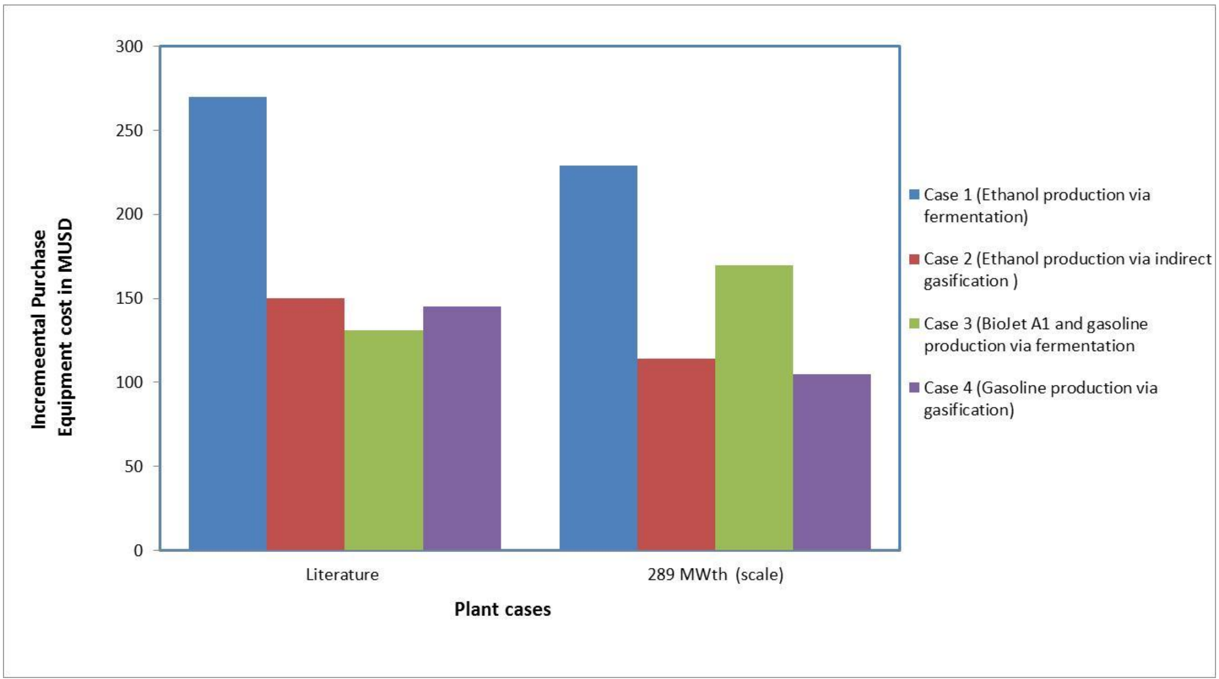


Figure 3.19. Comparison of incremental Purchase equipment costs associated with several ATJ technologies [69-72].

Figure 3.19 compares the four plant cases described previously. The results for the hypothetical 289 MWth plants indicate that the two fermentation processes have associated the highest costs with $230 million US and $170 million US for cases 1 and 3, respectively. The gasification-based fuels, instead, had incremental purchase equipment costs around $120 and $110 million US for cases 2 and 4, respectively, which are about half of the costs associated with the fermentation cases.

3.3.6 Commercialization – Stakeholders

All the processing steps required in the alcohol-to-jet technology pathway are currently in use at commercial scale in the petrochemical industry but the technology is still at pilot/demonstration levels (TRL 4-7, depending on the feedstock) regarding the conversion of alcohols from non-fossil derived petroleum, mainly due to the challenges associated with the production of alcohols. There are a significant number of stakeholders that are pursuing interesting emerging ATJ technologies at different steps of the entire value chain (from biomass to alcohols on the one hand, and from alcohols to jet-fuel on the other hand). A summary of ATJ processes in development is provided in Table 3.6. These often represent partnerships between alcohol production and alcohol conversion technology providers, and use different alcohol intermediates.

First generation ethanol made from starch-rich materials or from sugar feedstock is a mature commodity product with a worldwide annual production of over 13 billion US gallons (~49 billion litres) in 2007 [73]. Due to availability and sustainability concerns associated with this fuel product and technology, a significant number of ethanol producers are shifting their focus from first generation ethanol production from starch and sugars to second generation ethanol from lignocellulosic biomass and/or production of a higher energy density alcohol with better fuel characteristics as it is butanol. Similarly, the gasification of lignocellulosic biomass to alcohols needs further development before becoming commercially available.

Table 3.6. Stakeholders involved in the production of ATJ fuels.

Stakeholder	Location	Fuel products/status
GEVO [74]	USA	Production of renewable isobutanol from multiple renewable feedstocks (grains, sugar cane and non-food-based or cellulosic-feedstocks) through fermentation with a proprietary yeast biocatalyst consisting of microorganisms. GEVO is expecting to begin commercial production of isobutanol in 2012.
LanzaTech [75]	New Zealand	Production of fuels and chemicals from carbon monoxide containing gases from several industrial sectors (steel manufacturing, oil refining, chemical production) and gases generated by gasification of forestry and agricultural residues, municipal waste and coal by means of Lanzatech's proprietary microbes in a bioreactor [76]. Lanzatech operates a pilot plant producing ethanol since 2008 and a demonstration plant was in ground breaking in 2011.
Swedish Biofuels [77]	Sweden	Production of gasoline, diesel and fully synthetic jet-fuel through the formation of an alcohol intermediate mixture (C2-C5 alcohols) via fermentation of a wide range of non-food feedstocks (grain crops, agricultural and forestry waste, wood) This technology has been proven at pilot scale [78].
ZeaChem [79]	USA	Production of advanced cellulosic ethanol and fuels through the processing of hardwood, softwood, switch grass and corn stover by using a hybrid system that combines biochemical (fermentation) and thermochemical (gasification) processing steps.
Ineos Bio [13]	USA	Production of ethanol through the fermentation of syngas that originates from the gasification of organic materials. INEOS Bio has currently a pilot plant facility.

3.3.7 Strengths and challenges

Strengths:

- All steps necessary to convert alcohol to jet-fuel are based on processes that are currently used at commercial scale in the petrochemical industry.
- Large feedstock flexibility: forestry and agricultural residues, starches and sugars, industrial waste gasses
- ATJ-SPK contains aromatics and thus it does not require blending with the conventional petroleum-derived jet-fuel.
- The process requires small amounts of external hydrogen and hydroprocessing (~1 Kg H_2/800 Kg dry biomass (obtained from experts in the field).
- When processing biomass to alcohols through fermentation, the reactions are highly selective, resulting in high amounts of desired products.

Challenges:

- The alcohol production costs are very high as compared to food-derived alcohols, especially if derived from lignocelluloses; particularly the costs associated with pre-treatments, enzymes and distillation (energy).
- There is limited experience with alcohols other than methanol/ethanol and with optimising the process for the production of kerosene
- Inherent challenges to working with living microorganisms in commercial fermentation processes to produce the alcohols [67]
  - Production rates when working with living microorganisms are low by chemical refinery standards.
    - Example: The conversion rate of lignocelluloses to ethanol is in the range of 30-60%
  - Microorganisms are variable sensitive to impurities that inhibit their activity, including their own by-products

3.4 Other technologies

3.4.1 Pyrolysis-to-Jet – Synthetic Paraffinic Kerosene (PTJ – SPK)

Pyrolysis-to-Jet Synthetic Paraffinic Kerosene (PTJ-SPK) has not been yet considered for ASTM certification as synthetic aviation fuel. However, a relevant number of stakeholders are currently focusing on this technology. This renewable aviation fuel is produced through the thermo-chemical conversion of lignocellulosic biomass from industrial, agricultural, municipal or forestry waste, in the absence of oxygen, atmospheric pressure and rapidly heating (residence times < 2 seconds) to moderate temperatures (~500 °C). As a result, biomass decomposes to generate mostly gases, vapours and solid product referred to as char. After cooling and condensation, a dark brown mobile liquid, referred to as pyrolysis oil, with a heating value that is approximately half of that characterizing petroleum-derived oil, is formed. The chemical composition of biomass-based pyrolysis oils depends on the biomass feedstock to a large extent and is highly complex and thus complicated to analyse in all its details. The main components comprise mainly of water, carboxylic acids, carbohydrates and lignin derived substances [80].

The pyrolysis oil is not a drop-in fuel as it has a very high oxygen content (up to 50%) and it is immiscible with petroleum, due to its acidity (corrosiveness). It is also inherently unstable so cannot be easily stored, and is unstable upon heating, with issues of coke formation [81]. In order to reduce the acidity as well as water and oxygen content and make pyrolysis oil more miscible with petroleum, the pyrolysis process needs to be followed by upgrading of the pyrolysis oil produced, as indicated in Figure 3.20, through hydrotreating. It is worth noting that the upgraded fuel stream can be produced either at a dedicated plant or co-fed in oil refineries. In fact, some opinions in the aviation biofuels sector consider that the co-feeding of pyrolysis oil into refineries will be the only economically feasible option for the production of renewable jet-fuel through this technology due to the significant amounts of hydrogen that would be required for the hydrotreating step, leading to prohibitively high costs and emissions. Another economically viable approach might be the production of road transport fuels, together with small proportions of jet-fuel components, such as aromatics. Furthermore, there has been increasing interest over the last few years in new processes for upgrading pyrolysis oils with lower hydrogen requirements and in developing new catalytic processes to produce better quality oils directly [1]. Several companies such as Dynamotive [82], Ensyn [83], BTG [14] and UOP [29] are working on the development of the pyrolysis technology, which is at the pilot-scale and/or early commercial stage. UOP and Ensyn, for instance, launched a joint venture called Envergent

