ALTERNATE

D3.2 – Alternative Fuel Pathway Selection

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Abstract

The present document corresponds to the deliverable D3.2 of the ALTERNATE project, Alternative Fuel Pathway Selection. It provides an overview of available fuel conversion technologies for the production of sustainable aviation fuels, and the selected pathways by the European and the Chinese partners for further examination under ALTERNATE WP3.

Keywords

Sustainable aviation fuels, biomass, biofuels, conversion pathways

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Acronyms and Terminology

Term	Definition
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-jet
CEF	CORSIA Eligible Fuels
CHJ	Catalytic Hydrothermolysis Jet
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
FT	Fischer-Tropsch
GHG	Greenhouse Gas Emissions
HEFA	Hydroprocessed Esters and Fatty Acids
ICAO	International Civil Aviation Organization
LCA	Life Cycle Assessment
SAF	Sustainable Aviation Fuels
SPK	Synthesized Paraffinic Kerosene
SPK/A	Synthesized Paraffinic Kerosene with Aromatics

1. Introduction

Aviation industry is a major contributor to the global economy with 42 million jobs, and an economic impact of €1.4 trillion.[1] The COVID-19 pandemic is currently significantly impacting the aviation sector, but the long-term growth forecasts remain high.[2] Aviation is responsible for approximately 3% of the total anthropogenic CO_2 emissions.[3] Adding up other flight emissions, like different nitrogen oxides (NO_x), particles and water vapor, the total climate impact reaches approximately 5% of total anthropogenic radiative forcing (RF).[4] Having no commercially available alternatives to current-technology aircraft such as solar or electric aircrafts, international aviation is bound to be mostly dependent on liquid hydrocarbons by 2050. Meanwhile, the aviation industry is forced to keep global greenhouse gas (GHG) emissions from international flights at 2020 levels, in line with the environmental goals set by the International Civil Aviation Organization.[5] To achieve this, ICAO Member States have agreed on developing the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and the Committee on Aviation Environmental Protection (CAEP) within ICAO has developed specific measures.[6] One of the measures to reduce GHG emissions from aviation under CORSIA is the deployment of sustainable aviation fuels (SAF) from biomass feedstocks to be used as "drop-in fuels", i.e. fuels that can be used without any modifications to the aircraft or the infrastructure. However, research is underway to find more efficient and cost-effective technologies to produce SAF, since there is a large price gap between petroleum-based jet fuel and SAF. Given that fuel costs constitute around 20% of an airline's operating cost [7], there is also a clear need for policy support to make SAF price competitive.

International standards for aviation turbine fuels (Jet A and Jet A1) are determined by the American Society for Testing and Materials (ASTM) International. However, the Standard Specification for Aviation Turbine Fuels, ASTM D1655[8], is not sufficient for jet fuel that contains synthetic hydrocarbons from non-conventional sources (e.g. sustainable aviation fuels). Consequently, candidates for SAF are subjected to the ASTM D4054 Evaluation Process[9] "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives" before they are granted an Annex in D7566 "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons".[10] Once a fuel receives D7566 specification it can be re-designated as D1655 aviation turbine fuel and regarded as such.

The ASTM D4054 evaluation is a two-phase process consisting of 9 individual steps.[11] After each phase the data gathered for the candidate fuel is reviewed by the Original Equipment Manufacturers (OEM). The fuel must be found to be fit for purpose (FFP) for use in aircraft engines by the OEM before going further for the Federal Aviation Administration's (FFA) approval and ASTM Balloting Process. To guide the fuel producers through this iterative and lengthy OEM Review Process, FAA established the D4054 Clearinghouse under its Center of Excellence for Alternative Jet Fuels and Environment (ASCENT) program.[12] The D4054 Clearinghouse expedites the OEM Review procedure managing the testing of the candidate fuel in 6 stages. This fast-track Annex reduces the testing time and expenses while maintaining the safety of the overall procedure.

As of December 2020, there are seven drop-in fuels authorized as annexes to the ASTM D7566.[13] The most recent authorization, Annex 7, was reviewed under the D4054 Clearinghouse Fast-Track Annex, while the other six followed the regular ASTM D4054 procedure. Additionally, co-processing is added as an Annex A1 to ASTM D1655, which is the Standard Specification for

Aviation Turbine Fuels. These 8 pathways are listed in Table 1 with the corresponding maximum blending ratios with petroleum-based jet fuel.

Table 1. List of ASTM approved pathways with potential feedstocks.

