



Sustainable Aviation Fuels

**Internship Project for DMT
Environmental Technology**

Stamatis Diakakis
EES-2019-390

Master Programme Energy and
Environmental Sciences, University of Groningen



university of
groningen

faculty of science
and engineering

energy and sustainability
research institute groningen

Internship project report of Stamatis Diakakis

Report: EES-2019-390

Supervised by:
Gideon Laugs (ESRIG)
Benny Bakker (DMT)

University of Groningen
Energy and Sustainability Research Institute Groningen, ESRIG
Nijenborgh 6
9747 AG Groningen
T: 050 - 363 4760
W: www.rug.nl/research/esrig

LIST OF CONTENTS

List of Figures	4
List of Tables	5
Summary	7
1 Introduction	8
1.1 Popular Jet fuels.....	9
1.2 Host Organization	9
1.3 Problem statement and research objectives.....	10
1.4 Methodology.....	10
2 SAF pathways	11
2.1 Regulatory for SAF	11
2.2 Overview of SAF production technologies-pathways.....	11
2.2.1 Hydrotreated Esters and Fatty Acids (HEFA)	12
2.2.2 Alcohol-to-Jet (AtJ).....	12
2.2.3 Direct Sugar to Hydrocarbon (DSHC)	12
2.2.4 Hydrotreated Depolymerize Cellulosic Jet (HDCJ)	13
2.2.5 Co – processing	13
2.2.6 Fischer-Tropsch Synthesis (FTS)	13
2.2.7 DME.....	15
2.3 House of Quality	15
3 Technical Design & Analysis	19
3.1 Technology feasibility	19
3.1.1 Fischer-Tropsch technology feasibility.....	19
3.1.2 Fischer Tropsch PFD	26
3.1.3 DME technology feasibility	28
3.1.4 DME PFD	30
4 Process Feasibility & Total Capital Investment (TCI).....	32
4.1 Process feasibility – feedstock capacity.....	32
4.1.1 FTS from dry or wet biomass (BTLd, BTLw).....	32
4.1.2 FTS from CO ₂ and H ₂ (PTL).....	32
4.1.3 Direct DME synthesis	32
4.2 Total Capital Investment (TCI)	32
4.2.1 TCI for BTLd	33
4.2.2 TCI for BTLw	34
4.2.3 TCI for PTL (CO ₂ & H ₂).....	34
5 Market Focus & Aspects	34

5.1	Economic & geography aspects /	35
5.2	Politics – Taxation	36
5.3	Environment.....	36
5.4	Commercial Airlines:.....	37
5.5	Commercial Airports	37
5.6	Aviation Industries:	38
5.7	Oil/Energy Companies.....	38
5.8	Army / Navy / Air Force.....	39
6	Discussion.....	39
7	Conclusion.....	41
8	References	43
9	Appendix A	48
	Feedstock capacity estimation.....	48
10	Appendix B	50
11	Appendix C	59
	Who is involved in buying the technology?	59
	What are their choice criteria in order to buy the technology?	59
	When do they buy/use the product?.....	59
	Why do they buy/use the product?.....	59
	Where do they buy?	59
	How do they use the product?	60

LIST OF FIGURES

Figure 1:	Kerosene consumption forecasts (Kaltschmitt M. , 2018).....	8
Figure 2:	HEFA PFD (Kaltschmitt M. , 2018).....	12
Figure 3:	ATJ PFD (Kaltschmitt M. , 2018).....	12
Figure 4:	DSHC PFD (Kaltschmitt M. , 2018)	13
Figure 5:	HDCJ PFD, through pyrolysis (Kaltschmitt M. , 2018)	13
Figure 6:	BTL via gasification PFD (Kaltschmitt M. , 2018).....	14
Figure 7:	BTL via anaerobic digestion PFD (Kaltschmitt M. , 2018)	14
Figure 8:	PTL PFD (Kaltschmitt M. , 2018).....	15
Figure 9:	GTL PFD (Kaltschmitt M. , 2018)	15
Figure 10:	Final Scores of HoQ.....	18
Figure 11:	Fixed-bed and Slurry-bubble reactors (Speight, 2011)	20
Figure 12:	Chain growth probability of product distribution in FTS (Huve, 2017).....	21
Figure 13:	Hydrogen concentration in relation with product distribution (K. Atsonios, 2015).....	22
Figure 14:	Reactor types (Kaltschmitt M. , Biokerosene, 2018)	23
Figure 15:	BTL from dry biomass input	26
Figure 16:	BTL from wet biomass input	27

Figure 17: PTL from CO ₂ and H ₂	28
Figure 18: Reaction temperature for the different reactor types	29
Figure 19: Direct DME production from syngas.....	30
Figure 20: DME production with methanol production step.....	30
Figure 21: DME production from CO ₂ and H ₂ input.....	31
Figure 22: Top 20 jet fuel consumers 2018 (indexmundi, 2019)	35
Figure 23: World map of kerosene consumption (ChartsBin, 2016)	35
Figure 24: The 6Ws model	36
Figure 25: Airports fuelling SAF (AviationBenefitsBeyondBorders, 2019).....	37
Figure 26: Relation of Scale with TCI	54
Figure 27: BTLd TCI for several production scales	56
Figure 28: PTL TCI for several production scales	58

LIST OF TABLES

Table 1: Properties of fuels according to ASTM D1655 (ICAO, Sustainable Aviation Fuels Guide, 2018)	9
Table 2: Potential pathways considering DMT's boundaries.....	16
Table 3: House of Quality.....	17
Table 4: Ranking of SAF production routes based on House of Quality	18
Table 5: Ranking of pathways to be researched	19
Table 6: Overview of the main characteristics of FT catalysts (Huwe, 2017)	20
Table 7: Biogas composition based on the gasification agent (Kaltschmitt M. , Biokerosene, 2018)..	24
Table 8: Product distribution from LTFT jet fuel refinery (Klerk, 2010).....	25
Table 9: Product distribution from HTFT jet fuel refinery (Klerk, 2010)	25
Table 10: Distribution of the final products of LTFT and HTFT synthesis (Kaltschmitt M. , Biokerosene, 2018)	26
Table 11: Reactions for DME production.....	29
Table 12: Scale factors	33
Table 13: Ranking of busiest Airports of 2019 (Chrisman, 2019)	38
Table 14: Experimental TBP results for North Sea Condensate (Curtis H. Whitson & Michael R. Brule, 2000)	48
Table 15: Required feedstock for BTL process from dry and wet biomass	50
Table 16: Required feedstock for 1000L synthetic kerosene from CO ₂ and H ₂	51
Table 17: Required feedstock for DME production from CO ₂ and H ₂ - scaling up.....	52
Table 18: BTLd TCI for several production scales	53
Table 19: BTLw TCI for several production scales.....	55
Table 20: PTL TCI for several production scales.....	57

SUMMARY

The sector of aviation is considered a significant contributor to GHG emissions, being responsible currently for the 2-3% of the manmade CO₂. According to literature, if no action is taken, it is expected to reach 22% of the global carbon budget by 2050. In this respect, the sector plans to decrease the CO₂ emissions related to fuel combustion by promoting carbon-neutral growth from 2020, aiming to achieve a reduction of 50% below the 2005 levels by 2050.

According to literature, in the long-term, the aviation is turning towards electric power. The technology however is not yet mature enough to power commercial flights. The mid-step solution until electricity exploitation, is considered the promising technology of Sustainable Aviation Fuels (SAF). This technology presents the potential for the aviation sector to grow, while reducing the GHG emitted from aircrafts. SAF are produced from sustainable feedstock and are blended with Conventional Aviation Fuels (CAF). There are many technology routes to produce SAF, each one connected with the feedstock type. Considering their full lifetime, SAF emit around 80% less CO₂ compared to CAF.

According to EASA, SAF started being used in Europe by 2011; however, their market started growing the past years. Considering the commitments of the sector SAF market is expected to be one of the most active markets from 2020.

This research was conducted in favor of the R&D department of DMT environmental technology, a company acting in the biogas upgrading field. Their background together with their constant intention to keep up with the trends, induces the field of SAF an attractive one for the company to follow.

During this internship project, the different SAF production technologies were technically assessed, concluding to the most applicable for DMT. The Fischer – Tropsch synthesis (FTS) route, which exploits CO₂ and H₂ is considered the most relevant, followed by the FTS from biomass feedstock. The process was designed with process flow diagrams, while the feedstock-to-fuel efficiency was assessed by developing an excel tool. The process feasibility was assessed based on a 1000 L/d production plant, while the Total Capital Investment was calculated via the six tenth rule, showing that the wet biomass to fuel process is the most economically feasible. Finally, the focus market was assessed according to a stakeholder analysis.

The result is that the most relevant pathway for DMT implies the PTL from CO₂ and H₂.

1 INTRODUCTION

Since the Industrial Revolution, the energy production is predominantly related to the combustion of fossil fuels. Their characteristics as fuel, encompassing cost, abundance, transportation and storage convenience, have been the reason for their intense exploitation as energy source. Currently, their combustion provides more than 70% of the worldwide energy, reaching about 134,000 TWh of energy production in 2017 (Ritchie & Roser, 2019). The fossil fuels combustion though, is responsible for the increased concentration of particles -CO₂, NO, CH₄, etc.- in the atmosphere, which promote the occurrence of the “greenhouse effect”, leading to global temperature increase.

According to the IPCC the quantitative increase in CO₂ concentration in the atmosphere from the pre-industrial era (1880), is of the order of 130 ppm (reaching 410 ppm to date) and taking into consideration the increasing trends of population and economy, the atmospheric CO₂ concentration is expected to keep rising. This concentration is already affecting the mean global temperature, which according to J.M. Ketzer (Ketzer, 2014) has been increased for about 0.8 °C the last centuries.

The International Energy Agency supports that about 32.8 Gt and 33.4 Gt of CO₂ related to fossil fuels combustion were emitted in 2017 and 2018 respectively (IEA, 2019). The same IEA research presents also that 8 Gt of the total CO₂ in 2018 comes from the transportation sector, where 12% relate to the aircrafts (ATAG, facts & figures, 2019). This percentage is translated into 895 Mt of CO₂ emitted in 2018 (ATAG, facts & figures, 2019). The air traffic stats and the increasing passenger numbers (50% increase in 2017 compared to 2005) (EASA, European Aviation Environmental Report 2019, 2019), demonstrate the rising trend of the sector. In addition, according to Eurocontrol (Eurocontrol, 2015), the flight numbers are expected to increase by 1.9%, by 2040. According to UNFCCC, the aviation related CO₂ emissions have grown about 83 Mt since 1990, reaching 171 Mt in 2016 and it is expected to double until 2050. The main pollutants from combusting fossil-based kerosene are carbon dioxide, nitrogen oxides, sulfur oxides and carbon monoxide (EASA, European Aviation Environmental Report 2019, 2019).

The Global Economy published in 2019 (theglobaleconomy, 2019) that about 111,000 barrels per day, constituted the global average jet fuel consumption in 2018. According to the same source, the Netherlands are placed 13rd in the global jet fuel consumption, with 83 barrels per day (theglobaleconomy, 2019).

Figure 1 presents the amount of kerosene consumed together with a forecast until 2040 (Kaltschmitt M. , Biokerosene, 2018).

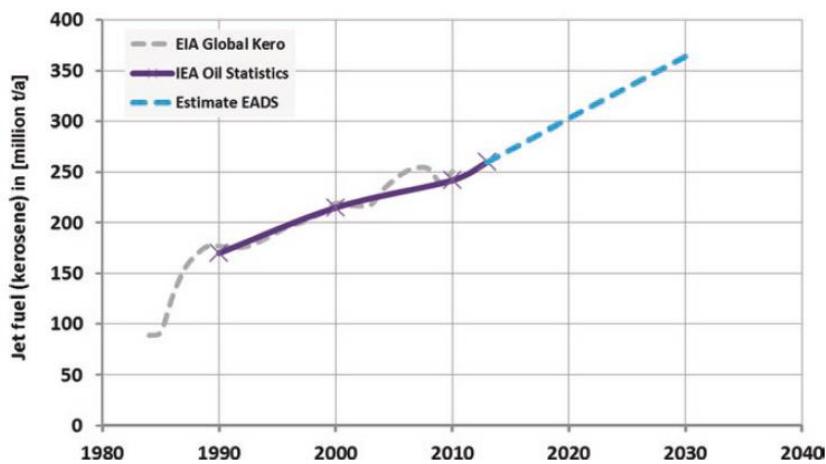


Figure 1: Kerosene consumption forecasts (Kaltschmitt M. , 2018)

In order to prevent this boost in GHG concentration in the atmosphere, green fuels have to be introduced in the aviation sector. According to IATA (IATA, 2015), electric energy is the future of

aviation fuels. There are already projects of electric powered aircrafts; however, the technology is not considered mature enough to sustain the commercial aviation. It is predicted that electricity will be available as far as 2040 and 2050 (IATA, 2015). A proven method to sustain and reduce the GHG emissions of aircrafts until 2050 is considered the utilization of Sustainable Aviation Fuels (SAF).

SAF are non-fossil-based fuels, which can be blended with conventional kerosene without any equipment modification requirement. They are also mentioned as “bio”, “synthetic”, “green” or “drop-in” aviation fuels, because of their feedstock nature. Dry or wet Biomass, captured CO₂ (Carbon Capture and Utilization) and H₂, municipal wastes or waste fats and oils constitute feedstock for SAF production (Kaltschmitt M., 2018). The latter name of SAF relates to their principle of utilization, since they are dropped-in and mixed with conventional jet fuels. Their blending percentage varies according to the different type of SAF. The SAF utilization will reduce the overall CO₂ emissions in regard of their whole footprint (from production to combustion). According to IATA (IATA, Environment, 2019) the CO₂ reduction can reach even 80% compared to fossil kerosene in some cases.

1.1 Popular Jet fuels

Jet fuels or aviation fuels are a combination of different long chain hydrocarbons. The main hydrocarbon groups composing the jet fuels are paraffins, olefins, napthenes and aromatics (Heminghaus, 2006). In order Jet fuels to be commercially applied, they should meet specific criteria (Table 1):

Property	Comment	Value or range
Density @ 15°C		775.0 – 840.0 kg/m ³
Flash point	Lowest temperature at which vapours of the material will ignite, when given an ignition source	min. 38°C
Freezing point	Temperature at which wax crystals formed in the fuel as it cools completely disappear when the fuel is rewarmed	max. -47°C
Aromatics content	Related with smoke and soot formation	max. 25%, volume
Sulphur content	Produces harmful emissions	max. 0.30%, mass
Net heat of combustion	Energy liberated when completely burned, at constant pressure	42.8 MJ/kg

Table 1: Properties of fuels according to ASTM D1655 (ICAO, Sustainable Aviation Fuels Guide, 2018)

The most popular jet fuels are considered the Jet A, Jet A-1 and JP-8. The first one is popular in the USA, while Jet A-1 is used for the rest of the world. JP-8 is the military version of Jet A-1, with anti-icing and anti-corrosion supplements, and it fuels the NATO aircrafts (Heminghaus, 2006). There are also JP- and JP-5 being exploited by the air force, however JP-8 is the kerosene based aviation fuel (Kaltschmitt M., 2018). According to Pires (Anamaria P. P. Pires, 2018), jet fuels carbon atom composition varies from C₇ to C₁₇ with the shorter fraction representing the military fuel.

1.2 Host Organization

The research was conducted in favor of the Research & Development (R&D) department of DMT environmental technology. The company occupied the leadership in biogas upgrading and conditioning world market, with lot of technological installments globally. In addition, DMT acts in the field of hydrolysis. The product-technologies of DMT are:

- the Carborex® MS, a membrane technology that separates carbon dioxide from methane.
- the Sulfurex®, a technology purifying syngas from hydrogen sulphide (H₂S), in order to present corrosion problems,
- and the Turbotec® which through thermal hydrolysis enhances the performance of the anaerobic digestion.

DMT is a company operating towards (in favor of) a more sustainable future; with the outer purpose associating with the environmental cleanup (dmt-et, 2019).

1.3 Problem statement and research objectives

The outer problem of this research associates with the increasing trends of GHG concentration in the atmosphere. SAF constitute a verified method to achieve reduction of CO₂, NOx, CH₄, N₂O, CO and SO₂, particles, produced from conventional jet fuel combustion (ATAG, Air Transport Action Group, 2018). The final step of the sustainable aviation trajectory is believed to be the utilization of electricity (1 Introduction). In long-term, batteries will substitute kerosene and bio-kerosene, presenting zero emissions. Norway has already announced all the domestic flights will be electrically powered by 2040 (Irfan, 2019). There are already on-going plans, tests and research for electric airplanes (Eurocontrol, 2015). In short-term though, bio-kerosene will subsidize the conventional fossil-based fuels until the technology is mature enough to utilize electricity.

This research was conducted in favor of the R&D department of DMT; in respect of investigating the company's prospect of entering the SAF market. The potential pathways for SAF production had to be evaluated in order to conclude to the one (or more) production paths suitable for DMT to intervene. Therefore, a research question with sub-questions can be derived:

- What is/are the most relevant technology/technologies for DMT to produce SAF?
 - What is the technical assessment?
 - What is the feedback-to-fuel efficiency?
 - What is the economic value?
 - What should be the focus market of the final product?

In addition, the potential strategy of DMT in the SAF boundaries will be assessed. Based on DMT, the potential strategies vary:

1. providing already existing DMT technology for a SAF production process, or
2. developing new technologies (new for DMT) for the SAF production process, or
3. developing-combining technologies to produce a complete SAF production process.

The first option is feasible by introducing the cleaning tecnology (Sulfurex), since the biogas-upgrading technologies can be provided for particular SAF production pathways. The second option encompasses the development of new gas-related technologies, further than the field of biogas conditioning e.g. reactors, catalysts, etc. According to the third case, the company will be providing the knowledge in order to collect and combine the complete SAF production route. The units-parts of the route will be mainly purchased from external manufactors.

This paper will present an analytic and detailed outline and evaluation of the potential routes to be followed, based on the company's background. In additiona and according to the research question, further aspects will be taken into consideration (technology, market, economy) to reach the final SAF production pathway/pathways suitable for DMT to follow.

1.4 Methodology

In order to attain an integrated view of this topic, this research took into consideration several variables that can be classified into three main categories: Finance, Marketing and Product Development & Engineering. Therefore, various methods related to these three categories were applied.

The implemented methodology, is demonstrated in respect of the research question and the sub-questions:

To start with, for the product development research, the "House of Quality" (HoQ) is applied between the potential SAF production pathways that can be followed from DMT. The HoQ is a method to

conduct a quick assessment between several technologies. The outcome of HoQ is a ranking of the options based on specific requirements. In order to attain a better image of the production processes, they are designed via “PFD” diagrams. “Technology Feasibility” was conducted to present the technical aspects of the potential methods and their system boundaries. The feedstock to fuel efficiency for each route was investigated by literature research and stoichiometry application. In addition, an excel tool calculating the feedstock required for a specific pathway and feedstock was formed. For the finance part, the rule of six-tenths was applied based on reference plants acquired by literature. This is an empirical method commonly used by the industry to calculate cost in relation with scale. Then, an excel model was formed to calculate the Total Capital Investment for each selected scale for every SAF production technology.

Finally, the potential markets were investigated and assessed. In this respect, the methods of “6 W’s End-customer’s Requirements” was applied and a “stakeholder’s analysis” was conducted. The first one relates to problem stating, while answering basic market-associated questions. The stakeholder analysis executes an investigation of the current and future market attributes, considering the various influences and end-buyers (geography, politics, taxation, etc.).

2 SAF PATHWAYS

2.1 Regulatory for SAF

There is a variety of regulations related to aviation, extending from technical quality and safety codes to environment. Several organisations relate to this regulatory framework, like the International Civil Aviation Organization (ICAO), the European Civil Aviation Conference (ECAC), the European Aviation Safety Agency (EASA) and the Eurocontrol. In order to introduce a new product in the market of aviation fuels, it has to go through the inspection of the American Society for Testing and Materials (ASTM). ASTM is the institution that certifies the use of a new jet fuel type for commercial use. The certified ASTM civil drop-in fuels should meet the properties of Jet A-1 (Table 1). In regard of the military fuel, NATO exceptionally certifies it through the DefStan 91-91 code (ICAO, Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme, nd). ASTM is also authorizing the blending percentage of conventional fuels with each particular “drop-in” fuel. The blending ratio relates with the specific product properties amount of CAF used. The blending occurs before the fuels are stored in the airport (Kaltschmitt M. , 2018). Environment related policies have been also established for aviation fuels promoting the SAF. Some of them are considered the CORSIA, which is a policy addressing the CO₂ increase and the RED I and II, related to the use of renewables (ICAO, Sustainable Aviation Fuels Guide, 2018).