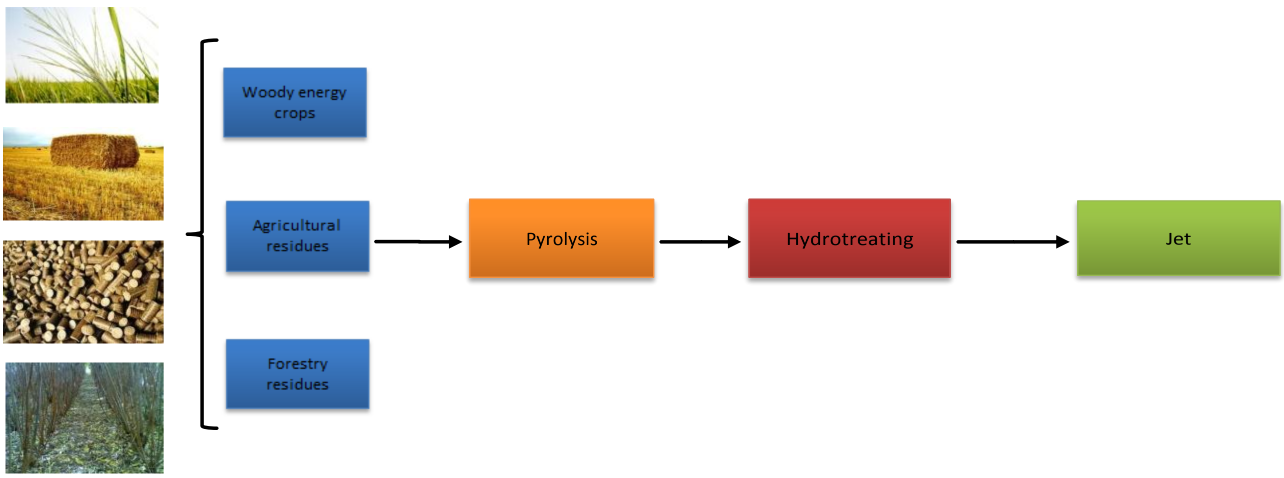


Figure 3.20. Overview of the biomass feedstocks and technological pathways for the pyrolysis-to-jet technology

Technologies [84] in 2009 to produce byrolysis oil for heat, power and transport fuel applications. Dynamotive, on the other hand, announced also in 2009, their achievement in scalable production of renewable diesel and gasoline, via a secondary upgrading step from pyrolysis oil, and that early testing of bench scale products shows that the upgraded products have a jet fraction of around 30%.

3.4.2 Fermented Renewable Jet – Synthetic Paraffinic Kerosene (FRJ – SPK)

Fermented Renewable Jet Synthetic Paraffinic Kerosene (FRJ-SPK) is envisaged as an aviation fuel with large potential but, similarly to PTJ-SPK, it has neither been tested nor considered for ASTM certification. This aviation fuel is produced from sugars either through their fermentation by genetically designed microorganisms that directly metabolise them into hydrocarbon or through catalytic chemical processing (see Figure 3.21). A number of companies are involved in this technology. Startups, such as LS9 [85] and Amyris [86] are trying to genetically engineer the metabolic systems of microbes in order to ferment sugars

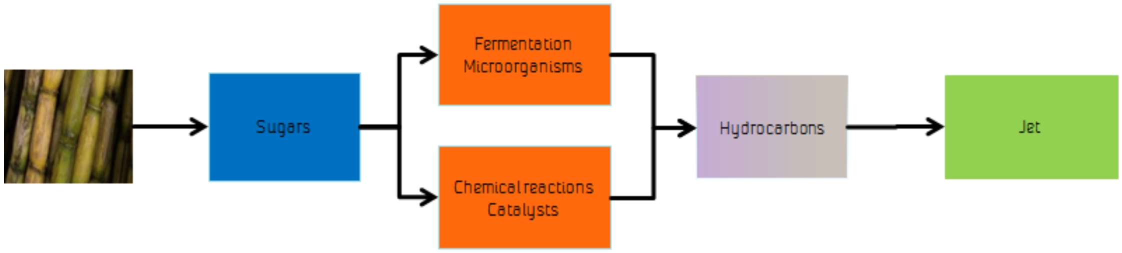


Figure. 3.21. Overview of the biomass feedstocks and technological pathways for the fermented renewable jet technology

into useful hydrocarbons [87]. Other researchers, such as an initiation at the University of Wisconsin-Madison [88], focus on chemical reactions instead of microbial fermentation. They use catalysts at high temperatures to convert glucose into hydrocarbon biofuels. In the first reactor, a sugar-water solution is passed over a platinum-rhenium catalyst at about 500 K. This strips five out of six oxygen atoms from the sugar, creating a mixture of various hydrocarbon compounds, such as alcohols and organic acids. The compounds form an oil-like layer that floats on top of the solution. The oil is transferred to the second reactor, where it is passed over various solid catalysts, resulting in a range of hydrocarbon molecules that make up gasoline, diesel, and jet-fuel. The alcohols and organic acids in the oil from the first step could also be used to make plastics and industrial chemicals. Although these emerging technologies are still under R&D, they are claimed as economic processes with high specificity of the product and high potential in the future.

4 Comparison methodologies between HEFA, FT and ATJ technologies and fuels

Table 4.1 summarizes the key parameters associated with the three most relevant technologies for the production of biojet-fuel in Norway in the near-future.

Table 4.1. Key parameters associated with the HEFA, FT and ATJ technological pathways.

	HEFA-SPK	FT-SPK	ATJ-SPK
Feedstock	Conventional oil crops: soybean, palm oil, rapeseed, coconut, corn New oil crops: jatropha, camelina and halophytes Microalgae	Lignocellulosic biomass: energy crops, agricultural and forestry residues, wastes	Sugars: sugarcane, sugar beets, molasses, and fruits Starches: corn, cassava, potatoes, and root crops Lignocellulosic biomass: energy crops, agricultural and forestry residues
By-products	Diesel, fractions of propane, naphtha and LPG, natural pesticides, nutriceuticals plastics, animal feed, heat and chemicals	Diesel, gasoline, naphtha, chemicals (hydrogen, methanol,)	*From sugars and starches:* - Diesel (from alcohol production) - Proteins and fats (from jet fuel production) *From lignocellulosic biomass:* - Diesel (from alcohol production) - Lignin and small amounts of proteins (from jet-fuel production)
Costs	- Low CAPEX - High OPEX: high feedstock prices, low yields (little oil content in the crop), large hydrogen requirement	- High CAPEX: gasification, gas cleaning and FT steps - Low OPEX: use of residues as feedstocks, high conversions	- Low CAPEX - High OPEX: micro-organisms and pre-treatments
Certification	Certification since July 2011 by the ASTM D1655 standard, up to 50% blending with petroleum-based jet kerosene	Certification since September 2009 by the ASTM D1655 standard, up to 50% blending with petroleum-based jet kerosene	Under ASTM certification. Expected to be approved as fully synthetic aviation fuel with 100% replacement of the petroleum-based jet kerosene by 2014
Commercialization	Pilot plants under construction – TRL: 5-6	The majority of the developments are in the pilot or demonstration scale – TRL: 7-8	*From sugars and starches:* - Developments at pilot/demonstration scale – TRL: 6-7 *From lignocellulosic biomass:* - Developments at pilot scale - - TRL: 4-5

Advantages	- Wide range of feedstocks can be processed - Product life cycle emissions significantly lower compared to fossil fuels (80-85% including only biomass conversion processes) - Very pure and high quality product with a chemical composition similar to conventional jet-fuel	- Wide spectra of potential products - Large feedstock flexibility - Product life cycle emissions much lower compared to fossil fuels (90-95% including only biomass conversion processes) - High conversions - Relatively low external hydrogen requirement when applying certain gasification systems (indirect gasification)	- All steps necessary to convert alcohol to jet-fuel are at commercial scale in the petrochemical industry. - Large feedstock flexibility - ATJ-SPK does not require blending with petroleum-derived jet-fuel - Little amount of external hydrogen required - High specificity when processing biomass to alcohols through fermentation
Challenges	- High investment cost of the plants - High feedstock prices - Feedstock availability (competing with biodiesel producers for the same feedstock) - Sustainability concerns - Low oil yields - Large amounts of hydrogen required	- High capital costs - Biomass gasification still requires optimization, particularly with regards to tar minimization - Large amounts of hydrogen required	- High alcohols production costs, particularly from lignocellulosic biomass - Limited experience with alcohols other than methanol/ethanol - Low production rates when working with microorganisms - High sensitivity of microorganisms towards impurities

5 Conclusions and recommendations

The main alternative renewable jet-fuels and the corresponding production technologies have been assessed on the basis of a detailed systematization and semi-quantitative comparison in terms of biomass resources, economics, sustainability, and potential speed of near-term commercialization, in order to identify the most promising value chains for the production of renewable jet-fuel by 2020-2025 in Norway.

HEFA-SPK is envisaged as a near-term solution. This fuel has been already certified by ASTM since 2011 and the technology is commercially available when processing conventional oil crops and is expected to be competitive with aviation kerosene. However, substantial concerns and uncertainties associated with these feedstocks in terms of impact feedstock prices, low yields as well as sustainability and availability have led to a focus shift from conventional oil crops to new oil crops and microalgae, which are not converted at commercial scale yet. The consolidation of the HEFA technology will strongly depend on oil prices. In a scenario with HEFA oils produced at the historic low prices for vegetable oils, oil crops would contribute significantly to the production of alternative jet-fuels. Additionally, the rate of uptake for this technology will depend on the availability of these feedstocks. In a Norwegian context, the limited cropland and cold climate conditions make the oil seed production a challenge and thus HEFA-SPK technology not likely for fuel purposes.

Biomass derived FT-SPK, on the other hand, was the first biofuel to be certified for aviation purposes and is expected to be on the market within the coming decade, although not necessary at competitive prices. Besides feedstock flexibility, the maturity of the gasification and FT technologies, the high conversion rates and the potential large reduction in GHG emissions, the latter significantly larger than that obtained through the HEFA technology, makes this technology very attractive. The main bottleneck for its commercialization is the high capital costs associated with the highly complex gasification unit and the capex required for large scale plants that are needed to make the technology profitable. Substantial efforts are being conducted on the reduction of the aforementioned capital costs by optimizing, among other aspects, gasification designs. In addition, and despite the fact that operational costs are relatively low as compared to other technologies, with little or no external hydrogen requirement, the focus is also set on the utility of challenging low-value feedstocks such as waste and agricultural and forestry residues. The fact that lignocellulosic biomass, which is the most suitable feedstock for this technology, is the largest biomass source potential in Norway, makes this technological pathway of particular relevance for the domestic production of jet-fuel in the near-midterm future.