ASTM reference	Year of certification	Conversion pathway	Feedstock type	Blend ratio by volume
D7566 Annex 1	2009	*FT-SPK*: Fischer-Tropsch synthetic paraffinic kerosene	Coal, natural gas, biomass	50 %
D7566 Annex 2	2011	*HEFA-SPK*: Hydroprocessed esters and fatty acids synthetic paraffinic kerosene	Fats, oils and greases	50 %
D7566 Annex 3	2014	*HFS-SIP*: Hydroprocessed fermented sugars to synthetic isoparaffins	Sugars	10 %
D7566 Annex 4	2015	*FT-SPK/A*: Fischer-Tropsch synthetic paraffinic kerosene with aromatics	Coal, natural gas, biomass	50 %
D7566 Annex 5	2016	*ATJ-SPK*: Alcohol to jet synthetic paraffinic kerosene	Sugar/starch producing feedstocks and cellulosic biomass	50 %
D1655 Annex 1	2018	Co-processing	Fats, oils and FT Biocrude	5 %
D7566 Annex 6	2020	*CHJ*: Catalytic hydrothermolysis synthesized kerosene	Fats, oils and greases	50 %
D7566 Annex 7	2020	*HC-HEFA-SPK*: Hydroprocessed hydrocarbons, esters and fatty acids synthetic paraffinic kerosene	Bio-derived hydrocarbons and lipids (Algae)	10 %

A technology approved under ASTM can be used as a blend with conventional, petroleum-derived jet fuel up to the blending limit.

With regard to international aviation, additional sustainability criteria were set under CORSIA in an effort to specify those fuels that deliver potential environmental benefits. A CORSIA eligible fuel (CEF) was defined as a SAF that provides at least 10% GHG emissions reduction compared to conventional aviation fuel.[14] Another prerequisite is that the biomass used for a CEF should not be produced in land with high carbon stocks, in order to mitigate GHG emissions from direct land conversion or land use change (LUC). Further GHG emissions arise from market-mediated land substitution across uses, what is known as induced land use change (ILUC). For the selection of biomass feedstocks and jet fuel production pathways with lower GHG emissions, CAEP has developed specific methodologies for calculating life cycle emission values (LS_f) for SAF, including emissions from ILUC. Currently, this includes 16 different feedstocks for the various production pathways considered. There is no obligation for airlines to only use "CORSIA-eligible fuels". However, if an airline uses an ASTM approved fuel that is not CORSIA-eligible, then a claim cannot be made towards the reduction of CO_2 offsetting requirements due to the use of that fuel.

2. ALTERNATE Objectives

As discussed in the introduction, the availability and utilization of SAFs are essential to reach the environmental goals set for international aviation. However, these fuels are not yet produced in volumes sufficient to meet the expected demand. Currently, there are only two commercial-sized facilities worldwide dedicated to the production of sustainable aviation fuels, the World

Energy (formerly AltAir) fuel refinery in USA California, and Neste oil Porvoo plant in Finland. It has to be noted that the Neste oil plant only does batch-wise production. However, currently there is significant investment being made into SAF[15], and existing and planned renewable diesel production can also partially be levied for SAF production.

ALTERNATE aims to enlarge the aviation sustainable fuel framework in both technical and economic areas, starting with the possible use of more feedstocks and sustainable production pathways than the existing ones. Within WP3, our aim is to evaluate the environmental effects of these feedstocks and fuel production pathways using a globally harmonized Life Cycle Assessment (LCA) approach. Ultimately, a catalogue of feasible feedstocks/pathways for the 2020-2050 period will be prepared. This will help underline the potential environmental benefits from SAFs and contribute to their widespread use in the future.

This deliverable includes an assessment of the ASTM approved SAFs and their state of the art in the EU and China. In the final section, selected pathways for life cycle assessment for Task 3.4 will be listed.

3. Pathways

Petroleum-based jet fuel is a mixture of n-alkanes, isoalkanes, cycloalkanes and aromatics. Synthetic paraffinic kerosene (SPK) is similar in molecular composition to petroleum-based jet fuel. However, it lacks the aromatic components which are required to ensure the swelling in aircraft components and prevent fuel leaks. As a result, SPKs have been certified for use up to a certain percentage to maintain minimum aromatic content in the jet fuel blend.[16]

Below are the drop-in fuels from Table 1 that are qualified for commercial use through the D4054 process, and received the ASTM D7566 certification. Details of the conversion processes and type of feedstocks use are provided.

3.1. Fischer-Tropsch (FT) SPK

FT synthesis is a process developed in the 1920s that converts synthesis gas (syngas) into a mixture of hydrocarbons at moderate temperatures using metal-based catalysts. SPK produced with this process could be blended with petroleum-based jet fuel up to 50% by volume. Other fuel co-products from this pathway may include diesel and naphtha.

