# *D2.2 – Life Cycle Inventories for feedstock and fuel production, and distribution*

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## Abstract

The present document corresponds to the deliverable D2.2 of the ALTERNATE project. It provides the Life Cycle Inventories (LCI) necessary for the life cycle assessment (LCA).

## Keywords

Sustainable aviation fuels (SAF), life cycle assessment, biofuels, life cycle inventories

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## Acronyms and Terminology

| Term | Definition |
|---|---|
| ATJ | Alcohol-to-jet |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| FT | Fischer-Tropsch |
| GHG | Greenhouse Gas Emissions |
| GREET | The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model |
| HEFA | Hydroprocessed Esters and Fatty Acids |
| HFS-SIP | Hydroprocessed Fermented Sugars to Synthetic IsoParaffins |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventories |
| SAF | Sustainable Aviation Fuels |
| SPK | Synthetic Paraffinic Kerosene |

# 1. Introduction

This deliverable contains the life cycle inventories (LCI) necessary for the LCA of greenhouse gas emissions (GHG) from sustainable aviation fuels (SAF) production.

In section 2, LCIs of feedstock production and distribution have been presented. Feedstocks that were previously selected for analysis are grouped into the following categories: lipid feedstocks, lignocellulosic biomass, sugary and starchy crops. A generalized system boundary for SAF production from each feedstock type is given within its relevant section. If there is any deviation from this system boundary, it is explained under the corresponding subsection for that specific feedstock.

In section 3, LCIs of fuel conversion and fuel transportation and distribution (T&D) steps are included. Fuel conversion pathways included are hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch (FT), Alcohol-to-jet (ATJ) and hydroprocessed fermented sugars to synthetic isoparaffins (HFS-SIP).

# 2. Life cycle inventories: Feedstock production and transportation

ALTERNATE will try to capture the variability of the LCI parameters by following a stochastic approach where possible. For this, depending on data availability, probability distribution types are assigned to key parameters using the curve-fitting functionality of Oracle® Crystal Ball, which is a spreadsheet-based application used for simulations and forecasting. When there are enough data points the software can calculate, and rank the goodness-of-fit statistics including the Kolmogorov-Smirnov, the Anderson-Darling, and the Chi-squared statistics for the fitted distributions. In the end the highest-ranking fit is selected. When there is not enough data, other distribution types are assumed (e.g. triangular) or single-point values are used. Consequently, at times the data is presented as a range rather than point values, and the raw data used for the fittings along with the data sources are provided in the Appendix section of this deliverable. Information regarding the transportation steps is included cumulatively for each feedstock type at the end of each section.

## 2.1. Lipid feedstocks

The feedstocks included in this category are oils derived from the following oilseed crops: jatropha (*Jatropha curcas*), pennycress (*Thlaspi arvense*), castor (*Ricinus communis*), energy tobacco (*Nicotiana tabacum,* Solaris), salicornia (*Salicornia bigevolii*) and yellow horn (*Xanthoceras sorbifolia*). Microalgae and used cooking oil are also included.

For ALTERNATE, the main pathway that will be considered for SAF production from lipid feedstocks is HEFA. The system boundary of oilseed feedstocks consists of feedstock cultivation, feedstock transportation, oil extraction, oil transportation, HEFA conversion, and HEFA jet fuel transportation and distribution. The $CO_2$ absorbed during biomass growth is considered to offset the emissions from fuel combustion.

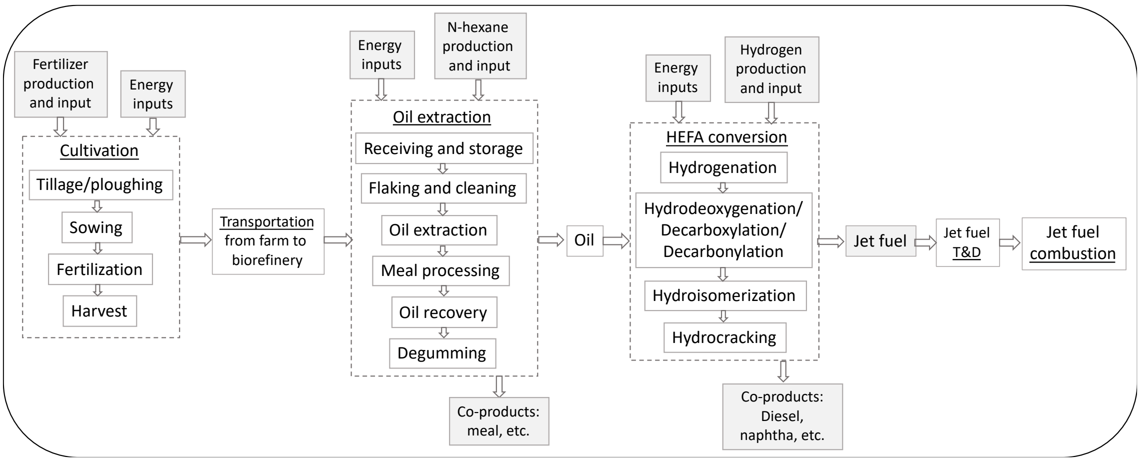

Figure 1. General system boundary for HEFA jet fuel production from oilseed crops.

Cultivation step for oilseeds consists of the typical farming practices from tillage, sowing and fertilization to harvesting. Farming practices from different parts of the world are utilized for the crops that are currently less represented in Europe such as jatropha and salicornia.

Feedstock recovery from the oilseeds necessitates an extraction step. This can be done by the mechanical pressing of seeds followed by extraction with a non-polar solvent, such as n-hexane, in order to increase the oil yield. This type of solvent extraction is used at large scale production facilities and it provides up to 99% oil extraction efficiency. However, there may not be any commercial oil extraction facilities available for the discussed feedstocks in this study. As a result, assumptions were made for the energy consumption for the extraction step using data from similar crops such as soybean and rapeseed. For ALTERNATE, the modified model by Sheehan et al.[1] on soybean oil extraction was used to calculate the energy inputs of the oil extraction step. The following process steps are included: receiving and storage of the seeds, seed preparation (flaking and cleaning), oil extraction, meal processing, oil recovery, solvent recovery, oil degumming and waste treatment.

The seeds are assumed to be dried at the farm in the open air. Hexane amount needed for the extraction is adjusted according to the data from Schneider et al. 2013[2], which is an LCA study on the EU oilseed crushing practices. The amount of oil contained in the seed is another variable. The effect of this change on the oil extraction step is also captured by assuming low, baseline and high values for the oil content, and calculating the utilities for the extraction step accordingly.

### 2.1.1. Jatropha (*Jatropha curcas*)

Jatropha is a species that can grow well in dry and hot conditions. There are a few studies on jatropha cultivation on marginal lands in the Calabria region of Southern Italy.[3,4]

Jatropha fruit is composed of an outer capsule (husk) that contains a few seeds. Each seed has an outer shell, and a kernel that contains the oil. The seed can be directly processed at this stage yielding de-oiled seed cake and oil. Alternatively, the shells can be separated from the kernel via decortication, and the kernel is then processed producing kernel meal and oil (Figure 2).

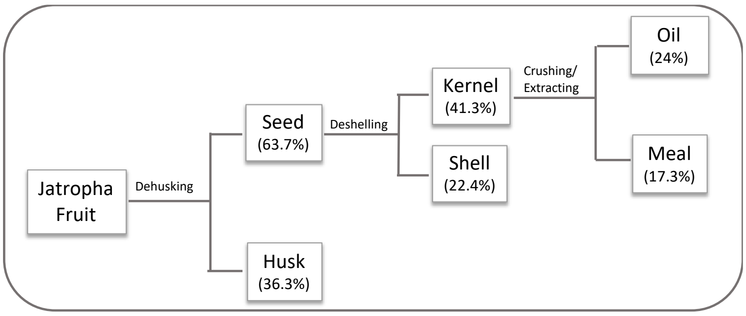

Figure 2. General scheme for jatropha oil production.