ATJ is another promising technology for the production of renewable jet-fuel. It is currently under certification and it is expected to be approved in 2014. Similarly to FT-SPK, one of the main advantages associated with this process is the wide spectrum of feedstocks, including sugars, starches and lignocellulosic materials that can be processed. Besides, the fact that all the steps necessary to convert alcohols to jet-fuel are at commercial scale in the petrochemical industry and that the amount of external hydrogen required for the process is relatively small compared to HEFA-SPK, are two additional arguments to select this technological pathways for the production of aviation fuels. Availability and sustainability concerns on the use of sugars and starches for fuel purposes have impacted negatively into the development of aviation fuels from these sources and have strengthened the focus on the production of ATJ-SPK from lignocellulose. The production of alcohols through fermentation of lignocellulosic materials has a significant number of remaining challenges such as pre-treatment and high enzymes costs, low production rates and high sensitivity of the microorganisms towards impurities that require further improvements before it can be commercialized. In a Norwegian context, and in line with the arguments given above, the production of alcohols should be based on lignocellulosic biomass resources. Alternatively, a second scenario where the alcohols are imported to Norway for further conversion in an ATJ unit could also be considered. This will totally depend on the importation costs of these alcohols. This approach is already taken in other geographical markets.

Other alternative technological pathways such as pyrolysis-to-jet and fermented-renewable-jet are still at an early stage of commercialization and therefore have not been selected as main candidates.

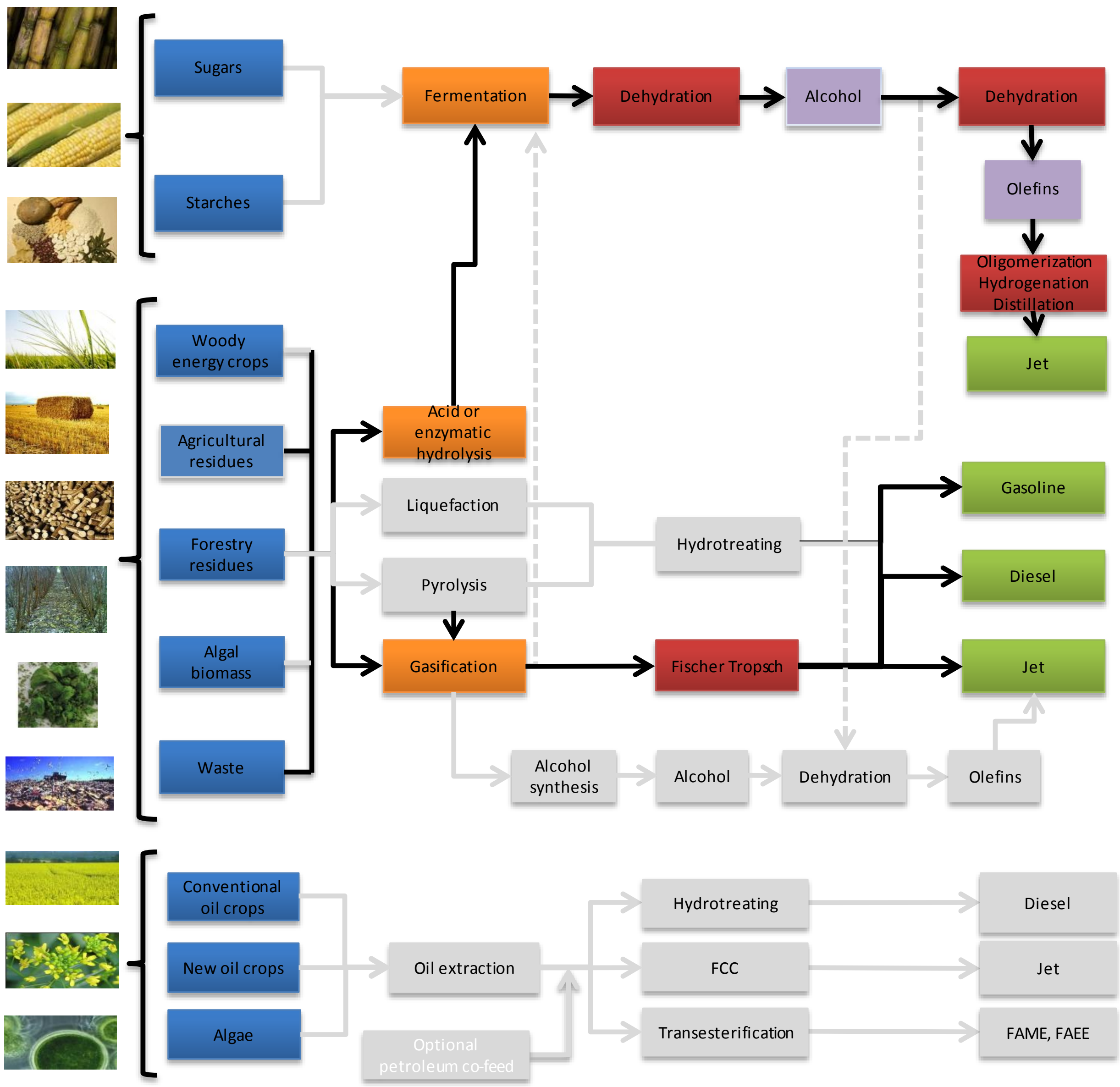


Figure 5.1. Highlight of the two most promising technologies for the production of bioJet A-1 in Norway by 2020-2025.

Based on the discussions above, it can be concluded that the most promising technologies for the production of renewable jet-fuel in Norway within the coming decade will be FT- and ATJ-based. Figure 6.1 highlights these two selected pathways.

These conclusions are in line with the expected deployment of the HEFA, FT and sugar platform jet biofuels in Europe within 2050 reported recently by [89]

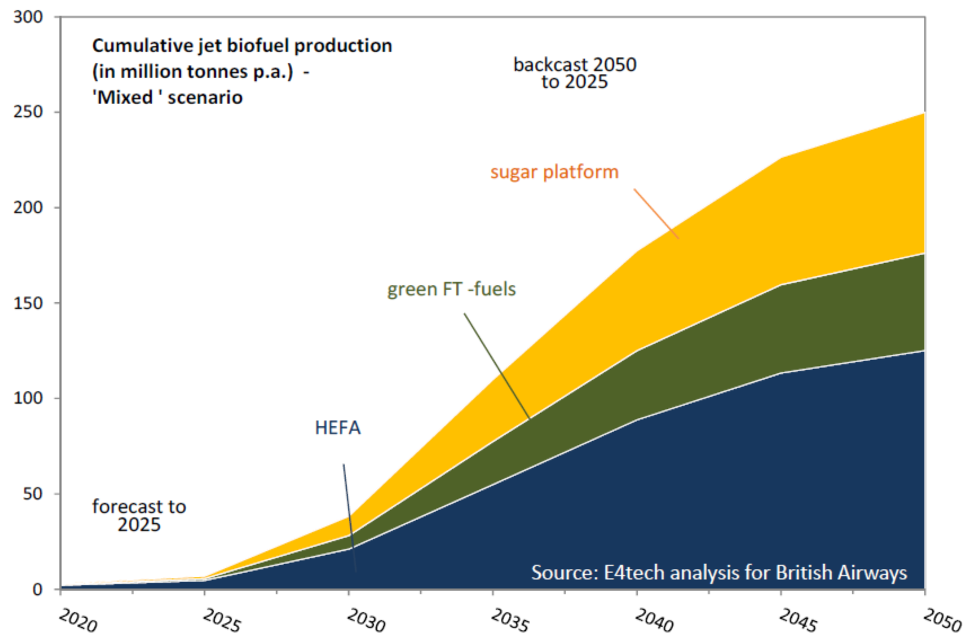


Figure 5.2. Deployment of jet-fuel production technologies. Adapted from [89].

It is important to keep in mind that the information has been deduced and triangulated based on sources from the open literature and in-house expertise, thus offering a semi-quantitative assessment. In order to benchmark key process parameters such as carbon and energy efficiencies, nutrient balances, required input of external energy, costs, etc. into a deeper, more accurate level, it is recommended for further work to conduct detailed techno-economic evaluations for both the FT and ATJ routes to jet-fuel.

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7 Appendices

7.1 Questionnaire

1. Objectives
Objectives of questionnaire: Collect available data on bio Jet A-1 production from the stakeholders plants Identify the strenghts and weaknesses associated to the bio Jet A-1 production processes

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2. Key information on specific bio Jet A-1 production plant

Jet A-1 facility

Plant name		
Plant Location	town, country	
Start-up date	dd/mm/yy	

Facility type

Select the right facilty option

Lab-scale	
Pilot-scale	
Demonstration	
Commercial	

Time perspective - provide information on the expected time to commercialize your technology

Plant capacities & operation

Provide information on the facility characteristics in the table below. Further details could be given in the "Comments" field.

Biomass input	MW_biomass		*Based on Lower Heating Value*
Mean annual biomass input	GWh fuel/year		*Based on Lower Heating Value*
Mean annual biomass input	Tonnes/year		*Based on Lower Heating Value*
Jet A-1 production	L/Kg biomass		
Jet A-1 production	L/ year		
Electrical capacity	MW_elec		*Nominal design capacity*
Thermal capacity	MW_therm		*Nominal design capacity*
Biomass to fuels efficiency	%		*Based on energy*
Electrical efficiency	%		*Nominal gross electrical efficiency*
Thermal efficiency	%		*Nominal gross thermal efficiency*
Hours of operation per year	Hours/Year		
Land use	Km^2		*Area needed for plant and feedstock storage. Not relevant for lab-scale*

Comments (Please add further details here)

3. Feedstock - nature and size of the feedstock

Select the right feedstock option and specify the feedstock nature, particle size and water content within each category utilized. Further details could be given in the "Comments" field

	Feedstock used	Nature	Particle size, delivered to plant (cm)	Water content (wt. %)	Cost (euro/Kg)	Comments
Forest-based						
Agricultural-based						
Crops (Camellina, Jatropha)						
Macroalgae						
Microalgae						
Sugar cane						
MSW						

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4. Technologies

Main technologies

Select the right applied technology and fill in the corresponding information in the tables below according to the selected technology.
Please specify the technology if the selected choice is "Others".