Pathway details:

FT pathway starts with the gasification of a feedstock to produce syngas. Gasification is a mature technology and any carbon source can be utilized as feedstock.[17] Coal, natural gas, and biomass are among the common feedstocks used for gasification. Among biomass feedstocks, lignocellulosic biomass (e.g., agricultural residues, forest residues, perennial energy crops) is promising since it is abundant and cheaply available. However, due to the variability in the carbon content of different biomass resources, the efficiency of the FT reaction can be affected making the whole process more complex. This is why only pilot and demonstrative FT plants based on biomass exist to date, while commercial facilities currently employ coal and natural gas.[18]

Biomass feedstocks need to be pretreated prior to gasification in order to reduce particle size and moisture content. Gasification takes place at high temperatures with limited amounts of oxygen, and consequently syngas is produced. Syngas is a mixture of CO and H_2, but raw syngas contains other gases such as CO_2 and CH_4 in small amounts. Syngas produced from biomass is generally inferior in quality since it has higher impurity and oxygen content. High oxygen content can result in lower H_2/CO ratio than required for the FT reaction. Syngas from biomass may also contain impurities such as NO_x and SO_x gases, char, etc., which can poison and deactivate the FT catalysts resulting in a reduced efficiency. These impurities should be removed, and the H_2/CO ratio has to be adjusted before the FT synthesis.

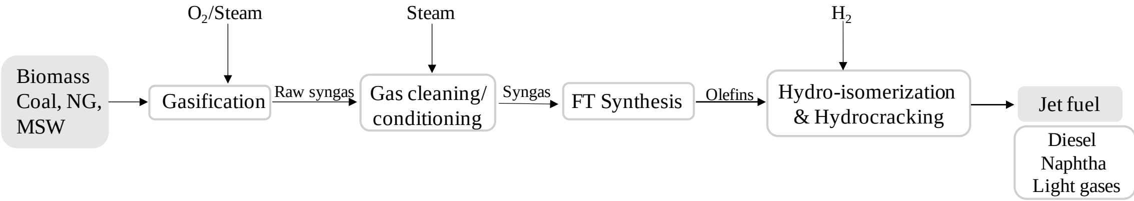


Figure 1. General process scheme for Fischer-Tropsch pathway.

The cleaned syngas is subsequently compressed and sent into the FT reactor for the synthesis of small chain olefins. FT synthesis takes place at moderate temperatures between 200°C to 350°C using a metal-based catalyst (e.g. iron, cobalt, nickel, etc.). The distribution of liquid hydrocarbon products depends on the composition of syngas, reaction conditions, type of catalyst and FT reactor used. After the synthesis, conventional refinery processes such as hydrocracking, hydroisomerization and fractionation processes are necessary to obtain the finished jet fuel mixture. This jet fuel would have a low aromatics content and almost negligible sulphur content.

FT fuels from agricultural and forestry residues, municipal solid waste, poplar, miscanthus and switchgrass are among the CORSIA eligible fuels. The calculated LS_f values for these fuels range between -22 gCO_2e/MJ and 8.3 gCO_2e/MJ fuel[19], much lower than the emissions from petroleum-based jet fuel (89 gCO_2e/MJ), showing the potential benefits of using FT fuels. However, the technical difficulties in the processing of biomass, along with the high capital needed for the construction and operation of these facilities, make the commercialization of this pathway harder.

3.2. Hydroprocessed esters and fatty acids (HEFA) SPK

HEFA is a highly mature and commercially available conversion technology that provides the largest share of commercial SAFs produced today. Lipidic feedstocks such as plant oils, waste oils and algal oils are used as feedstocks for the HEFA pathway, and are converted into a synthetic jet fuel blend composed of paraffins. Over the years, successful flight trials have been carried out by major airlines using HEFA fuels from jatropha, camelina, used cooking oil, and others.[20] HEFA fuels can be blended with petroleum-based jet fuel up to 50% by volume.