In the current scenario, the latter case is assumed. As a result, the by-products of the oil extraction process are husks, shells and meal. The meal is toxic, and it needs to be detoxified to be used as animal feed.[5] There have been reports on the use of meal directly as a fertilizer.[6] The husk and shell could be combusted to produce electricity to cover the needs of the oil extraction step. The oil extraction step of jatropha also includes the energy input for the briquetting of husks.

Table 1. Probability distribution functions of key parameters for the cultivation step of jatropha (per kg of seeds)[7–11]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Jatropha seed yield* | kg/ha | 2500 | - | Stratton et al. 2010 |
| *Seed moisture content* | % | 7 | - | Reinhardt et al. 2008 |
| *Seed oil content* | % | [34, 35, 37] | Triangular | Stratton et al. 2010 |
| *Oil extraction efficiency* | % | 96 | - | Stratton et al. 2010 |
| *Nitrogen, N* | g/kg seeds | [7.0, 27.6, 15.6] | Lognormal | Stratton et al. 2010, Kumar et al. 2012, Estrin, A. 2009, Pandey et al. 2011, Hou et al. 2011 |
| *Phosphorus ($P_2O_5$)* | g/kg seeds | [0, 24.5, 20.0] | Lognormal | |
| *Potassium ($K_2O$)* | g/kg seeds | [5.4, 27.3, 24.7] | Lognormal | |
| *Pesticides* | g/kg seeds | [0, 4.8, 9.6] | Triangular | |
| *Diesel* | MJ/kg seeds | [0.14, 1.1, 0.52] | Lognormal | |

*Lognormal distributions: [low, mean, standard deviation], triangular distributions: [low, mode, high]

Table 2. Ranges of inputs and outputs for the oil extraction step (per kg jatropha oil)[7]

| | *Parameter* | *Min*[a] | *Baseline*[b] | *Max*[c] |
|---|---|---|---|---|
| *Input* | Jatropha seeds (kg) | 2.62 | 2.77 | 2.85 |
| | Natural gas (MJ) | 1.84 | 1.81 | 1.86 |
| | Electricity (MJ) | 0.61 | 0.70 | 0.72 |

| | | | | |
|---|---|---|---|---|
| | N-hexane (MJ) | 0.17 | 0.18 | 0.18 |
| *Output* | Co-product, meal (kg) | 0.68 | 0.72 | 0.74 |
| | Co-product, husk (kg) | 1.43 | 1.51 | 1.56 |
| | Co-product, shell (kg) | 0.88 | 0.93 | 0.96 |

*Oil content of the seeds was assumed to be [a]37 wt%, [b]35 wt% and [c]34 wt% for min, baseline and max scenarios respectively.

Table 3. Energy content of jatropha oil and oil extraction by-products.[12]

| | *LHV (MJ/kg)* |
|---|---|
| *Jatropha oil* | 39.5 |
| *Jatropha meal* | 18.0 |
| *Jatropha husk* | 15.5 |
| *Jatropha shell* | 19.0 |

### 2.1.2. Pennycress (*Thlaspi arvense*)

Pennycress has the potential to serve as a winter crop in rotation with conventional summer crops such as sunflower, soybean and corn. It can be used as feedstock in the EU for biofuels with a low impact on the food supply or land use.[13]

The cultivation of pennycress is considered to be done in rotation with other crops. Aerial seeders are used in order to distribute the pennycress seeds while the previous crop in rotation is still in the field.[14,15]

Seed oil content for pennycress has been reported to be within a range of 25-36 wt%.[15] The oil extraction step for pennycress yields a meal that is rich in protein content (31%).[14] The meal was reported to contain high levels of glycosinolates, which can limit its use as animal feed. Still, there are studies on successful use of pennycress as animal feed up to certain levels.[16]

Table 4. Probability distribution functions of key parameters for the cultivation step of pennycress (per kg of seeds).[13,14,17–22]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Pennycress seed yield* | kg/ha | 1000 | - | Zanetti et al. 2019 |
| *Seed moisture content* | % | 12 | - | Fan et al. 2013 |
| *Seed oil content* | % | [29, 34, 36] | Triangular | Mousavi-Avval et al. 2021 |
| *Oil extraction efficiency* | % | 96 | - | |
| *Nitrogen, N* | g/kg seeds | [27.8, 68.5, 138.9] | Beta | |

| | | | | |
|---|---|---|---|---|
| *Phosphorus ($P_2O_5$)* | g/kg seeds | [0, 31.8, 22.5] | Lognormal | Lopez et al. 2021,<br>Zanetti et al. 2019<br>Markel et al. 2018,<br>Dose et al. 2017,<br>US EPA 2015,<br>Fan et al. 2013,<br>Stevens, J. 2021 |
| *Potassium ($K_2O$)* | g/kg seeds | [0, 18.2, 11.7] | Lognormal | |
| *Diesel* | MJ/kg seeds | [0.163, 0.169, 0.174) | Triangular | |

*Lognormal distributions: [low, mean, standard deviation], triangular/beta distributions: [low, mode, high]

Table 5. Ranges of inputs and outputs calculated for the oil extraction step (per kg pennycress oil).

| | *Parameter* | *Min*$^a$ | *Baseline*$^b$ | *Max*$^c$ |
|---|---|---|---|---|
| *Input* | Pennycress seeds (kg) | 2.55 | 2.70 | 3.16 |
| | Natural gas (MJ) | 2.94 | 3.11 | 3.65 |
| | Electricity (MJ) | 0.50 | 0.53 | 0.62 |
| | N-hexane (MJ) | 0.17 | 0.18 | 0.21 |
| *Output* | Co-product, meal(g) | 1.50 | 1.65 | 2.12 |

Oil content of the seeds was assumed to be $^a$36 wt%, $^b$34 wt% and $^c$29 wt% for min, baseline and max scenarios respectively.

Table 6. Energy content of pennycress oil and meal.[14]

| | *LHV (MJ/kg)* |
|---|---|
| *Pennycress oil* | 36.6 |
| *Pennycress meal* | 18.6 |

### 2.1.3. Castor (*Ricinus communis*)

Castor is originally a tropical season crop that can also grow in temperate climates as an annual crop.[23] The by-products from the oil extraction step are meal and husk. Depending on the type of harvesting (mechanical or manual) the husk can be left at the field or collected and sold to be used for its energy.[24] The meal is toxic and it cannot be used as animal feed without detoxification. However, it can be used as fertilizer.[25]

Table 7. Probability distribution functions of key parameters for the cultivation step of castor (per kg of seeds)[23,26–32]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Castor seed yield* | kg/ha | 1100 | - | Carrino et al. 2020 |
| *Seed moisture content* | % | 3.5 | - | Perdomo et al. 2013 |
| *Seed oil content* | % | [40, 47, 49] | Triangular | Amouri et al. 2017 |

| | | | | |
|---|---|---|---|---|
| *Oil extraction efficiency* | % | 96 | - | |
| *Nitrogen, N* | g/kg seeds | [11.8, 44.0, 30.4] | Lognormal | Yousaf et al. 2018,<br>Shinde et al. 2018,<br>Khoshnevisan et al. 2017,<br>Alexopolou et al. 2015,<br>Campbell et al. 2014 |
| *Phosphorus ($P_2O_5$)* | g/kg seeds | [3.9, 15.2, 9.7] | Lognormal | |
| *Potassium ($K_2O$)* | g/kg seeds | [0, 11.8, 9.9] | Lognormal | |
| *Diesel* | MJ/kg seeds | 1.16 | - | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high]

Table 8. Ranges of inputs and outputs calculated for the oil extraction step (per kg castor oil)

| | *Parameter* | *Min*[a] | *Baseline*[b] | *Max*[c] |
|---|---|---|---|---|
| *Input* | Castor seeds (g) | 2.05 | 2.14 | 2.51 |
| | Natural gas (MJ) | 2.37 | 2.47 | 2.90 |
| | Electricity (MJ) | 0.40 | 0.42 | 0.49 |
| | N-hexane (MJ) | 0.14 | 0.14 | 0.17 |
| *Output* | Co-product, meal(g) | 1.01 | 1.10 | 1.47 |

Oil content of the seeds was assumed to be [a]49 wt %, [b]47 wt % and [c]40 wt % for min, baseline and max scenarios respectively.

