NISA Nordic Initiative for Sustainable Aviation NIRAS SDU LIFE CYCLE ENGINEERING

Nordic GTL

– a pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO_2

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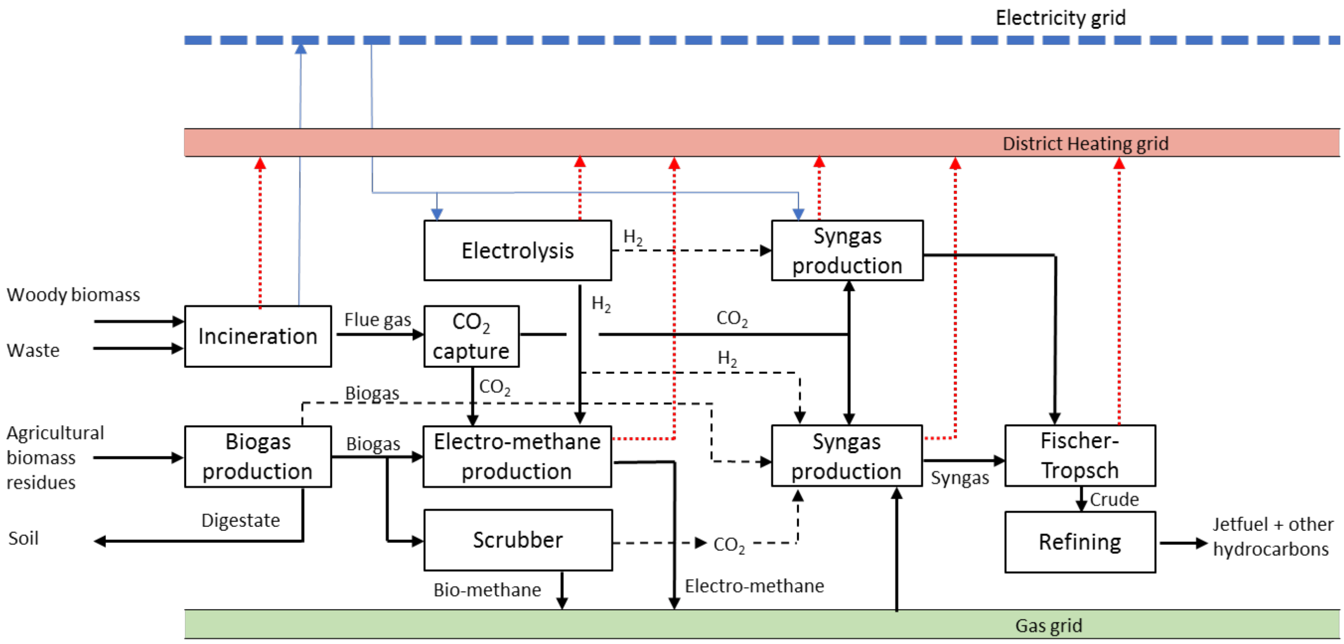
Erik Wormslev and Martin Porsgaard



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Preface, aim and acknowledgements

The study at hand is a pre-feasibility study, and the aim is to provide an indication of the technical and economic feasibility of producing aviation fuel from feedstocks of biogas, CO_2 and sustainable hydrogen. The study aims, further, to identify actors and stakeholders of this aviation fuel supply chain and to provide the platform for a continued feasibility analysis and the formation of a consortium of partners. As a final step, after the more in-depth feasibility analysis, it is the hope and ambition of the authors of the study that such a consortium of actors in the whole supply- and demand chain will be able to agree on a Memorandum of Understanding allowing for the investment in a full-scale gas-to-liquid sustainable aviation fuel production.

The study has been limited to a few man-months of work, beginning April 2019 and ending with the publication of this report October 2019. The project partners and main contributors have been:

- SDU, University of Southern Denmark, PhD student Anders Winther Mortensen, PhD student Kasper Dalgas Rasmussen and Professor Henrik Wenzel
- NIRAS, Director of Innovation, Climate Change & Energy Erik Wormslev and Consultant Stine Sandermann Justesen
- NISA, Nordic Initiative for Sustainable Aviation, Project Director Martin Porsgaard

The project was funded by several parties, i.e. Copenhagen Airport (CPH A/S), Association of Danish Aviation (BDL), SAS, Nature Energy A/S, Amager Resource Center A/S (ARC), Nordic Energy Research, Danish Energy, and the work was commented on during meetings with these funding partners, i.e.