Pathway details:

The HEFA process produces paraffin-rich, straight chain hydrocarbon liquids from the triglyceride molecules in the lipid feedstock. The first step for the upgrading of lipid feedstock into jet fuel is hydrogenation, which is the catalytic addition of hydrogen to saturate the double bonds of the lipid chain. Hydrogen addition is also used to remove the carbonyl group and to break the glycerol compound, forming propane and chains of free fatty acids (FFA).[21]

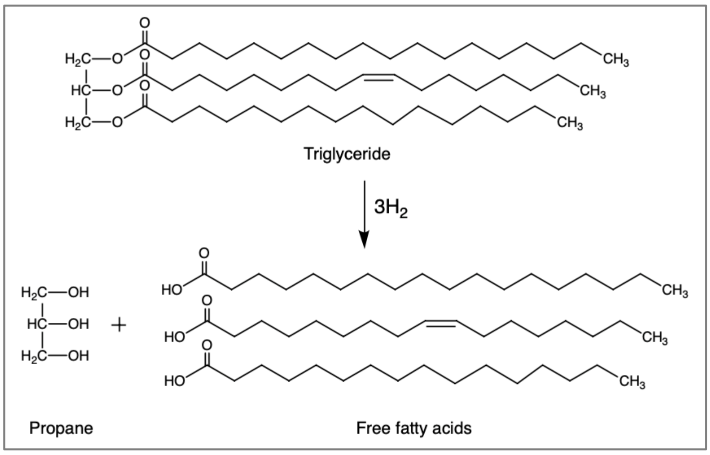


Figure 2. Conversion of triglycerides into free fatty acids.

After this, the carboxylic acid that remains attached to the FFA has to be removed, and this can be done in three different ways: hydrodeoxygenation, decarboxylation and decarbonylation. Finally, hydro-isomerization and hydrocracking are required to improve the biofuel qualities (e.g. better cold flow properties), and to adjust the product slate. The chain length of the triglycerides from vegetable oils is mostly within the diesel range.[22] Therefore, additional hydrocracking is needed to obtain jet fuel range hydrocarbons. As a result, jet fuel is produced along with co-products such as diesel, naphtha and light gases. The product slate can be adjusted according to market needs.

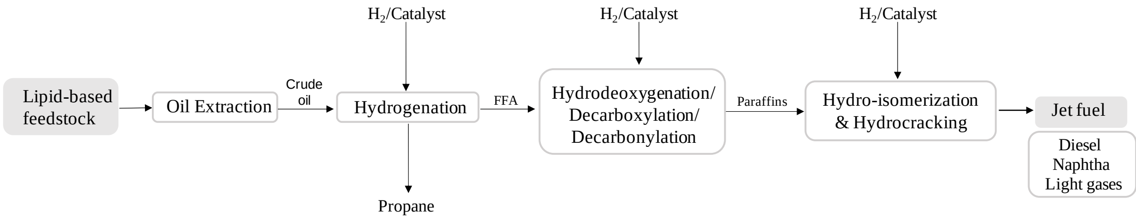


Figure 3. General process flow for the HEFA pathway.

The fatty acid profile of the lipidic feedstock is important for the HEFA process since the amount of unsaturated fatty acids would determine the hydrogen supply of the process. The chain length of the feedstock is also important. Higher chain length fatty acids would need more hydrocracking which would result in the production of more co-products. If the hydrocracking amount is not adjusted well, the process will give lighter range products like propane mix (C_1-C_4) and naphtha (C_5-C_8), which are less valuable than diesel and jet fuel (C_9-C_{15}).[22] Overall, these factors will affect the minimum selling price for the HEFA jet.

SINOPEC, China Petrochemical Corporation, produced and tested jet fuel from vegetable oils and animal fats. The final yield of jet biofuel, with a freezing point lower than -48 °C, can reach to 35%-45% with 7%-11% diesel and 23%-29% naphtha.[23]

HEFA fuels from tallow, used cooking oil, palm fatty acid distillate, corn oil, soybean oil, rapeseed oil, and palm oil are among the CORSIA eligible fuels. Calculated LS_f values for these fuels range between 13.9 gCO_2e/MJ (used cooking oil) and 76.5 gCO_2e/MJ fuel (palm oil).[19]

3.3. Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)

The HFS-SIP pathway (also known as direct sugars-to-hydrocarbons), developed by Amyris Inc., involves the fermentation of sugars from crops such as sugar cane, sugar beet, starches, and lignocellulosic biomass into farnesene ($C_{15}H_{24}$). Farnesene is a hydrocarbon with chain length in the jet fuel range, which is then upgraded into farnesane ($C_{15}H_{32}$) to be used in up to 10% blends by volume with petroleum-based jet fuel.

Pathway details:

The first step for this conversion pathway is pretreatment, which is the extraction of sugars from the biomass by enzymatic hydrolysis. Concentrated sugars are then converted into the intermediate, farnesene, by fermentation. Process residues from the pretreatment step (e.g. bagasse, pulp, etc.) can be utilized to provide energy for the system, and the excess could be converted into electricity. This pathway is different from others in the sense that the final product is not a mixture of hydrocarbons, but a single paraffinic molecule instead.