Table 9. Energy content of castor oil and meal.[27,33]

| | *LHV (MJ/kg)* | *References* |
|---|---|---|
| *Castor oil* | 36.2 | Amouri et al. 2017 |
| *Castor meal* | 21.7 | Jayant et al. 2021 |

### 2.1.4. Energy tobacco (Solaris, *Nicotiana tabacum*)

Energy tobacco which is also known as Solaris, unlike the tobacco used for smoking, contains no nicotine in the leaves and maximizes the production of flowers/seeds reducing the leaf growth.[34]

The meal from oil extraction step can be used as animal feed with its high crude protein content (33%).[35]

Table 10. Probability distribution functions of key parameters for the cultivation step of energy tobacco (per kg of seeds)[34,36–38]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Energy tobacco seed yield* | kg/ha | 2100 | - | Fatica et al. 2019 |
| *Seed moisture content* | % | 5 | - | Grisan et al. 2016 |

| | | | | |
|---|---|---|---|---|
| *Oil content* | % | [33, 38, 40] | Triangular | Giannelos et al. 2002 |
| *Oil extraction efficiency* | % | 96 | - | |
| *Nitrogen, N* | g/kg seeds | [11.8, 56.1, 22.8] | Lognormal | Fatica et al. 2019, Carvalho et al. 2019, Grisan et al. 2016, |
| *Phosphorus ($P_2O_5$)* | g/kg seeds | [7.3, 36.8, 17.3] | Lognormal | |
| *Potassium ($K_2O$)* | g/kg seeds | [0, 31.7, 25.5] | Lognormal | |
| *Herbicides* | g/kg seeds | 0.41 | - | |
| *Insecticides* | g/kg seeds | 0.33 | - | |
| *Diesel* | MJ/t seeds | 0.13 | - | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high]

Table 11. Ranges of inputs and outputs calculated for the oil extraction step (per kg energy tobacco oil).

| | *Parameter* | *Min*[a] | *Baseline*[b] | *Max*[c] |
|---|---|---|---|---|
| *Input* | Tobacco seeds (g) | 2.47 | 2.60 | 2.99 |
| | Natural gas (MJ) | 2.85 | 3.00 | 3.46 |
| | Electricity (MJ) | 0.48 | 0.51 | 0.58 |
| | N-hexane (MJ) | 0.17 | 0.18 | 0.20 |
| *Output* | Co-product, meal(g) | 1.43 | 1.56 | 1.96 |

Oil content of the seeds were assumed to be [a]40 wt %, [b]38 wt % and [c]33 wt % for min, baseline and max scenarios respectively.

Table 12. Energy content of tobacco oil and meal.[35,39]

| | *LHV (MJ/kg)* | *References* |
|---|---|---|
| *Energy tobacco oil* | 39.4 | Carvalho et al. 2019 |
| *Energy tobacco meal* | 13.4 | Rossi et al.2013 |

### 2.1.5. Salicornia (*Salicornia bigelovii*)

Salicornia is a member of the halophyte family, which is known for its ability to grow in brackish water on marginal lands.[40]

The amount of seed oil produced from salicornia is small compared to the straw biomass of the plant.[41] On the other hand, salicornia straw can be gasified and converted into other energy products via Fischer Tropsch (FT) synthesis, pyrolysis, etc.[42]

Table 13. Probability distribution functions of key parameters for the cultivation step of salicornia (per kg of seeds).[41–44]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Salicornia seed yield* | kg/ha | 2000 | - | Warshay et al. 2016 |
| *Seed moisture content* | % | 6.4 | - | Makkawi et al. 2021 |
| *Seed oil content* | % | [26, 28.2, 33] | Triangular | Glenn et al. 1999 |
| *Oil extraction efficiency* | % | 96 | - | |
| *Nitrogen, N* | g/kg seeds | [0, 50.6, 133] | Triangular | Stratton et al. 2010 |
| *Diesel* | MJ/kg seeds | [19.6, 26.7, 36.8] | Triangular | |

* Triangular distributions: [low, mode, high]

Table 14. Ranges of inputs and outputs calculated for the oil extraction step (per kg salicornia oil).

| | *Parameter* | *Min*[a] | *Baseline*[b] | *Max*[c] |
|---|---|---|---|---|
| *Input* | Salicornia seeds (g) | 3.75 | 3.46 | 2.95 |
| | Natural gas (MJ) | 2.53 | 4.04 | 6.74 |
| | Electricity (MJ) | 0.24 | 0.38 | 0.63 |
| | N-hexane (MJ) | 0.20 | 0.23 | 0.25 |
| *Output* | Co-product, meal (kg) | 2.71 | 2.42 | 1.91 |
| | Co-product, straw (kg) | 27.1 | 25.0 | 21.3 |

Oil content of the seeds were assumed to be [a]33 wt%, [b]28.2 wt% and [c]26 wt% for min, baseline and max scenarios respectively.

Table 15. Energy content of Salicornia oil and oil extraction by-products.

| | *LHV (MJ/kg)* | *References* |
|---|---|---|
| *Salicornia oil* | 38.9 | Folayan et al. 2019 |
| *Salicornia meal* | 18.0 | Stratton et al. 2010 |
| *Salicornia straw* | 16.3 | Stratton et al. 2010 |

### 2.1.6. Yellow horn (*Xanthoceras sorbifolia*)

Xanthoceras sorbifolia is identified as a bio-energy crop that can be cultivated on marginal land in China. Wild or cultivated trees were widely found in 18 provinces of China, namely, Beijing, Inner Mongolia, Shaanxi, Shanxi, Hebei, Henan, Shandong, Anhui, Liaoning, Ningxia, Gansu, Xinjiang, Sichuan, Tibet, Qinghai, Heilongjiang, Jiangsu and Jilin. X. sorbifolia is a multipurpose plant besides of oil production. The trunks and branches of X. sorbifolia are used as traditional

Mongolian medicine for the treatment of rheumatoid arthritis and adenophyma. The leaves contained 16 amino acids while the defatted seed kernel meal contained rich proteins with an excellent amino acid profile. Cultivation and oil extraction data for xanthoceras is provided in Tables 16 and 17 respectively.