- CPH A/S, Head of Environmental Affairs Inger Seeberg, Energy Director Niels Hunderup and Project Manager Jesper Abery Jacobsen
- BDL, Association of Danish Aviation, Head of Secretariat Per Henriksen
- SAS, Head of Environment and CSR Lars Andersen Resare
- Nature Energy, Sales Director Jonas Svendsen
- ARC, Head of Environmental Affairs Jonas Nedenskov
- Nordic Energy Research, Senior Advisor Svend Søyland
- Danish Energy, Senior Advisor Nikolaj Nørregård Rasmussen and Senior Advisor Morten Stryg

Two ongoing research projects, V-SUSTAIN financed by the Villum Foundation and SYMBIO financed by Innovation Fund Denmark, allowed SDU to provide co-funding, which we would like to acknowledge.

The framework conditions, cases and stakeholders identified in the study are Nordic, but with a Danish majority. However, the study is technology oriented and fully transparent on scenarios and calculations assumptions and as such fully transferable to all Nordic countries and other countries outside the Nordic for that matter. Moreover, the study allows for a pre-feasibility assessment of all combinations of feedstocks from pure biogas to bio-methane, electro-methane and CO_2 and hydrogen.

October 24th, 2019, on behalf of the authors

Review process

A draft version of this report was sent to a number of external experts and leading supply chain actors for critical review and in all, we received comments and feed-back from 16 reviewers. Some of these reviews were followed by a dialogue, during which we got further inputs.

None of the reviewers were paid to do the review, and we have not asked them for a written review with the purpose of publishing this in the report, and therefore we do not do this, just like we do not mention the reviewers by name. We received the reviews with great appreciation and acknowledged and included most of the review comments. The reviewers have all been positive to the report, results and conclusions. We find that the results and conclusions presented in the report in the version at hand reflect the feed-back we have got well, but all results and conclusions are the author's based on our own knowledge and judgement from this pre-feasibility study and our best ability to include the points of the reviewers.

List of abbreviations

ASTM – American Society for Testing and Materials

bcfd – billion cubic feet per day

bpd – barrels per day

CAPEX – Capital Expenditure

CCU – Carbon Capture and Utilization

CCS – Carbon Capture and Storage

DAC – Direct Air Capture

DEF STAN – Defence Standard

DME – Dimethyl Ether

FT – Fischer-Tropsch

GGFR – Global Gas Flaring Reduction partnership

GTL – Gas-To-Liquids

IVL – IVL Swedish Environmental Research Institute

LUT - Lappeenranta University of Technology

LNG – Liquefied Natural Gas

MSA – Methane sulfonation

NPV – Net Present Value

O&M – Operation and maintenance

OCM – Oxidative Coupling of methane

OP – Oxidative Pyrolysis

OPEX – Operational Expenditure

POX – partial oxidation

PtL – Power to Liquids

PtX – Power to X (Can be gasses or liquids)

RISE – Research Institute of Sweden

SAF – Sustainable Aviation Fuel

Syngas – Synthesis gas

TCM – Technology Centre Mongstad

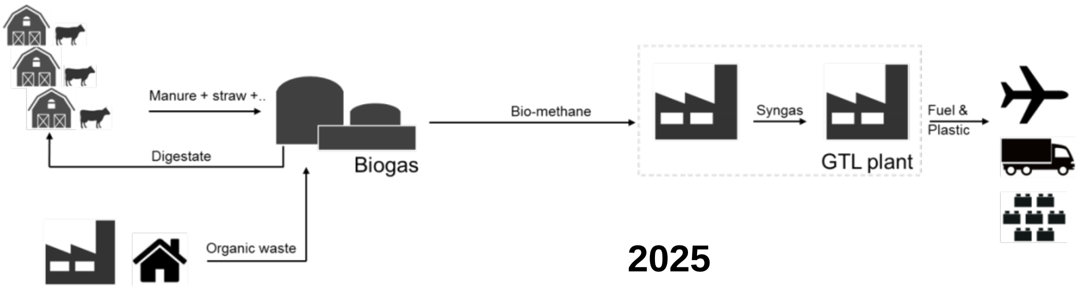
TSO – Transmission System Operator

UCOME – Used Cooking Oil Methyl Ester

Executive summary

The purpose of this pre-feasibility study is to identify technological pathways and processes for producing sustainable aviation fuel based on renewable feedstocks of biogas, bio-methane, electro-methane, hydrogen and CO_2 and to make a preliminary assessment of their feasibility including their economic/commercial viability. The aims are, further, that this pre-feasibility study can form the platform for a subsequent detailed feasibility analysis and become the basis for a Memorandum of Understanding between key stakeholders in this supply-demand chain of aviation fuel and as such help generate the necessary background for the investment in production capacity in the Nordic countries.