2.2 Overview of SAF production technologies-pathways

The ASTM has currently approved six SAF production pathways. Different types of feedstock-inputs and different blending percentages characterize these methods. The SAF production pathways are listed below (Neuling & Kaltschmitt, 2014), (Kaltschmitt M. , 2018):

- Hydrotreated Esters and Fatty Acids (HEFA)
- Alcohol-to-Jet (AtJ)
- Direct Sugar to Hydrocarbon (DSHC)
- Hydrotreated Depolymerize Cellulosic Jet (HDCJ)
- Co-processing
- Fischer-Tropsch (FT)

Another potential SAF is the Dimethyl ether (DME), however it is not yet certified by ASTM. Summarizing, the certified technologies are the HEFA, the FT and the AtJ. The other three exploit the principles of the previous technologies.

2.2.1 Hydrotreated Esters and Fatty Acids (HEFA)

Through HEFA, vegetable oils and fats are processed and treated into SAF. The oils-feedstock of this process can be used cooking oil (or fats), oil-rich organisms (algae, Jatropha, camelina) (Kaltschmitt M., 2018). HEFA method encompass three main process steps:

The oils are firstly *hydrogenated* in order to clear away the oxygen. As the content of H₂ decreases, the formation of carbon monoxide is promoted (*Decarbonylation*). When H₂ quantity is very low, carbon dioxide starts to form (*Decarboxylation*) (Figure 2) (Kaltschmitt M., 2018).

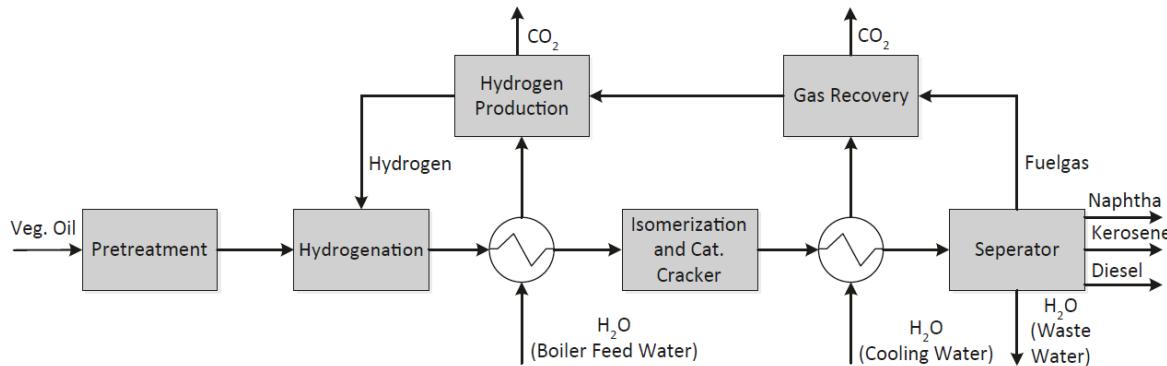


Figure 2: HEFA PFD (Kaltschmitt M., 2018)

HEFA is the most technically mature method to produce SAF. Since it was the first one to be certified, it is considered the most commercialized and yet the most popular. Therefore, HEFA synthetic paraffinic kerosene has powered most of the “green-fuel” flights to date (IRENA, Biofuels for Aviation: Technology brief, 2017). According to Kaltschmitt (Kaltschmitt M., 2018, p. 719), there is already quite a market associated to HEFA. In Finland, Neste produces about 38,000 t/a, UOP, Alt Air and Emerald Biofuels are some of the most significant producers in USA (Kaltschmitt M., 2018, p. 719).

- The blending ratio of HEFA is considered 50%.

2.2.2 Alcohol-to-Jet (AtJ)

Alcohol-to-Jet exploits mainly ethanol and butanol, derived from sugar (sugar canes, corn, and wheat) fermentation. The process of producing jet fuels via AtJ follows three main steps. The product is first fermented, then dehydrated and oligomerized.

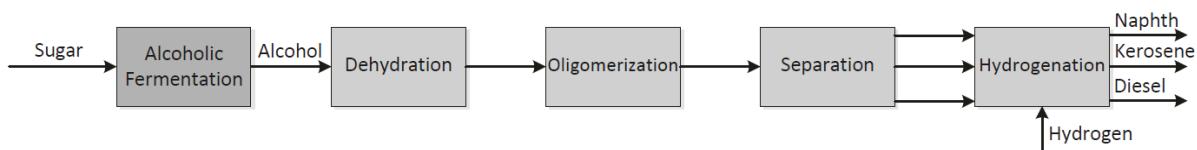


Figure 3: ATJ PFD (Kaltschmitt M., 2018)

Biofuel production via the ATJ route is currently market implied from the American company GEVO. The GevoATJ jet fuel, produced from the conversion of higher alcohols has been supplying Chicago airport since November of 2017 (GEVO, 2019). The Finish Company St1 Nordic Oy, has already announce the future specifications of the AtJ plant, for developing higher hydrocarbon products (ST_1, 2019). Terrabon and LanzaTech are also acting in this field (Kaltschmitt M., 2018, p. 720).

- The blending percentage of this method is 30%.

2.2.3 Direct Sugar to Hydrocarbon (DSHC)

Sugar molecules from sugar beets, sugar canes, lignocellulos etc., turned into hydrocarbons, through fermentation. During this process, microorganisms-enzymes-funguses produce hydrocarbons from

sugar yeast. These hydrocarbons are called Farnesene. The Farnesene is hydrotreated and upgraded to Farnasane. The final product can be used as jet fuel (Figure 4). (Kaltschmitt M. , 2018)

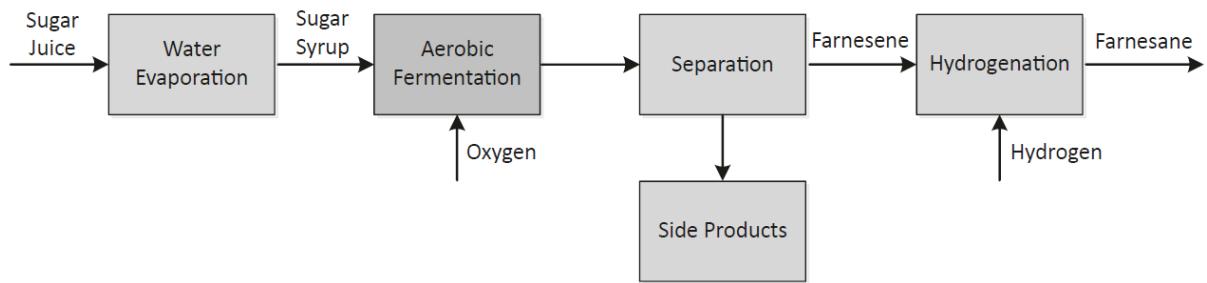


Figure 4: DSHC PFD (Kaltschmitt M. , 2018)

Amyris, Solazymes and LS9 are the most significant companies acting in this production method. Their operating plants production produce respectively 40000, 50000 and 700 tons per year. They also present scaling up future plants.

- The bio-fuels produced via this pathway can be blended in a percentage of 10% with the conventional fuels.

2.2.4 Hydrotreated Depolymerize Cellulosic Jet (HDCJ)

Through pyrolysis, this method implies the conversion of biomass into crude oil. The biomass is pretreated e.g. torrefied, dried and then goes through pyrolysis. The product then is hydrotreated with H₂ input and separated into the different carbon chain fractions. This process is characterized by low rates of kerosene production (Figure 5) (Kaltschmitt M. , 2018).

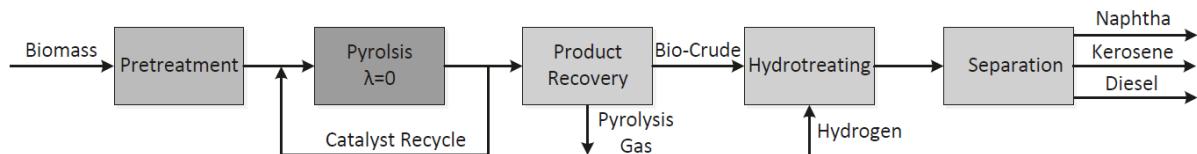


Figure 5: HDCJ PFD, through pyrolysis (Kaltschmitt M. , 2018)

Kior is considered the most significant company implying this method, with 7800 t/a produced in USA.

- The blending percentage of HDCJ is 50% (Lamoureux, Lew, & Biddle, 2014).

2.2.5 Co – processing

This method can be applied in relation with HEFA and HDCJ. The method of Co-processing associates with the oil mid-product of the HEFA and HDCJ processes. Oils produced from pyrolysis are blended with reach paraffinic fats-oils, resulting in jet fuels production (highly depended on the type and ratio of the blended oils). Additionally, the co-processing can be integrated in the fossil fuel production. Co-processing is not generally considered as a pathway to produce fuels than a way to blend them.

2.2.6 Fischer-Tropsch Synthesis (FTS)

Fischer-Tropsch (FT) is a catalytic chemical process to produce liquid fuels from syngas. The main principle of FT process is considered the production of liquid hydrocarbons from biomass derived syngas or from combining CO₂ and H₂, or from coal/gas. These methods are categorised to Biomass-to-Liquid (BTL) the first, and Power-to-Liquid (PTL) the latter. The products of FTS vary from carbon chains of five atoms and greater (C₅₊). The carbon chains can be formed continuously until the reaction is stopped.

2.2.6.1 BTL

The Biomass-to-Liquid process converts solid wet or dry biomass into biogas through two particular methods, the gasification and the anaerobic digestion.

2.2.6.1.1 BTL – GASIFICATION

The BTL through gasification exploits solid, dry biomass mostly derived from lignocellulos and woody biomass in general. The process starts by biomass pre-treatment, which varies from crushing, pelleting, and drying. Via gasification step, biogas is produced. The biogas is then upgraded to synthesis gas, which is a composition of H₂ and CO. The ratio of the later building blocks is adjusted and syngas enters the FTS reactor (Figure 6) via gasification PFD .

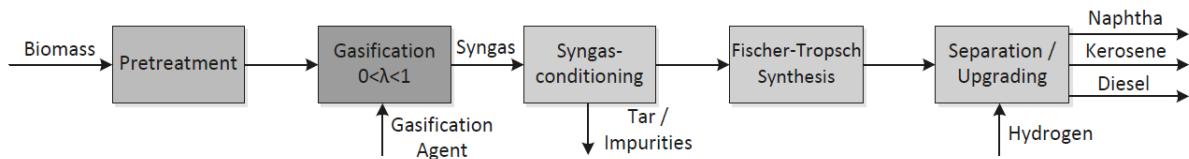


Figure 6: BTL via gasification PFD (Kaltschmitt M. , 2018)

2.2.6.1.2 BTL – ANAEROBIC DIGESTION

In this type of BTL, biogas is produced through an anaerobic digester. The input-feedstock of this method is generally wet biomass, varying from municipal waste to manure. The process does not require any pre-treatment to the feedstock and the produced biogas does not contain tar and char as the one from gasification. The process after the digester preserves the same primary steps as the one with gasifier. The syngas is conditioned, adjusted and introduced in the FTS to produce higher hydrocarbons (Naqi, 2018) (Figure 7).

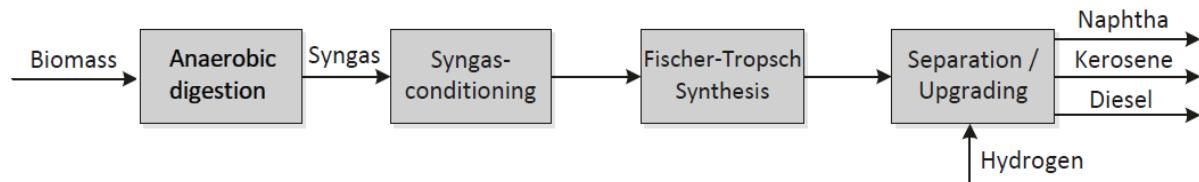


Figure 7: BTL via anaerobic digestion PFD (Kaltschmitt M. , 2018)

Significant currently operating BTL plants are producing in principle FT diesel. Shell's BTL plant in Qatar and Malaysia and Sasol's plant in Qatar (Boerigter, 2006). The European demonstration projects are: from GreenSky, which was announced at 2016 to produce bio-jet for British Airways and biodiesel (50000 of both fuels annually). The BioTfuel project from TOTAL in France, which operates from 2012. The Fulcrum Bioenergy and Sierra Biofuels cooperation project announced in 2014, which scopes to produce jet fuels and diesel (375 million gallons jet fuel over 10 years) and some other pilot plants (ETIP, 2019).

2.2.6.2 PTL

The PTL method illustrates the process of liquid fuel production from a power source. PTL can be achieved through fossil-based or sustainable power input. In order to design a sustainable PTL process, the power input should be from renewable sources (like wind, solar, etc.), exploiting the electricity for hydrogen production via electrolysis. Additionally, in respect of the sustainable process, captured CO₂ should be utilized. CO₂ is then turned into CO. Hydrogen and Carbon monoxide are combined to produce synthesis gas. The syngas is conditioned and adjusted to get into the FTS. This method can excessively contribute to aviation's environmental footprint (Figure 8).

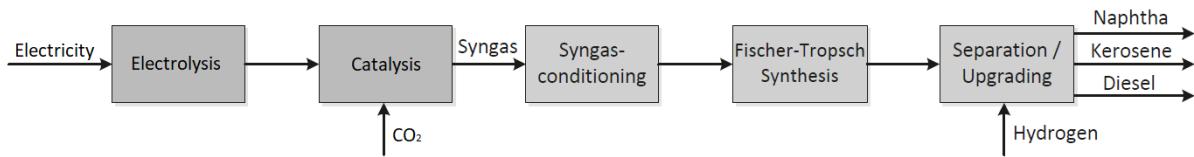


Figure 8: PTL PFD (Kaltschmitt M. , 2018)

The PTL process can be also carried out with non-renewable input. Coal is gasified, synthesis gas is produced and FTS synthesis is attained. This process however is characterized by a poor sustainability factor. In the case that the non-renewable source of power is natural gas, the process is called gas-to-liquid (GTL).

2.2.6.3 GTL

This process converts natural gas into long-chain liquid hydrocarbons either via the FTS method or through methanol production. In first case, the natural gas is processed, turned into syngas and enters the FT reactor. In the second case, the methane of natural gas goes through partial combustion to produce methanol (Figure 9).

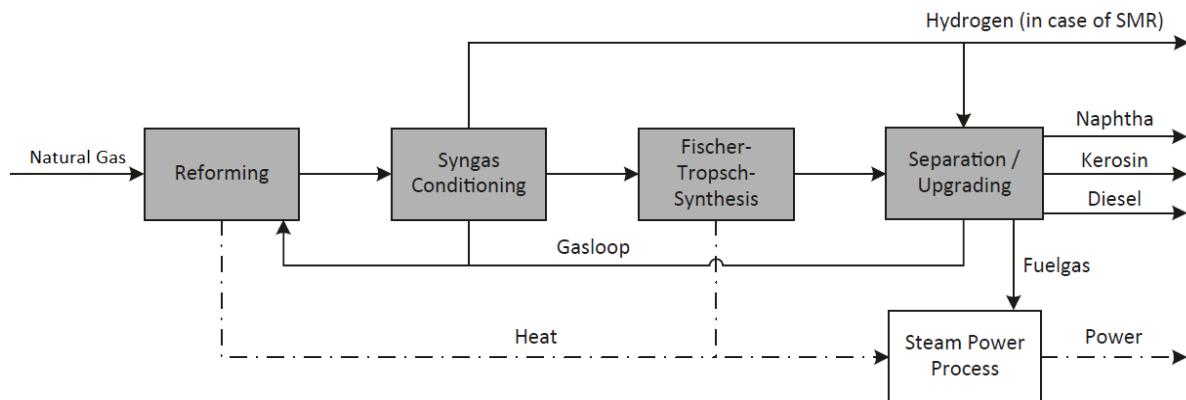


Figure 9: GTL PFD (Kaltschmitt M. , 2018)

- The blending percentage of the FTS products is considered 50%.

The company with the most intense activity in the field of FTS is Shell, with the Bintulu and Pearl installations, converting natural gas into liquid hydrocarbons. In addition, SkyNRG is currently planning to install an FTS process route in Rotterdam's airport.

2.2.7 DME

DME can be produced via two different ways, the indirect and the direct. The indirect route includes the production of methanol. The methanol is produced through conventional synthesis, and then dehydrated in an acid catalyst to form the DME. For this method, two different reactors are used. One for methanol synthesis and one for DME. In the direct path, DME and methanol are produced in the same reactor. The second DME synthesis method is more economically feasible (Spivey & Kumar, 2017). For these processes, the inputs can be biomass (syngas) or CO_2 and H_2 .

DME is not yet certified as SAF from ASTM; it presents a promising sustainable aviation fuel option though. There is no extended research conducted in regard of its blending percentage with conventional fuels; however, it will be evaluated as a potential choice for DMT, since the company supports the promising perspective of the fuel.

2.3 House of Quality

This method takes into consideration several customer requirements to determine the specifications of a variety of similar products (in this case SAF production routes) (Hauser & Clausing, 1988). These

specifications are attributed different weights based on their significance. The “House of Quality” is applied between the potential candidate-technologies to be followed by DMT, in order to clarify the most suitable route. The pathways are:

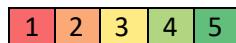
A.	Fischer-Tropsch from Dry Biomass input (FTSd) - biokerosene
B.	Fischer-Tropsch from Wet Biomass input (FTSw)- biokerosene
C.	Fischer-Tropsch from natural gas input (GTL)- synthetic kerosene
D.	Fischer-Tropsch from CO ₂ and H ₂ input (PTL)- synthetic kerosene
E.	Utilization of CO ₂ and H ₂ (DME-methanol)- synthetic kerosene
F.	Alcohol-to-Jet fuels with ethanol intermediate step (AtJ)- biokerosene

Table 2: Potential pathways considering DMT’s boundaries

*DSHC method was considered the same as AtJ since the feedstock exploited is the same, while the production technology is similar.

The *End-Buyer requirements* of the HoQ are considered theoretical parameters, which are monitored from the Buyers perspective. The requirements used are attributed weights according to their importance level (yellow column), based on the customer’s perspective.

Additionally, the scores of each method in the respective requirement criterion is presented in a scale number (1-5) with 1 being the least suitable:



Finally, the HoQ method will return a hierarchy from the most to least suitable method in respect of DMT’s influence.

Row #	Weight Char	Relative Weight	Importance (1-5)	Requirement (Explicit and Implicit)	Technology		A.	B.	C.	D.	E.	F.
1	■	11%	4	Complexity of the process (easy to operate)			4	5	4	3	4	2
2	■	14%	5	Current efficiency of the process (input/output ratio)			3	3	5	3	?	4
3	■	14%	5	Energy consumption of the process (operation)			2	4	1	1	1	2
4	■	8%	3	Process sensitivity to malfunctions			3	4	3	4	4	3
5	■	8%	3	Maturity of technology (readiness today)			5	5	5	4	2	4
6	■	8%	3	Sustainability of feedstock			3	3	1	5	5	3
7	■	11%	5	Availability of feedstock			3	3	2	5	5	3
8	■	9%	4	Potential production volume			3	3	2	4	4	2
9	■	8%	3	CO ₂ emissions of the entire process			3	3	2	5	4	3

10	I	3%	1	DMT reputation on the field	5	5	3	1	2	2
11	■	11%	4	Future exploitation in terms of sustainability (5-10 yrs)	3	3	1	5	5	3
12	■	11%	4	Current feedstock cost (cost/efficiency)	3	3	4	3	3	2
				Target (1-5)	3.5	3.5	3.5	3.5	3.5	3.5
				Rating	3.72	4.20	3.24	4.24	3.71	3.27
				Relative Weight	16.6%	18.8%	14.5%	18.9%	16.6%	14.6%
				Weight Chart						
				Position	3	2	6	1	4	5

Table 3: House of Quality

From Table 3, the best SAF production route for DMT is considered the FT from CO₂ and H₂. The method is considered quite fresh in the market, but the high sustainability of the feedstock and the promising future perspective places it in the first position. Additionally, it is based on an already mature technique, the FTS. The BTL via anaerobic digestion of wet biomass is second, because of the process maturity and low energy consumption. DMT has also along experience in the field of biomass treatment. The FTS of biogas from dry biomass is third, while the DME synthesis is fourth. DME production is based on a mature technique. DMT possess the principals of DME production from biogas, though the synthesis via CO₂ and H₂ could be quite new in respect of DMT's knowledge boundaries. Therefore, the score in the corresponding categories is close to average. In addition, DME is not yet certified for blending with conventional fuels. The market for DME as aviation fuel is not yet mature; though, positive perspective surrounds this method. The Alcohol-to-Jet method is one place above the last position, since it scores the average (3) and below in most of the requirements. GTL is considered the least suitable for DMT to follow. The detailed explanation and justification of the scores in each requirement is given in the excel file of HoQ accompanying this document. The final scores of all the methods are presented in Figure 10.