Table 16. Inputs for the cultivation step of yellow horn (per kg of seeds).[45]

| *Parameter* | *Unit* | *Value* |
|---|---|---|
| *Xanthoceras seed yield* | kg/ha | 879-2542 |
| *Seed oil content* | % | 30-70 |
| *Oil extraction efficiency* | % | > 95 |
| *Nitrogen, N* | g/kg seeds | 54 |
| *P2O5* | g/kg seeds | 15 |
| *K2O* | g/kg seeds | 66 |
| *Diesel* | MJ/kg seeds | 0.69 |
| *Gasoline* | MJ/kg seeds | 0.19 |
| *Electricity* | MJ/kg seeds | 1.26 |

Table 17. inputs and outputs for the oil extraction step (per kg yellow horn oil).[45]

| | *Parameter* | *Value* |
|---|---|---|
| *Input* | Xanthoceras seeds (g) | 2.85 |
| | Electricity (MJ) | 2.53 |
| *Output* | Co-product, oil cake (kg) | 1.85 |

### 2.1.7. Microalgae

The microalgae industry is currently trying to achieve a broad range of products, from bio-nutrient and animal feed, to jet biofuels. The species of *Nannochloropsis oceanica* is considered as an ideal algal species characterized by its rapid growth and high lipid content in China. The challenge of the tolerance of high CO2 concentration has been overcome by gradually increasing CO2 concentration to even purified CO2 by coupling the pH control and aeration control. The cultivation conditions should be modified by coupling the influence of specific productivity with lipid content and $CO_2$ fixation.

For comparison with the other oil seeds for biofuel, the system boundary includes feedstock cultivation and harvesting stage as well as oil extraction and refining of jet fuel. Nannochloropsis cultivation data have been collected in practical industry in a year in China.

Three different ways are considered for the production of SAF from microalgae: Hydrotreating the lipid extracted from algae slurry into jet fuel (HEFA-wet), hydrotreating the lipid extracted from algae powder into jet fuel (HEFA-dry), and hydrotreating hydrothermal biocrude into jet fuel (HTL-HEFA). HTL-HEFA (also known as CHJ) consumes the lowest energy, whereas HEFA-wet and HEFA-dry consume 1.5 times, and 5.5 times more energy than HTL-HRJ. The hydrogen utilization is the main energy consumer in HTL-HEFA processes with about 50% of the total energy consumption. The electricity utilization is the main energy consumption in HEFA-wet, process with around 40%, while the thermal heat is the main energy consumption in HEFA-dry process with around 80%. Details for the HEFA pathway for algae is in Section 3.1.

Figure 3. System boundary for SAF production from microalgae.

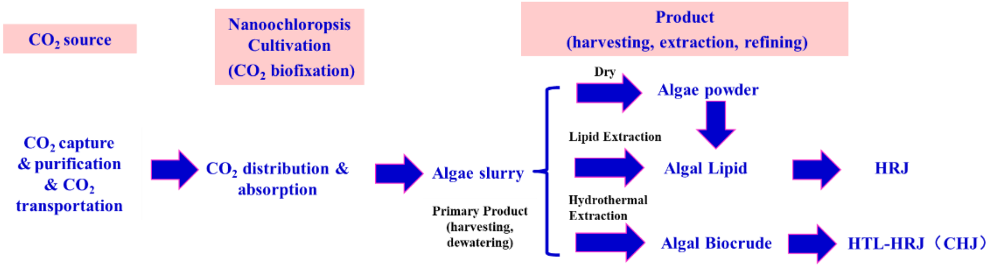

Table 18. Inputs for microalgae production (per kg microalgae) in China.[45]

| *Parameter* | *Unit* | *Value* |
|---|---|---|
| *Yield* | g/m2/d | 3.0-15 |
| *Oil content* | % | 12.6-44.5 |
| *Nitrogen, N* | g/kg seeds | 12.3 |
| *P2O5* | g/kg seeds | 2.85 |
| *Diesel* | MJ/kg seeds | 0.03 |
| *Electricity* | MJ/kg seeds | 12.4 |

Table 19. Inputs and outputs for the oil extraction step (per kg algal oil) in China.[45]

|  | *Parameter* | *Value* |
|---|---|---|
| *Input* | Algae (g) | 2.5 |
|  | Electricity (MJ) | 4.05 |
|  | Steam (MJ) | 6.83 |
|  | N-hexane (MJ) | 2.03 |
|  | Methanol (MJ) | 2.94 |

| | | |
|---|---|---|
| *Output* | Co-product, oil cake (kg) | 1.50 |

### 2.1.8. Used cooking oil (UCO)

UCO is considered a waste product, and the system boundary for LCA includes transportation, purification (rendering) and refining stages.

Table 20. Inputs for rendering stage of used cooking oil in China.[45]

| | *Parameter* | *Value* |
|---|---|---|
| *Input* | Crude-UCO | 1.02 |
| | Electricity (MJ) | 0.25 |
| | Steam (MJ) | 0.74 |
| *Output* | Rendered-UCO (kg) | 1 |

Table 21. Transportation of used cooking oil in China.[45]

| *Region* | *Transport mode* | *Distance (km)* | *Share (%)* |
|---|---|---|---|
| *China* | Tanker | 500 | 60 |
| | Truck | 200 | 10 |
| | Rail | 400 | 30 |

### 2.1.9. Transportation step for lipid feedstocks

Data related to the transportation step for the oilseed crops have been adapted from rapeseed transportation in the EU based on a report by the Joint Research Center's (JRC).[46] For China, data from AF-3E have been included.[45] AF-3E is a tool developed by Beihang University, and the main inventory data is derived from original Chinese government yearly data releases.

Table 22. Transportation of oilseed crops to the biorefinery in the EU and China.[45,46]

| *Region* | *Transport mode* | *Payload (t)* | *Distance (km)* | *Share (%)* |
|---|---|---|---|---|
| *EU* | Truck | 27 | 163 | 77.1 |
| | Barge | 8800 | 376 | 6.4 |
| | Rail | - | 309 | 16.5 |
| *China* | Truck | 27 | 150 | 90 |
| | Rail | - | 500 | 10 |

## 2.2. Lignocellulosic biomass

The feedstocks included in this category are reed canary grass (*Phalaris arundinacea*), giant reed (*Arundo donax*) and agricultural residues. SAF production from giant reed and reed canary grass within the EU consortium of ALTERNATE is considered to be through Fischer-Tropsch (FT) and alcohol-to-jet (ATJ) pathways. Agricultural residues will be only considered for land use change in the Chinese context.

The system boundary for lignocellulosic feedstocks for the ATJ pathway consists of feedstock cultivation, feedstock transportation, ethanol fermentation, ethanol transportation, ATJ conversion, and jet fuel transportation and distribution. The $CO_2$ absorbed during biomass growth is considered to offset the emissions from fuel combustion.

During the fermentation stage of the process, non-hydrolyzed celluloses and lignin from the biomass are valorized through combustion in a combined heat and power (CHP) system to generate heat and electricity. Electricity produced at this stage is generally in excess, and can be sold back to the grid.[47,48] Additional details about the ATJ pathway, and inputs for this process are provided in section 3.2.

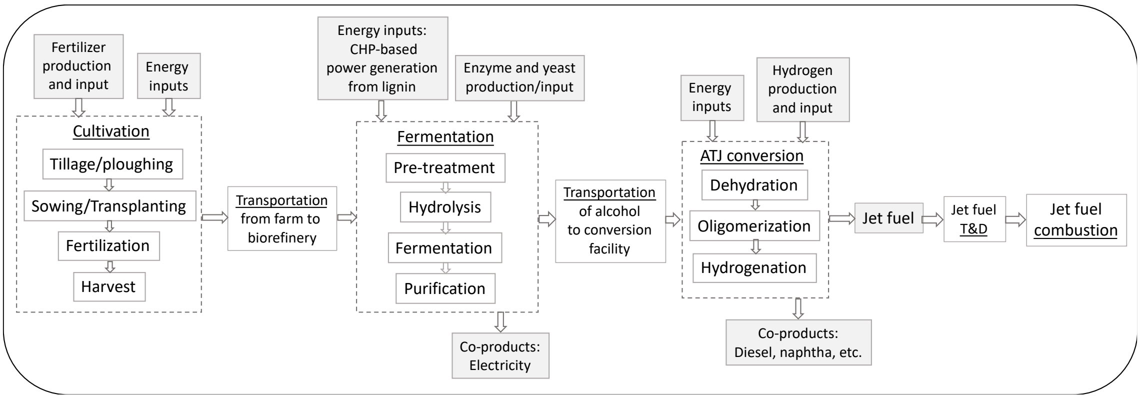

Figure 4.General system boundary for SAF production from lignocellulosic biomass-ATJ pathway.