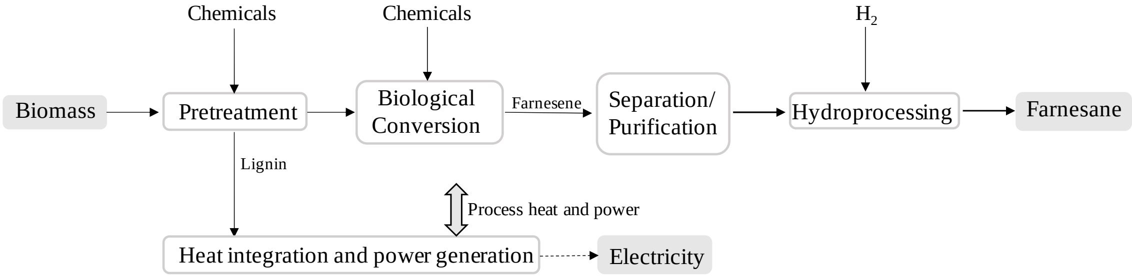


Figure 4. General process flow for the HFS-SIP pathway.

HFS-SIP from sugar cane and sugar beet are among the CORSIA eligible fuels. LS_f values of 44.1 gCO_2e/MJ and 52.6 gCO_2e/MJ have been calculated for sugar cane and sugar beet respectively.[19]

3.4. Fischer-Tropsch (FT) SPK/A

FT SPK/A is primarily the same process as the FT-SPK, but it includes the addition of alkylated light aromatics (e.g. benzene) into the fuel blend. As mentioned before, the hydrocarbon mix produced by the FT-SPK process contains mostly paraffins and low amounts of aromatic components. However, around 20% of aromatic content is required in a jet fuel blend to ensure the swelling in aircraft components and prevent fuel leaks. With the addition of aromatics, the synthetic jet fuel blend more closely resembles its petroleum-based counterpart, which is desired. Similar to FT-SPK, jet fuel produced through this pathway could be blended with petroleum-based jet fuel up to 50% by volume.

3.5. Alcohol-to-jet (ATJ)

Alcohol-to-jet pathway includes the dehydration of alcohols followed by oligomerization, hydrogenation and fractionation to yield jet fuel. ATJ aims to eventually include all alcohols, but currently fuel from the upgrading of ethanol (approved in 2018) and isobutanol (approved in 2016) are certified to be used in 50% blends by volume with petroleum-based jet fuel. Other potential feedstocks for ATJ include methanol, isopropanol, and long-chain fatty alcohols.

Pathway details:

Ethanol and isobutanol can be derived from different feedstocks and procedures.[24] Fermentation of sugars, starches or more complex carbohydrates is one of the common methods. Crops such as sugar cane and sugar beet, rich in simple sugars, and those that contain more complex forms of sugars such as starch containing corn, wheat, cassava can be used as feedstocks. Extraction of sugars from these feedstocks is relatively easy. In the European Union (EU), corn (42%) is the primary feedstock for ethanol production, followed by wheat (33%) and sugar beet (18%).[25]

Lignocellulosic biomass (e.g. perennial grasses like miscanthus, switchgrass, etc.) can alternatively be used as raw material for fermentation. However, the amount of starch only represents a small percentage of the total plant biomass in these crops, while the rest is cellulose and hemicellulose. These polymeric sugars can also be converted into simple sugars through hydrolysis, although the process is more difficult, and the conversion technologies have to be improved for more efficient production.[26]

Alcohols can also be produced through fermentation of syngas by bacteria. Syngas can be produced by gasification of biomass, municipal solid waste, waste gases from industrial processes, and other carbon sources. It is mainly a mixture of carbon monoxide and hydrogen. These gases are used by acetogenic bacteria for the production of ethanol and butanol.[27]

The conversion of alcohols into jet fuel is a three-step process that includes alcohol dehydration, oligomerization and hydrogenation (Figure 5). All these processes consist of well-known technologies, commercially available. However, they have to be integrated with biomass processing systems and optimized in order to increase the overall efficiency of the process.

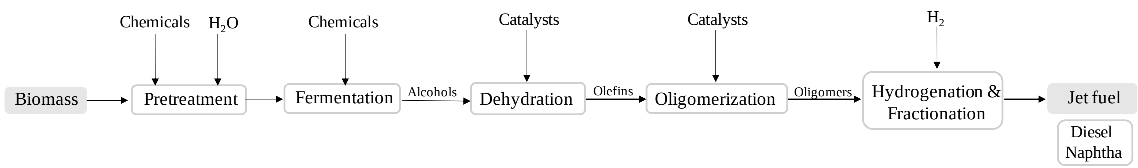


Figure 5. General process flow for Alcohol-to-jet pathway.