	Technology applied	Comments
HEFA		
Gasification - Fischer Tropsch		
Alcoho-to-Jet		
Fermented-Renewable-Jet		
Hybrid systems		
Others		

HEFA

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of reactor, temperature, pressure, catalyst, reactants, etc.)
Oil extraction		
Oil processing		
Oil refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Gasification - Fischer Tropsch

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of pre-treatment, reactors, temperature, pressure, catalysts, gasifying agent, reactants,etc.)
Pre-treatment		
Gasification		
Gas conditioning		
Acid Gas Removal		
FT		
Syngas refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Alcohol to Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (technology for alcohol production, temperature, pressure, catalysts, etc.)
Fermentation		
Dehydration		
Oligomerization		
Distillation		
Hydrogenation		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

4. Technologies

Fermented Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, etc.)
Engineered biochemical Fermentation (genetically engineered microbes)		
Aqueous phase reforming + conventional chemical processing		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Pyrolysis Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, carrier gas, etc.)
Pre-treatment		
Pyrolysis		
Char combustion		
Upgrading		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Hybrid systems

Provide information on the hybrid systems technologies in the table below. Further details could be given in the "Technologies specifications" field,

		Technology specifications (combination of technologies, technology specifications as described above)
Combination of technologies		
Technology patented by your company		

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5. Jet A-1 and by products

Jet A-1

Provide information on the characteristics of your Jet A1 produced. Use the "Comments" field for furter details.

		Comments
Energy content		
Density		
Production Cost		
Selling price		

Provide information if testing of your Jet A1 fuel has been carried out. Select the right testing option and use the "Comments" field for further details

	Comments
Laboratory	
Jet motor rig	
Test flight	
Commercial flight	

By-products

Provide information on the characteristics of the by-products from your Jet A1 production. Use the "Comments" field for furter details.
Costs - amount you have to pay to get rid of the by-product
Selling price - income for selling the by-product

Feed, chemicals and materials	Production (Kg/Year)	Density (Kg/L)	Cost (Euro/kg)	Selling price (Euro/kg)
Biochemicals				
Biomaterials				
Nutrients				
Residues				

Excess Energy	Production		Exported to external customer		Selling price (Euro/kWh)	Type customer
	MW	MWh/Year	MW	MWh/Year		
Heat						
Power						

Comments (Please add further details here)

6. Advantages and challenges associated to the applied technology
Provide information on the advantages and challenges associated to your technology (fuel flexibility, capital costs, funding, sustainability, GHG reduction, etc.
Advantages
Challenges

7.2 Answers to questionnaires

7.2.1 Neste Oil

1. Objectives
Objectives of questionnaire: Collect available data on bio Jet A-1 production from the stakeholders plants Identify the strenghts and weaknesses associated to the bio Jet A-1 production processes

2. Key information on specific bio Jet A-1 production plant

Jet A-1 facility

Plant name		
Plant Location	town, country	Two units in Porvoo, Finland; one unit in Singapore; one unit in Rotterdamn, the Netherlands
Start-up date	dd/mm/yy	Porvoo 2007 and 2009, Singapore 2012, Rotterdamn 2011

Facility type

Select the right facilty option

Lab-scale	
Pilot-scale	
Demonstration	
Commercial	X

Time perspective - provide information on the expected time to commercialize your technology

Plant capacities & operation

Provide information on the facility characteristics in the table below. Further details could be given in the "Comments" field.

Biomass input	MW_biomass		*Based on Lower Heating Value*
Mean annual biomass input	GWh fuel/year		*Based on Lower Heating Value*
Mean annual biomass input	Tonnes/year		*Based on Lower Heating Value*
Jet A-1 production	L/Kg biomass		
Jet A-1 production	L/ year		
Electrical capacity	MW_elec		*Nominal design capacity*
Thermal capacity	MW_therm		*Nominal design capacity*
Biomass to fuels efficiency	%		*Based on energy*
Electrical efficiency	%		*Nominal gross electrical efficiency*
Thermal efficiency	%		*Nominal gross thermal efficiency*
Hours of operation per year	Hours/Year		
Land use	Km^2		*Area needed for plant and feedstock storage. Not relevant for lab-scale*

Comments (Please add further details here)

Total annual renewable fuel capacity 2 million tons. Main product renewable diesel. Ability to produce renewable aviation fuel at all four plants, investment for logistics needed. Currently renewable aviation fuel is produced in Finland, on batch basis, some thousand tons per year. This fulfills the current demand. In the future, when the market developes and the demand is higher, production is also possible on continuous basis (both diesel and aviation fuel) in Rotterdam and/or Singapore.

3. Feedstock - nature and size of the feedstock

Select the right feedstock option and specify the feedstock nature, particle size and water content within each category utilized. Further details could be given in the "Comments" field

	Feedstock used	Nature	Particle size, delivered to plant (cm)	Water content (wt. %)	Cost (euro/Kg)	Comments
Forest-based						Demonstration plant in JV with Stora Enso in central Finland (Fischer-Tropsch). Pilot plant in construction in Finland (Microbial reactor).
Agricultural-based						See the above (Microbial reactor)
Crops (Camellina, Jatropha)						Some volumes have been used as a feedstock
Macroalgae						N/A
Microalgae						Research and pilot cooperation in Finland, the Netherlands and Australia
Sugar cane						N/A
MSW						N/A

4. Technologies

Main technologies

Select the right applied technology and fill in the corresponding information in the tables below according to the selected technology.
Please specify the technology if the selected choice is "Others".

	Technology applied	Comments
HEFA	x	
Gasification - Fischer Tropsch		
Alcoho-to-Jet		
Fermented-Renewable-Jet		
Hybrid systems		
Others		

HEFA

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of reactor, temperature, pressure, catalyst, reactants, etc.)
Oil extraction		
Oil processing		
Oil refining	x	Feedstock pre-treatment and NExBTL renewable fuel proces
Technology patented by your company	x	NExBTL
Technology readiness level (TRL) *	9	

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Gasification - Fischer Tropsch

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of pre-treatment, reactors, temperature, pressure, catalysts, gasifying agent, reactants,etc.)
Pre-treatment		
Gasification		
Gas conditioning		
Acid Gas Removal		
FT		
Syngas refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Alcohol to Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (technology for alcohol production, temperature, pressure, catalysts, etc.)
Fermentation		
Dehydration		
Oligomerization		
Distillation		
Hydrogenation		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Fermented Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, etc.)
Engineered biochemical Fermentation (genetically engineered microbes)		
Aqueous phase reforming + conventional chemical processing		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Hybrid systems

Provide information on the hybrid systems technologies in the table below. Further details could be given in the "Technologies specifications" field,

		Technology specifications (combination of technologies, technology specifications as described above)
Combination of technologies		
Technology patented by your company		

5. Jet A-1 and by products

Jet A-1

Provide information on the characteristics of your Jet A1 produced. Use the "Comments" field for furter details.

		Comments
Energy content		
Density		
Production Cost		
Selling price		

Provide information if testing of your Jet A1 fuel has been carried out. Select the right testing option and use the "Comments" field for further details

	Comments
Laboratory	
Jet motor rig	
Test flight	
Commercial flight	

By-products

Provide information on the characteristics of the by-products from your Jet A1 production. Use the "Comments" field for furter details.
Costs - amount you have to pay to get rid of the by-product
Selling price - income for selling the by-product

Feed, chemicals and materials	Production (Kg/Year)	Density (Kg/L)	Cost (Euro/kg)	Selling price (Euro/kg)
Biochemicals	Small volumes of renewable propane and naphta			
Biomaterials				
Nutrients				
Residues				

Excess Energy	Production		Exported to external customer		Selling price (Euro/kWh)	Type customer
	MW	MWh/Year	MW	MWh/Year		
Heat						
Power						

Comments (Please add further details here)

6. Advantages and challenges associated to the applied technology
Provide information on the advantages and challenges associated to your technology (fuel flexibility, capital costs, funding, sustainability, GHG reduction, etc.
Advantages
Technology flexible to use wide range of different vegetable oils, tallow and fish oil as feedstock. All feedstock carefully chosen based on strict sustainability and quality criteria. Product life cycle emissions significantly lower compared with fossil fuels. Very pure and high quality product, chemical composition similar to fossil fuel.
Challenges
Investment cost of the plant high. Feedstock price high.

7.2.2 Ineos

1. Objectives
Objectives of questionnaire: Collect available data on bio Jet A-1 production from the stakeholders plants Identify the strenghts and weaknesses associated to the bio Jet A-1 production processes

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2. Key information on specific bio Jet A-1 production plant

Jet A-1 facility		Bio ethanol production only
Plant name		Indian River Bio Energy Center. JV between Ineos Bio andNew Plant energy Florida
Plant Location	town, country	Verona Beach, Florida, USA
Start-up date	dd/mm/yy	Q3 2012

Facility type

Select the right facilty option

Lab-scale		
Pilot-scale	(x)	Pilot plant has run 40 000 hrs since 2003 in Fayetteville, Ark. USA
Demonstration		
Commercial	x	

Time perspective - provide information on the expected time to commercialize your technology

Commercial delivery from Q1 2013

Plant capacities & operation

Provide information on the facility characteristics in the table below. Further details could be given in the "Comments" field.