For the FT pathway the system boundary is given at Figure 5 for the lignocellulosic biomass. The system boundary for lignocellulosic feedstocks for the FT pathway consists of feedstock cultivation, feedstock transportation, FT conversion, and jet fuel transportation and distribution. The $CO_2$ absorbed during biomass growth is considered to offset the emissions from fuel combustion. Additional details about the FT conversion are included in section 3.3.

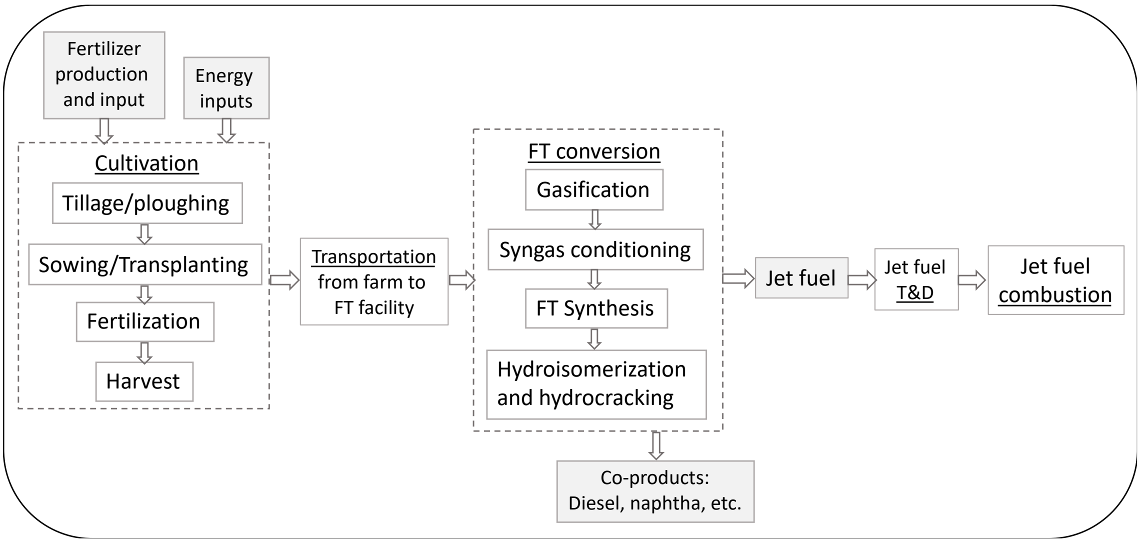

Figure 5. General system boundary for SAF production from lignocellulosic biomass-FT pathway.

### 2.2.1. Giant reed (*Arundo donax*)

Giant reed is a perennial herbaceous plant that originates from Asia, but it is suitable for cultivation in a wide variety of climates. Its cultivation has been studied in Southern Europe; and depending on site conditions, it was shown to give high biomass yields, similar to miscanthus (3-37t dry matter/ha-yr). [49–51] It is resistant to drought, and it requires low irrigation and nitrogen input.

Giant reed has to be propagated through rhizomes since its seeds are sterile.[51] The cultivation of giant reed includes site preparation (tillage), rhizomes planting, fertilization and harvesting steps. Data from long term field experiments that have been performed mostly in Italy by several groups have been collected for the cultivation step (Table 23). Inputs for the ethanol conversion step are listed in Table 25.

Table 23. Probability distribution functions of key parameters for the cultivation step of giant reed (per kg of dry biomass).[47,52–57]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Nitrogen, N* | g/kg dry matter | [3.0, 5.1, 1.3] | Lognormal | Zucaro et al. 2018,<br>Fernando et al. 2018,<br>Forte et al. 2018,<br>Zucaro et al. 2016,<br>Bosco et al. 2016,<br>Fazio et al. 2014,<br>Monti et al. 2009 |
| *P2O5* | g/kg dry matter | [0, 7.0, 4.8] | Lognormal | |
| *K2O* | g/kg dry matter | [0,10.6, 6.7] | Lognormal | |
| *Herbicide* | g/kg dry matter | [0, 0.1, 0.1] | Lognormal | |
| *Diesel* | MJ/kg dry matter | [0.31, 0.60, 0.24] | Lognormal | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high]

### 2.2.2. Reed canary grass (*Phalaris arundinacea*)

Reed canary grass (RCG) is a perennial grass suitable for cool temperate climates. In the past, some field trials were performed in Sweden and Finland.[58] More recently, RCG was shown to give better yields than miscanthus and switchgrass in the challenging soil conditions of North East England with a lower cost.[59] Farming description and data from Lewandowski et al.[51] have been utilized to calculate the energy needs of the cultivation step. Inputs for farming and ethanol conversion steps are listed in Tables 24 and 25 respectively.

Table 24. Probability distribution functions of key parameters for the cultivation step of reed canary grass (per kg of dry biomass).[51,60–63]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Nitrogen, N* | g/kg dry matter | [8.3, 15.4, 5.8] | Lognormal | Epie 2015,<br>Lindvall 2014,<br>Järveoja 2013,<br>Kandel 2013,<br>Lewandowski et al. 2003 |
| *P2O5* | g/kg dry matter | [0, 4.2, 2.9] | Lognormal | |
| *K2O* | g/kg dry matter | [0, 11.0, 6.7] | Lognormal | |
| *Diesel* | MJ/kg dry matter | 0.31 | - | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high]

*Conversion of lignocellulosic biomass into ethanol*

Several publications on bioethanol production from giant reed and reed canary grass have been found.[47,54] However, data was not available due to non-disclosure agreements with the industrial partners. Data from Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) on corn stover and miscanthus have been used as a proxy while the search for data is ongoing.

Table 25. Inputs and outputs for the conversion of lignocellulosic grasses into ethanol (per MJ EtOH).[48]

| | *Data source* | [48] |
|---|---|---|
| *Input* | Feedstock (g) | 0.14 |
| | Natural gas (MJ) | 0 |
| | Diesel (MJ) | 0.0024 |
| | Electricity (MJ) | 0 |
| | Cellulase (g) | 1.41 |
| | Yeast (g) | 0.35 |
| | $H_2SO_4$ (g) | 3.33 |
| | $NH_3$ (g) | 0.30 |
| | NaOH (g) | 3.46 |
| | CaO (g) | 1.37 |
| *Output* | Ethanol (MJ) | 1 |

| | |
|---|---|
| Electricity (MJ) | 0.108 |

### 2.2.3. Agricultural residues

In China, agricultural residues are burned in the open causing harmful environment impacts.[64] On the other hand, using these residues for SAF production might be more beneficial.[65] The Chinese consortium of ALTERNATE will focus on the land use change emissions from agricultural residues. Different utilization pathways will be considered for the agricultural residues (Figure 6).

Figure 6. System boundary for agricultural residues.