Ethanol by itself is not compatible as a blendstock fuel for the aviation industry due to its high volatility (low flash point), high water absorption and lower energy density.[16] In the EU ethanol is used in certain blends with gasoline for road transport, helping it to burn cleaner. The United States (US) is the main producer of renewable ethanol in the world, accounting for 60% of the market, followed by Brazil (30%) and the EU (7%). Butanol has similar physical properties to ethanol, which prevents its usage for aviation in its pure form. Butanol has two isomers that can be upgraded into jet fuel, normal-butanol (straight chain) and isobutanol (branched). They can be fermented using the same feedstocks for ethanol. ATJ pathway offers opportunities for alcohol producers to enter the aviation market.

In China grain-based ethanol accounts for the largest portion of the nationwide bioethanol production. Tapioca, a starch extracted from the roots of the cassava plant, is also an important feedstock along with the syngas produced from the gasification of biomass. A study by the Chinese Academy of Sciences[28] stated that bioethanol production from sweet sorghum can be given priority in China due to its potential environmental benefits.

Isobutanol-to-jet from agricultural and forestry residues, sugar cane, corn grain, miscanthus and switchgrass are among the CORSIA eligible fuels. These have LS_f values ranging between -10.7 gCO_2e/MJ (miscanthus) and 77.9 gCO_2e/MJ (corn grain). Ethanol-to-jet from sugar cane (32.8 gCO_2e/MJ) and corn grain (90.8 gCO_2e/MJ) are also in the list of CORSIA eligible fuels.[19]

3.6. Co-processing

Co-processing is the simultaneous transformation of biogenic feedstocks with petroleum-based distillates to produce finished fuels. This can be done in the existing petroleum refineries using the available infrastructure. Co-processing receives attention due to its potential to produce low carbon fuels at lower costs. The supply of drop-in biofuels may also increase with increased co-processing at the refineries. Co-processing of up to 5% (by volume) of lipids is approved by the Annex 1 of ASTM D1655.

Pathway details:

For the production of SAF, biogenic intermediates can be introduced at various insertion points in a refinery (Figure 6). Process steps such as fluid catalytic cracking (cracking using a catalyst), hydrocracking (cracking using hydrogen), and hydrotreatment can be used for co-processing. The amount of biogenic content in the finished product can be identified by mass balance, energy content or carbon dating.[29]

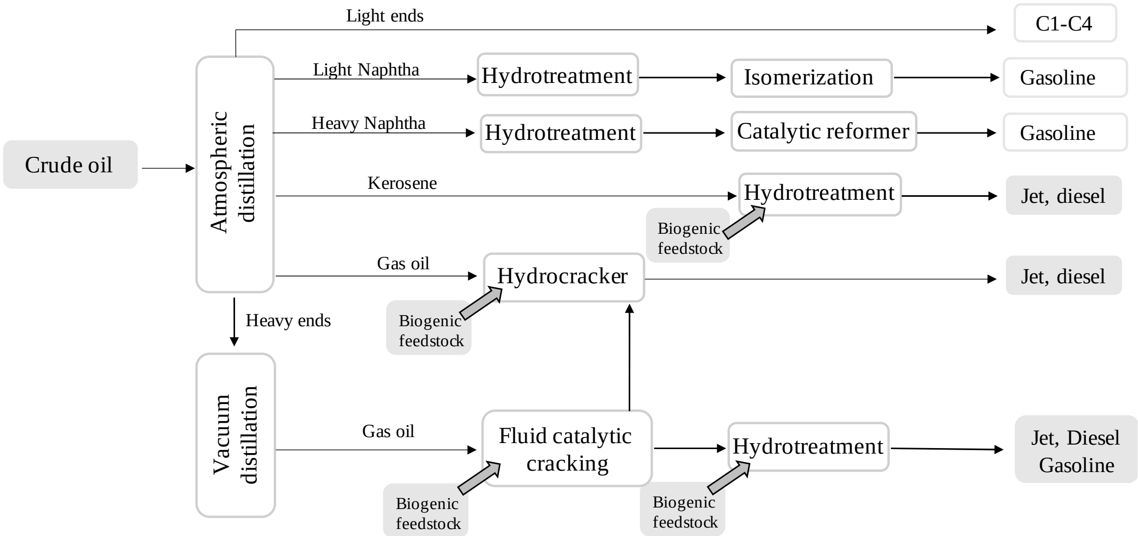


Figure 6. Simplified diagram showing the potential insertion points of biogenic feedstocks for co-processing at a petroleum refinery (adapted from S.van Dyk et al. 2019).[30]

Co-processing is already practiced at the European level, in companies like Preem (Sweden), Neste (Finland) and Repsol (Spain). The co-processing refinery units will be put into practical use in the near future in China. There have been no associated reports on the LCA of co-processing refinery units in China. Co-processing of lipids currently doesn't have an LCA value assigned in the CORSIA program, but it is an item on the list of pathways to be designated a value in the future.