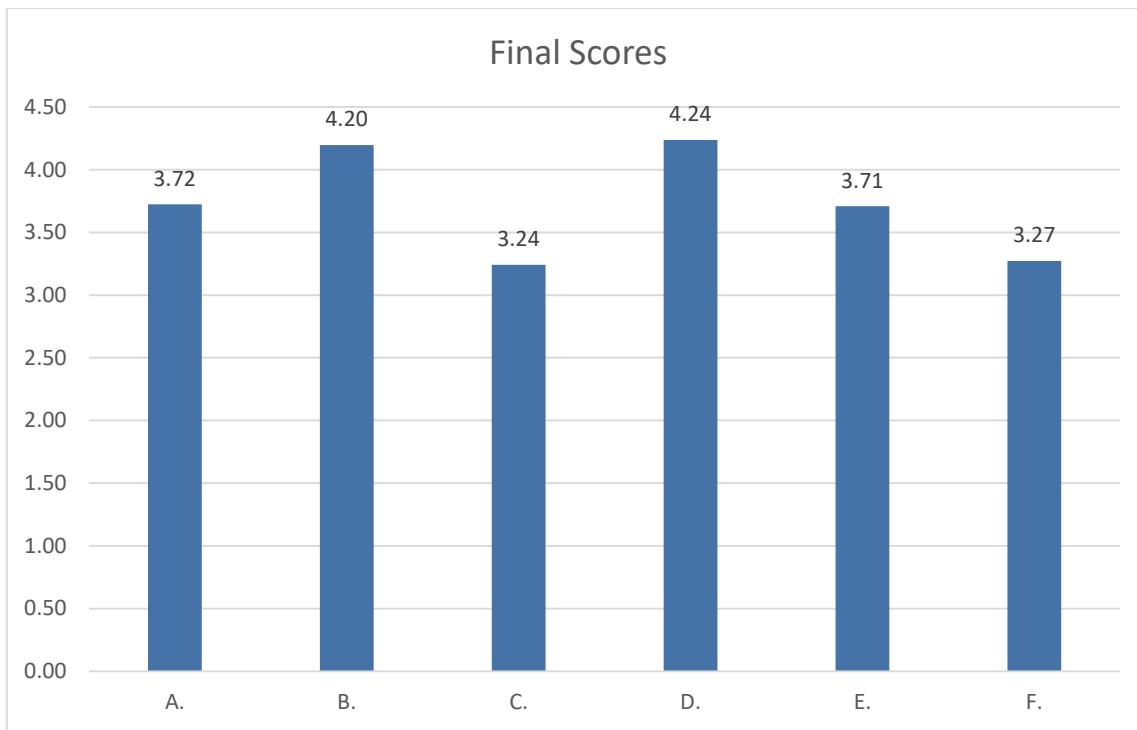


Figure 10: Final Scores of HoQ

Table 4 illustrates the ranking of SAF production pathways suitable for DMT to follow the HoQ application.

Ranking of SAF pathways	
1	Fischer-Tropsch from CO ₂ and H ₂ input (PTL)- synthetic kerosene
2	Fischer-Tropsch from Wet Biomass input (FTSw)- biokerosene
3	Fischer-Tropsch from Dry Biomass input (FTSd) - biokerosene
4	Utilization of CO ₂ and H ₂ (DME-methanol)- synthetic kerosene
5	Alcohol-to-Jet fuels with ethanol intermediate step (AtJ)- biokerosene
6	Fischer-Tropsch from natural gas input (GTL)- synthetic kerosene

Table 4: Ranking of SAF production routes based on House of Quality

In addition to the low score of AtJ in the HoQ, the ICAO's guide (ICAO, Sustainable Aviation Fuels Guide, 2018) includes a reference price for the production cost of the AtJ SAF through various methods and feedstock. According to Guolin (Guolin Yao, 2017), in an estimation of cost per produced liter, AtJ is currently the costliest fuel in the market, therefore DMT would not like to take interest with this type. HEFA the most economical (~\$1-1.25/L), while the BTL from gasification cost per liter produced is around \$1.5/L. AtJ cost varies based on the nature of feedstock from \$2 to \$6/L.

Since AtJ occurs in the fifth position of HoQ ranking and together with the high production cost, AtJ is excluded as a potential SAF pathway for DMT. Additionally, it is a method not suitable in regard of DMT's profile (1.2 Host Organization). Therefore, it is excluded as well from the research. Furthermore, GTL, which is placed in the bottom of HoQ ranking, will be excluded as well. The poor sustainability related to its feedstock's nature induces the option of GTL nonsensical as an alternative option for conventional aviation fuels.

Ranking of SAF pathways to be researched	
1	Fischer-Tropsch from CO ₂ and H ₂ input (PTL)- synthetic kerosene

2	Fischer-Tropsch from Wet Biomass input (FTSw)- biokerosene
3	Fischer-Tropsch from Dry Biomass input (FTSd) - biokerosene
4	Utilization of CO ₂ and H ₂ (DME-methanol)- synthetic kerosene

Table 5: Ranking of pathways to be researched

3 TECHNICAL DESIGN & ANALYSIS

The first overview of the potential pathways resulted to bottle-up (Table 2) to the most relevant SAF pathways according to DMT (Table 5). Fischer-Tropsch is the most relevant method qualified according to HoQ, in contrast, DME can be also implied from the company. In this chapter, these pathways will be presented from their technological point of view, e.g. Process Flow Diagrams, Technical Feasibility, System boundaries etc.

3.1 Technology feasibility

In this chapter, the two selected technologies will be presented in detail. In addition, with the PTL term will be referred only the CO₂ and H₂ input plants and not the GTL.

3.1.1 Fischer-Tropsch technology feasibility

According to paragraph 2.2.6, FTS is divided into four different routes; BTLw, BTLd, PTL and GTL. Every one of these processes follows the main principle steps of FTS. First, the synthesis gas is produced, followed by the FT synthesis and the product upgrading.

Synthesis gas or syngas is an important intermediate product in the chemical industry. Syngas is mainly utilized by the ammonia industry (Yunlei, et al., 2017). Other main applications of syngas are the production of hydrogen for refineries e.g. hydrogenation, methanol, and synthetic hydrocarbons. Syngas composition consists of hydrogen and carbon monoxide. Additionally, there is carbon dioxide contents, in various ratios. The composition and ratio of syngas components can be adjusted through several processes (steam reforming, partial oxidation, autothermal reforming) and is directly connected with the type of feedstock (de Jong, Higson, Walsh, & Wellisch, 2012). Syngas can be produced from biogas, from natural gas or from CO₂ and H₂ combination; therefore; the input process can be natural gas reforming (PTL), CO₂ from CCU and H₂ from electrolysis, gasification of biomass (BTL), biomass anaerobic digestion (BTL), or a combination of all the above.

The FT synthesis via CO₂ exploitation is based on the utilization of the principle of reverse water-gas shift reaction (RWGS), turning CO₂ into CO. The RWGS is illustrated as the direct way to turn CO₂ into CO. Another method to directly convert CO₂ into CO is through catalysts. The indirect way includes formation of methanol or reactions with syngas. The first method is considered more economically feasible and with decreased environmental impact. The CO₂ and H₂ input can be categorized as PTL

The syngas preparation depends on the feedstock, whose main requirement is to encompass carbon.

3.1.1.1 FTS reaction

To start with, the FTS reactor types are categorized to (Speight, 2011):

- circulation fluidized bed reactor,
- fluidized bed reactor,
- tubular fixed bed reactor
- and slurry phase reactor

The main principle of FTS is the conversion of syngas into a large range of linear hydrocarbons (Huve, 2017). The production of hydrocarbons from syngas relates to the hydrogenation of CO through metal catalysts. The catalysts used for the FT reactor can be iron, nickel, cobalt and ruthenium (Kaltschmitt

M., 2018). Together with the alkanes produced from FTS, there are also by-products like olefins and waxes.

Active metal	Price	FT activity	WGS activity	Hydrogenation activity
Nickel (Ni)	++++	+	+/-	+++++
Iron (Fe)	+	+	+++	
Cobalt (Co)	+++	+++	+/-	+++
Ruthenium (Ru)	+++++	+++++	+/-	+++

Table 6: Overview of the main characteristics of FT catalysts (Huve, 2017)

Based on Speight's study and according to DMT's requirements, the most suitable option of reactor type for producing middle distillates e.g. kerosene and jet fuels are the fixed and slurry – bed reactors.

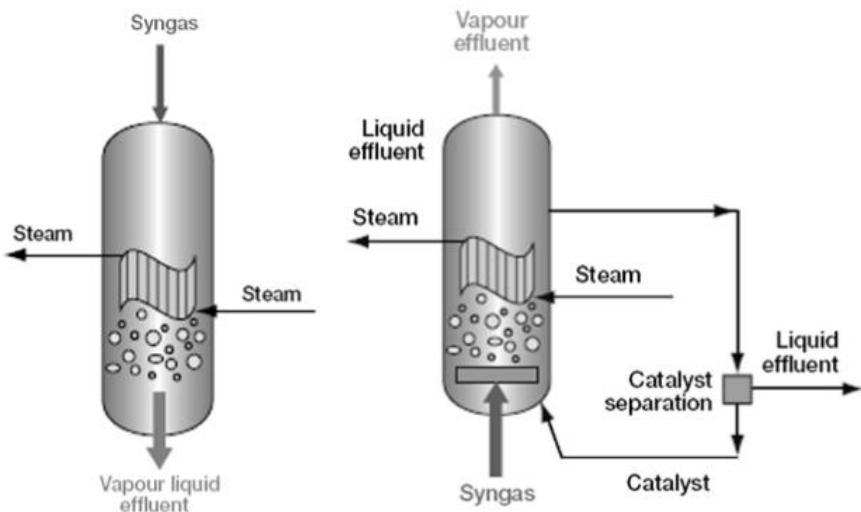


Figure 11: Fixed-bed and Slurry-bubble reactors (Speight, 2011)

The fixed-bed reactor provides the convenience of scaling-up the production by implementing more tubes; however, the production rate is limited per train, while its maintenance is considered economically, safety and timely not efficient (Speight, 2011, p. 314).

The slurry-bed reactor is the most promising type of reactor in respect of catalyst quantity and productivity. In addition, higher capacities of liquid can be produced per train (at least 15,000 bpd per train), while it can maintain constant production (Speight, 2011, p. 316). According to the same reference, the iron catalyst is considered more suitable for feedstock that produce syngas of lower hydrogen composition (biomass, residue, waste), while cobalt catalysts are more relevant for syngas richer in H₂, like the one produced from natural gas reforming (Speight, 2011, p. 311). For the CCU related CO₂ and electrolysis derived H₂, the most suitable type of catalyst seems to be the cobalt, since it presents high FT activity in acceptable price (Table 6).

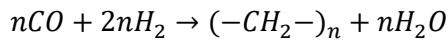
Both catalyst can be used for low temperature (LTFT) and high temperature FTS (HTFT), either for fixed-bed or slurry reactor. The operation temperature and type of catalyst are employed based on the desired product output. Specifically, the HTFT synthesis (300-350 °C) and iron catalyst are used to produce gasoline and lighter olefins. On the other hand, LTFT synthesis (200-240 °C) together with cobalt catalyst is relevant for producing heavier and linearly longer hydrocarbons (olefins and paraffins) (Huve, 2017). The operating pressure for both is adjusted to 20 – 25 bars (A. Lappas, 2016).

In case of biomass feedstock, Klerk (Klerk, 2010) supports that kerosene production via a Co-based LTFT reaction is easier to be achieved, in comparison with HTFT, while it is easier to refine the LTFT

product into jet fuel and kerosene. On the other hand, according to Zhang (Chundong Zhang, 2019, p. 295) the Fe-based HTFT FT synthesis is preferred for PTL.

Based on the above, for jet fuel/kerosene production via BTL processes, a slurry reactor with LTFT and Co-based is proposed while a Fe-based HTFT would be suitable for the PTL from CO₂ and H₂ input.

In this reactor, the syngas enters from the bottom, rises up as bubbles and reacts on the catalyst surface. The main equation for long hydrocarbon formation is (Huve, 2017):



Where (-CH₂-)_n are the hydrocarbons.

Light gases like unreacted syngas, methane or carbon dioxide move towards the upper part of the reactor and reenter the process in a previous step (Jager, 1994), therefore, stream recycling is achieved.

The major reactions occurred in the reactor during the FTS are presented in accordance with the related products (van der Laan, 1999):

1	Paraffins	$(2n + 1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$
2	Olefins	$2nH_2 + nCO \rightarrow C_nH_{2n} + nH_2O$
3	WGS	$CO + H_2O \leftrightarrow CO_2 + H_2$

The FTS reaction can operate continuously, producing long carbon chain hydrocarbons (C₅₊). The product selectivity of FTS can be interpreted with the Anderson-Schultz-Flory (ASF) statistical distribution. The latter demonstrates a probability of chain growth (α), which is associated with the chain growth rate (r_p) and the rate of chain termination (r_t). The r_t leads to the final product (Huve, 2017).

$$\alpha_n = \frac{r_{p,n}}{r_{p,n} + r_{t,n}}$$

The long-term FTS reaction causes poisoning and deactivation of the catalyst (Huve, 2017). Figure 12 illustrates the predicted probability for the distribution and fractions of products.

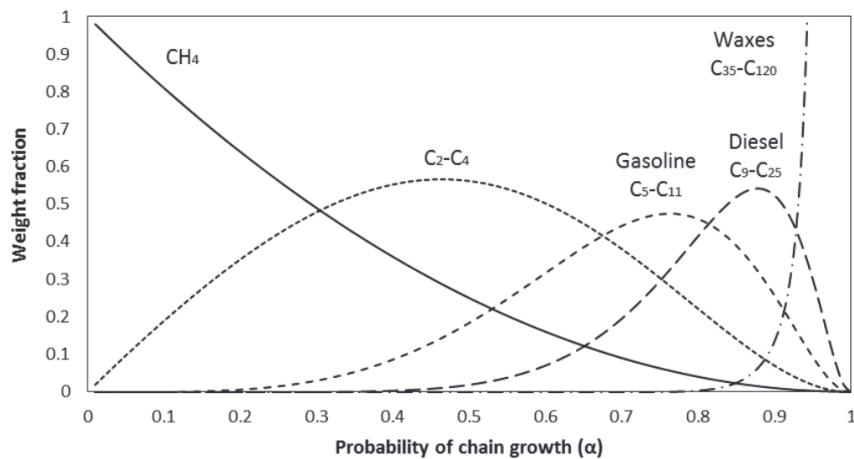


Figure 12: Chain growth probability of product distribution in FTS (Huve, 2017)

Short-chain hydrocarbons require low probability, since r_t presents greater value than r_p . On the other hand, long chain fractions have greater α value.

In addition, according to Atsonios (K. Atsonios, 2015) the chain growth probability, is connected with the partial pressures of the two gases during FTS (CO & H₂) together with the reaction temperature (Figure 13).

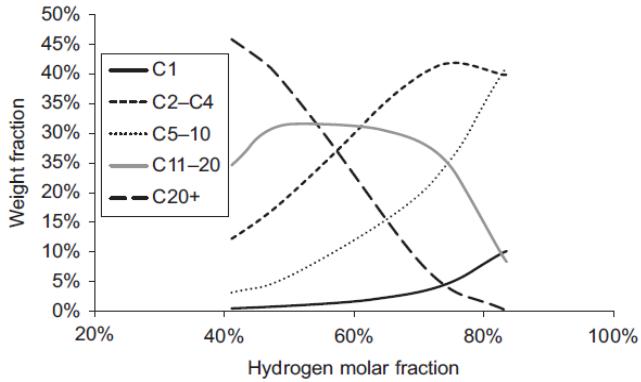


Figure 13: Hydrogen concentration in relation with product distribution (K. Atsonios, 2015)

Shorter hydrocarbon chains require less H₂ pressure, while for longer, the inlet H₂ should be introduced in the FTS at high-pressure values.

The reactor's volume – capacity is selected based on the desired production rate. In Appendix B is presented a variety of potential process production volumes and the reactor capacity should be selected in relation with the attributed production rate. Additionally, the excel file of process feasibility and scaling up, escorting this document, provides the capability to inspect every potential capacity.

3.1.1.2 Synthesis gas production and conditioning (before FTS)

In order the FT reactor to operate in its highest conversion yield, the syngas H₂:CO ratio should be close or equal to 2 (van der Laan, 1999). Syngas of this composition ratio is more efficiently converted into hydrocarbons through a Co-based reactor. In order to achieve this ratio, there are particular processes, based on the syngas nature:

- Water Gas Shift Reaction (WGS):
$$CO + H_2O \rightarrow CO_2 + H_2$$
- Reverse Water Gas Shift Reaction (RWGS):
$$CO_2 + H_2 \rightarrow CO + H_2O$$

WGS reaction implies the reaction of carbon monoxide with steam yielding carbon dioxide and hydrogen. This process is applied in order to reduce the CO amount, while increasing H₂. RWGS reaction scopes to the opposite. The WGS reaction is one of the reactions occurring in the FT reactor during the FT synthesis as side reaction (Huve, 2017).

Additionally, there are equipment units that can adjustment the H₂:CO ratio of syngas to the desired magnitude, e.g. the technology produced from Air Liquide[©] called ALaS (AirLiquide, 2019).

For converting biogas into syngas, there are several potential methods. The selection of biogas conversion process relates with the biogas composition.

- Steam Methane Reforming (SMR):
$$CH_4 + H_2O \rightarrow CO + 3H_2$$
- Autothermal Reforming (ATR):
$$2CH_4 + O_2 + CO_2 \rightarrow 3H_2 + 3CO + H_2O$$
- Partial Oxidation (POX) and Catalytic Partial Oxidation (CPOX):
$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO$$

These methods are applied for the BTL (both for BTLD and for BTLw) process, since existing methane has to be converted into syngas. The conversion steps are also included for PTL route from natural gas (GTL) or coal. In PTL from CO₂ and H₂, the CO₂ is converted to CO via an electro-catalyst or RWGS reaction and then H₂ is added to form syngas. Therefore, methane is not included in the later process. The syngas ratio for PTL from CO₂ and H₂ can be monitored and regulated from controlled provision of H₂ and CO₂.

The sulfur (S) and nitrogen (N₂) content of biogas is the primary cause of the catalyst deactivation and poisoning. In order to decrease, and even eliminate this poisoning effect, the removal of S and N₂ is required (Kritinger, 2002). Sulfur is met in biogas in the form of hydrogen sulfide (H₂S). Biogas produced via both ways (BTLD, BTLw) include H₂S. In this respect, the Sulfurex® is an equipment unit cleaning the syngas from Sulphur. Nitrogen has to be cleaned as well; therefore, another biogas conditioner for N₂ should be introduced. Sulfurex though requires low temperature biogas, therefore the latter has to go through cooler units first.

Before biogas is turned into syngas, it has to be conditioned. The steps of conditioning include the removal of sulfur and nitrogen. In addition, biogas conditioning differs in respect of its production way. The one produced from gasification contains tar and char, while tar and char are absent in the biogas produced from anaerobic digestion. Therefore, the extra conditioning step on biogas produced from dry biomass gasification addresses the tar and char removal. The equipment units implied for this purpose are called cyclones.

3.1.1.2.1 GASIFICATION

For the gasification step in BTLD, there is a variety of gasifiers to be used (Figure 14) (Kaltschmitt M. , Biokerosene, 2018):

- fixed – bed,
- fluidized – bed,
- entrained – bed,
- staged systems
- and plasma

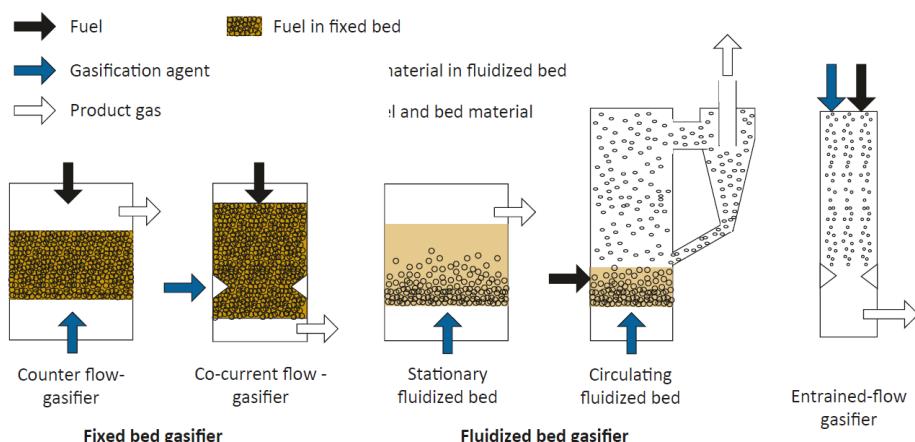


Figure 14: Reactor types (Kaltschmitt M. , Biokerosene, 2018)

The gasification agents are also in variety (Kaltschmitt M. , Biokerosene, 2018):

- oxygen,
- steam,
- CO₂,
- and mixtures of all the above

In case of BTLD, the selected gasifier is an Entrained Flow Gasifier. The gasification agent of this type is O₂, while according to Kaltschmitt (Kaltschmitt M., Biokerosene, 2018, p. 502), it is considered the most suitable gasifier type for the FTS process (Table 7). The O₂ for the gasification is collected from an Air Separation Unit (ASU) (Boerigter, 2006).