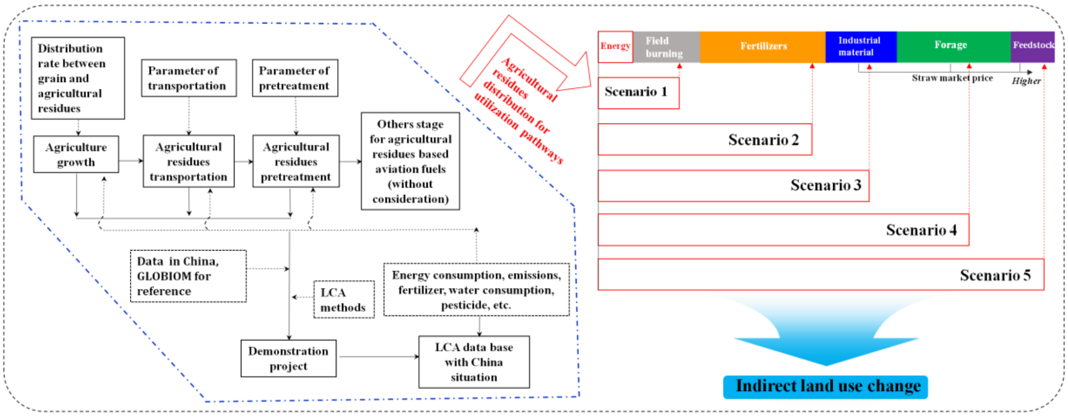

Table 26. Base parameters for agricultural residues transportation vehicle.[65]

| *Speed at full load (km/h)* | *Speed at no load (km/h)* | *Oil consumption at full load (kg/kWh)* | *Oil consumption at no load (kg/kWh)* | *Ratio of vehicle rated power to rated load mass of vehicle (kW/kg)* |
|---|---|---|---|---|
| 25 | 35 | 0.382 | 0.310 | 0.0072 |

Table 27. Direct environmental emissions factors from transportation tools (g/MJ).[65]

| *GHG emissions* | | *Criteria emissions* | | | | |
|---|---|---|---|---|---|---|
| $CH_4$ | $CO_2$ | NMVOC | CO | $NO_x$ | PM | $SO_2$ |
| 0.0042 | 74.0371 | 0.0853 | 0.4739 | 0.2843 | 0.0413 | 0.0160 |

Table 28. Emission factors for agricultural residues open burning (g/kg).[64,66]

| Crops | *Emission factors/(g/kg)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $PM_{2.5}$ | $SO_2$ | $NO_x$ | CO | $NH_3$ | $CH_4$ | NMVOC | $CO_2$ |
| Wheat | 7.60 | 0.85 | 3.30 | 60.00 | 0.37 | 3.40 | 7.50 | 1460.00 |
| Corn | 11.70 | 0.44 | 4.30 | 53.00 | 0.68 | 4.40 | 10.00 | 1350.00 |
| Rice | 12.95 | 0.90 | 3.10 | 34.70 | 0.78 | 3.20 | 6.05 | 1460.00 |

### 2.2.4. Transportation step for lignocellulosic biomass

LCA studies on ethanol production from giant reed in Italy assumed a regional supply scenario with an average distance of 70 km and 100 km for giant reed and ethanol transportation respectively. The value for giant reed transportation is similar to what has been suggested at CORSIA for miscanthus in the EU (82.6 km). If the fermentation facility is co-located with the ATJ plant, transportation of ethanol will not be necessary.

Table 29. Transportation steps for lignocellulosic biomass in the EU.[47,54]

| | *Transport mode* | *Payload (t)* | *Distance (km)* | *Share (%)* |
|---|---|---|---|---|
| *Transportation of biomass* | Truck | 27 | 70 | 100 |
| *Transportation of ethanol* | Truck | 27 | 100 | 100 |

## 2.3. Sugary and starchy crops

### 2.3.1. Wheat (*Triticum aestivum*)

Wheat is one of the common crops that are available in most parts of the world. It is also an important crop for biofuels production in the EU, since along with corn, it is widely used for bioethanol production.[67] Although it is a food resource, it is important to explore the potential for wheat through ATJ pathway considering it is not currently being investigated under CORSIA.

Publications for wheat cultivation in the EU have shown typical fertilization inputs and yields (Table 30). The average yield for wheat in the EU is around 4 t/ha per year.[68] Moisture content of wheat is taken to be around 14 %.[46]

Table 30. Probability distribution functions of key parameters for the cultivation step of wheat (per kg of dry biomass).[46,68–71]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Nitrogen, N* | g/kg dry matter | [17.4, 20.4, 2.2] | Lognormal | Edwards et al. 2019,<br>Belboom 2015,<br>GHGenius Model,<br>Biograce 2015 |
| *P2O5* | g/kg dry matter | [2.9, 5.7, 3.0] | Lognormal | |
| *K2O* | g/kg dry matter | [0.8, 6.42,5.1] | Lognormal | |
| *Herbicide* | g/kg dry matter | [0.35, 0.61, 1.2] | Triangular | |
| *Diesel* | MJ/kg dry matter | [0.4, 0.7, 0.2] | Lognormal | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high

*Conversion of wheat into ethanol*

The system boundary for wheat is similar to lignocellulosic feedstocks (Figure 4). Distiller's dried grains with solubles (DDGS) is produced as co-product from the alcohol production process, instead of electricity. Data on wheat to ethanol conversion is collected from a JRC report[46] on GHG emissions in the EU, and also compared with another LCA report by ADEME (The French Environment and Energy Management Agency).[72]

Table 31. Inputs and outputs for the conversion of wheat grain into ethanol (per MJ EtOH).

| | *Data source* | 46 | 72 |
|---|---|---|---|
| *Input* | Feedstock (kg) | 0.11 | 0.11 |
| | Natural gas (MJ) | 0.47 | 0.48 |
| | Electricity (MJ) | 0.049 | 0.053 |
| | $NH_3$ (g) | 0.23 | 0.073 |
| | NaOH (g) | 0.56 | 0.39 |
| | $H_2$SO4 (g) | 0.45 | 0.34 |
| | Alpha-amylase (g) | 0.05 | N/A |
| | Glyco-amylase (g) | 0.01 | N/A |
| *Output* | Ethanol (MJ) | 1 | 1 |
| | DDGS (kg) | 0.041 | N/A |

The transportation of wheat and ethanol is adapted from an LCA study on wheat ethanol.[46] In this study bioethanol is meant to be the end product for use in road transport. If the fermentation facility is co-located with the ATJ plant, transportation of ethanol will not be necessary.

Table 32. Transportation steps for wheat and ethanol in the EU.[46]

| | *Transport mode* | *Payload (t)* | *Distance (km)* | *Share (%)* |
|---|---|---|---|---|
| *Transportation of wheat* | Truck | 27 | 100 | 100 |
| *Transportation of ethanol* | Truck | 40 | 305 | 13.2 |
| | Tanker | 15000 | 1118 | 31.6 |
| | Barge | 1200 | 153 | 50.8 |
| | Train | - | 381 | 4.4 |

### 2.3.2. Sweet sorghum (*Sorghum bicolor (L) Moench*)

Cultivation of sweet sorghum is investigated under multiple EU-funded projects, and found to be highly promising with its higher efficiency than cereals and sugar beet for bioethanol production in the EU.[67,73] It is also a promising crop for conversion to farnesene through which jet fuel-range farnesane can be produced.[74]

Table 33. Probability distribution functions of key parameters for the cultivation step of sweet sorghum (per kg of dry biomass).[75–79]

| *Parameter* | *Unit* | *Range** | *Distribution* | *References* |
|---|---|---|---|---|
| *Nitrogen, N* | g/kg dry matter | [2.6, 4.3, 1.0] | Lognormal | Forte 2017<br>Cai 2013<br>Fazio 2011<br>Bennett 2009<br>Köppen 2009 |
| *P2O5* | g/kg dry matter | [0, 1.9, 1.1] | Lognormal | |
| *K2O* | g/kg dry matter | [0, 1.8, 1.4] | Lognormal | |
| *Herbicide* | g/kg dry matter | [0, 0.13, 0.25] | Triangular | |
| *Diesel* | MJ/kg dry matter | [0.26, 0.32, 0.05] | Lognormal | |

*Lognormal distributions: [low, mean, standard deviation], Triangular distributions: [low, mode, high].