3.7. Catalytic Hydrothermolysis SK (CHJ)

Catalytic hydrothermolysis is a pathway developed by the Applied Research Associates (ARA), Inc. in the USA that recently obtained an ASTM certification.[31] Similar to HEFA-SPK, lipidic feedstocks such as plant oils, waste oils and algal oils can be used as feedstocks for the CHJ pathway. While FFAs are produced through propane cleavage of triglycerides, in the HEFA pathway, they are produced through thermal hydrolysis in the CHJ. FFAs are then converted into a mixture of paraffins, cycloparaffins and aromatics and the final CHJ blend can be used up to 50% blend by volume with petroleum-based jet fuel.

Pathway details:
Oils from soybean, jatropha and tung were utilized as feedstocks for CHJ fuel.[31] The pathway starts with oil harvesting from lipidic feedstocks. The resulting triglycerides undergo pre-conditioning reactions like conjugation and cyclization to produce cyclic molecules. Crop wastes from oil extraction are also utilized through a fermentation step that produces hydrogen and alcohols that can be dehydrated into alkenes.

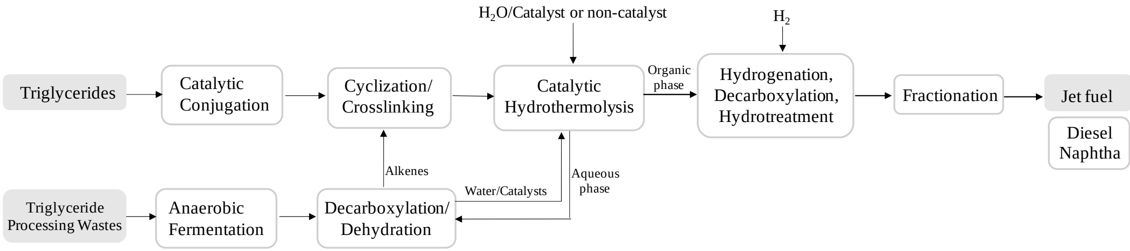


Figure 7. Process scheme for Catalytic Hydrothermolysis pathway (adapted from Li et al. 2010).[31]

The combined products are then subjected to catalytic hydrothermolysis conditions, which uses high temperature water to catalyze processes such as cracking, hydrolysis, decarboxylation, isomerization, and cyclization. The temperature range for the CH process is 240-470°C, below the temperature range for traditional catalytic cracking (400-650°C).

CHJ currently does not have an LCA value assigned in the CORSIA program, but it is an item on the list of pathways to be designated a value in the future.

3.8. Hydroprocessed hydrocarbons, esters and fatty acids (HC-HEFA) SPK

HC-HEFA is the first fuel to receive expedited review under ASTM D4054 Clearinghouse fast-track review process. A procedure developed by the Japanese IHI Corporation is used for the consistent production of bio-jet fuel from microalgal oil produced by Hyper Growth Botryococcus Braunii (HGBb) type of algae. HC-HEFA fuel can be blended with petroleum-based jet fuel up to 10% by volume since fuels that are approved under the fast-track review will be limited to a maximum of 10% blends.[32]

Pathway details:
HC-HEFA pathway consists of the same feedstock-to-fuel production steps as the HEFA pathway, although the utilized feedstock is different. Bio-derived hydrocarbons and lipids are converted into jet fuel range paraffins in the HC-HEFA pathway. Currently only the squalene-like hydrocarbons from HGBb type of algae are recognized as feedstocks for this process. Stable cultivation of HGBb was achieved in 1500m^2 open pond in 2015, and currently trials are ongoing for large scale cultivation tests in a total area of 15000m^2.

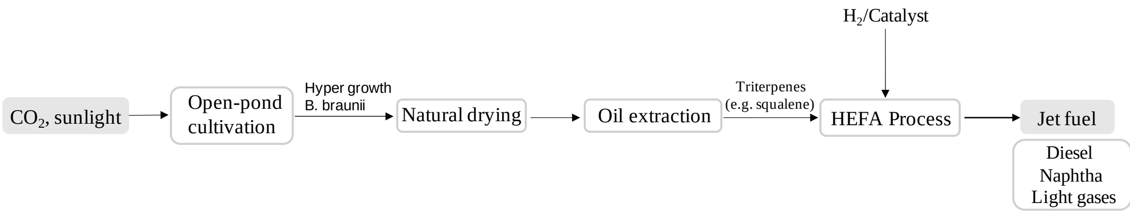


Figure 8. Process scheme for the HC-HEFA pathway.