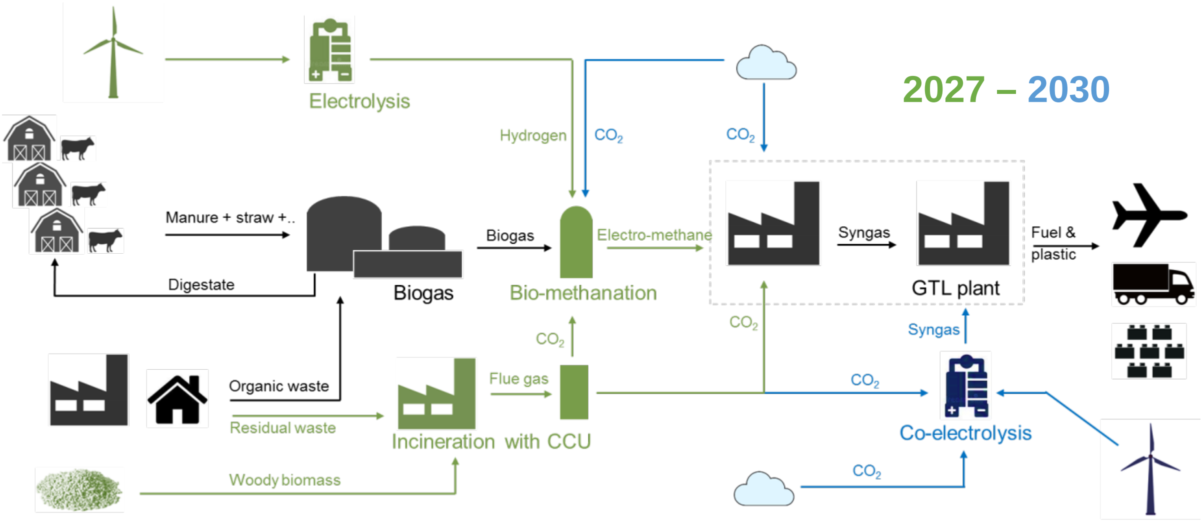
A benefit of the proposed pathway is that it builds on a backbone of existing large-scale technology, i.e. the so-called gas-to-liquid or GTL technology where liquid fuels are produced from methane via synthesis gas. Synthesis gas, or syngas, is a mix of hydrogen and carbon monoxide, being an intermediate in the conversion of methane to liquid fuels. Several of such large-scale GTL plants are in operation across the world converting natural gas into liquid fuels. The same technology can be applied to bio-methane and green syngas. Such a plant can in principle be contracted 'tomorrow' – after a detailed feasibility study for a specific location – and be built and in operation by 2025 at the latest. The Figure below shows the pathway.



Production of GTL jet fuel, other fuels and plastics based on feedstock of bio-methane. The applied technology is mature and already existing and a jet fuel factory based on this technology can be in full scale operation by 2025

The pathway is robust and flexible in the sense that feedstocks can be any type of methane and syngas. The merit of this is that the feedstock of bio-methane can be supplemented by electro-methane or syngas made from hydrogen and CO_2 and by syngas made from electricity and CO_2, producing thereby so-called electro-fuel via the same GTL technology. The fuels are the same, only the feedstock is different. The technology for producing electro-methane is documented in demonstration scale by several stakeholders and judged to be available for operation in full scale by 2027 at the latest. Moreover, production of syngas directly from CO_2 and electricity by so-called co-electrolysis is successfully demonstrated and judged to be available in full scale by 2030, potentially even before so this is a conservative estimate. Techniques for carbon capture are well known and implemented in full scale, for example on many biogas plants, and applying the technique on flue gases from waste and biomass incineration is under development and judged to be available in full scale by 2027. Finally, techniques for direct capture of CO_2 from the atmosphere is successfully demonstrated in pilot scale and judged to be available in full scale by 2030.