Biomass input	MW_biomass		*Based on Lower Heating Value*	
Mean annual biomass input	GWh fuel/year		*Based on Lower Heating Value*	
Mean annual biomass input	Tonnes/year	100000	*Based on Lower Heating Value*	
Ethanol production	L/Kg biomass	0,4	*Based on dry ashfree biomass*	
Ethanol production	L/ year	30000000		
Electrical capacity	MW_elec	6	*Nominal design capacity*	gross production
Thermal capacity	MW_therm		*Nominal design capacity*	
Biomass to fuels efficiency	%		*Based on energy*	
Electrical efficiency	%		*Nominal gross electrical efficiency*	
Thermal efficiency	%		*Nominal gross thermal efficiency*	
Hours of operation per year	Hours/Year			
Land use	Km^2		*Area needed for plant and feedstock storage. Not relevant for lab-scale*	

Comments (Please add further details here)

![SINTEF]

3. Feedstock - nature and size of the feedstock

Select the right feedstock option and specify the feedstock nature, particle size and water content within each category utilized. Further details could be given in the "Comments" field

	Feedstock used	Nature	Particle size, delivered to plant (cm)	Water content (wt. %)	Cost (euro/Kg)	Comments
Forest-based						
Agricultural-based						x start up on vegetative and agricultural waste
Crops (Camellina, Jatropha)						
Macroalgae						
Microalgae						
Sugar cane						
MSW						x (later)

Feedstock flexibility - Unlike conventional bioethanol technologies, which use food crops, or even the emerging cellulosic fermentation technologies, which can convert cellulose and hemi-cellulose but not lignin, the INEOS Bio process can convert all ligno-cellulosic materials as well as other carbon materials into ethanol. The range of organic materials that can be used includes, but is not limited to;

- The biogenic portion of municipal solid waste (MSW), which includes garden and food wastes
- Organic commercial & industrial wastes
- Wood waste
- Forestry residues and products (e.g. brash, bark, saw dust, wood chippings)
- Agricultural residues (e.g. sugar cane bagasse, corn stover, straw)
- Ligno-cellulose energy crops (e.g. trees, coppice, miscanthus and switch grass)

4. Technologies

Main technologies

Select the right applied technology and fill in the corresponding information in the tables below according to the selected technology.
Please specify the technology if the selected choice is "Others".

	Technology applied	Comments
HEFA		
Gasification - Fischer Tropsch		
Alcoho-to-Jet		
Fermented-Renewable-Jet		
Hybrid systems	x	Gasification to syntesis gas- bacterial fermentation of syn gas, distillation- anhydrous ethanol
Others		

HEFA

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of reactor, temperature, pressure, catalyst, reactants, etc.)
Oil extraction		
Oil processing		
Oil refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Gasification - Fischer Tropsch

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of pre-treatment, reactors, temperature, pressure, catalysts, gasifying agent, reactants,etc.)
Pre-treatment		
Gasification		
Gas conditioning		
Acid Gas Removal		
FT		
Syngas refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Alcohol to Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (technology for alcohol production, temperature, pressure, catalysts, etc.)
Fermentation		
Dehydration		
Oligomerization		
Distillation		
Hydrogenation		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Fermented Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

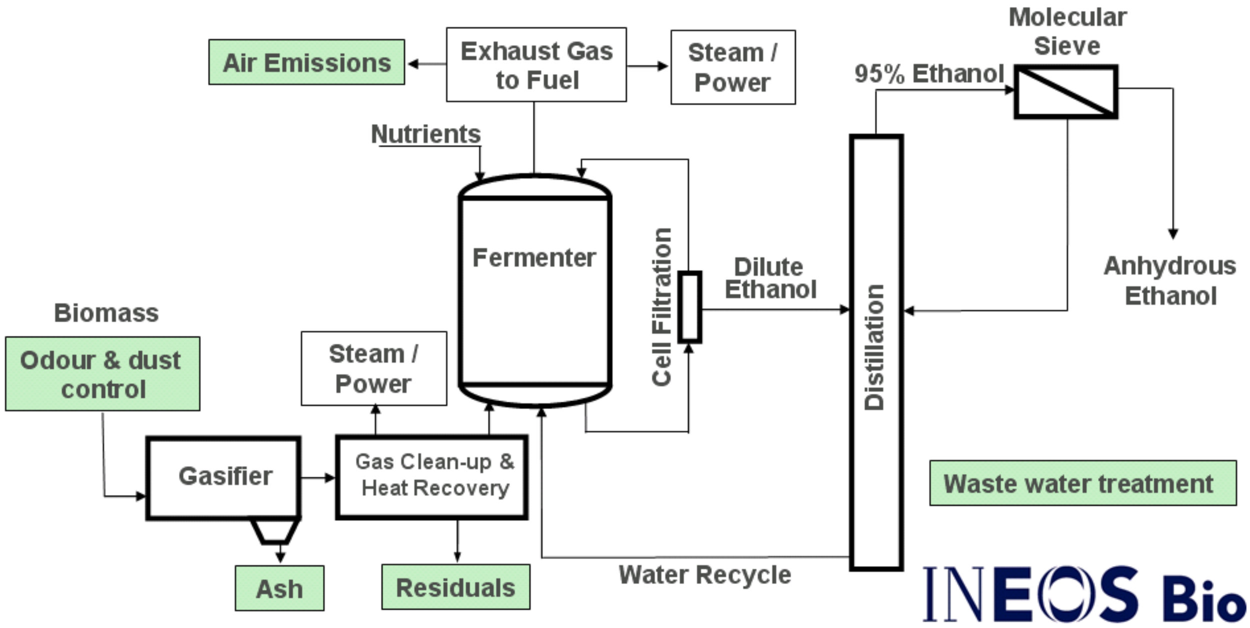
	Technology applied	Technology specifications (temperature, pressure, catalysts, etc.)
Engineered biochemical Fermentation (genetically engineered microbes)		
Aqueous phase reforming + conventional chemical processing		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Hybrid systems

Provide information on the hybrid systems technologies in the table below. Further details could be given in the "Technologies specifications" field,

		Technology specifications (combination of technologies, technology specifications as described above)
Combination of technologies		
Technology patented by your company	Globally protected by patents	



5. Jet A-1 and by products

Jet A-1

Provide information on the characteristics of your Jet A1 produced. Use the "Comments" field for furter details.

		Comments
Energy content		
Density		
Production Cost		
Selling price		

Provide information if testing of your Jet A1 fuel has been carried out. Select the right testing option and use the "Comments" field for further details

	Comments
Laboratory	
Jet motor rig	
Test flight	
Commercial flight	

By-products

Provide information on the characteristics of the by-products from your Jet A1 production. Use the "Comments" field for furter details.
Costs - amount you have to pay to get rid of the by-product
Selling price - income for selling the by-product

Feed, chemicals and materials	Production (Kg/Year)	Density (Kg/L)	Cost (Euro/kg)	Selling price (Euro/kg)
Biochemicals				
Biomaterials				
Nutrients				
Residues				

Excess Energy	Production		Exported to external customer		Selling price (Euro/kWh)	Type customer
	MW	MWh/Year	MW	MWh/Year		
Heat						
Power						

Comments (Please add further details here)

SINTEF

Advantages and challenges associated to the applied technology
Provide information on the advantages and challenges associated to your technology (fuel flexibility, capital costs, funding, sustainability, GHG reduction, etc.
Advantages
Raw material flexibility GHG reduction 90% compared to gasoline in cars Sustainable , as the process may use all kind of waste and do not need to reduce agricultural aeras for food production.
Challenges

7.2.3 BTG

1. Objectives
Objectives of questionnaire: Collect available data on bio Jet A-1 production from the stakeholders plants Identify the strenghts and weaknesses associated to the bio Jet A-1 production processes

2. Key information on specific bio Jet A-1 production plant

Jet A-1 facility

Plant name		
Plant Location	town, country	
Start-up date	dd/mm/yy	

Facility type

Select the right facilty option

Lab-scale	
Pilot-scale	
Demonstration	
Commercial	

Time perspective - provide information on the expected time to commercialize your technology

Plant capacities & operation

Provide information on the facility characteristics in the table below. Further details could be given in the "Comments" field.

Biomass input	MW_biomass		*Based on Lower Heating Value*
Mean annual biomass input	GWh fuel/year		*Based on Lower Heating Value*
Mean annual biomass input	Tonnes/year		*Based on Lower Heating Value*
Jet A-1 production	L/Kg biomass		
Jet A-1 production	L/ year		
Electrical capacity	MW_elec		*Nominal design capacity*
Thermal capacity	MW_therm		*Nominal design capacity*
Biomass to fuels efficiency	%		*Based on energy*
Electrical efficiency	%		*Nominal gross electrical efficiency*
Thermal efficiency	%		*Nominal gross thermal efficiency*
Hours of operation per year	Hours/Year		
Land use	Km^2		*Area needed for plant and feedstock storage. Not relevant for lab-scale*

Comments (Please add further details here)

3. Feedstock - nature and size of the feedstock

Select the right feedstock option and specify the feedstock nature, particle size and water content within each category utilized. Further details could be given in the "Comments" field

	Feedstock used	Nature	Particle size, delivered to plant (cm)	Water content (wt. %)	Cost (euro/Kg)	Comments
Forest-based						
Agricultural-based						
Crops (Camellina, Jatropha)						
Macroalgae						
Microalgae						
Sugar cane						
MSW						

4. Technologies

Main technologies

Select the right applied technology and fill in the corresponding information in the tables below according to the selected technology.
Please specify the technology if the selected choice is "Others".

	Technology applied	Comments
HEFA		
Gasification - Fischer Tropsch		
Alcoho-to-Jet		
Fermented-Renewable-Jet		
Pyrolysis	Rotating cone	Fast pyrolysis process based on mechanical mixing of biomass and hot sand
Hybrid systems		
Others		

HEFA

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of reactor, temperature, pressure, catalyst, reactants, etc.)
Oil extraction		
Oil processing		
Oil refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Gasification - Fischer Tropsch

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of pre-treatment, reactors, temperature, pressure, catalysts, gasifying agent, reactants,etc.)
Pre-treatment		
Gasification		
Gas conditioning		
Acid Gas Removal		
FT		
Syngas refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Alcohol to Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (technology for alcohol production, temperature, pressure, catalysts, etc.)
Fermentation		
Dehydration		
Oligomerization		
Distillation		
Hydrogenation		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Fermented Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, etc.)
Engineered biochemical Fermentation (genetically engineered microbes)		
Aqueous phase reforming + conventional chemical processing		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Pyrolysis Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, carrier gas, etc.)
Pre-treatment	drying/sizing	10 wt% moisture; particles < 6 mm; heat for drying povided by pyrolysis process
Pyrolysis	fast pryrolysis	mechanical mixing; non catalytic
Char combustion	fluidized bed	part of pyrolysis process
Upgrading	HDO	Hydrotreatment at elevated pressure (~150-200 bar), 2 stage process, proprietry catalyst (PICULA™)
Technology patented by your company		patents/patent applications on pyrolysis process (owned by daughtercompany BTG Bioliquids BV), pyrolysis hydrotreatment process, and 1 stage HDO catalyst
Technology readiness level (TRL) *	4 - 6	Technology under development; next stage would be prototype demonstration

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Hybrid systems

Provide information on the hybrid systems technologies in the table below. Further details could be given in the "Technologies specifications" field,

		Technology specifications (combination of technologies, technology specifications as described above)
Combination of technologies		
Technology patented by your company		

5. Jet A-1 and by products

Jet A-1

Provide information on the characteristics of your Jet A1 produced. Use the "Comments" field for furter details.