Compound	Unit	Oxygen gasification (entrained flow)	Oxygen/steam gasification (fluidized bed)	Steam gasification	CO ₂ gasification [10]
CO	[vol.-%]	40–60	20–30	20–25	35–45
CO ₂	[vol.-%]	10–15	25–40	20–25	25–35
H ₂	[vol.-%]	15–20	20–30	30–45	15–25
CH ₄	[vol.-%]	0–1	5–10	6–12	7–10
N ₂	[vol.-%]	0–1	0–1	0–1	0–1
H ₂ /CO ratio ^a	–	0.4	1	1.7	0.5
LHV	[MJ/Nm ³]	10–12	10–12	10–14	10–13
Tar content	[g/Nm ³]	<0.1	1–20	1–10	1–10

Table 7: Biogas composition based on the gasification agent (Kaltschmitt M., Biokerosene, 2018)

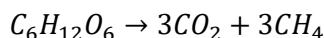
In order to provide better fuel quality, biomass is pre-dried and introduced in a torrefaction unit before enters the gasifier. The torrefaction process occurs at around 200 to 300 °C (Austin, 2010).

3.1.1.2.2 ANAEROBIC DIGESTION (AD)

The biogas produced from anaerobic digestion is clean from tar and char. It contains methane, carbon dioxide and monoxide, hydrogen, nitrogen and sulfur. The anaerobic digester exploits the reactions occurred from microorganisms in the absence of oxygen (Koyama, 1963). The bacteria promote the hydrolysis of the wet, organic wastes to produce biogas. It is considered a more economical option to produce biogas, in comparison with gasification. The chemical process of ad follows the consecutive steps:

- Hydrolysis,
- acidogenesis,
- acetogenesis,
- and methanogenesis (Bulletin, 2011).

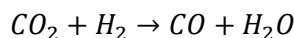
The overall process can be described in the following equation:



Anaerobic digestion process can be categorized based on different aspects, like temperature, spatial extend, solid content (Naqi, 2018, p. 7). Based on Naqi's study, a high-solid (HD-AD) single stage digester should be implied.

3.1.1.2.3 CO₂ FROM CCU AND H₂

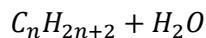
For the PTL process, the CO₂ can either be from CCU or from an air separator unit. In reality, the CCU is considered a more suitable source of CO₂ because great amounts can be gathered from the intense emissions of industrial chimneys. The hydrogen required is produced from an electrolyzer, powered by renewables turning the hydrogen into green. The CO₂ is turned into CO via an electrocatalyst or via RWGS reaction:



The syngas ratio is then adjusted and enters the FTS reactor.

3.1.1.3 Products upgrading and separation (after FTS)

After the FTS process, the output is separated into three distinct streams: water, fuel gas and liquid hydrocarbons:



Water has to be separated from hydrocarbons, which is accomplished via water separators. According to literature (Xiufeng Li, 2007), the Separatory Funnel is the most suitable type of separator for mixtures of two immiscible liquid phases, with different densities. Therefore, the denser hydrocarbons C_nH_{2n+2} will stay in the lower level, while water will be deposited in the upper part¹. Water is separated and recycled into the process.

The output-product stream of the FTS reactor contains also hydrocarbons with longer carbon chains than it is required for jet fuels and kerosene. The desired products of synthesis according to Pires (Anamaria P. P. Pires, 2018), are distributed from C_7 to C_{17} , including every type of jet fuels that is being assessed in this research (Jet A, Jet A-1 and JP 8). The long-chain products (C_{20+} - waxes) are cracked into shorter though hydrocracking. Excess H_2 is introduced during the hydrocracking process (high $H_2:HC$ ratio) to produce lighter hydrocarbons. The utilized H_2 can be produced from electrolysis or through recycling of waste streams derived from other process step e.g. PSA (K. Atsonios, 2015). Additionally, conversion of naptha, distillate and residues into kerosene can boost the jet fuel production rate (Klerk, 2010). The hydrocracking process is more efficient in the LTFT process, while the low temperature synthesis products require less hydrotreating than those derived from HTFT (Klerk, 2010).

The final step of the process is the distillation, where the fuel fractions are separated. The distillation columns, which are used nearly in every refinery, separate the products based on their boiling point. The final products of the LTFT and HTFT jet fuel oriented refinery are presented in Table 8 and Table 9 respectively.

Product description	Total product ^a (mass %)	Transportation fuels (vol %)
hydrogen	0.0	—
methane	0.0	—
fuel gas	7.4	—
liquid petroleum gas	11.4	—
motor-gasoline (EN228)	19.6	26.4
jet fuel (Jet A-1)	57.0	73.6
diesel fuel (EN590)	0.0	0.0
unrecovered organics	4.3	—
water	0.3	—

^a Excludes H_2 , CO , CO_2 and H_2O from LTFT synthesis.

Table 8: Product distribution from LTFT jet fuel refinery (Klerk, 2010)

Product description	Total product ^a (mass %)	Transportation fuels (vol %)
hydrogen	0.1	—
methane	0.0	—
fuel gas	23.8	—
liquid petroleum gas	4.1	—
motor-gasoline (EN228)	18.2	30.7
jet fuel (Jet A-1)	43.0	69.3
diesel fuel (EN590)	0.0	0.0
unrecovered organics	10.5	—
water	0.3	—

^a Excludes H_2 , CO , CO_2 and H_2O from HTFT synthesis.

Table 9: Product distribution from HTFT jet fuel refinery (Klerk, 2010)

¹ A combination of the 22L funnel separators from Aldrich® could be used (SigmaAldrich, 2019).

Motor-gasoline and jet fuel are the transportation fuels that constitute the output stream of both refineries. Ethylene, propylene, α -olefins, alcohols, ketones, solvents, waxes and naptha are by-products that can also be exploited. The final product distribution of the two types of synthesis, LTFT and HTFT are presented in Table 10.

Component	LTFT	HTFT
in wt.-%		
CH_4	4	7
$\text{C}_2 - \text{C}_4$ olefins	4	24
$\text{C}_2 - \text{C}_4$ paraffins	4	6
Naphtha	18	36
Middle distillate	19	12
Wax	48	9
Oxygen containing compounds	3	6

Table 10: Distribution of the final products of LTFT and HTFT synthesis (Kaltschmitt M., Biokerosene, 2018)

3.1.2 Fischer Tropsch PFD

The illustrated PFDs present only the main equipment units for the FTS and DME processes, excluding compressors, heaters, and coolers, while the process recycles streams (H_2 and tail gases – unconverted gases). However, only the main reaction steps are presented.

The process flow diagrams (PFD) of the several ways to exploit the FT technology and produce liquid fuels are presented in this chapter. There are two main paths of FT according to the input. Biomass-to-Liquid from dry (BTLd) and wet (BTLw) biomass are presented first, followed by the Power-to-Liquid (PTL) from CO_2 and H_2 inputs.

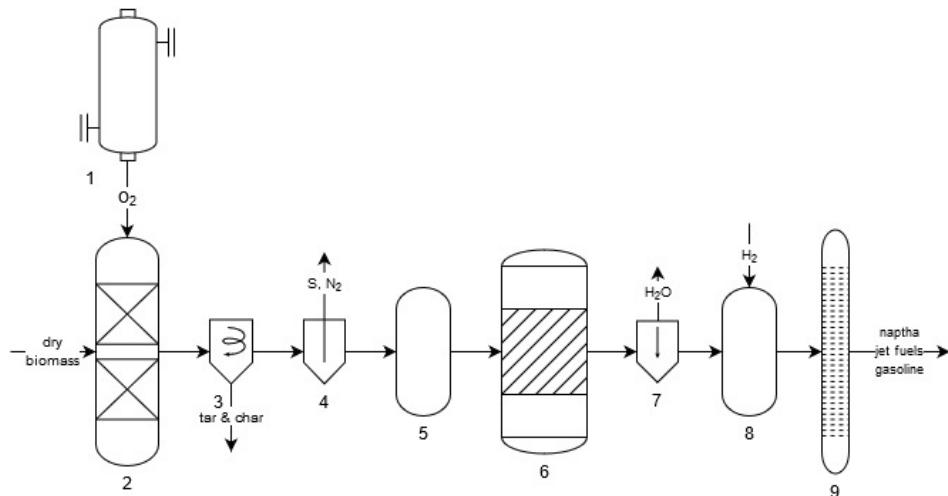


Figure 15: BTL from dry biomass input

Figure 15 equipment units				
No.	Unit	Explanation	Conditions	Reference
1	ASU	Providing the O_2 for gasification	1200 °C	(Frederik Trippe, 2011)
2	Gasifier	Biogas production from biomass gasification (Entrained Flow)	>1200 °C, 40 bar	(Kaltschmitt M., 2018)

3	Cyclone separators	Separation of tar and char	-	-
4	Biogas conditioning	Separation of sulfur and nitrogen from biogas	-	-
5	SMR	Conversion of biogas into syngas	~900 °C, 30 bar	(Y Zhu, 2011)
6	FTS reactor	Co-based FTS slurry bubble reactor	200-240 °C /20-25 bar	(Speight, 2011)
7	Separator funnel	Water separation from FT oil	-	(Xiufeng Li, 2007)
8	Hydrocracker	Cracking long chain hydrocarbons into shorter	~240 – 360 °C	(K. Atsonios, 2015)
9	Distillation column	Separating the FT products	-	(De Falco)

In the BTLd process the biomass can be pretreated before gasification. The biogas produced is conditioned to enter the FTS reaction. The products are separated from water, hydrocracked and exit in different

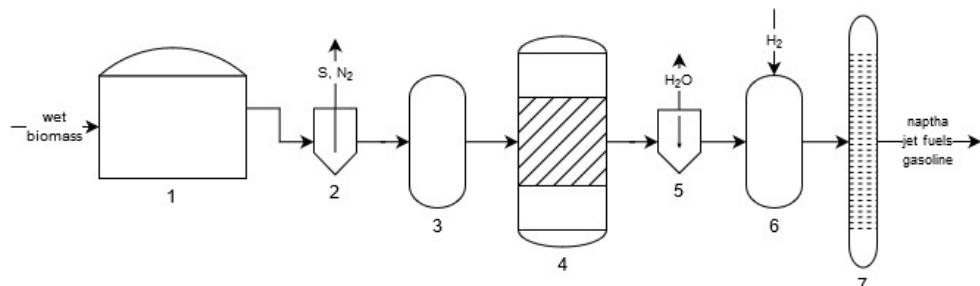


Figure 16: BTL from wet biomass input

Figure 16 equipment units				
No.	Unit	Explanation	Conditions	Reference
1	Digester	Biogas production from wet biomass anaerobic digestion	HS-AD, single-staged 37-55 °C	(Naqi, 2018)
2	Biogas conditioning	Separation of sulfur and nitrogen from biogas	-	-
3	SMR	Conversion of biogas into syngas	~900 °C, 30 bar	(Y Zhu, 2011)
4	FTS reactor	Co-based FTS slurry bubble reactor	200-240 °C /20-25 bar	(Speight, 2011)
5	Separator funnel	Water separation from FT oil	-	(Xiufeng Li, 2007)
6	Hydrocracker	Cracking long chain hydrocarbons into shorter	~240 - 360 °C	(K. Atsonios, 2015)
7	Distillation column	Separating the FT products	-	(De Falco)

Wet biomass is digested and the produced biogas is converted into syngas to enter the FTS (Figure 16). The only difference with BTLd process steps occurred in the absence of cyclones for tar & char removal.

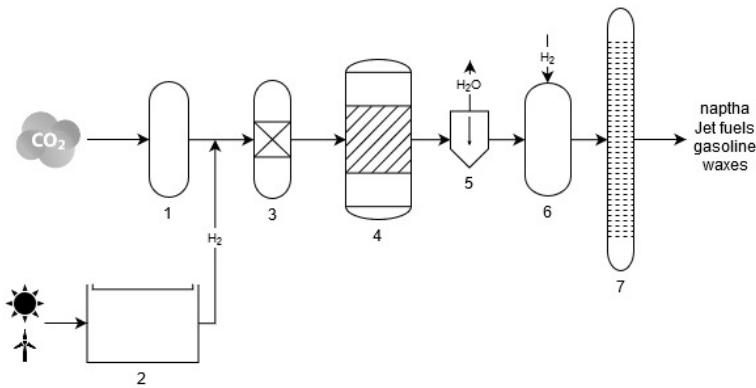


Figure 17: PTL from CO_2 and H_2

Figure 17 equipment units				
No.	Unit	Explanation	Conditions	Reference
1	Electrocatalyst or RWGS	Conversion of CO_2 into CO	200- 375 °C	(L.Pastor-Pérez, 2017)
2	Electrolyzer	Production of green H_2 through water electrolysis, with renewable energy	-	
3	$\text{H}_2:\text{CO}$ ratio adjuster	Adjust the $\text{H}_2:\text{CO}$ ratio	-	
4	FTS reactor	Fe-based FTS slurry bubble reactor	300-350 °C /20-25 bar	(Chundong Zhang, 2019)
5	Separator funnel	Water separation from FT oil	-	(Xiufeng Li, 2007)
6	Hydrocracker	Cracking long chain hydrocarbons into shorter	~240 - 360 °C	(K. Atsonios, 2015)
7	Distillation column	Separating the FT products	-	(De Falco)

Figure 17 illustrates the process flow diagram of the PTL route. CO_2 from CCU is converted into CO via an electro-catalyst (electro-catalyst presents a very high conversion efficiency, e.g. $\approx 90\%$). The latter uses atoms of Au and Cu to achieve this conversion (Tingting Zheng K. J., 2018). A RWGS reaction can be applied also instead of a catalyst. The H_2 required, is supplied from an electrolyzer, which is powered from renewables, therefore the product can be assumed “green”. The syngas composition ratio is adjusted close to 2 and enters the FTS. CO_2 and H_2 storage is required for this method.

3.1.3 DME technology feasibility

The information for the DME reaction were all provided by DMT. The company has broad knowledge and experience in the DME and methanol production from biogas; however, DME production from CO_2 and H_2 combination is considered a new field for her.

DME can be produced from CO_2 and H_2 , but also from biomass related syngas. The DME reaction occurs at $\text{H}_2:\text{CO}_2$ ratio from 2 to 4 (ideally 3). Furthermore, it can be produced also directly and indirectly. The indirect path encompass the methanol production step.

The gas enters the reactor at 220 °C and 35 bar. The reaction catalysts are either pellet or hybrid. The catalyst that will be used for the DME reactor is a Bi-functional catalyst. This catalyst is a combination of a methanol synthesis component (Cu/ZnO -based) and an acid (zeolite or alumina) catalyst at a ratio

of 1:1. The catalyst is designed to operate at high pressure and temperature around 50 °C so it does not cause any problem in the DME synthesis process. Problems might occur if we do not manage obtaining an effective cooling of the reactor, which may cause local peak temperatures and possible catalyst deactivation. The reaction process in the DME reactor includes both the production and dehydration of methanol.

According to DMT, the reaction conditions imply from temperature of 200 to 280 °C, to prevent the formation of methane, while the pressure is 30 to 70 bar. The reactors are categorized based on the reaction type, to Adiabatic, Isothermal and Membrane reactor.

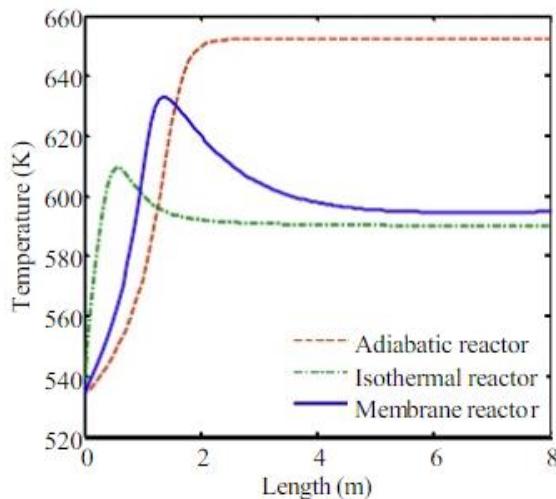


Figure 18: Reaction temperature for the different reactor types

Figure 18, illustrates the temperature profile inside the reaction zone in different types of reactor. At the entrance of the membrane reactor, temperature increases and hot spot develop as can be seen and then decreases slowly. This temperature reduction, in the second part of the reactor, leads to shift methanol dehydration reaction in the DME production.

Temperature of the outlet product is around 280 °C and the pressure is a bit lower than the inlet one. The dimethyl ether produced needs to be purified due to the presence of H₂O, CO₂, CH₃OH and traces of CO, CH₄, H₂ and O₂.

According to De Falco (De Falco), the reactions occurred in the DME reactor are presented below:

1	Methanol Formation from CO	$CO + 2H_2 \rightarrow CH_3OH$
2	Methanol formation from CO ₂	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
3	WGS	$CO + H_2O \leftrightarrow CO_2 + H_2$
4	Methanol Dehydration	$2CH_3OH \rightarrow CH_3OCH_3 + H_2O$
5	Overall	$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$

Table 11: Reactions for DME production

3.1.3.1 DME purification

The outlet stream from the reactor is 6 – 4 tons per hour containing DME, methanol, CO₂, water and traces of CO, CH₄, H₂ and O₂. After the reaction DME has to be purified.

In case of the feed entering the DWC reactor is between 4 and 6 tons per hour, we obtain around 25.23 mol per hour of DME (around 1,2 tons per hour).

DME production process implies two distillation columns. The first associates with the DME collection, will the second one separate methanol from water.

3.1.4 DME PFD

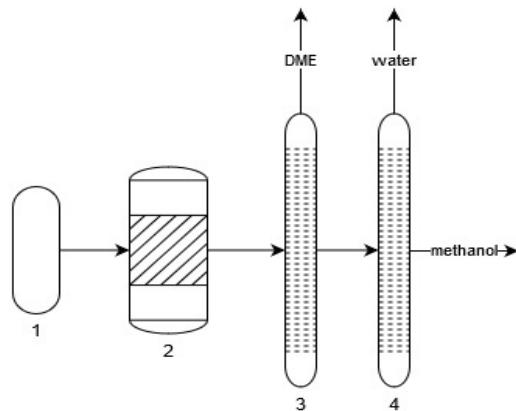


Figure 19: Direct DME production from syngas

Figure 19 equipment units				
No.	Unit	Explanation	Conditions	Reference
1	ATR	Conversion of CH ₄ to syngas and water, O ₂ input needed	~1000 °C, 25-29 bar	(Kaltschmitt M. , 2018)
2	DME reactor	Production of DME	200-280 °C/30-70 bar	(dmt-et, 2019)
3	Distillation column	Collection of DME	-	(De Falco)
4	Distillation column	Collection of H ₂ O and methanol	-	(De Falco)

Figure 19 illustrates the process flow diagram of direct production of DME from syngas input. Therefore, wet or dry biomass can be the feedstock. For that case, a gasifier or a digester is required to produce the biogas, followed by the respective biogas conditioning units. An Autothermal Reformer is implied for the biogas to syngas conversion. After the DME production, DME is separated and collected in the first distillation column, while water and methanol is collected at the second (De Falco).