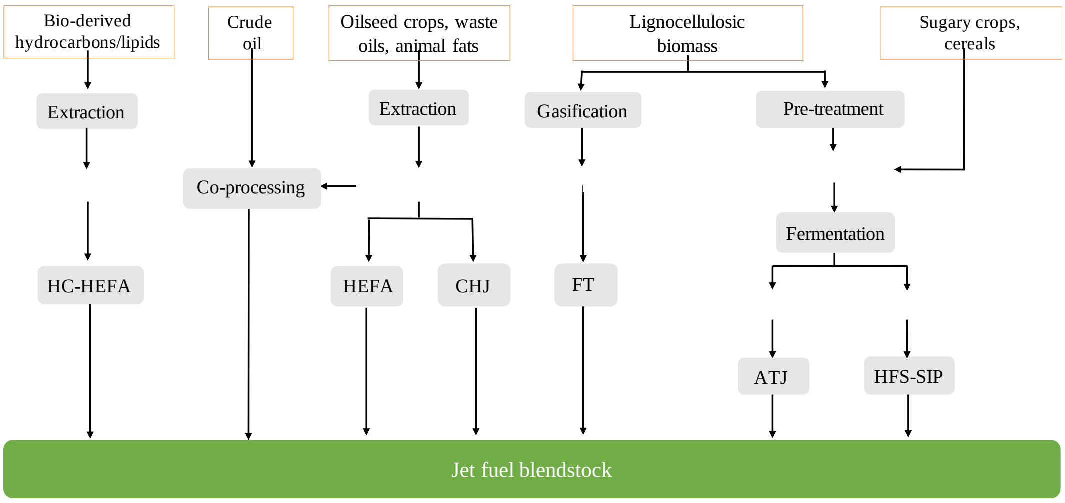
As B. braunii converts simple inorganic compounds and sunlight to potential hydrocarbon fuels and feedstocks for the chemical industry, it attracted attention in China as well. Studies are focusing on the culture optimization of the algae, synthesis pathway of hydrocarbons, product isolation and strain screening.[33,34] HC-HEFA currently doesn't have an LCA value assigned in the CORSIA program, but it is - like co-processing and CHJ on the list of pathways to be designated a value in the future.

4. Selected Pathways for ALTERNATE

For ALTERNATE, the Chinese and the European partners will be focusing on various pathways in accordance with the previously prioritized feedstocks (available in Deliverable 2.1). The European consortium categorized these feedstocks in 3 different groups. Oilseed crops is the first group to be explored which includes castor, jatropha, pennycress, salicornia bigelovii, and tobacco plants. The second group consists of lignocellulosic feedstocks; reed canary grass and giantreed. Finally, sweet sorghum and wheat constitute the final group which are starch-based feedstocks.

The pathway selection is driven by the existing commercial and environmental interest into different pathways as documented by the ongoing efforts and by the availability of data on the fuel conversion step. We note that not all of the possible feedstock-pathway combinations will be studied.

Figure 9 gives a simplified review of the feedstock types with the matching ASTM approved pathways. Among these, the European consortium plans to focus on **HEFA-SPK, FT-SPK, ATJ and HFS-SIP**. For the Chinese side, Beihang University will work on **HEFA-SPK** and **FT-SPK/A** pathways which need further assessment to improve the accuracy. Tianjing University will focus on the **ATJ** and **SIP** pathways. For the ATJ pathway grains, tapioca from cassava, and other biomass will be investigated. For **HFS-SIP**, bagasse and beet residue will be explored. In addition, the Chinese side will also work on some novel pathways such as **pyrolysis** and **hydrothermal liquefaction** (HTL), which do not have an ASTM certification yet. Different species of algae, waste sludge, and biomass will be investigated for the HTL pathway. For the pyrolysis, algal oil, along with the algae residue and other agricultural residues such as corn stover will be explored as feedstocks. Finally, **co-processing** with lipids such as jatropha, xanthoceras, algae and used cooking oil will be studied. Co-processing of biocrude derived from different feedstock with kerosene will be investigated and optimized.



*Currently, triterpenes produced by the *Botryococcus braunii* species of algae is the only recognized feedstock for this pathway.

Figure 9. Simplified diagram of feedstocks types and corresponding ASTM approved pathways.

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