		Comments
Energy content		
Density		
Production Cost		
Selling price		

Provide information if testing of your Jet A1 fuel has been carried out. Select the right testing option and use the "Comments" field for further details

	Comments
Laboratory	
Jet motor rig	
Test flight	
Commercial flight	

By-products

Provide information on the characteristics of the by-products from your Jet A1 production. Use the "Comments" field for furter details.
Costs - amount you have to pay to get rid of the by-product
Selling price - income for selling the by-product

Feed, chemicals and materials	Production (Kg/Year)	Density (Kg/L)	Cost (Euro/kg)	Selling price (Euro/kg)
Biochemicals				
Biomaterials				
Nutrients				
Residues				

Excess Energy	Production		Exported to external customer		Selling price (Euro/kWh)	Type customer
	MW	MWh/Year	MW	MWh/Year		
Heat						
Power						

Comments (Please add further details here)

6. Advantages and challenges associated to the applied technology
Provide information on the advantages and challenges associated to your technology (fuel flexibility, capital costs, funding, sustainability, GHG reduction, etc.
Advantages
Basically, fast pyrolysis can use any biomass feedstock/residue. The resulting oil is considered as 2nd fuel, no competition with food or land for food. (It may even improve economics of food production). GHG reduction calculations have been carried out for the chain biomass-kerosene/diesel and a 82-85% emission savings is obtained. Costs of kerosene by the pyrolysis route has been estimated: around 1300 eur/ton for a first plant decrasing to about 750 Eur/ton for a Nth plant
Challenges

7.2.4 Solena

1. Objectives
Objectives of questionnaire: Collect available data on bio Jet A-1 production from the stakeholders plants Identify the strenghts and weaknesses associated to the bio Jet A-1 production processes

2. Key information on specific bio Jet A-1 production plant

Jet A-1 facility

Plant name		Green Sky London
Plant Location	town, country	East London, United Kingdom
Start-up date	dd/mm/yy	2015 Q4

Facility type

Select the right facilty option

Lab-scale	
Pilot-scale	
Demonstration	
Commercial	X

Time perspective - provide information on the expected time to commercialize your technology

The project is in the Engineering and Planning & Permitting Stages. These two activities are being carried out in parallel and are forecast to be finalized by Q3 2013, at which time Financial closing of the project would be achieved. Thereafter, construction of the project begins (2013Q4), which lasts two years. The project would start up and commissioning during 2015Q4.

Plant capacities & operation

Provide information on the facility characteristics in the table below. Further details could be given in the "Comments" field.

Biomass input	MW_biomass	316	*Based on Lower Heating Value*
Mean annual biomass input	GWh fuel/year	2 528	*Based on Lower Heating Value*
Mean annual biomass input	Tonnes/year	563 136	*Based on Lower Heating Value*
Liquid Fuels production*	L/Kg biomass	0,260	
Liquid Fuels production*	L/ year	145 421 360	*Please see note below*
Electrical capacity	MW_elec	29,5	*Nominal design capacity*
Thermal capacity	MW_therm	*88,5*	*Nominal design capacity. In alternate configuration when no electric power is produced.*
Biomass to fuels efficiency	%	57,0%	*Based on energy (Not overall plant efficiency, which is 72.9%. Please note below)*
Electrical efficiency of power island	%	*See Note Below*	*Nominal gross electrical efficiency*
Thermal efficiency	%	*See Note Below*	*Nominal gross thermal efficiency*
Hours of operation per year	Hours/Year	8 000	
Land use	Km^2	0,10	*Area needed for plant and feedstock storage. Not relevant for lab-scale*

Comments (Please add further details here)

* Solena's Integrated Gasification BTL plant produces a total of 145.4 million liters of liquid fuels annually. This figure includes ***Synthetic Paraffinic Kerosene*** (59 million liters), ***clean diesel*** (56.9 million liters) and ***bionaphtha*** (29.5 million liters). The overall specific Liquid Fuels Production is thus ***0.26 Liters per kilogram of RDF***. In addition, in its standard configuration, the BTL produces ***renewable power*** (gross power output = 29.5 MW; net power output = 2.9 MW), thus making it a highly efficient, self-sustainable advanced biorefinery. Alternatively, the plant can be configured to maximize heat output in the form of steam, in which case the plant outputs 88.5 MWth of steam for industrial or heating applications (no power is produced in this scenario). In the latter scenario, the overall *GROSS* energy efficiency calculation, which includes *ALL* forms of energy produced (SPK + diesel + naphtha + steam) divided by *ALL* forms of energy input (RDF biomass + catalyst + small amount of natural gas + power). The sum of all energy inputs is 368.1 MW (thermal capacity) and the sum of all gross energy outputs is 268.6 MW, which yields a ***GROSS energy efficiency of 72.9%***. In table above, the 57% efficiency is calculated by dividing the energy content in the fuels (180.1 MW) by the energy content in the biomass input (316

3. Feedstock - nature and size of the feedstock

Select the right feedstock option and specify the feedstock nature, particle size and water content within each category utilized. Further details could be given in the "Comments" field

	Feedstock used	Nature	Particle size, delivered to plant (cm)	Water content (wt. %)	Cost (euro/Kg)	Comments
Forest-based	X					The project in Stockholm will utilize forestry residuals
Agricultural-based						
Crops (Camellina, Jatropha)						
Macroalgae						
Microalgae						
Sugar cane						
MSW	X	*See note*	5 cm ± 1cm	< 20%	*See note*	The feedstock used by the plant is RDF produced from MSW. Its price is commercially sensitive information that cannot be disclosed.

4. Technologies

Main technologies

Select the right applied technology and fill in the corresponding information in the tables below according to the selected technology.
Please specify the technology if the selected choice is "Others".

	Technology applied	Comments
HEFA		
Gasification - Fischer Tropsch	X	Solena's high-temperature plasma gasification technology in combination with microchannel Fischer-Tropsch process.
Alcoho-to-Jet		
Fermented-Renewable-Jet		
Pyrolysis		
Hybrid systems		
Others		

HEFA

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of reactor, temperature, pressure, catalyst, reactants, etc.)
Oil extraction		
Oil processing		
Oil refining		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Gasification - Fischer Tropsch

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (Type of pre-treatment, reactors, temperature, pressure, catalysts, gasifying agent, reactants,etc.)
Pre-treatment	N/A	The feedstock is pre-treated off-site and delivered to specifications.
Gasification	Solena Fuels	High-Temperature Plasma Gasification. O_2 injection, sub-stoichiometric conditions. No combustion
Gas conditioning	Alstom	SynGas cooling by Alstom.
Acid Gas Removal	Haldor Topsoe / UOP	Acid gas scrubbers and Selexol-Selectox process for Sulfur recovery. H_2 PSA membrane for H_2 sieving.
FT	Oxford Cat. / Velocys	Microchannel FT process by Velocys-Oxford Catalysts.
FT Product Refining	Undisclosed	FT wax is upgraded by an undisclosed technology partner.
Technology patented by your company	Solena Fuels	Solena owns patents to high temperature Plasma Gasification Vitrification of Organic Material
Technology readiness level (TRL) *		TRL 9

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Alcohol to Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (technology for alcohol production, temperature, pressure, catalysts, etc.)
Fermentation		
Dehydration		
Oligomerization		
Distillation		
Hydrogenation		
Technology patented by your company		
Technology readiness level (TRL) *		

*TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Fermented Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, etc.)
Engineered biochemical Fermentation (genetically engineered microbes)		
Aqueous phase reforming + conventional chemical processing		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Pyrolysis Renewable Jet

Provide information on the facility characteristics in the table below. Further details could be given in the "Technology specifications" field,

	Technology applied	Technology specifications (temperature, pressure, catalysts, carrier gas, etc.)
Pre-treatment		
Pyrolysis		
Char combustion		
Upgrading		
Technology patented by your company		
Technology readiness level (TRL) *		

*) TRL - http://en.wikipedia.org/wiki/Technology_readiness_level

Hybrid systems

Provide information on the hybrid systems technologies in the table below. Further details could be given in the "Technologies specifications" field,

		Technology specifications (combination of technologies, technology specifications as described above)
Combination of technologies		
Technology patented by your company		

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5. Jet A-1 and by products

Jet A-1

Provide information on the characteristics of your Jet A1 produced. Use the "Comments" field for furter details.

		Comments
Energy content	GJ/Tonne	45,5
Density	kg/L	0,773
Production Cost	$/Barrel	45 (without capex)
Selling price	$/Barrel	at market price for petroleum-based Jet fuel

Provide information if testing of your Jet A1 fuel has been carried out. Select the right testing option and use the "Comments" field for further details

	Comments
Laboratory	
Jet motor rig	
Test flight	
Commercial flight	

By-products

Provide information on the characteristics of the by-products from your Jet A1 production. Use the "Comments" field for furter details.
Costs - amount you have to pay to get rid of the by-product
Selling price - income for selling the by-product

Feed, chemicals and materials	Production (Kg/Year)	Density (Kg/L)	Cost (Euro/kg)	Selling price (Euro/kg)
Biochemicals				
Biomaterials				
Nutrients				
Residues				
Other	Please see note below about production of additional liquid fuel products			

Excess Energy	Production		Exported to external customer		Selling price (Euro/kWh)	Type customer
	MW	MWh/Year	MW	MWh/Year		
Heat	88,5	708 000	88,5	708 000	N/A	Industrial / District Heating
Power	29,4	235 200	2,6	20 800	0,18	National Grid

Comments (Please add further details here)

The Jet Fuel produced by Solena's BTL plant meets UK's ***DEF STAN 91-91*** Standard Specifications for Turbine Fuel, Aviation Kerosine Type, Jet A-1 and ***ASTM D7566*** Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. In addition, the Plant produces ***56.9 million Liters/year of clean diesel*** (energy content = 49.8 GJ/Tonne; Density = 0.776 kg/L) and ***29.5 million Liters/year of bionaphtha*** (energy content = 40.3 GJ/tonne; Density = 0.651 kg/L). The clean diesel meets ***ASTM D975*** Standard Specification for Diesel Fuel Oils.
As noted in the key info tab, the BTL plant can be configured for power production, in which case the plant produces 29.5 MW, OR for steam production (in which case the plant outputs 88.5 MW of steam but zero power).
The BTL plant's by products include slag (inert vitrified basaltic glass, approx. 1 tonne/hr. - feedstock dependant) and sulfur (in sulfuric acid or sulfur cake form).