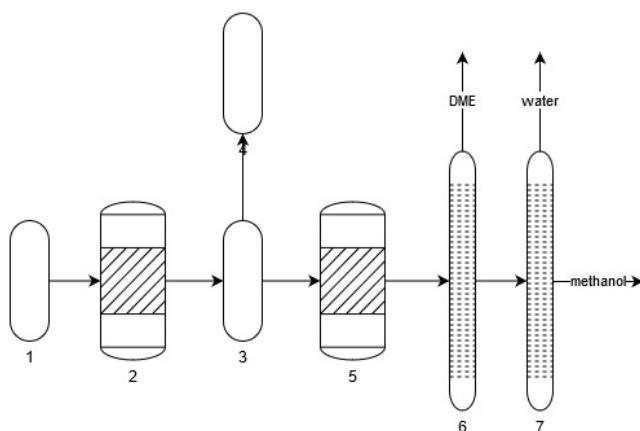


Figure 20: DME production with methanol production step

Figure 20 equipment units				
No.	Unit	Explanation	Conditions	Reference
1	ATR	Conversion of CH ₄ to syngas and water, O ₂ input needed	~1000 °C, 25-29 bar	(Kaltschmitt M. , 2018)

2	Methanol reactor	(Lungi) Production of methanol	150-280 °C/10-100 bar	
3	Separator funnel	Separates the methanol	-	(Xiufeng Li, 2007)
4	Methanol storage tank	Storing methanol	Based on plant scale	
5	DME reactor	Production of DME	200-280 °C/30-70 bar	(dmt-et, 2019)
6	Distillation column	Collection of DME	-	(De Falco)
7	Distillation column	Collection of H ₂ O and methanol	-	(De Falco)

Figure 20 presents the production process of indirect production of DME. The input is again syngas from biogas. The process is called indirect, because of the existence of a middle step of methanol (MeOH) production. Methanol can be either stored (methanol production process) or used to form DME via dehydration (CH₂OH). The two distillation columns function as in Figure 19.

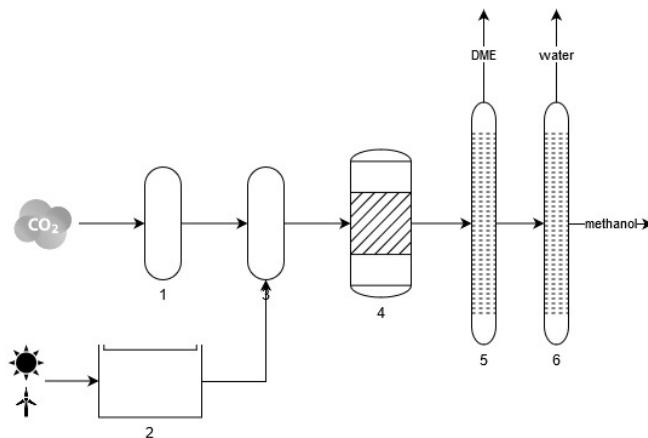


Figure 21: DME production from CO₂ and H₂ input

Figure 21 equipment units			
No.	Unit	Explanation	Conditions
1	Electrocatalyst or RWGS	Conversion of CO ₂ into CO	200- 375 °C
2	Electrolyzer	Production of green H ₂ through water electrolysis, with renewable energy	-
3	WGS	Adjust the H ₂ :CO ratio	-
4	DME reactor	Production of DME	200-280 °C/30-70 bar
5	Distillation column	Collection of DME	Distillation column
6	Distillation column	Collection of H ₂ O and methanol	-

CO₂ and H₂ can also constitute feedstock for the DME process. CO₂ collected from CCU and green H₂ can be combined to yield syngas. The WGS reaction adjusts the ratio of H₂:CO between 2 and 4 and the distillation columns collects DME, MeOH and H₂O.

* For both DME and FTS processes, the potential pathways can be combined and form one output stream in the end. This means that a stream of syngas produced from biomass can be combined with a syngas produced from CCU and green hydrogen and give one final production stream of FT liquid.

4 PROCESS FEASIBILITY & TOTAL CAPITAL INVESTMENT (TCI)

4.1 Process feasibility – feedstock capacity

The calculation of feedstock capacity required for each particular method is estimated in respect of producing 1000L of the fuel (jet fuel or DME).

4.1.1 FTS from dry or wet biomass (BTLd, BTLw)

The feedstock capacity estimation for the BTL process was conducted according to the study of Boerrigter (Boerigter, 2006). The conversion efficiencies of gasification and anaerobic digestion (ad) were considered as the average value of the min and max efficiency values of gasification and ad. According to Worley & Yale (M. Worley, 2012), the gasification efficiency varies from 65 to 80%; therefore, the estimation for the feedstock-product relation, 77% was used. According to (Ran Mei, 2016), the efficiency of ad varies from 20 to 70%; thus, 65% was used.

In order to produce 1000L of BTL fuel, 0.77 MW of dry biomass (via gasification), or 0.91MW of wet biomass (via ad) are required. The conversion efficiency from syngas to FT products (C5+) is considered 71%, while the energy value of the FT products is 36.3 MJ/L (Boerigter, 2006, p. 19). Appendix B presents a variety of input to output capacities for BTLd and BTLw. Additionally, the excel file provides the possibility to adjust the efficiency values and inspect the outcome.

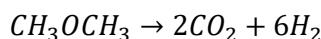
1000L FTS jet fuels	
555 kg	H ₂
4.1 tons	CO ₂

4.1.2 FTS from CO₂ and H₂ (PTL)

In order to calculate the feedstock capacity required for the PTL via Fischer-Tropsch and CO₂-H₂ input, the equation of Fischer-Tropsch was applied. The main obstacle in this case is that the products from FTS contain a variety of hydrocarbon fractions from C₇ to C₂₁₊. For this estimation, it is assumed that the C₂₁ is the longest hydrocarbon of the process. This means that the synthesis is stopped in a particular time. This assumption is based on the jet fuels carbon atom composition (C₇-C₁₇). Additionally, the larger carbon chains (C₂₁₊) are cracked via hydrocracking to shorter (Appendix A). The calculation is conducted for H₂ and CO. The catalytic conversation of CO₂ to CO is considered 90% (Tingting Zheng K. J., 2018).

4.1.3 Direct DME synthesis

Combining equations 2 and 4 from Table 11 and after stoichiometry application the equation below is formed:



The calculation of the CO₂ & H₂ input required to produce 1000L of DME directly is 4.03 kg of CO₂ and 0.55 kg of H₂ (Appendix A). A list of required inputs based on the desired output is presented in Appendix B, Table 17.

4.2 Total Capital Investment (TCI)

The estimation of the total capital investment of each refinery will be calculated according to the study conducted by Boerigter (Boerigter, 2006). In this study, the author makes an estimation of the TCI of the refinery type that he is researching, based on a reference plant. The reference plant used is the Sasol's ORYX-1 GTL plant in Qatar. It produces 34000 bbl of fuel per day and the associated TCI reaches 1800 million US\$ or 52000 \$/bbld (Boerigter, 2006). The decision to follow this method, in order to gain a first image of the refinery economic aspect is based on the difficulty to acquire economic details for the already existing project, since the cost data of these projects are not usually accessible from the public.

The method used in the reference paper is the sixth-tenths factor rule. It is an empirical method to calculate costs and scale sizes used in industry. The basic version of this rule is presented below:

$$C_B = C_A \times \left(\frac{S_B}{S_A} \right)^x$$

Where C_B and C_A is the economic values of the reference and researching plant or equipment respectively, while S_B and S_A are the scales. The “x” is the scale factor, which ranges from 0.3 to 0.8 (typically 0.6) for equipment, while 0.4 to 0.9 for plants (typically 0.7). For this study, a scale factor based on the researching scale will be used for further accuracy (Table 12).

Therefore,

$$C_B = C_A \times \left(\frac{S_B}{S_A} \right)^{1-\text{scale factor}} \quad (1)$$

Where C_B is the researching TCI, $C_B = \text{TCI}_{\text{reference}}$, which is 1800 million US\$ in that case, the S_B is the researching plant's scale and the S_A is the reference scale expressed in bbl/d. The latter is 34000 bbl/d in this case.

The scale factor value associates with the plant's production capacity. The values of this factor are presented in Table 12 and are formed in respect of Boerigter study.

Scale Factor	scale bbl/d
0.4	<1,000
0.5	1,000-5,000
0.6	5,000-20,000
0.7	20,000-60,000
0.9	60,000-100,000

Table 12: Scale factors

Boerigter divides the TCI value into three subcategories (Boerigter, 2006):

- the Inside Battery Limit (ISBL) which represents the equipment costs
- the Outside Battery Limit (OSBL) which stands for the costs
- and the Owner Costs.

The ISBL consists of the equipment unit cost; the OSBL is the service facilities, the storage, the distribution and the land purchase. The OSBL is fixed to 100% of ISBL value. The values of ISBL plus the OSBL represent the EPC costs (Engineering, Procurement and Contracting). The Owner's costs are divided into three categories, the indirect costs, the working capital and the start-up costs. The first relates to the R&D, the engineering and construction services. The second stands for salaries and wages and the third for modifications, labor and loss in production. The total Owner's costs is estimated 20% of the EPC value. Finally, the TCI is the sum of EPC and Owner's costs (Boerigter, 2006).

The TCI for the DME production plant is excluded since the fuel is not considered commercial yet.

4.2.1 TCI for BTL

There are no specific publications with TCI of BTL from dry biomass, therefore, it is calculated based on a reference plant from Haalemmers study (Geert Haalemmers, 2012). This study presents three cases of BTL plant, with three different gasifier types (a Fluidized bed, an entrained flow and an entrained flow with recycling), an entrained flow gasifier (see paragraph 3.1.1.2.1) presents an ISBL of 489.3 million US\$, while adding the feature of recycling the unreacted gas, the ISBL cost falls at 486 million US\$. The presented projects yield 14 and 16 tons of C_{5+} per hour respectively, which is translated to 1288.5 bbl/d and 1472.5 bbl/d.

Therefore, the reference plant from simple entrained flow BTLD of 1288.5 bbl/d is:

- ISBL = 489.3 million US\$
- OSBL = 489.3 million US\$
- EPC = 978.6 million US\$
- Owner's costs = 195.72 million US\$
- TCI = EPC + Owner's costs = 1174.32 million US\$

Thus,

$$TCI_{BTLD} = 1174.3 \text{ million US\$} \times \left(\frac{\text{Scale [bbl/d]}}{1288.5 \text{ [bbl/d]}} \right)^{1-\text{scale factor}}$$

For a 1000L/d scale BTLD about 50 million US\$ are required. The capability to inspect the various TCIs of the corresponding scales is provided in the "process feasibility and scaling up" excel file. The scale factor in the excel file is automatically adapted on the selected production scale.

Therefore, the TCI required for a BTLD plant of 1000L/d is estimated 10.37 million US\$ or 9.44 million €. Table 18 in Appendix B presents a variety of scale to TCI relations. It is obvious that the relation of TCI to output capacity applies the economy of scales. After a particular production scale, which in this case is the 60000 bbl/d the TCI starts to decrease.

4.2.2 TCI for BTLw

According to IRENA (IRENA, Biogas for Road Vehicles, 2018), the capital-related costs for a BTLw is lower than a BTLD. This difference relates to the fact that there are already existing facilities for feedstock storage before digestion process, since municipal waste handling requires their collection and treatment, beyond the case of being used for biogas production. Additionally, the biogas from BTLw process requires less cleaning than in BTLD. For this estimation, again the Boerigter's method will be used. However, a different reference plant will be considered. From the study of Naqi (Naqi, 2018), the ISBL cost of a BLw plant producing 2.60 million gallons of FT diesel per year, is 13.9 million US\$.

The TCI of the reference plant is: 33.36 million US\$. The production capacity of the plant assuming that operates constantly during the year is estimated 169.6 bbl/d. Therefore, from equation (1), for a 6.3 bbl/d or 1000 L/d plant, the TCI is 4.63 million US\$. The ISBL is also divided into the equipment parts based on Naqi's study (Naqi, 2018). The "Process feasibility and scaling up" file presents a variety of TCI-scale relation. The economies of scale take place in BTLw as well.

4.2.3 TCI for PTL (CO₂ & H₂)

For estimating the TCI of the PTL route, the base case scenario of Zhang's study is used as the reference plant (Chundong Zhang, 2019). The study presents a variety of plant scenarios. The inspecting scenarios-plants are hybrid plants of PTL and PTG process. This study is used since there is no commercial PTL plant exploiting CO₂ and H₂ yet. The reference plant has a production capacity of 2822 bbl/d and a TCI of 1358.24 million US\$. Thus, applying equation (1), a 1000L/d PTL plant is estimated at a TCI of 9.19 million US\$.

The EPC and Owner's cost values for the 1000L/d plant are 7.65 and 1.53 million US\$ respectively (see process feasibility and scaling up excel file).

5 MARKET FOCUS & ASPECTS

As it was referred in a previous chapter, the Sustainable Aviation Fuels are considered the short-term "green" solution for powering the aviation sector. SAF market is already growing, and will keep growing until 2050 at least. Currently, there are many commercial airline companies investing on SAF like KLM, British Airways and Lufthansa. Fuel producers also devote to this technology (ExxonMobil, Shell, TOTAL, BP etc.) (prnewswire, 2019). The aviation sector is generally defined by constant growth

the last 10 years. According to the study of Mazareanu (E.Mazareanu, 2018), the global traffic growth was estimated about 7.4% at 2018, while currently (2019) is measured 5%. This means that the 38.1 million flights at 2018 reached the 39.4 million in 2019 globally. This signifies that the SAF market is definitely growing.

The market structure of SAF depends primarily on two main aspects, the economy and politics and secondly the environmental impact, which is of lower significance.

5.1 Economic & geography aspects /

A market for SAF production technology is directly connected with the flight intensity of the area. Busier regions, like North America, Europe and South/East Asia present a higher potential to buy this technology. These regions demonstrate as the highest kerosene consumers (kerosene related emitters). They are considered in general, the most economically active parts of the planet, since population traffic, economic revenue, trade movement and GDP values are of the highest worldwide. USA presents the highest consumption of kerosene in 2019, with an average utilization of 1,4 million bbl per day. China is second with a much lower consumption (388,000 bbl/day), followed by Russia and UK (indexmundi, 2019).

The top 20 countries-consumers of kerosene for 2019 are presented in Figure 22:

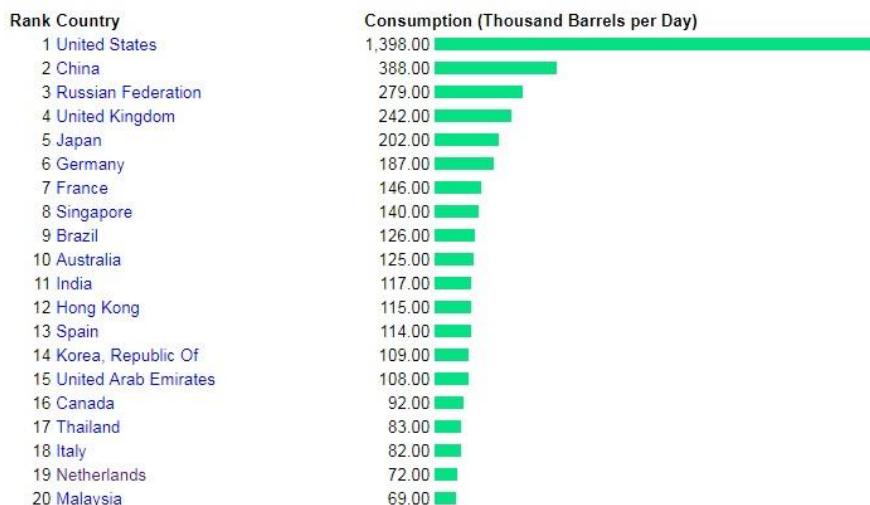


Figure 22: Top 20 jet fuel consumers 2018 (indexmundi, 2019)

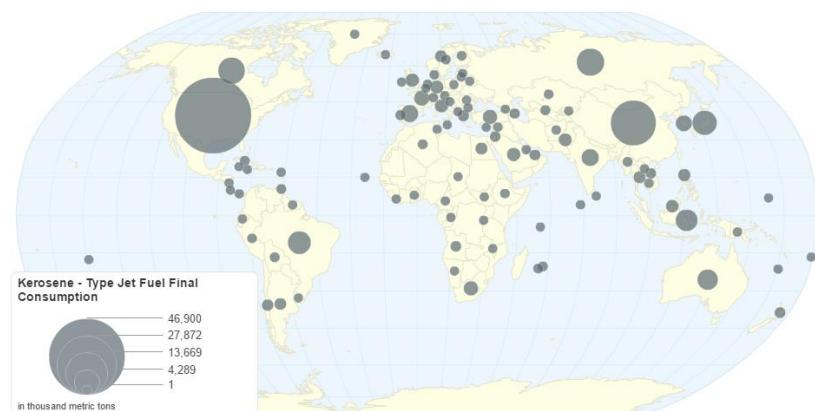


Figure 23: World map of kerosene consumption (ChartsBin, 2016)

The area with the highest kerosene consumption presents the highest potential to buy the SAF technology. These areas can be seen in Figure 23 based on the emission intensity. It can be seen that kerosene consumption is connected with each country's economic situation, meaning that strong economies tend to present more intense air traffic. The latter is verified from Figure 22 (FocusEconomics, 2018). Therefore, end-buyers located in countries with sufficient and stable economies are more likely to purchase SAF production technology.

Another aspect related to economy is the cost of feedstock and its availability. According to ICAO (ICAO, Sustainable Aviation Fuels Guide, 2017) the technical effort increases on the contrary with the feedstock price.

5.2 Politics – Taxation

The RED and RED II programs establish a framework for energy production from renewables, while the CORSIA program promotes the fuel blending from 2021 (EASA, Sustainable Aviation Fuels, 2016). Tax regimes are moving towards adjusting for aviation emissions in favour of SAF. Therefore, according to (ICAO, Sustainable Aviation Fuels Guide, 2017), renewable products will present lower taxation, while those with higher GHG-related emissions, will demonstrate higher tax rates (2.1 Regulatory for SAF). For Jet fuels, there are 2.65 kg CO₂/L and the taxation is 0.032\$/L. The tax per CO₂ emitted is going to increase in order to reduce the concentration of the main GHG in the atmosphere and boost the economic revenue.

5.3 Environment

The outer reason for SAF research is the reduction of GHG emissions concentration in the atmosphere. Therefore, the environmental benefit is the trigger for DMT to research and invest on SAF technology.

Since 1970, ICAO focuses on the environmental impact of aviation in regard of noise and local air quality around airports. Currently though, the target is towards the overall climate change. However, for most of the end-buyers and considering the business perspective of the market, the environmental impact of fuel combustion – GHG concentration is considered secondary. Instead, economy and competitiveness are the fundamental triggers, in respect of market values.

The three aspects presented above constitute the essential triggers for an end-buyer to acquire a SAF production technology, with the main aspect from the market perspective, being the economy.

In respect of the customers, buying this technology from DMT the 6W Customer Analysis is applied, from the company's perspective (since the project is still in the research level).

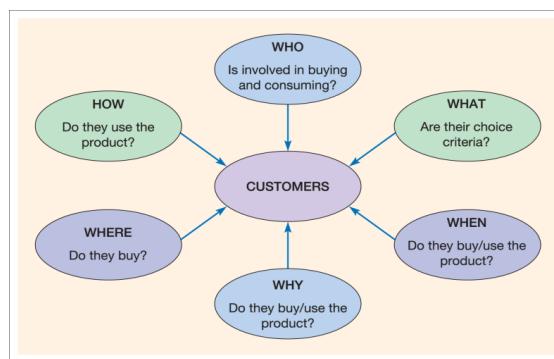


Figure 24: The 6Ws model

Acquiring answers to these questions, an abstract business insight of the external environment can be formed (Appendix C).

The effect of the end buyers of the product are presented:

5.4 Commercial Airlines:

The introduction of SAF can constitute an economic burden for the airline companies; however, this cost can be shared between society and airline customers, by implementing a balanced tax regime. Furthermore, since the aviation is turning towards SAF (at least until 2050), it would be feasible for the airlines to autonomously produce sustainable fuels, decreasing the expenses of buying from oil suppliers. Therefore, decentralized production of SAF can be occurred based on the airline desires. Additionally, engaging in SAF production projects and programs creates positive range, and benefits the reputation of the airline name. SAF have also present better efficiencies than CAF (SkyNRG, 2019).

Commercial Airlines		
Prospect	Effect	Result
Economic burden	-	Shared cost between society & passengers
SAF much more costly than CAF	-	Shared cost between society & passengers
Self-supplied	+	Less expenses
Name reputation	+	Increase in customers
Less/No aviation emission taxes	+	Less expenses
Better fuel efficiency	+	Less expenses

More and more commercial airlines utilize SAF for their flights (SAS, KLM, Finnair, Lufthansa, Interjet, etc.). KLM already purchased a SAF production unit in order to produce their own drop-in fuel, while British Airways in collaboration with GreenSky, and aim to produce their own green fuels from waste exploitation.

5.5 Commercial Airports

Commercial Airports are the supplying location for aviation fuels. Airports presenting constant traffic and intense economic activity demonstrate the highest fuel consumption. The Hartsfield in Atlanta, the Beijing's airport, Heathrow, the Schiphol and Charles de Gaulle present the highest potential to provide SAF themselves (Figure 25). Therefore, they constitute potential buyers for the SAF production technology. Through acquiring production units, the drop-in fuel production can be decentralized, reducing the transportation costs, while reputation and local air quality can be improved.