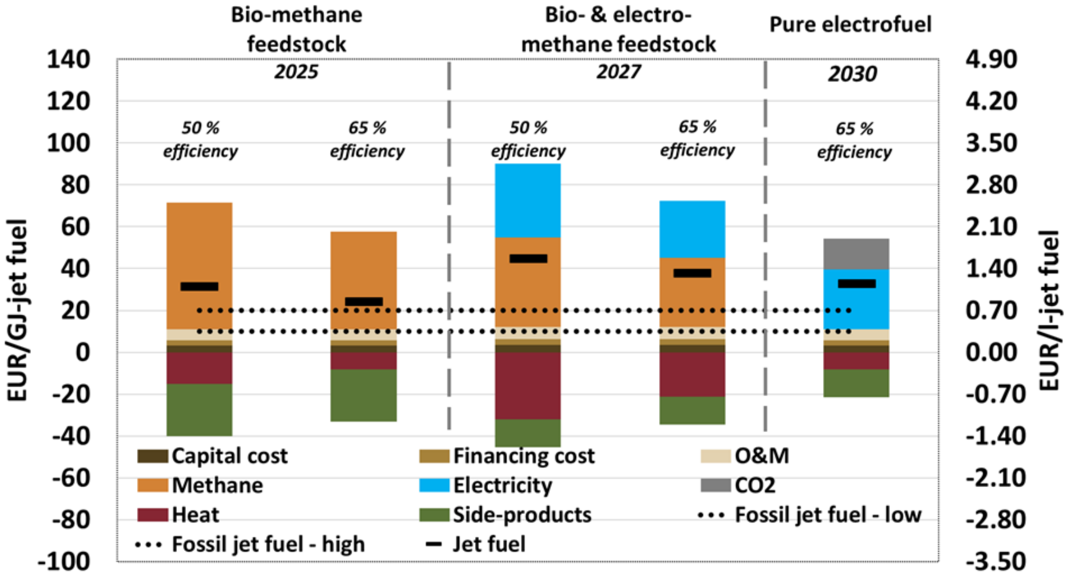
This ability to integrate methane, CO_2, electricity and hydrogen in one and the same supply chain is a key feature of the pathway. First, it allows the flexibility of shifting between the feedstocks for economic optimization with fluctuating electricity prices and with shifting availability of CO_2 from biomass flue gas between summer and winter. Second, the bio-methanation of the CO_2 content of biogas and the recycling of any CO_2 and CO off-gas emissions from the GTL back to a methanation allow for an almost 100 % carbon conversion efficiency from methane to liquid fuels. Together with using flue gas CO_2 and atmospheric CO_2 as feedstock, it makes the pathway fully sufficient and a real and globally scalable solution. Third, being based on biogas and CO_2, the fuels will be practically CO_2 neutral. See the illustration next page.



Supplementing the GTL jet fuel supply chain by feedstocks of electro-methane, CO_2 and hydrogen. The technologies are documented in pilot scale/demonstration facilities and judged to be available in full scale by 2027 (green color) or 2030 (blue color)

The biogas feedstock is further motivated by biogas facilities being attractive agricultural management facilities allowing agriculture to reduce its greenhouse gas emissions significantly and allowing for optimized nutrient management and soil carbon management as well as advanced treatment and value addition to biomass feedstocks. Moreover, storing bio-methane on the gas grid allows for the most cost-efficient balancing of the fluctuating wind and solar power, as gas turbines and motors constitute the cheapest back-up capacity installed, and as such the pathway provides the supplementing service of efficiently and sufficiently storing electricity in the renewable energy system.

Finally, locating electrolysis, bio-methanation and GTL on district heating grids constitute a significant economic advantage of the pathway, and any location allowing the use of the process heat loss from these units will have a high competitive advantage. The Figure below shows our cost calculations based on our best estimates of feedstocks prices, investments costs, etc.



Estimated break-even sales price for jet fuel, black rectangles, for three feedstocks of bio-methane (left), bio- and electro-methane (middle) and pure electro-fuel based on CO_2 and electricity or hydrogen (right) with different side-product prices. Assuming a conversion efficiency of 50 % for smaller scale plants and 65 % for larger scale plants as the low-high range. The sales price of the side-products is assumed equivalent to the cost of second generation bio-ethanol by 2025 and liquefied bio-methane by 2027 and onwards. All prices are an-factory for inputs and ab-factory for products (as opposed to an-airport)

The graph shows the break-even prices for the produced jet fuel. Included in the calculation is an assumption of 5 % interest rate on the investment, so the shown prices indicate the level, above which the return on investment is expected to exceed 5 %. The graph shows our base case assumptions of electricity costs, bio-methane cost, investment costs, side-product sales price, heat sales price, etc. Sensitivity analyses are made to show the significance of varying assumptions, please see details in the report.