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Advantages and challenges associated to the applied technology

Provide information on the advantages and challenges associated to your technology (fuel flexibility, capital costs, funding, sustainability, GHG reduction, etc.

Advantages

Solena Fuels Corporation is a global sustainable fuel company building a platform for the production of price competitive, certified, drop-in liquid jet and diesel fuels with the flexibility to use a variety of waste biomass feedstocks, including urban, agricultural, and forest waste. Solena is considered an industry leader and top choice for many of the world's leading airlines as a producer of biojetfuel with a number of projects in development around the world: British Airways – London, Qantas - Sydney, SAS - Sweden, Alitalia – Rome, Lufthansa - Germany, and the U.S. (a consortium of 10 airlines led by American, FEDEX and United Continental). Solena is participating in the Qantas – Shell led Gryphon Study advising the Australian Government on how to establish a biofuel industry.

List of Advantages:

Strong BTL plant Economics enables Solena to offer sustainable transportation fuel at competitive prices to petroleum-based fuel.

Jet fuel FT derived synthetic biofuel is certified for use in the Aviation Industry by the United States Air Force and by the Federal Aviation Administration and is specifically covered by a new ASTM standard for Alternatives to conventional Aviation Fuel containing Synthesized Hydrocarbons D-7665. This specification allows up to a 50 % blend of FT fuel with conventional Jet A. No testing, changes to fuel infrastructure or engine modifications necessary.

Ultra clean synthetic sustainable FT fuels, helps reduce green house gas and eliminate SO_2 in transportation emissions addressing energy and environment concerns in addition to negligible particulate matter content. The industry accepted fuel meets and exceeds ETS standards based on both Roundtable on Sustainable Biofuels (RSB) schemes and Renewable Energy Directive (RED) methodology for Life Cycle Analysis (LCA) evaluation and is not connected to food and land/ indirect land use issues.

Feedstock Flexibility Secures Sustainable Supply Chain; Solena's technology can use a wide range of low-cost, carbon-bearing materials (like residential and industrial waste) mixed with forestry and agricultural residuals which provides long term feedstock availability.

High Temperature Plasma Gasification is to date the only existing technology which successfully can gasify a mixture of feedstock including household waste because of the system tolerance to the variations in the feedstock energy values. With one of the highest energy conversion efficiency in the industry, the Solena plasma gasification/ depolymerization process has proven to be an economically viable, as well as less expensive than any other thermal process.

The gasification process is environmentally benign, no toxic waste by-products or emissions.

Best in Class Technology Partners. Solena Fuels spent over six years integrating its patented gasification technology into a proprietary BTL design. Extensive technical work has been performed to finalize Solena's preferred technology providers, which include Velocys Inc. (Fischer-Tropsch (FT) system), Oxford Catalysts Group (FT catalysts), GE (power island), Honeywell International (controls and instrumentation), and other top-tier global technology providers.

Industry Accepted Technologies. The project utilizes a combination of gasification, FT processing, FT upgrading, and power gen systems derived from technologies presently in commercial-scale use and successfully operating for decades.

Premier Engineering Partner. The Company is partnering with Fluor Corp. to perform pre-FEED (Front-End Engineering and Design) and FEED services for the Project, working toward a fully-wrapped, guaranteed max-price, performance-guaranteed EPC contract.

Binding Commitments and Co-Development; Fully-executed, binding agreements with BA, including a 10-year take-or-pay off-take for 100% of the jet fuel produced by GreenSky London in addition to advanced negotiations for multiple long term bankable fuel purchase agreements with credit worthy top aviation and shipping industry players.

Challenges

Still limited governmental support and incentives for sustainable aviation fuel in many countries in spite of IATA' s commitment to support biofuels by all its members. The preferred choice is incineration of urban waste as the primary waste handling method in spite of the many problems connected to incineration such as toxic emissions. The structural preference for incineration restricts the availability of residential and industrial waste.

7.3 Characteristic data

7.3.1 Hydroprocessed Esters and Fatty Acids

	Study/Case	Mathew et al 2007 [23]	
	Study case description	Converts vegetable oils into Butane, Pentane, Naptha, Jet and Diesel through hydroprocessing process	
	Boundary conditions	Vegetable oils input 999882 (tonnes/year) and	
	Sub processes	The sub process steps are hydrotreatment or hydrodeoxygenation, Isomerizer &catalytic cracking and sepration process	
	Feedstock (nature)	**Vegetable oils**	
		Mass flow	**Energy**
Feedstock	Vegetable oil feedstock input (tons/year)	999882 (tonne/year)	1000 MWth
	Jet A1 production (liter/year)	53622 kL/year	
Jet A1	Jet A1 density (kg/l)	0,804 kg/l	
	Operating hours per year	8000	
Other products	Component	**C4-C5**	
	Production	9456 kL /year	8 MW *
	Component	**Naphtha**	
	Production	8344 kL/year	9.77 MW *
	Component	**Jet**	
	Production	53622 k-L/year	54.77 MW *
	Component	**Diesel**	
	Production	281423 kL year	310 MW *
	Total Production of other products	**352846 kL per year**	382 MW *
Energy	Req input of external electricity		
	Power production		
	Electricity export		
	Heat export (excess heat)		
	Yield of Jet A1 produced (liters/vegetable oil)		
Energy Efficiencies	Energy efficiency, Biomass, jet A1		**6 %**
	Energy efficiency, Biomass, Liquid		**38 %**
CAPEX		**Description**	
	Reference year		2010
	First planth or nth plant		
	Processing step 1 (description, CAPEX)	Hydrotreater	13.34 MUSD
	Processing step 2 (description, CAPEX)	Isomerizer	40.023 MUSD
	Processing step 3 (description, CAPEX)	Saturated gas plant	13.34 MUSD
	Processing step 4 (description, CAPEX)	storage and cooling water system	13.34 MUSD
	Processing step 5 (description, CAPEX)	Offsite green field	40.023 MUSD
	Processing step 6 (description, CAPEX)	Onsite hydrogen production on site	40.023 MUSD
		Other costs	35 MUSD
	Total fixed capital investement	total plant cost for 6500 BPD	195 MUSD

* The energy balances are calculated based on a typical HHV for the vegetable oils (32.5 MJ/l)

Reference:

Matthew N Pearlson, Technoeconomic and environemntal assessment of Hydroprocessed distillate fuels, MIT Thesis, 2011

7.3.2 Fischer-Tropsch

Ekbom et al - 2009 [44]		NREL - Swanson et al 2010 [45]		Kei Yamashita et al., 2004 [43]		Kei Yamashita et al., 2004 [43]		Kei Yamashita et al., 2004 [43]	
Converts biomass into bio-jet fuel through gasification of biomass, Fischer Tropsch synthesis and upgrading		Converts biomass into liquid transportation fuel through high-temperature gasification of biomass,		Convert biomass into heavy FT crude and light FT crudes		Convert biomass into heavy FT crude and light FT crudes		Convert biomass into heavy FT crude and light FT crudes	
Biomass input: 864000 tons/year wood chips, 50% moisture. Production of 50 kton/year bio-jet fuel on site. Recovery of low-grade heat for industrial and district heat use. Export of excess heat.		Biomass input: 14880000 tons/year (dry), 25 % moisture. Production of diesel and gasoline, with methane and LPG as co-products. Export of excess electricity. **No Jet A1 production.**		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**		Biomass input: 623049 tonnes per year wood residues, **No Jet A1 production**	
Pretreatment, gasification, gas cleaning and conditioning, Fischer-Tropsch synthesis, HPC and distillation, Power and steam production, air separation		Pretreatment, gasification, gas cleaning and conditioning, Fischer-Tropsch synthesis, Hydroprocessing, Power generation, air separation		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,		Pretreatment, gasification, gas cleaning and conditioning (water ags shift), Fischer-Tropsch synthesis, combined cycel power generation,	
chipped wood biomass and wood residues		**Corn stover**		**wood**		**wood**		wood	
Pressurized Fluidized Bed (Andritz/Carbona)		Entrained flow gasifier		BCL (Circulating fluidized bed) Indirect gasification		IGT(Bubbling fluidized bed)Directly oxygen		TPS (Bubbling fluidized bed)Directly air	
Mass flow	**Energy**		**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**
864000 tons/year (50% moisture)	289 MWth	14880000 (dry)	389 MWth	623049	430 MWth	623049	430 MWth	623049	430 MWth
62,2 million liters/year	74,8 MW	0	-	-	-	-	-	-	-
0,804 kg/l		-	-	-	-	-	-	-	-
8000		7440		7440		7440		7440	
Heavy diesel + UCO	754 kg/m3, 930 kg/m3	**Diesel (hexadecane)**		**heavy FT Liquids (C10-C19 chains)**		**heavy FT Liquids (C10-C19 chains)**		**heavy FT Liquids (C10-C19 chains)**	
21,4 kton/year	32,2 MW	61,67 wt%							
Naphta	687 kg/m3	**Gasoline**		**Light FT liquids (C5-C10 chains)**		**Light FT liquids (C5-C10 chains)**		**Light FT liquids (C5-C10 chains)**	
17,9 kton/year	27,9 MW	26,1 wt%							
		LPG							
		8,77 wt%							
		Methane							
		3,46 wt%							
39,3 kton/year	60,1 MW	100 wt%	193,2 MW		66.7 MW		78.8 MW		78.8 MW
	21,2 MW		22,06 MW		self produced		self produced		self produced
	19,4 MW		35,88 MW		40.4 MW		34.4MW		34.4MW
	need 1,8 MW		13,8 MW						
istrict heat, 5000 h/yea	96,9 MW		0		0		0		0
iomass)	143.98	0	0		-		-		-
		34 %		34 %		34 %		34 %	
	25 %		0		-		-		-
	46 %		49 %		16 %		18 %		18 %
	79 %		52.50 %		39.02 %		38.32 %		23.45 %
Description		**Description**		**Description**		**Description**		**Description**	
	sep.2009		2007		corrected to 2010		corrected to 2010		corrected to 201
	b)		nth		nth		nth		nth
Preprocessing		Preprocessing	23 MUSD	Pretreatment	21.67 MUSD	Pretreatment	21.700	Pretreatment	21.7 MUSD
Gasification plant	03 MSEK (176 MUSD)	Gasification plant	68 MUSD	Gasification plant	17.200	Gasification plant	74.000	Gasification plan	74 MUSD
Gas cleaning & conditioning	535 MSEK (81 MUSD)	Gas cleaning	34 MUSD	Gas cleaning	28.010	Gas cleaning	28.000	Gas cleaning	28 MUSD
FT-plant	156 MSEK (175 MUSD	FT-plant	49 MUSD	water gas shift (Gas conditioning)	12.380	water gas shift (Gas conditioning)	7.700	water gas shift (Gas conditioning)	7.7 MUSD
Boiler and steam turbine plant	284 MSEK (43 MUSD)	Power generation	46 MUSD	FT reactor	32.050	FT reactor	40.200	FT reactor	40.2 MUSD
		Hydroprocessing	33 MUSD	FT Upgrade	20.122	FT Upgrade	20.100	FT Upgrade	23.100
Air separation plant	178 MSEK (27 MUSD)	Air separation plant	24 MUSD	Air separation plant	-	Air separation pla	40.2MUSD	Air separation pl	-
				Compressor	22.440	Compressor	20.100	Compressor	26.3 MUSD
	794 MSEK (120 MUSD)		33 MUSD	Power geenration	77.440	Power geenration	92.900	Power geenratio	92.900
	4070 MSEK (618 MUSD		310 MUSD		232MUSD		308 MUSD		256 MUSD