The main steps for this process are: pretreatment of the biomass (enzymatic hydrolysis for the extraction of sugars from the biomass), biological conversion into farnesene (process residues from the pretreatment step, bagasse, can be converted into energy), and hydroprocessing of farnesene into jet fuel.

# 3. Life cycle inventories: Fuel production and distribution

## 3.1. 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.[39] The HEFA process produces paraffin-rich hydrocarbon liquids from the triglyceride molecules in the lipid feedstock. The main process steps for this pathway are as follows: hydrogenation, hydrodeoxygenation/decarboxylation/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.

HEFA data from CORSIA have been taken as a starting point for ALTERNATE's EU consortium. In CORSIA, The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) and JRC's E3 database have been used as data sources. GREET uses the HEFA production technology by Honeywell UOP, whereas E3 uses NEXBTL technology by Neste.

The data will later be adapted according to the feedstock, where necessary, since the fatty acid profile of the lipidic feedstock is important for the HEFA process. 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.

Table 34. Range for inputs and outputs for the HEFA conversion in the EU (per MJ jet fuel).[48]

| | *Parameter* | *Range** | *Distribution* |
|---|---|---|---|
| *Input* | Feedstock oil (kg/kg jet fuel) | [1.23, 1.25, 1.27] | Triangular |
| | Natural gas (MJ) | [0.082, 0.14, 0.19] | Triangular |

| | | | |
|---|---|---|---|
| | Hydrogen (MJ) | [0.092, 0.054, 0.017] | Triangular |
| | Electric (MJ) | [0.0046, 0.0062, 0.0077] | Triangular |
| *Output* | Propane mix (MJ) | [0.074, 0.037, 0] | Triangular |
| | Naphtha (MJ) | [0.023, 0.016, 0.010] | Triangular |

*Range for triangular distributions is [low, mode, high].

In China, the HEFA inputs from AF-3E model have been utilized. This tool is an integrated computerized model for aviation fuel assessment on energy, environment, and economy developed by Beihang University. The main inventory data is derived from original Chinese government data releases.

Table 35. Inputs and outputs for the HEFA conversion in China (per MJ jet fuel).[45]

| | | *Jatropha* | *Xanthoceras* | *Microalgae* | *UCO* |
|---|---|---|---|---|---|
| *Input* | Feedstock oil (kg/kg jet fuel) | 1.25 | 1.54 | 1.54 | 1.25 |
| | Hydrogen (MJ) | 0.126 | 0.155 | 0.155 | 0.126 |
| | Electricity (MJ) | 0.132 | 0.132 | 0.132 | 0.132 |
| *Output* | Naphtha (MJ) | 0.06 | 0.25 | 0.19 | 0.01 |

## 3.2. Alcohol-to-Jet (ATJ)

Alcohol-to-jet pathway includes the dehydration of alcohols followed by oligomerization, hydrogenation and fractionation to yield jet fuel. For ALTERNATE we will focus on the conversion of ethanol (EtOH) and iso-butanol (i-BuOH) into jet fuel.

### 3.2.1. Ethanol-to-Jet

The ethanol-to-jet pathway was recently updated for CORSIA by a group of technical experts, including researchers from U Hasselt. A broad literature search has been done yielding the following data sets in Table 36.

If the fermentation and ATJ facilities are co-located, natural gas and electricity inputs for the ATJ conversion step will be zero. The surplus energy from the combustion of the lignocellulosic biomass would be sufficient to cover the needs of this process.[48]

Table 36. Inputs for EtOH-to-jet conversion (per MJ of jet fuel).

| | *Data source* | [48] | [80] | [81] |
|---|---|---|---|---|
| *Input* | Ethanol (MJ) | 1.06 | 1.10 | 1.05 |
| | Hydrogen (MJ) | 0.06 | 0.14 | 0.03 |
| | Natural gas (MJ) | 0.18 | 0.19 | 0.18 |

| | | | | |
|---|---|---|---|---|
| | Electricity (MJ) | 0.024 | 0.02 | 0.02 |
| *Output* | Jet fuel (MJ) | 1 | 1 | 1 |

### 3.2.2. Iso-butanol-to-Jet

Data from CORSIA for the EU is taken as a starting point for iBuOH-to-jet conversion.

Table 37. Inputs for iBuOH-to-jet conversion (per MJ of jet fuel).

| | *Data source* | [48] |
|---|---|---|
| *Input* | iBuOH (MJ) | 1.02 |
| | Hydrogen (g) | 0.030 |
| | Natural gas (MJ) | 0.23 |
| | Electricity (MJ) | 0.021 |
| *Output* | Jet fuel (MJ) | 1 |

## 3.3. Fischer-Tropsch (FT) SPK

FT pathway starts with the gasification of a feedstock to produce syngas. Then, the cleaned and conditioned syngas is used for the FT synthesis to produce SAF.

Data from CORSIA and other literature have been compiled and listed in Table 38. The energy from the gasification of the biomass is assumed to cover the energy needs of the conversion process. Therefore, no additional energy inputs have been listed for this pathway.

Table 38. Conversion efficiency and product slate for Fischer-Tropsch pathway.

| | *Data source* | [48] | [7,42] | [48] |
|---|---|---|---|---|
| | FT Conversion efficiency (%) | 50 | 45 | 41 |
| *Product slate (Energy %)* | Jet fuel | N/A | 25 | N/A |
| | Diesel | N/A | 55 | N/A |
| | Naphtha | N/A | 20 | N/A |

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

The HFS-SIP pathway (also known as direct sugars-to-hydrocarbons) 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. Data from CORSIA for the EU is listed in Table 39.

Table 39. Inputs for HFS-SIP conversion (per MJ of jet fuel).

| | *Data source* | [48] |
|---|---|---|
| *Input* | Farnesene (MJ) | 1.03 |
| | Hydrogen (g) | 0.91 |
| *Output* | Jet fuel (MJ) | 1 |

## 3.5. Transportation and distribution (T&D) of jet fuel

The data set from JRC's report on GHG default emissions from biofuels in the EU have been used for jet fuel T&D.[46] This data is estimated for the renewable diesel-like fuel from hydrotreated vegetable oil produced in the EU. A similar data set is also used for the ethanol and biodiesel (fatty acid methyl esters-FAME) transport within the EU in the same report.