As evident from the graph, we judge the jet fuel from this pathway to be available at costs from just above the high end of today's fossil jet fuel prices to approximately 2 times the high fossil jet fuel price. Comparing this to costs of available bio-jet fuels today, we find this price level attractive. Firstly, it is on the same level as today's available bio-fuels. Secondly, it is unquestionable that the fuel from this pathway is climate friendly, which is not the case for all bio-fuels. Thirdly, and maybe most importantly, this pathway is scalable and globally sufficient, which is not the case for existing bio-fuels on the market. It is, thus, a real solution to aviation industry's need for sustainable fuels.

To conclude, we find the outcome of this pre-feasibility study promising. Key stakeholders in all parts of the supply and demand chain express interest in looking more into the possibilities including a more in-depth feasibility study. We, therefore, recommend such a study to be initiated with the aim of providing sufficient decision support for forming a consortium and deciding on a model for ownership and investment.

We find it worth-while to coin this pre-feasibility assessment out in a clear and brief overview, as this is an efficient way of communicating the characteristics of the pathway. Further, we wish to put it up as a yard-stick for any other emerging fuel pathway to compare to, and we encourage other technology developers and pathways to address the here identified sustainability performance criteria in the same concrete and holistic way. See the overview in the Table below.

Characterization and quantification of the performance of the studied jet fuel supply pathway on the key sustainability performance criteria of technical, economic and environmental feasibility

Sustainability criterion	Performance according to pre-feasibility assessment
Cost-efficiency – economic feasibility	
From biogas and bio-methane	0.7 – 1.1 EUR/L jet fuel in the period 2025 and onwards
From bio- and electro-methane	0.9 – 1.4 EUR/L jet fuel in the period 2027 and onwards
From CO_2 and electricity	0.7 – 1.2 EUR/L jet fuel in the period 2030 and onwards
Fuel feasibility & accreditation	
ASTM and DEF STAN compliance	Technically compliant with ASTM and DEF STAN requirements
Technical readiness level of technologies in the supply chain	
From biogas and bio-methane	TRL 9 for the whole supply chain
From electro-methane	TRL 8 for electro-methane production, TRL 9 for the rest
From CO_2 and hydrogen	TRL 8 for carbon capture from waste & biomass flue gas, TRL 7-8 for syngas production, TRL 9 for the rest
System level efficiency and feasibility	
Area and carbon efficiency	No land use and close to 100 % carbon efficiency
Sufficiency	Up to around 200 EJ/year of hydrocarbons globally using only sustainable biomass. Supplemented by direct air capture of CO_2, the pathway is fully sufficient
Energy system integration	Most cost-efficient balancing of fluctuating electricity of all. Most cost-efficient sources of CO_2 for assimilating electricity & hydrogen into fuel supply. Almost full utilization of process heat
Agricultural system integration	Improved plant availability of N. Full N, P and K recycling and better re-distribution among farmers. Full return of hard-degradable carbon to agricultural soils for soil-C maintenance
Environmental feasibility	
Climate change	Negative carbon footprint for biogas and bio-methane feedstock. Around zero carbon footprint for other feedstocks. In both cases not-including the stratospheric water vapor and other high altitude emission impacts
Biodiversity	No land use implies low biodiversity impact
Soil quality	Good agricultural soil quality management with respect to N, P, K and C

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NISA’s background and motivation

Aviation has a huge challenge in finding sustainable alternatives to fossil fuels. Central aviation actors in the Nordic region strive to reduce emissions, to move away from the use of fossil fuels to become more sustainable in the long term. In recent years, a great number of analyses and reports have been prepared in the effort to find long-term, sustainable and commercially available solutions. It is a work that still is going on both in the Nordic countries and internationally. Some countries have taken initiatives to promote the development and use of sustainable aviation fuels and also at the global level, the UN organization ICAO, has launched a program to help reduce aviation emissions. Air traffic in the EU is subject to an emission trading system, a quota duty that takes a share of the aircraft emissions. In addition, some countries have introduced taxes and duties that in various ways intend to limit emissions.

New aircraft and improved route planning have historically proven to contribute about a 1% reduction per year, which is positive, but far from sufficient when air traffic grows on average 4-5% per year, both historically and estimated in the coming decades.