Figure 25: Airports fuelling SAF (AviationBenefitsBeyondBorders, 2019)

Commercial Airports		
Prospect	Effect	Result

Economic burden	-/+	Shared cost between society & passengers, reduction in transportation costs
Self-supplied	+	Decentralized production
Name reputation	+	Increase in customer numbers
Less CO ₂ emissions	+	Better local air quality

The airports with the highest intensity in air traffic can be occurred in the countries with the higher GDP values (Table 13).

No.	City	Airport	Million passengers in 2019
1	Atlanta	Hartsfield-Jackson Atlanta International Airport	107.4
2	Beijing	Beijing Capital International Airport	101
3	Dubai	Dubai International Airport	89.1
4	Los Angeles	Los Angeles International Airport	87.5
5	Tokyo	Tokyo's Haneda Airport	87.1
6	Chicago	Chicago's O'Hare International Airport	83.3
7	London	London's Heathrow Airport	80.1
8	Hong Kong	Hong Kong International Airport	74.5
9	Shanghai	Shanghai Pudong International Airport	74
10	Paris	Paris Charles de Gaulle Airport	72.2
11	Amsterdam	Amsterdam Airport Schiphol	71
12	New Delhi	New Delhi's Indira Gandhi International Airport	69.9
13	Guangzhou	Guangzhou Baiyun International Airport	69.8
14	Frankfurt	Frankfurt Airport	69.5
15	Dallas	Dallas/Fort Worth International Airport	69.1

Table 13: Ranking of busiest Airports of 2019 (Chrisman, 2019)

5.6 Aviation Industries:

Aviation Industries are committing much development in respect of SAF to date. In addition, in respect of the aviation-industry and considering the engineering aspect of the drop-in fuel in the turbine, no adjustment has to be done on the aircraft engine, since SAF have almost identical characteristics with CAF. However, since a nearly new fuel is introduced in the market, despite the positivity surrounding its name, long-term research and experimentation has to be implied about its effect on the turbine. Therefore, the aircraft industries can constitute potential buyers mainly for research purposes.

Aviation Industries		
Prospect	Effect	Result
No adjustment on turbine	+	No economic charge
Experiments	+	Increase confidence for SAF

5.7 Oil/Energy Companies

Many oil and energy companies are already producing their own SAF, supplying commercial airports. In addition, the lobby of fuels generally consists from the big names of the Oil industry, like Shell, BP, TOTAL etc. Shell is the biggest stakeholder of SAF in Netherlands, collaborating with SkyNRG, TOTAL acts mainly in France, while Air BP supplying airports in Sweden. By the end of 2017, about 150,000 flights have been powered by biofuels (Feuvre, 2019). SAF consumption is increasing and the production technology is required for the oil/energy companies, to produce their own SAF, to

distribute the production units for decentralized SAF production and to keep up with the trending market. This technology will make the oil/energy company competitive and capable to keep up with the current trends.

Oil/Energy Industries		
Prospect	Effect	Result
Name reputation	+	More customers
Distribute production units	+	Decentralized production
Experiments	+	Increase confidence for SAF

5.8 Army / Navy / Air Force

The Navy has always been a pioneer in energy innovation. The Navy promotes greener energy and an environmental friendly approaches in respect of fueling. The US army has been working in sustainability since 2000, collaborating with the academy (Kidd, 2012). In particular, an R&D department dedicated to bio jet fuels research and development is established since 2007 in the US navy (Kaltschmitt M., 2018). The US Navy already conducts flights based on the HEFA fuel. In addition, the Royal Dutch Air Force, already supplies her F-16 Falcons with SAF, since January of 2019 (SkyNRG, 2019).

Army / Navy / Air Force		
Prospect	Effect	Result
Name reputation	+	Keeping-up with the trends
Environmental friendly approach	+	Increase confidence for SAF

6 DISCUSSION

According to “2.2 Overview” and “1.2 Host Organization” one can conclude to the most relevant pathways in respect of the company’s boundaries, while taking into consideration the possibility of broadening its technology-related acting field. The most relevant SAF production routes for DMT imply those associated with biogas/natural gas associated pathways. These methods are the Fischer – Tropsch, AtJ and DME routes. However, the type of feedstock for these routes varies. Dry and wet biomass, captured CO₂ together with H₂ produced from electrolysis and alcohols are feedstock that these types of SAF routes exploit. As a result, the lipid / algae routes were excluded and no further investigation was conducted on them. Applying the method of House of Quality, four relevant options were aroused in accordance with DMT’s boundaries. The best option is considered the PTL method from CO₂ and H₂, followed by the BTL from wet biomass. The FTS from gasification is placed third. The DME fuel was also investigated considering the company’s interest for this fuel. Dimethyl ether is not considered a certified SAF method.

From technical perspective, the three cases from chapter 1.3 “Problem statement and research objectives” were assessed in respect of the company. The result from technology feasibility and PFDs is a clear view of the types and function aspects of the equipment units required for every process. In addition, the three strategy cases were addressed, concluding to these results:

Following case 1, DMT is able to develop the syngas conditioning equipment units for every one of the processes presented in chapter 3 “Technical Design & Analysis”. The biogas conditioning steps are inside the company’s boundaries and small developments are required in order DMT to produce the biogas upgrading equipment units completely. Therefore, modest development in respect of DMT’s production technology is required for this case.

The long-year experience of the company in the field of biogas signifies their knowledge in relation with further equipment units, like DME reactors. This knowledge can be extended to develop FTS

reactors; however, lot of time and capital investment has to be devoted in research and education in order the company to be able to commercialize the new units. Case 2 can be implemented but numerous and longer-term steps are required in order to be tangibly applied.

Case 3 implements the combination of DMT's technology together with technologies produced from other manufacturers, to form a complete production pathway. Therefore, DMT's role in that case is exploiting its conditioning equipment units while importing and combining technologies to structure the entire SAF production pathway. This option implies the most efficient in respect of time and cost perspective. Knowledge can be attained by researching the aspects and details of the SAF production pathways, which can be implemented in scope of developing case 2 in the future.

Therefore, case 3 is the most relevant to be followed currently from DMT.

The efficiencies associated with feedstock quantity to fuel production capacity, cannot be compared between the routes, since they exploit different types of feedstock and in different chemical state. However, it can be compared between the BTL (wet and dry biomass in MW) and PTL (H₂ and CO₂ for PTL and DME in kg) couples though. Therefore, the BTLD is more feedstock feasible than BTLw, while DME is better than PTL from CO₂ and H₂. The feedstock required for each process in greater scales is estimated in the excel file, while a tool for estimating the PTL was formed.

Due to the limited literature related to the economic data and the considering the long time-investment required to receive quotation papers from the equipment producers, the economic estimation was conducted by estimating the TCI values. The empirical method of six-tenth rule was applied, while the estimation was conducted based on references that consider a ±30% error. The most economically feasible route to produce SAF, based on the TCI, is considered the BTL via digestion. The route of producing 6.3 bbl/d presents a TCI of 4.63 million US\$. The BTLD route is the most costly, primarily because of the gasifier units costs and secondly because of the tar removal step. The PTL pathway presents a rational TCI value; however, the OPEX costs related to PTL are expected to be high, considering the intense energy consumption of the electrolysis unit. The TCIs follow the market of scales rule; therefore, they start to decrease after a particular value of scale (Appendix B). For BTLw, there is a first decrease of costs for the 20000 bbl/d scale production, while for BTLD the TCI remains the almost steady while scaling up from 10000 to 20000 bbl/d. All pathways present a drop of the TCI value after the 50000 bbl/d. The complete economic assessment of this project requires the values of CAPEX and OPEX, since costs are changing in respect of time and economic situations.

The trigger for researching for greener fuels in the aviation sector is directly connected with the environment and politic aspect, constituting the main reasons for the SAF business case in general. However, keeping up with the market trends and adapt to the technological evolution is defined as the main trigger for stakeholders to invest time and economic capital. The market of SAF is increasing, while it is expected to constitute one of the most active markets from 2020 and after. According to the current estimations, the interest on SAF will be kept high until at least 2050. Purchasing SAF production technology introduces positive effect to almost all the end-buyers. According to DMT, the company should focus on airports as starting point. Small provincial airports, like the local Eelde airport, which hosts the KLM pilot school, is considered a strong candidate to install a SAF production unit. Consequently, DMT would be able to contribute on the airport's green profile. In addition, since there is no pipeline network for kerosene distribution, by applying decentralized production, transportation costs will be reduced (since only 50% of CAF are required for the blending), decreasing also the track related emissions. Furthermore, local airports with moderate air traffic can be powered from small production units e.g. 1000L/day or less. In addition, following the example of Fulcrum Biofuels and Red Rock Biofuels who supply the navy with SAF (RenewableEnergyWorld, 2014), DMT can address also the Dutch Air Force. The military forces in general display also a greater potential to scale-up the production. A list of the candidate commercial and military airports of the Netherlands is presented:

Commercial Airports	Military Bases
Eelde Airport	
Den Helder Airport	Gilze-Rijen Air Base in Breda
Teuge Airport	
Enschede Airport	
Breda International Airport	Leeuwarden Air Base
Hoogeveen Airport	
Lelystad Airport	
Maastricht Aachen Airport	Volkel Airbase
Drachten Airport	

7 CONCLUSION

This research was conducted in favor of DMT Environmental Technology. It is a research associated with the potential of DMT to enter the market of sustainable aviation fuels technology. Since a major GHG source is considered the transportation subsector of aviation, a short-term solution to reduce these emissions is to reduce the combustion of fossil jet fuels. This can be achieved by blending the conventional kerosene with sustainable fuels. The consequence of SAF utilization is expected and estimated to reach emission reduction of even 80%, based on the CO₂ recycling.

The technology of SAF has already been introduced in the global market, with a number of airlines using it; however, it is yet considered fresh. SAF can be produced via different routes associated with the type of feedstock. The certified technology routes are the HEFA, which is currently the most popular, the FTS and the AtJ. Several methods are implemented in order to attain the most suitable pathway for DMT to interpret. Firstly, the potential technologies were evaluated in respect of the acting boundaries of the host organization, concluding to six routes applicable for DMT. Next, according to the HoQ assessment, the most relevant paths for the company are the PTL from CO₂ and H₂ exploitation, the BTL from digestion and the BTL from gasification and the uncertified method of DME. These options were then assessed from the technical, the efficiency and economic point of view.

The efficiencies can be compared based on the feedstock requirement only for the BTL routes, since PTL exploits CO₂ and H₂. Therefore, the BTL from gasification requires less biomass for producing 1000 L of fuels than a BTL via anaerobic digestion. The PTL feedstock to fuel efficiency can be estimated for every desired production capacity by using the total formed in excel.

The economic analysis was conducted based on the existing inadequate literature. Therefore, the estimated TCIs are not accurate enough and more research is required for precise values. A first image can be formed though, illustrating that BTLw is the most economic route, followed by PTL. The BTLD requires the highest TCI.

An abstract business approach was also formed in respect of DMTs strategy, which concluded to the fact that DMT should try develop a complete SAF pathway, exploiting also her commercial technology units for upgrading biogas. In addition, the focus market was evaluated, concluding that the most relevant customers are the commercial airports and particularly the local ones.

This study presents a first analysis of the potential routes of SAF production relevant for DMT. Therefore, in respect of the research question, the most applicable pathway for DMT is to construct a PTL route from equipment units produced from different manufactures. In addition, DMT's biogas condition technology can be implemented and developed.

No simulation software was used for this research; therefore, more accurate feasibility and economic results can be attained.

8 REFERENCES

- A. Lappas, E. H. (2016). *Handbook of Biofuels Production (Second Edition)*. Thessaloniki, Greece. doi:10.1016/B978-0-08-100455-5.00018-7
- AirLiquide. (2019). *Syngas Ratio Adjustment Applications*. Opgehaald van <https://www.airliquideadvancedseparations.com/syngas-ratio-adjustment-applications>
- Anamaria P. P. Pires, Y. H.-P. (2018). Chemical Composition and Fuel Properties of Alternative Jet Fuels. *bioresources*, 2632-2657.
- ATAG. (2018, October). *Air Transport Action Group*. Opgehaald van Facts & Figures: <https://www.atag.org/facts-figures.html>
- ATAG. (2019). Opgehaald van facts & figures: <https://www.atag.org/facts-figures.html>
- Austin, A. (2010, April 10). French torrefaction firm targets North America. *Biomass magazine*. Opgehaald van <http://www.biomassmagazine.com/articles/3665/french-torrefaction-firm-targets-north-america/>
- AviationBenefitsBeyondBorders. (2019). *The leading edge*. Opgehaald van Sustainable fuels: <https://aviationbenefits.org/environmental-efficiency/climate-action/sustainable-aviation-fuel/the-leading-edge/>
- Boerigter, H. (2006). *Economy of Biomass-to-Liquids (BTL) plants*.
- Bulletin, W. (2011). *Anaerobic Digestion*. Residua.
- ChartsBin. (2016, December 28). *Fuel Oil - Final Consumption by Country*. Opgehaald van Energy Statistics Database: <http://chartsbin.com/view/43283>
- Chrisman, J. (2019, 03 13). *This is the Busiest Airports in the World*. Opgehaald van Thrillist: <https://www.thrillist.com/news/nation/busiest-airport-in-the-world-2019>
- Chundong Zhang, R. G.-W.-M.-G. (2019). Direct conversion of carbon dioxide to liquid fuels and synthetic natural gas using renewable power: Techno-economic analysis. *Journal of CO2 Utilization*, 293-302.
- Collins, C. D. (2007). Implementing Phytoremediation of Petroleum Hydrocarbons. In *Methods of Biotechnology* (pp. 99-108). doi:10.1007/978-1-59745-098-0_8
- Curtis H. Whitson & Michael R. Brule. (2000). *Phase Behaviour*. Texas.
- De Falco, M. (sd). *Dimethyl Ether (DME) production*. Rome: University UCBM. Opgehaald van <http://www.oil-gasportal.com/dimethyl-ether-dme-production-2/?print=pdf>
- de Jong, E., Higson, A., Walsh, P., & Wellisch, M. (2012, January). Bio-based Chemicals Value Added Products from Biorefineries. *Bio-based Chemicals*.
- dmt-et. (2019). *dmt-et*. Opgehaald van dmt-et: <https://www.dmt-et.com/>
- E.Mazareanu. (2018). *Statista*. Opgehaald van Number of flights performed by the global airline industry from 2004 to 2019 (in millions): <https://www.statista.com/statistics/564769/airline-industry-number-of-flights/>

- EASA. (2016). *Sustainable Aviation Fuels*. Opgehaald van <https://www.easa.europa.eu/eaer/climate-change/sustainable-aviation-fuels>
- EASA. (2019). *European Aviation Environmental Report 2019*. European Environmental Agency. doi:10.2822/309946
- ETIP. (2019). *FT-Liquids*. Opgehaald van ETIP bioenergy: <http://www.etipbioenergy.eu/value-chains/products-end-use/products/ft-liquids>
- Eurocontrol. (2015). *European Aviation in 2040*.
- Feuvre, P. L. (2019, March 18). *IEA*. Opgehaald van Commentary: Are aviation biofuels ready for take off?: <https://www.iea.org/newsroom/news/2019/march/are-aviation-biofuels-ready-for-take-off.html>
- FocusEconomics. (2018, November 8). *The World's Top 10 Largest Economies*. Opgehaald van <https://www.focus-economics.com/blog/the-largest-economies-in-the-world>
- Frederik Trippe, M. F. (2011). Techno-economic assessment of gasification as a process step within. *Fuel Processing Technology*, 2169-2184.
- Geert Haarlemmer, G. B.-A. (2012). Second generation BtL type biofuels – a production cost analysis. *Energy & Environmental Science*. doi:10.1039/c2ee21750c
- GEVO. (2019). *gevo.com*. Opgehaald van low carbon renewable jet fuel: <https://gevo.com/jet-fuel/>
- Guolin Yao, M. D. (2017, January 19). Stochastic techno-economic analysis of alcohol-to-jet fuel production. *Biology of Biofuels*.
- Hauser, J. R., & Clausing, D. (1988). *The House of Quality*. Qatar Foundation.
- Heminghaus, G. (2006). *Aviation fuels technical review*. Chevron Corporation.
- Huve, J. (2017). *Highly selective, active and stable Fischer-Tropsch catalyst using entrapped iron nanoparticles in silicalite-1*. Lyon.
- IATA. (2015). Opgehaald van <https://www.iata.org/whatwedo/environment/Documents/safr-1-2015.pdf>
- IATA. (2019). *Environment*. Opgehaald van Sustainable Aviation Fuels: <https://www.iata.org/policy/environment/Documents/saf-what-is-saf>
- ICAO. (2017). *Sustainable Aviation Fuels Guide*. Opgehaald van https://www.icao.int/environmental-protection/knowledge-sharing/Docs/Sustainable%20Aviation%20Fuels%20Guide_vf.pdf
- ICAO. (2018). *Sustainable Aviation Fuels Guide*. UNDP.
- ICAO. (nd). *Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme*. Opgehaald van https://www.icao.int/environmental-protection/CORSIA/Documents/Resolution_A39_3.pdf
- iea. (2018). *International Energy Agency*. Opgehaald van Global Energy & CO2 Status Report: <https://www.iea.org/geco/oil/>
- IEA. (2019). *iea.org*. Opgehaald van CO2 emissions Statistics: <https://www.iea.org/statistics/co2emissions/>

- indexmundi. (2019). *Index mundi*. Opgehaald van Jet Fuel Consumption by Country: <https://www.indexmundi.com/energy/?product=jet-fuel&graph=consumption&display=rank>
- IRENA. (2017). Biofuels for Aviation: Technology brief. *International Renewable Agency*.
- IRENA. (2018). *Biogas for Road Vehicles*. IRENA.
- Irfan, U. (2019, Apr 9). vox.com. Opgehaald van Forget cars. We need electric batteries big enough for planes to fly on clean electricity: vox.com/2019/3/1/18241489/electric-batteries-aircraft-climate-change
- Jager, B. K. (1994). A Slurry bed reactor for low temperature Fischer - Tropsch. *Third Natural Gas Conversion Symposium* (pp. 419-425). Science BV. doi:10.1016/s0167-2991(08)63906-3
- K. Atsonios, K. P. (2015). *Review of palladium membrane use in biorefinery operations*. Thessaloniki: Elsevier. doi:10.1533/9781782422419.2.345
- Kaltschmitt, M. (2018). *Biokerosene*. Berlin: Springer.
- Kaltschmitt, M. (2018). *Biokerosene*. Germany: Springer.
- Kaltschmitt, M. (2018). *Biokerosene*. Germany: Springer. doi:10.1007/978-3-662-53065-8
- Ketzer, J. (2014). Brazilian Alas of CO₂ Capture and Geological Storage. Rio Grande do Sul: ediPUCRS.
- Kidd, R. (2012, May 1). *Susatainability News*. Opgehaald van ASU: <https://sustainability.asu.edu/news/archive/sustainable-army-creating-a-net-zero-bootprint/>
- Klerk, A. d. (2010, December 21). Fischer-Tropsch fuels refinery design. *Energy & Environmental Science*. doi:10.1039/c0ee00692k
- Koyama, T. (1963). Gaseous Metabolism in Lake Sediments and Paddy Soils and the Production of Atmospheric Methane and Hydrogen. *Geophysical Research*, 3971-3972.
- Kritinger, J. A. (2002). *The role of sulfur in commercial iron-based Fischer–Tropschcatalysis with focus on C2-product selectivity and yield*. South Africa: Elsevier.
- L.Pastor-Pérez, F. E.-G. (2017). CO₂ valorisation via Reverse Water-Gas Shift reaction using advanced Cs doped Fe-Cu/Al₂O₃ catalysts. *Journal of CO₂ Utilization*, 423-428.
- Lamoureux, J., Lew, L., & Biddle, T. (2014). *KiOR Hydrotreated Depolymerized Cellulosic Jet (HDCJ) fuel evaluation*. Washington: Pratt & Whitney.
- longreads. (2018). *Trends in the Netherlands 2018*. Opgehaald van Economy, Figures - Energy: <https://longreads.cbs.nl/trends18-eng/economy/figures/energy/>
- M. Worley, J. Y. (2012). *Biomass Gasification Technology Assessment*. Atlanta, Georgia: Harris Group Inc. Opgehaald van <https://www.nrel.gov/docs/fy13osti/57085.pdf>
- Naqi, A. (2018). *Conversion of Biomass to Liquid Hydrocarbon Fuels via Anaerobic Digestion: A Feasibility Study*. Florida: University of South Florida.
- Neuling, U., & Kaltschmitt, M. (2014). *Conversion routes for production of biokerosene - status and assessment*. Berlin: Springer. doi:10.1007/s13399-014-0154-2
- Peretti, I. (2019, September 9). Chicken Manure to Megawatts. *Biomass magazine*.

prnewswire. (2019, July 25). *Aviation Fuel Market to Expand at 5.22% CAGR, Boeing Teams up With WWF and RSB to Ensure Sustainability in Brazil's Aviation Biofuel Market: Fortune Business Insights*. Opgehaald van <https://www.prnewswire.com/in/news-releases/aviation-fuel-market-to-expand-at-5-22-cagr-boeing-teams-up-with-wwf-and-rsb-to-ensure-sustainability-in-brazil-s-aviation-biofuel-market-fortune-business-insights-874666070.html>

Ran Mei, T. N.-T. (2016, September 26). Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active microbial populations through the lens of microbial activity. *Scientific Reports*. Opgehaald van <https://www.nature.com/articles/srep34090>

RenewableEnergyWorld. (2014, 9 19). *US Navy, DOE, USDA Award \$210 Million to Three Companies for Drop-in Biofuels.* Opgehaald van <https://www.renewableenergyworld.com/2014/09/19/us-navy-doe-usda-award-210-million-to-three-companies-for-drop-in-biofuels/#gref>

Ritchie, H., & Roser, M. (2019). *Fossil Fuels*. Opgehaald van Our World in Data: <https://ourworldindata.org/fossil-fuels>

Sigmalrich. (2019). *Aldrich large separatory funnel*. Opgehaald van <https://www.sigmalrich.com/catalog/product/aldrich/z102628?lang=en®ion=NL>

SkyNRG. (2019). <https://skynrg.com/sustainable-aviation-fuel/saf/>. Opgehaald van <https://skynrg.com/sustainable-aviation-fuel/saf/>

Speight, J. G. (2011). Hydrocarbons for Synthesis Gas. In J. G. Speight, *Handbook of Industrial Hydrocarbon Processes* (pp. 281-323). Elsevier. doi:10.1016/b978-0-7506-8632-7.10008-8

Spivey, J., & Kumar, N. (2017). *Direct conversion of Syngas to Chemicals Using Heterogeneous Catalysts*.