Table 40. Transportation and distribution data for jet-fuel for EU/China.[46]

| | *Transport mode* | *Payload (t)* | *Distance (km) EU/China* | *Share (%) EU/China* |
|---|---|---|---|---|
| *Transportation of jet fuel* | Truck | 27 | 305/80 | 11.4/1.5 |
| | Tanker | 15000 | 1118/0 | 27.2/0 |
| | Barge | 1200 | 153/450 | 43.8/62.0 |
| | Rail | - | 381/198 | 3.8/35.5 |
| | Pipeline | - | 5 | 13.8/1.0 |
| *Distribution of jet fuel* | Truck | 27 | 150 | 100 |

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# Appendix

Table 41. Inputs for the cultivation step of jatropha (per kg seeds).

| *Data source* | 7 | 7 | 7 | 8 | 9 | 9 | 9 | 10 | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Total N (g)* | 34.2 | 36.6 | 38 | 17.0 | 7.0 | 35.2 | 61.5 | 12.4 | 19.4 | 15.2 |
| *$P_2O_5$ (g)* | 13.5 | 14.0 | 14.4 | 24.4 | 9.8 | 50.6 | 91.4 | 31.8 | 5.4 | 17.2 |
| *K2O (g)* | 33.7 | 40.2 | 40.2 | 17.0 | 7.4 | 35.2 | 63.3 | 0 | 3.6 | 4.5 |
| *Pesticides* | - | - | - | 0.47 | 9.6 | 9.6 | 9.6 | - | 0.13 | - |
| *Gasoline (MJ)* | - | - | - | - | - | - | - | - | 0.011 | - |
| *Electricity (MJ)* | - | - | - | - | - | - | - | - | 0.006 | - |
| *Diesel (MJ)* | 1.32 | 1.50 | 1.61 | 0.81 | 1.57 | 1.57 | 1.57 | 0.32 | 0.14 | 1.03 |

Table 42. Inputs for the cultivation step of pennycress (per kg seeds).

| *Data source* | 17 | 14 | 18 | 18 | 19 | 20 | 20 | 20 | 20 | 21 | 21 | 22 | 22 | 13 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Total N (g)* | 27.8 | 38 | 35.5 | 71 | 81.8 | 47.0 | 89.7 | 92.5 | 100.5 | 43.0 | 82.0 | 56 | 71 | 138.9 | 52.6 |
| *$P_2O_5$ (g)* | 11.1 | 19 | - | 28.4 | 30.9 | - | - | - | - | 86.1 | 163.9 | 22 | 29 | - | - |
| *$K_2O$ (g)* | 11.1 | 14 | - | 28.4 | 30.9 | - | - | - | - | 28.7 | 54.6 | 22 | 29 | - | - |
| *Diesel (MJ)* | 0.17 | 0.16 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table 43. Inputs for the cultivation step of castor (per kg seeds).

| *Data source* | 28 | 29 | 29 | 29 | 29 | 29 | 29 | 23 | 23 | 23 | 30 | 31 | 31 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Total N (g)* | 33.3 | 13.5 | 22.5 | 19.5 | 18.4 | 16.9 | 11.8 | 82.7 | 98.2 | 168.0 | 107.6 | 40.7 | 53.9 | 67.4 |
| *$P_2O_5$ (g)* | 32.0 | 10.1 | 8.4 | 7.3 | 13.8 | 12.7 | 16.1 | 3.9 | 4.6 | 7.9 | - | 30.5 | 35.9 | 42.1 |
| *$K_2O$ (g)* | 12.6 | - | - | 7.3 | - | 6.3 | 11.8 | 2.8 | 3.4 | 5.8 | - | 20.4 | 27.0 | 33.7 |
| *Diesel (MJ)* | 1.16 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Table 44. Inputs for the cultivation step of energy tobacco (per kg seeds).

| *Data source* | 37 | 34 | 34 | 34 | 34 | 38 |
|---|---|---|---|---|---|---|
| *Total N (g)* | 11.8 | 77.3 | 47.7 | 80.6 | 61.9 | 57.1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| *$P_2O_5$ (g)* | 7.3 | 40.9 | 52.4 | 31.1 | 60.5 | 28.6 |
| *$K_2O$ (g)* | 8.1 | 63.6 | 19.4 | 0 | 65.7 | 33.3 |
| *Herbicide (g)* | 0.41 | - | - | - | - | - |
| *Insecticide (g)* | 0.33 | - | - | - | - | - |
| *Diesel (MJ)* | 0.13 | N/A | N/A | N/A | N/A | N/A |

Table 45. Inputs for the cultivation step of giant reed (per kg dry matter).

| *Data source* | 54 | 47 | 53 | 56 | 55 | 55 | 57 | 52 |
|---|---|---|---|---|---|---|---|---|
| *Total N (g)* | 3.69 | 6.38 | 6.17 | 4.76 | 2.99 | 7.25 | 3.81 | 5.91 |
| *P2O5 (g)* | - | - | 3.33 | 4.86 | 6.39 | 15.5 | 11.9 | - |
| *K2O (g)* | - | - | 21.4 | 11.5 | 5.89 | 14.3 | - | - |
| *Herbicide (g)* | 0.20 | 0.20 | 0.01 | 0.14 | 0.04 | 0.07 | - | - |
| *Diesel (MJ)* | 0.97 | 0.83 | N/A | 0.31 | N/A | N/A | 0.31 | 0.60 |

Table 46. Inputs for the cultivation step of reed canary grass (per kg dry matter).

| *Data source* | 61 | 60 | 62 | 63 | 51 |
|---|---|---|---|---|---|
| *Total N (g)* | 24.5 | 19.2 | 8.43 | 8.25 | 16.5 |
| *P2O5 (g)* | 3.7 | - | 9.76 | 3.9 | 3.53 |
| *K2O (g)* | 19.6 | - | 4.77 | 15.1 | 15.3 |
| *Diesel (MJ)* | N/A | N/A | 0.35 | N/A | N/A |

Table 47. Inputs for the cultivation step of wheat (per kg dry biomass).

| *Data source* | 46 | 71 | 69 | 69 | 69 | 69 | 69 | 70 |
|---|---|---|---|---|---|---|---|---|
| *Total N (g)* | 22.78 | 24.26 | 18.02 | 17.44 | 21.51 | 21.51 | 19.65 | 18.0 |
| *P2O5 (g)* | 4.25 | 4.79 | 2.91 | 8.14 | - | 8.72 | 6.63 | 10.3 |
| *K2O (g)* | 3.57 | 3.64 | 4.65 | 12.21 | - | 15.70 | 10.81 | 0.80 |
| *CaCO3 (g)* | 43.69 | - | - | - | - | - | 0.36 | - |
| *Insecticide (g)* | 1.19 | 0.51 | - | 0.35 | - | 0.37 | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Diesel (MJ)* | 0.76 | 0.83 | N/A | N/A | N/A | N/A | N/A | 0.36 |

Table 48. Inputs for the cultivation step of sweet sorghum (per kg dry biomass).

| *Data source* | 77 | 79 | 75 | 78 | 76 |
|---|---|---|---|---|---|
| *Total N (g)* | 5.23 | 5.0 | 3.41 | 2.59 | 5.36 |
| *P2O5 (g)* | 1.41 | 2.0 | - | 3.88 | 2.0 |
| *K2O (g)* | 0.91 | 1.0 | - | 3.88 | 3.18 |
| *Herbicide (g)* | 0.14 | 0.25 | - | - | 0.24 |
| *Diesel (MJ)* | 0.27 | 0.26 | 0.37 | N/A | 0.36 |

Table 49. Inputs and outputs for the HEFA conversion step in the EU (per MJ jet fuel).

| | *Data source* | 48 | 48 |
|---|---|---|---|
| *Input* | Feedstock oil (kg/kg jet fuel) | 1.23 | 1.27 |
| | Natural gas (MJ) | 0.082 | 0.19 |
| | Hydrogen (MJ) | 0.092 | 0.0017 |
| | Electricity (MJ) | 0.0046 | 0.0077 |
| *Output* | Propane mix (MJ) | 0.074 | - |
| | Naphtha (MJ) | 0.023 | 0.0010 |