a) In-house estimate which includes utility feedstocks and off-sites comprising land and buildings, roads and pipelines and centrals and lines for electricity, water etc.

b) Except for the biomass gasification technology which has not been demonstrated at large scale for synthesis gas production, only proven and commercially available technology has been incorporated in the chosen plant configuration.

c) 14 September 2012: 100SEK = 15,17 USD

References:

Värmeforsk: Pilot study of Bio-jet A1 fuel production for Stockhol Arlanda Airport, ISSN 1653-1248, 2009

Swanson et al: Techno-Economic Analysis of Biofuels production based on gasification, NREL/TP-6A20-46587, November 2010

Kei Yamashita et al., 2004 Biomass gasification for the coproduction of Fischer-Tropsch liquids and electricity, Interim report, IR-04-047, www.iiasa.ac.at

7.3.3 Alcohol-to-Jet

	Study/Case	Humbird et al 2011 [69]		Dutta et al 2012 [70]		Pham et al 2010 [71]		Phillips et al 2011 [72]	
	Case description	Converts corn stover to ethabol by dilute-acid pretreatment, enzymatic saccharification, and co-fermentation and modification posibilites to jet via Ethanol		Converts lignocellolosic biomass to ethanol and a higher alcohols coproduct via indirect gasification, followed by gas-to-liquid synthesis.		Converts biomass feedstock into liquid fuels (gasoline and jet fuel) through fermentation, hydrogenation to mixed alcohols, and further conversion to		Converts biomass feedstock into gasoline through biomass gasification, methanol synthesis and MTG technologies	
	Boundary conditions	Biomass input: 700 830 tons/year (dry) corn stover. Product: Ethanol.		Biomass input: 700 830 tons/year (dry), 35 wt% moisture. Production of ethanol with higher alcohols as coproduct. **No Jet A1 production.**		Biomass input: 320 000 tonnes/year (dry). Production of gasoline and jet fuel. Self sufficient in hydrogen		Biomass input: 700500 tons/year (dry), wood chips, 50 wt% moisture. Production of gasoline with LPG as co-products. **No Jet A1 production**. Self	
	Sub processes	Feed handling, pretreatment and conditioning, enzymatic hydrolysis and fermentation, cellulase enzyme production, product recovery, wastewater treatment, storage, steam		Feedstock handling and drying, gasification, gas cleanup, alcohol synthesis, alcohol separation, steam and power generation, cooling water and utilities		Pretreatment with lime, fermentation, dewatering, thermal conversion, hydrogenation of ketones to mixed alcohols, oligomerization of alcohols to hydrocarbons		Feedstock preparation, Biomass gasification, syngas cleanup, methanol synthesis, MTG process, gasoline separation and finishing processes, power generation.	
	Feedstock (nature)	**Corn stover**		**Southern pine wood**		**Sorgum (energy crops)+ chicken manure (80:20)**		**Hybrid poplar wood chips**	
		Mass flow	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**	**Mass flow**	**Energy**
Feedstock	Biomass input (tons/year)	700 830 (dry)	364 MWth	700 830 (dry)	430 MWth	320000 (dry)	200 MWth	700500 (dry)	433 MWth
Jet A1	Jet A1 production (liter/year)	0		0	-	19 gallons/tonne biomass (daf)	Jet fuel	0	-
	Jet A1 density (kg/l)			-	-	-		-	-
	Operating hours per year	8410		8410		8000		8406	
Other products	Component	**Ethanol**		**Ethanol**		**Gasoline**		**Gasoline**	
	Production	0.2601 kg/kg feedstock		0,3189 kg/kg dry feedstock		62 gallons/tonne biomass (daf)		229.9 l/tonne dry feedstock	
	Component	**Heavy diesel**		**Higher alcohol products**				**LPG**	
	Production	0.26 kg/kg feedstock		0,0415 kg/kg dry feedstock				38.8 l/tonne dry feedstock	
	Component	**Jet A1 yield**							
	Production	0.116 kg/kg feedstock							
	Total Production of other products								
Energy	Req input of external electricity		0		self sufficient				self sufficient
	Power production		0						self sufficient
	Electricity export		0.923 kWh/liter		0				0
	Heat export (excess heat)								0
Other input	Nature	Enzymes				lime		Catalysts	
	Mass flow (kg/liter)	0.048864562				0,023 g CaO/g biomass			
	Nature	Sulfuric acid							
	Mass flow (kg/liter)	0.156130157							
	Nature	Ammonia							
	Mass flow (kg/liter)	0.082833314							
	Nature	Corn steep liquor							
	Mass flow (kg/liter)	0.091266392							
	Nature	Diammonium phosphate							
	Mass flow (kg/liter)	0.011191561							
	Nature	Natural gas							
	Mass flow (kg/liter)	0.143835203							
	Nature	Sodium Hydroxide							
	Mass flow (kg/liter)	0.1774887							
	Nature	Lime							
	Mass flow (kg/liter)	0.07053836							
Efficiencies	Carbon conversion efficiency							Ceff to liquid	31 %
Energy Efficiencies	Energy efficiency, Biomass, jet A-1		29 %		0				0
	Energy Efficiency (Biomass to desired product)			Ethanol	40 %			Gasoline	37.70 %
	Energy Efficiency, Biomass, liquid				45 %			Gasoline + LPG	42.60 %
	Energy efficiency, biomass, total		32 %						
CAPEX		**Description**		**Description**		**Description**		**Description**	
	Reference year		2007		2007				2007
	First planth or nth plant		nth		nth				nth
	Processing step 1 (description, CAPEX)	Stover Handling	$24 200 000	Feed handling	$18700000			Feed Handling and Preparation	$25 000 000
	Processing step 2 (description, CAPEX)	Dilute Acid Pretreatment	$32 900 000	Gasification	$12600000			Gasification	$14 600 000
	Processing step 3 (description, CAPEX)	Enzymatic Hydrolysis and	$31 200 000	Gas clean up	$34700000			Tar Reforming, Quench, and	$27 400 000
	Processing step 4 (description, CAPEX)	Ethanol Separation/Purifi	$22 300 000	Alcohol synthesis	$13200000			Acid Gas and Sulfur Removal	$12 100 000
	Processing step 5 (description, CAPEX)	Ethanol Dehydration	$31 800 000	Alcohol separation	$25800000			Methanol synthesis - compression	$10 500 000
	Processing step 6 (description, CAPEX)	Ethylene Oligomerization		cooling water and utilities	$4600000			Methanol conditioning/degassing	$4 800 000
	Processing step 7 (description, CAPEX)	Olefin Hydrogenation and Product Fractionation						MTG process	$21 600 000
	Processing step 8 (description, CAPEX)	Wastewater Treatment	$49 400 000						
	Processing step 9 (description, CAPEX)	Steam and Electricity Gen	$66 000 000					Steam System & Power Generation	$23 100 000
	Processing step 10 (description, CAPEX)	Utilities and Storage	$11 900 000					Utilities	$5 900 000
		Economic and technological uncertainty	low to high	Economic and technological uncertainty	30 %			Economic and technological uncertainty	medium
	Total purchase equipment cost (TPEC)		$269700000		$149720048	Fixed capital investment	$ 131 000 000	Total Installed equipment cost	$145 000 000

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References:

Humbird *et al.*, Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol, NREL/TP-5100-47764, May 2011.

Dutta, A., M. Talmadge, et al. (2012). "Techno-economics for conversion of lignocellulosic biomass to ethanol by indirect gasification and mixed alcohol synthesis." Environmental Progress & Sustainable Energy 31(2): 182-190.

Pham, V et al. (2010), Techno-economic analysisi of biomass to fuel conversion via the MixAlco process", J Ind Microbiol Biotechnology 37:1157-1168

Phillips *et al.*, Gasoline from Wood via Integrated Gasification, Synthesis, and Methanol-to-Gasoline Technologies. NREL/TP-5100-47594, January 2011.

7.4 Energy efficiencies - definitions

- Energy eff, biomass, Jet A-1 – Biomass input to Jet A-1 output
- Energy eff, biomass, liquid – Biomass input to all liquid output
- Energy eff, biomass, total – Biomass input to all liquid + heat export + electricity export
- Energy eff, Jet A-1 – All energy input to Jet A-1 output
- Energy eff, liquid - All energy input to liquid output
- Energy eff, total - All energy input to all liquid output + heat export + electricity export

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