ST_1. (2019, 09 18). *st1.eu*. Opgehaald van St1 constructs a biorefinery to produce renewable diesel and jet fuel: <https://www.st1.eu/st1-constructs-a-biorefinery-to-produce-renewable-diesel-and-jet-fuel>

theglobaleconomy. (2019). *Jet fuel consumption - Country rankings*. Opgehaald van https://www.theglobaleconomy.com/rankings/jet_fuel_consumption/

Tingting Zheng, K. J. (2018). *Recent Advances in Electrochemical CO₂-to-CO Conversion on Heterogeneous Catalysts*. doi:10.1002/adma.20180206

Tingting Zheng, K. J. (2018). *Recent Advances in Electrochemical CO₂-to-CO Conversion on Heterogeneous Catalysts*. Wiley online library. doi:10.1002/adma.201802066

V. K. Guda, P. H. (2015). Fast Pyrolysis of Biomass. Recent Advances in Thermo-Chemical Concerson of Biomass. In *Recent Advances in Thermochemical Conversion of Biomass* (pp. 177-211). Elsevier. doi:10.1016/B978-0-444-63289-0.00007-7

van der Laan, G. P. (1999). *Kinetics, Selectivity and Scale Up of the Fischer-Tropsch Synthesis*. Hoogeveen.

Xiufeng Li, H. X. (2007, April 20). Large-Scale Biodiesel Production From Microalga Chlorella protothecoides Through Heterotrophic Cultivation in Bioreactors. *Biotechnology Bioengineering*, pp. 764 - 771.

Y Zhu, S. T.-S. (2011). *Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels*. Pacific Northwest National Laboratory. Opgehaald van https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-19009.pdf

Yunlei, A., Lin, T., Yu, F., Yang, Y., Zhong2, L., & Sun, M. W. (2017, July). Advances in direct production of value-added chemicals via syngas conversion. *SCIENCE CHINA*. doi:10.1007/s11426-016-0464-1

•

9 APPENDIX A

Feedstock capacity estimation

Input for 1000L FTS with CO₂ and H₂

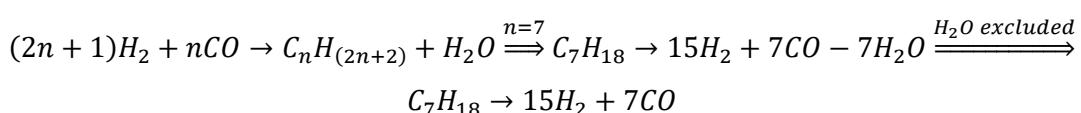
CO₂ and H₂ amount requirement for 1000L of jet fuel via FTS. FTS products vary from C₇ to C₂₁₊. The percentage of the various carbon chains in the final product is (Curtis H. Whitson & Michael R. Brule, 2000):

TABLE 5.1—EXPERIMENTAL TBP RESULTS FOR A NORTH SEA CONDENSATE														
Fraction	Upper <i>T_{bi}</i> (°F)	Average <i>T_{bi}*</i> (°F)	<i>m_i</i> (g)	<i>γ_i**</i>	<i>M_i</i> (g/mol)	<i>V_i</i> (cm ³)	<i>n_i</i> (mol)	<i>w_i</i> (%)	<i>x_{Vi}</i> %	<i>x_i</i> %	<i>Σw_i</i> %	<i>Σx_{Vi}</i> %	<i>K_w</i>	
C ₇	208.4	194.0	90.2	0.7283	96	123.9	0.940	4.35	4.80	7.80	4.35	4.80	11.92	
C ₈	258.8	235.4	214.6	0.7459	110	287.7	1.951	10.35	11.15	16.19	14.70	15.95	11.88	
C ₉	303.8	282.2	225.3	0.7658	122	294.2	1.847	10.87	11.40	15.33	25.57	27.35	11.82	
C ₁₀	347.0	325.4	199.3	0.7711	137	258.5	1.455	9.61	10.02	12.07	35.18	37.37	11.96	
C ₁₁	381.2	363.2	128.8	0.7830	151	164.5	0.853	6.21	6.37	7.08	41.40	43.74	11.97	
C ₁₂	420.8	401.1	136.8	0.7909	161	173.0	0.850	6.60	6.70	7.05	48.00	50.44	12.03	
C ₁₃	455.0	438.8	123.8	0.8047	181	153.8	0.684	5.97	5.96	5.68	53.97	56.41	11.99	
C ₁₄	492.8	474.8	120.5	0.8221	193	146.6	0.624	5.81	5.68	5.18	59.78	62.09	11.89	
C ₁₅	523.4	509.0	101.6	0.8236	212	123.4	0.479	4.90	4.78	3.98	64.68	66.87	12.01	
C ₁₆	550.4	537.8	74.1	0.8278	230	89.5	0.322	3.57	3.47	2.67	68.26	70.33	12.07	
C ₁₇	579.2	564.8	76.8	0.8290	245	92.6	0.313	3.70	3.59	2.60	71.96	73.92	12.16	
C ₁₈	604.4	591.8	58.2	0.8378	259	69.5	0.225	2.81	2.69	1.87	74.77	76.62	12.14	
C ₁₉	629.6	617.0	50.2	0.8466	266	59.3	0.189	2.42	2.30	1.57	77.19	78.91	12.11	
C ₂₀	653.0	642.2	45.3	0.8536	280	53.1	0.162	2.19	2.06	1.34	79.37	80.97	12.10	
C ₂₁₊			427.6	0.8708	370	491.1	1.156	20.63	19.03	9.59	100.00	100.00		
Sum			2,073.1			2,580.5	12.049	100.00	100.00	100.00				
Average			0.8034		172						11.98			
<small>Reflux ratio = 1 : 5; reflux cycle = 18 seconds; distillation at atmospheric pressure = 201.2 to 347°F; distillation at 10 mm Hg = 347 to 471.2°F; and distillation at 10 mm Hg = 471.2 to 653°F.</small>														
<small><i>V_i</i> = <i>m_i</i>/<i>γ_i</i>; <i>η</i> = <i>m_i</i>/<i>M_i</i>; <i>w_i</i> = 100 × <i>η_i</i>/2073.1; <i>x_{Vi}</i> = 100 × <i>V_i</i>/2580.5; <i>x_i</i> = 100 × <i>η_i</i>/12,049; <i>Σw_i</i> = <i>Σw_i</i>; <i>Σx_{Vi}</i> = <i>Σx_{Vi}</i>; and <i>K_w</i> = (<i>T_{bi}</i>+460)^{1/3}/<i>γ_w</i>.</small>														
<small>*Average taken at midvolume point.</small>														
<small>*Water = 1.</small>														

Table 14: Experimental TBP results for North Sea Condensate (Curtis H. Whitson & Michael R. Brule, 2000)

According to Table 14, each fraction exists in w_i percentage in the final product.

The first fraction of FTS, is the C₇. The feedstock (CO₂ and H₂) amount required to produce the C₇ amount contained in the 1000L (which according to Table 14 is 43.5L) of final product is estimated:



The mass of the C₇ fraction in the 1000L of FT product is estimated through the density equation:

$$\rho = \frac{m}{V} \rightarrow m = 725.8g/L \cdot 43.5L = 31572.3gr$$

The moles of C₇ in the 1000L f FT product are: $n = \frac{m}{M_r}$ the molar mass of C₇H₁₈ is 100.21 gr/mol.

$$\text{Therefore, } n = \frac{31572.3gr}{100.21gr/mol} = 315.06 \text{ mol}$$

In order to produce 315.06 mol of C₇H₁₈ needs:

$$\begin{aligned} 315.06 \text{ mol } C_7H_{18} &\rightarrow 315.06 \times 15 \text{ mol } H_2 + 315.06 \times 7 \text{ mol } CO \\ &\rightarrow 4725.9 \text{ mol } H_2 + 2205.4 \text{ mol } CO \end{aligned}$$

This means:

$$m = n \cdot Mr = 4725.9 \text{ mol} \times 2 \text{ gr/mol} = 9451.8 \text{ gr} = 9.45 \text{ kg of H}_2$$

$$m = n \cdot Mr = 2205.4 \text{ mol} \times 28.01 \text{ gr/mol} = 61773.2 \text{ gr} = 61.77 \text{ kg of CO}$$

The conversion from CO₂ to CO is occurred via an electro-catalyst of 90% efficiency. Therefore, the CO₂ input for 1000L of FT fuel is 61.77/90% = 68.63 kg of CO₂.

Thus, 21.98 kg of H₂ and 159.6 kg of CO₂ are required in order to produce only the C₇ fraction of the FT fuels.

The rest fractions until C₂₁₊ are calculated similarly (process feasibility and scaling up).

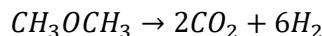
According to Klerk (Klerk, 2010) and Table 9, the 43% of the final FT liquid product is jet fuel. This means, that by producing 1000L of jet fuel, about 1300L of by-products will be additionally produced. Therefore, in order to produce 1000L of jet fuel from FTS, it needs to produce 2325L of FT liquid. This means that about 555 kg of H₂ and 4.1 tons of CO₂ are required for 1000L of FT jet fuel.

The excel file of “process feasibility and scaling up” provides the capability to attain the feedstock input required the desired process.

1000L FTS jet fuels	
555 kg	H ₂
4.1 tons	CO ₂

Input for 1000L DME from direct production

Feedstock requirement for 1000 L of DME. This calculation relates to the direct DME production process from CO₂ and H₂, while the stoichiometry gives:



Firstly, the mass of 1000L has to be attained.

The density of dimethyl ether is $\rho=2.11\text{kg/m}^3$, therefore from: $\rho = \frac{m}{V}$, the mass of 1000L DME is 2.11 kg.

The molar mass of DME is Mr=46.07 g/mol

The 1000L are: $n = \frac{2.11 \text{ kg}}{46.07 \text{ g/mol}} = 45.79 \text{ mol}$

So, $45.79 \text{ mol } CH_3OCH_3 \rightarrow 2 \cdot 45.79 \text{ mol } CO_2 + 6 \cdot 45.79 \text{ mol } H_2 \rightarrow 91.58 \text{ mol } CO_2 + 274.74 \text{ mol } H_2$

$CO_2 \rightarrow m = n \cdot Mr = 91.58 \text{ mol} \cdot 44.01 \text{ g/mol} = 4.03 \text{ kg}$

$H_2 \rightarrow m = n \cdot Mr = 274.74 \text{ mol} \cdot 2 \text{ gr/mol} = 0.55 \text{ kg}$

Therefore, in order to produce 1000L of DME directly, 4.03 kg of CO₂ and 0.55 kg of H₂ are required.

1000L DME directly	
0.55 kg	H ₂
4.03 kg	CO ₂

10 APPENDIX B

BTL inputs					
			Gasification	Anaerobic Digestion	
Output	Conversion efficiencies based on literature:		71%	77%	65%
Scale (bbld)	Scale (L/d)	FT products (MW)	Biosyngas (MW)	Biomass input (MW)	Biomass input (MW)
6.3	1001.61999	0.42081951	0.592703535	0.76974485	0.911851592
10.00	1589.873	0.667967476	0.940799262	1.221817223	1.447383479
15.00	2384.8095	1.001951214	1.411198892	1.832725834	2.171075219
20.00	3179.746	1.335934951	1.881598523	2.443634446	2.894766959
25.00	3974.6825	1.669918689	2.351998154	3.054543057	3.618458698
30.00	4769.619	2.003902427	2.822397785	3.665451668	4.342150438
40.00	6359.492	2.671869903	3.763197046	4.887268891	5.789533917
60.00	9539.238	4.007804854	5.644795569	7.330903337	8.684300876
125.00	19873.4125	8.349593446	11.75999077	15.27271528	18.09229349
500.00	79493.65	33.39837378	47.03996308	61.09086114	72.36917396
600.00	95392.38	40.07804854	56.44795569	73.30903337	86.84300876
800.00	127189.84	53.43739806	75.26394092	97.74537782	115.7906783
1000.00	158987.3	66.79674757	94.07992615	122.1817223	144.7383479
2000.00	317974.6	133.5934951	188.1598523	244.3634446	289.4766959
3000.00	476961.9	200.3902427	282.2397785	366.5451668	434.2150438
10000.00	1589873	667.9674757	940.7992615	1221.817223	1447.383479
20000.00	3179746	1335.934951	1881.598523	2443.634446	2894.766959
30000.00	4769619	2003.902427	2822.397785	3665.451668	4342.150438
40000.00	6359492	2671.869903	3763.197046	4887.268891	5789.533917
50000.00	7949365	3339.837378	4703.996308	6109.086114	7236.917396
60000.00	9539238	4007.804854	5644.795569	7330.903337	8684.300876
70000.00	11129111	4675.77233	6585.594831	8552.720559	10131.68436
75000.00	11924047.5	5009.756068	7055.994462	9163.629171	10855.37609
80000.00	12718984	5343.739806	7526.394092	9774.537782	11579.06783

Table 15: Required feedstock for BTL process from dry and wet biomass

PTL inputs

	Fractions	C-atoms	Production of FT liquid (L/d)	density (g/L)	mass (gr)	Molar Mass (g/mol)	n (mol)	n for H2 (mol)	n for CO (mol)	H2 mass (kg)	CO mass (kg)	CO2 mass (kg)	
hydrocarbon chains	2325.581395												
	C7H16	7	101.1627907	725.8	73423.95349	100.21	732.7008631	10990.51295	5128.906041	21.98102589	143.6606582	159.6229536	
	C8H18	8	240.6976744	747	179801.1628	114.23	1574.027513	26758.46772	12592.2201	53.51693544	352.7080851	391.8978723	
	C9H20	9	252.7906977	765.4	193486	128.2	1509.25117	28675.77223	13583.26053	57.35154446	380.4671275	422.7412527	
	C10H22	10	223.4883721	775.1	173225.8372	142.29	1217.413994	25565.69387	12174.13994	51.13138775	340.9976597	378.8862886	
	C11H24	11	144.4186047	780.8	112762.0465	156.31	721.40008	16592.20184	7935.40088	33.18440368	222.2705787	246.9673096	
	C12H26	12	153.4883721	797.1	122345.5814	170.33	718.2855715	17957.13929	8619.426858	35.91427858	241.4301463	268.2557181	
	C13H28	13	138.8372093	810.5	112527.5581	184.37	610.3355109	16479.05879	7934.361641	32.95811759	222.2414696	246.9349662	
	C14H30	14	135.1162791	823.5	111268.2558	198.39	560.8561712	16264.82897	7851.986397	32.52965793	219.934139	244.3712655	
	C15H32	15	113.9534884	873.6	99549.76744	212.41	468.6679885	14528.70764	7030.019828	29.05741529	196.9108554	218.7898393	
	C16H34	16	83.02325581	873.6	72529.11628	226.44	320.301697	10569.956	5124.827153	21.13991201	143.5464085	159.4960095	
	C17H36	17	86.04651163	873.6	75170.23256	240.46	312.6101329	10941.35465	5314.372259	21.8827093	148.855567	165.3950744	
	C18H38	18	65.34883721	873.6	57088.74419	254.49	224.3260803	8300.064973	4037.869446	16.60012995	113.1007232	125.6674702	
	C19H40	19	56.27906977	873.6	49165.39535	268.52	183.0977035	7140.810437	3478.856367	14.28162087	97.44276684	108.2697409	
	C20H42	20	50.93023256	873.6	44492.65116	282.54	157.4738131	6456.426338	3149.476263	12.91285268	88.21683012	98.01870013	
	C21H44	21	479.7674419	873.6	419124.8372	296.57	1413.240844	60769.35631	29678.05773	121.5387126	831.2823971	923.6471078	
Total mass in tons:				1895961.14						555.980704	3743.065412	4158.961569	
		Jet fuel in the total liquid fuel product (L)		by-products (L)									
Jet Fuel Output:		1000		motor gasoline		423.255814							
				liquid petroleum		95.34883721							
				gas		553.4883721							

Table 16: Required feedstock for 1000L synthetic kerosene from CO₂ and H₂

DME through methanol production - Inputs							
Output							
Scale (bbld)	Scale (L/d)	Moles of DME	Scale DME (kg)	CO2 input moles	H2 input in moles	CO2 input in kg	H2 input in kg
6.29	1000.030117	45.80124912	2.110063547	91.60249824	274.8074947	4.031425947	0.549614989
15.00	2384.8095	109.2239645	5.031948045	218.447929	655.3437871	9.613893356	1.310687574
20.00	3179.746	145.6319527	6.70926406	291.2639054	873.7917161	12.81852447	1.747583432
25.00	3974.6825	182.0399409	8.386580075	364.0798817	1092.239645	16.02315559	2.18447929
30.00	4769.619	218.447929	10.06389609	436.895858	1310.687574	19.22778671	2.621375148
40.00	6359.492	291.2639054	13.41852812	582.5278107	1747.583432	25.63704895	3.495166864
60.00	9539.238	436.895858	20.12779218	873.7917161	2621.375148	38.45557342	5.242750297
125.00	19873.4125	910.1997043	41.93290038	1820.399409	5461.198226	80.11577797	10.92239645
500.00	79493.65	3640.798817	167.7316015	7281.597634	21844.7929	320.4631119	43.6895858
600.00	95392.38	4368.95858	201.2779218	8737.917161	26213.75148	384.5557342	52.42750297
800.00	127189.84	5825.278107	268.3705624	11650.55621	34951.66864	512.740979	69.90333729
1000.00	158987.3	7281.597634	335.463203	14563.19527	43689.5858	640.9262237	87.37917161
2000.00	317974.6	14563.19527	670.926406	29126.39054	87379.17161	1281.852447	174.7583432
3000.00	476961.9	21844.7929	1006.389609	43689.5858	131068.7574	1922.778671	262.1375148
10000.00	1589873	72815.97634	3354.63203	145631.9527	436895.858	6409.262237	873.7917161
20000.00	3179746	145631.9527	6709.26406	291263.9054	873791.7161	12818.52447	1747.583432
30000.00	4769619	218447.929	10063.89609	436895.858	1310687.574	19227.78671	2621.375148
40000.00	6359492	291263.9054	13418.52812	582527.8107	1747583.432	25637.04895	3495.166864
50000.00	7949365	364079.8817	16773.16015	728159.7634	2184479.29	32046.31119	4368.95858
60000.00	9539238	436895.858	20127.79218	873791.7161	2621375.148	38455.57342	5242.750297

Table 17: Required feedstock for DME production from CO₂ and H₂ - scaling up

BTL with gasifier							
TCI breakdown							
Scale (bbld)	Scale (L/d)	Scale factor	TCI (million \$)	ISBL (million \$)	OSBL (million \$)	EPC (million \$)	Owner cost (million \$)
6.30	1001.61999	0.4	48.23171858	20.06	20.06	40.13	8.025757971
10.00	1589.873	0.4	63.63974154	26.47	26.47	52.95	10.58965299
15.00	2384.8095	0.4	81.16768557	33.77	33.77	67.53	13.50630288
20.00	3179.746	0.4	96.45981053	40.13	40.13	80.25	16.05091247
25.00	3974.6825	0.4	110.2788967	45.88	45.88	91.75	18.3504084
30.00	4769.619	0.4	123.0272057	51.18	51.18	102.36	20.47172703
40.00	6359.492	0.4	146.2057328	60.82	60.82	121.64	24.32863394
60.00	9539.238	0.4	186.4743738	77.57	77.57	155.15	31.0293358
125.00	19873.4125	0.4	289.6505883	120.49	120.49	240.99	48.1978579
500.00	79493.65	0.4	665.4423087	276.82	276.82	553.65	110.7296002
600.00	95392.38	0.4	742.3678533	308.83	308.83	617.65	123.5300108
800.00	127189.84	0.4	882.2311733	367.01	367.01	734.02	146.8032672
1000.00	158987.3	0.5	1034.515137	430.36	430.36	860.72	172.1433187
2000.00	317974.6	0.5	1463.025337	608.62	608.62	1217.24	243.447416
3000.00	476961.9	0.5	1791.832778	745.40	745.40	1490.80	298.1609742
10000.00	1589873	0.6	2665.295044	1108.76	1108.76	2217.53	443.5050953
20000.00	3179746	0.7	2673.392545	1112.13	1112.13	2224.26	444.8525196
30000.00	4769619	0.7	3019.187678	1255.98	1255.98	2511.96	502.3928297
40000.00	6359492	0.7	3291.332297	1369.19	1369.19	2738.39	547.6776942
50000.00	7949365	0.7	3519.206372	1463.99	1463.99	2927.98	585.5959403
60000.00	9539238	0.9	1724.192468	717.26	717.26	1434.53	286.9056267
70000.00	11129111	0.9	1750.976924	728.41	728.41	1456.81	291.3625602
75000.00	11924047.5	0.9	1763.099186	733.45	733.45	1466.90	293.3797046
80000.00	12718984	0.9	1774.514765	738.20	738.20	1476.40	295.2792569

Table 18: BTLD TCI for several production scales

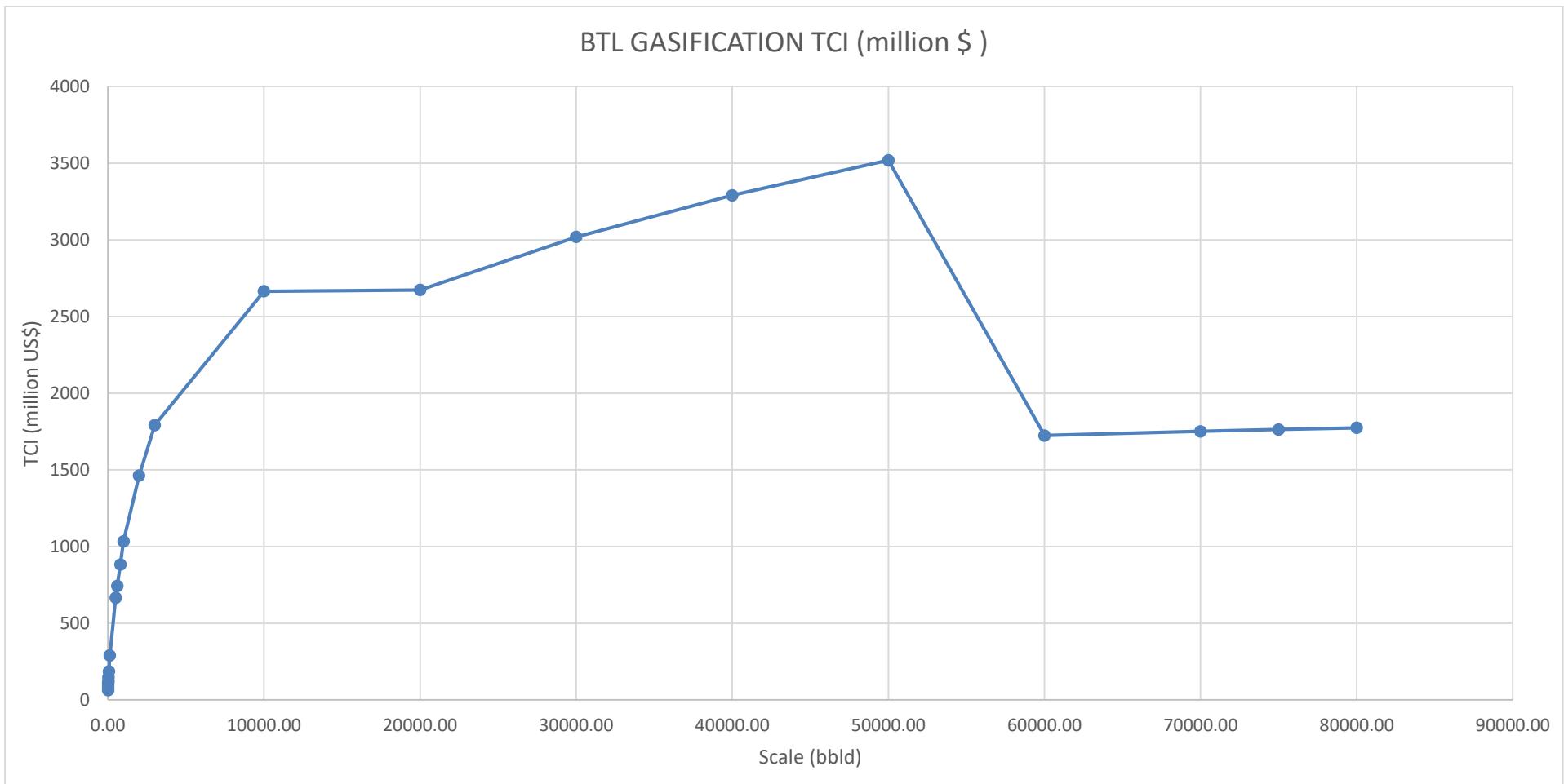


Figure 26: Relation of Scale with TCI

BTL with digester							
TCI Breakdown							
Scale (bbld)	Scale (L)	Scale factor	TCI (million \$)	ISBL (million \$)	OSBL (million \$)	EPC (million \$)	Owner's costs (million \$)
6.3	1001.61999	0.4	4.63	1.924279679	1.924279679	3.848559357	0.769711871
10.00	1589.873	0.4	6.10	2.539006799	2.539006799	5.078013598	1.01560272
15.00	2384.8095	0.4	7.78	3.238311479	3.238311479	6.476622957	1.295324591
20.00	3179.746	0.4	9.25	3.848414668	3.848414668	7.696829336	1.539365867
25.00	3974.6825	0.4	10.58	4.399748674	4.399748674	8.799497347	1.759899469
30.00	4769.619	0.4	11.80	4.908362356	4.908362356	9.816724712	1.963344942
40.00	6359.492	0.4	14.02	5.833105867	5.833105867	11.66621173	2.333242347
60.00	9539.238	0.4	17.88	7.439686137	7.439686137	14.87937227	2.975874455
125.00	19873.4125	0.4	27.78	11.55606222	11.55606222	23.11212445	4.62242489
500.00	79493.65	0.4	63.82	26.54885933	26.54885933	53.09771867	10.61954373
600.00	95392.38	0.4	71.20	29.61792398	29.61792398	59.23584796	11.84716959
800.00	127189.84	0.4	84.61	35.19798939	35.19798939	70.39597878	14.07919576
1000.00	158987.3	0.5	81.01	33.69818022	33.69818022	67.39636045	13.47927209
2000.00	317974.6	0.5	114.56	47.6564235	47.6564235	95.312847	19.0625694
3000.00	476961.9	0.5	140.31	58.36696027	58.36696027	116.7339205	23.34678411
10000.00	1589873	0.6	170.39	70.88413327	70.88413327	141.7682665	28.35365331
20000.00	3179746	0.7	139.54	58.04978518	58.04978518	116.0995704	23.21991407
30000.00	4769619	0.7	157.59	65.558347	65.558347	131.116694	26.2233388
40000.00	6359492	0.7	171.80	71.46766872	71.46766872	142.9353374	28.58706749
50000.00	7949365	0.7	183.69	76.41570418	76.41570418	152.8314084	30.56628167
60000.00	9539238	0.9	59.99	24.95697321	24.95697321	49.91394642	9.982789284
70000.00	11129111	0.9	60.92	25.34466714	25.34466714	50.68933427	10.13786685
75000.00	11924047.5	0.9	61.35	25.52013187	25.52013187	51.04026374	10.20805275
80000.00	12718984	0.9	61.74	25.68536765	25.68536765	51.37073531	10.27414706

Table 19: BTLw TCI for several production scales

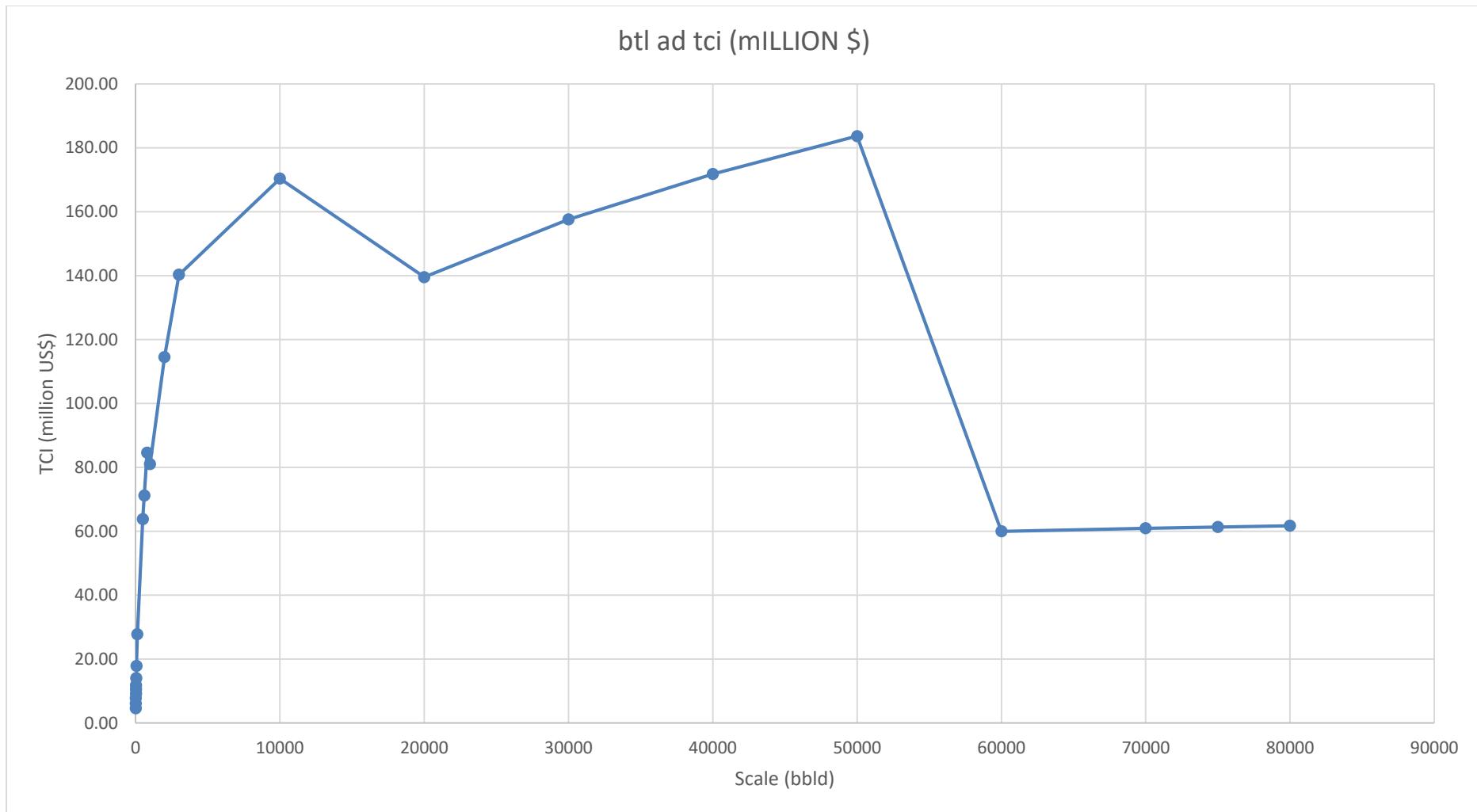


Figure 27: BTLD TCI for several production scales

PTL							
TCI Breakdown							
Scale (bbld)	Scale (L)	Scale factor	TCI (million \$)	ISBL (million \$)	OSBL (million \$)	EPC (million \$)	Owner's costs (million \$)
6.3	1001.61999	0.4	9.19	3.824173	3.824173	7.648346	1.5296692
10.00	1589.873	0.4	12.13	5.045836816	5.045836816	10.09167363	2.018334727
15.00	2384.8095	0.4	15.47	6.435583902	6.435583902	12.8711678	2.574233561
20.00	3179.746	0.4	18.38	7.648058454	7.648058454	15.29611691	3.059223382
25.00	3974.6825	0.4	21.02	8.743739422	8.743739422	17.48747884	3.497495769
30.00	4769.619	0.4	23.45	9.754521135	9.754521135	19.50904227	3.901808454
40.00	6359.492	0.4	27.87	11.5922889	11.5922889	23.1845778	4.63691556
60.00	9539.238	0.4	35.54	14.78508928	14.78508928	29.57017857	5.914035713
125.00	19873.4125	0.4	55.21	22.96567471	22.96567471	45.93134941	9.186269882
500.00	79493.65	0.4	126.83	52.76126551	52.76126551	105.522531	21.1045062
600.00	95392.38	0.4	141.49	58.86050061	58.86050061	117.7210012	23.54420024
800.00	127189.84	0.4	168.15	69.94991537	69.94991537	139.8998307	27.97996615
1000.00	158987.3	0.5	213.25	88.71333422	88.71333422	177.4266684	35.48533369
2000.00	317974.6	0.5	301.59	125.4596004	125.4596004	250.9192008	50.18384017
3000.00	476961.9	0.5	369.37	153.6560022	153.6560022	307.3120043	61.46240087
10000.00	1589873	0.6	594.23	247.197801	247.197801	494.395602	98.8791204
20000.00	3179746	0.7	644.64	268.1694509	268.1694509	536.3389018	107.2677804
30000.00	4769619	0.7	728.02	302.8563476	302.8563476	605.7126951	121.142539
40000.00	6359492	0.7	793.64	330.1553213	330.1553213	660.3106426	132.0621285
50000.00	7949365	0.7	848.59	353.0134929	353.0134929	706.0269858	141.2053972
60000.00	9539238	0.9	486.33	202.3144166	202.3144166	404.6288332	80.92576663
70000.00	11129111	0.9	493.89	205.4572685	205.4572685	410.9145369	82.18290739
75000.00	11924047.5	0.9	497.31	206.8796783	206.8796783	413.7593567	82.75187133
80000.00	12718984	0.9	500.53	208.219167	208.219167	416.4383339	83.28766678

Table 20: PTL TCI for several production scales

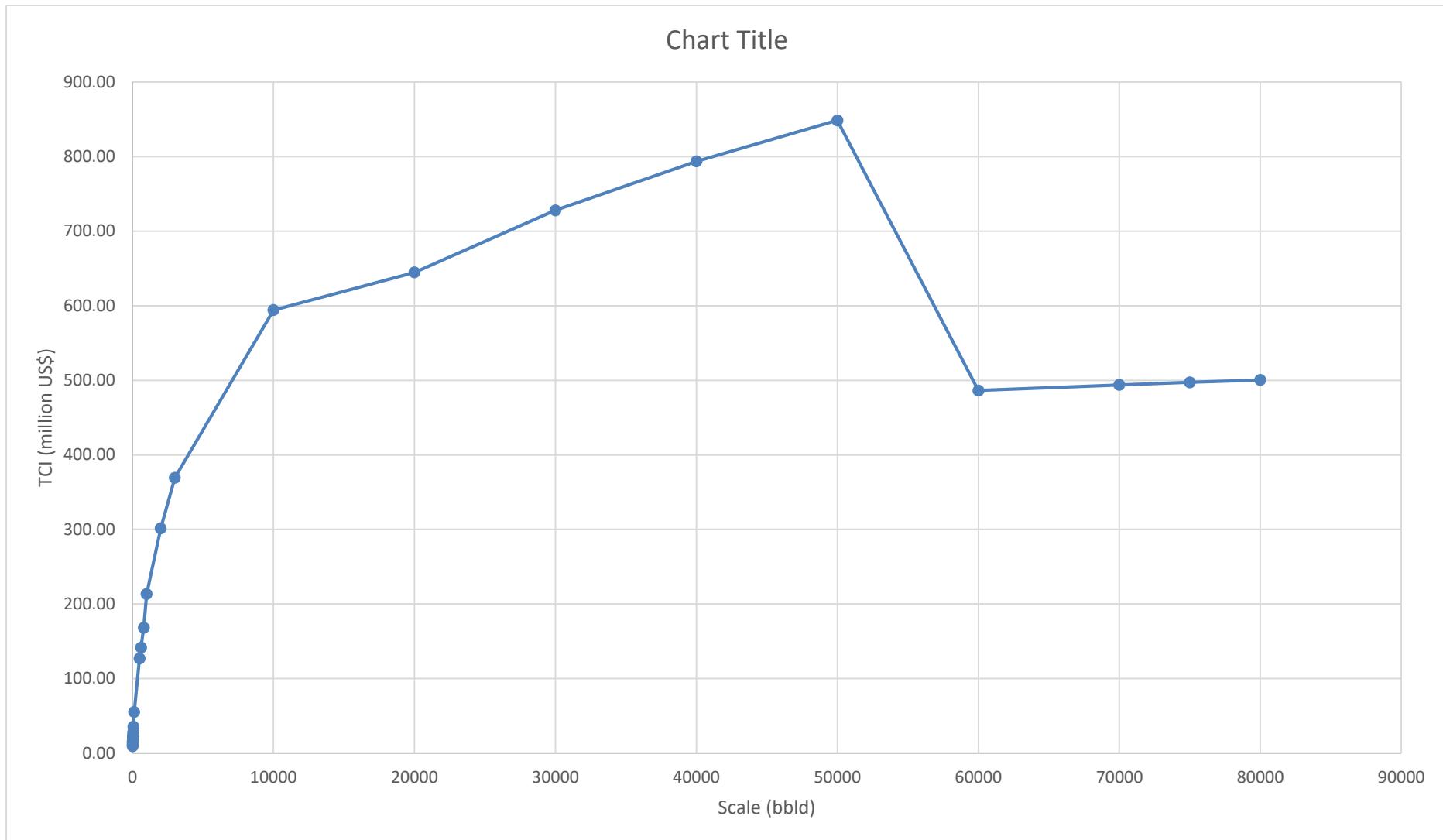


Figure 28: PTL TCI for several production scales

11 APPENDIX C

Who is involved in buying the technology?

- Commercial airlines
- Commercial airports
- Aviation Industries
- Oil/Energy companies
- Military / Air Force / Navy

What are their choice criteria in order to buy the technology?

- What is the type and price of feedstock in the SAF production process (biomass, CO₂ & H₂, etc.)?
- What is the cost of bio-kerosene production through the different pathways? (€/m³ production)?
- What is the cost and frequency of maintenance?
- Does the unit have any waste streams and if yes, can they be exploited (waste heat, waste energy, water, CO₂, H₂)?

When do they buy/use the product?

- When bio-kerosene price will be competitive with the one of conventional fossil fuel (or when the price difference is accepted to be charged on the passengers) [Jet A-1 price ≈ US\$ 0.50/L] [Bio-kerosene price ≈ US\$ 1.14-2/L].
- When national and international policies will oblige the utilization of non-fossil fuels, by high CO₂ taxations.
- From 2020, all airlines are projected to guarantee a carbon neutral growth without increasing CO₂ emissions until 2050 when aviation will be SAF powered. Therefore, the production of SAF is expected to increase.

Why do they buy/use the product?

- Because legislation is growing against GHG emissions, therefore SAF production and utilization will increase.
- Because according to plans, the aviation sector will be totally SAF depended by 2050.
- Because DMT can interpret with three different SAF pathways (PTL, BTL, DME).
- Because DMT has the knowledge in regard of biogas upgrading and desulfurization technologies, which constitute fundamental steps for the BTL and PTL routes of production.
- Because DMT is the leading producer of biogas upgrading facilities in the world in regard of membrane technology.
- Because of the long experience of DMT in the gas treatment sector, the company is able to expand their engagement in further fields.

Where do they buy?

- In general, via project developers

How do they use the product?

- See chapter of Technical Design & Analysis