Therefore, there is a great need to find sustainable alternatives to the large and growing use of fossil fuel for aviation. Research on this has been done for number of years, without being able to point out methods, technologies and feedstocks that can solve the long-term challenges.

There has been a comprehensive international focus on the development of biofuel, as a possible long-term solution to aviation challenges. A number of years of research and an initial production of sustainable biofuel indicate that it is a very slow process with a limited prospect of meeting the industry's commercial and volume related requirements. Development of electric, hydrogen and hybrid aircraft has exciting and decisive, but long-term, prospects when we look at solutions that may include larger aircraft. Current fleets and those on the drawing board so far will need liquid sustainable fuels. In this context, the focus of this project on using feedstocks of agricultural wastes for bio-methane production as well as CO_2 and hydrogen for the production of new fuel is promising and groundbreaking.

The pathway will not only benefit the aviation needs of sustainable fuels. Other energy-consuming sectors and even agriculture and plastic industry will also benefit from the approach of this project. Synergies in the production flow and on the output side intends to see this project as a fundamental contribution to a future strategic energy policy. The development project requires interaction and utilization of the synergies between renewable energy sources, electricity, gas and heat production in combination with the production of liquid fuels for transport modes on land, at sea and in the air.

A number of parties with both different and shared interests have therefore joined together in this pre-feasibility study to clarify the opportunities, perspectives and challenges of producing sustainable fuel, focused on jet fuel, based on the extensive emissions currently found at a number of various large process plants and presumably also from capturing CO_2 from the air.

1 Introduction

1.1 What is jet fuel?

Jet fuel is a type of aviation fuel developed for use in an aircraft powered by gas turbine engines. The most commonly used fuels for commercial aviation are called Jet A and Jet A-1, which are produced in accordance to a standardized international specification.

Jet fuel is a mixture of a large number of different hydrocarbons. Because the exact composition of jet fuel varies widely based on petroleum source, it is impossible to define jet fuel as a ratio of specific hydrocarbons. Jet fuel is therefore defined as a performance specification rather than a chemical composition. The range of molecular mass between hydrocarbons (or different carbon numbers) is defined by the requirements for the product, such as the freezing point or smoke point. Kerosene-type jet fuel (including Jet A and Jet A-1) has a carbon number distribution between about 8 and 16 (carbon atoms per molecule). Jet A-1 has a flash point higher than 38°C and a freezing point of -47°C.

Jet fuels are traditionally produced from crude oil using fractional distillation in refineries, where jet fuel is a middle distillate with a boiling point between 175°C and 288°C. This type of fuel contains few light or heavy hydrocarbons. The chains are between 8 and 16 carbon atoms long, but most hydrocarbon molecules are in the range of 10 and 13 carbon atoms. As a result, the density of this colorless to light-yellowish fuel ranges between 0.747 and 0.84 g/cm^3, so in most specifications, its density is higher than that of gasoline and lower than that of diesel fuel. The specific energy of the fuel Jet A1 is 43.1 MJ/kg. In contrast to diesel or gasoline engines, it is continuously combusted in the aircraft turbines and therefore causes comparatively few residues. Jet fuel exhaust mainly consists of carbon dioxide, some water vapor, and lots of hot air.

1.2 Jet fuel demand in the Nordic countries

The geographical focus of our study is the Nordic countries. A projection of the jet fuel demand in the Nordic countries can be seen from Table 1.

Table 1: Aggregated and projected Nordic demands for jet fuel [1]

Year	**2014**		**2025**		**2050**	
Unit	*Million liters*	*Petajoule*	*Million liters*	*Petajoule*	*Million liters*	*Petajoule*
Denmark*	1,200	45	1,300	50	1,900	70
Sweden	1,000	38	1,300	45	1,200	45
Norway	1,200	44	1,500	55	1,400	50
Finland	900	34	1,100	40	1,100	40
Iceland	240	9	300	10	300	10
Total	**4,540**	**170**	**5,500***	**200***	**5,900***	**215***

*For Denmark the projected demand for jet fuel has been updated, taking into account the newest consumption from 2017 and with 1,5% pa. projection. The projection for the rest of the Nordic countries are from 2014. For 2030 the projected jet fuel demand is 53 PJ for Denmark.

As can be seen from Table 1, the demand for jet fuel in the Nordic countries is projected to increase from around 170 PJ in 2014 to around 210 PJ in 2025 and then decrease slightly towards 2050 to around 200 PJ.

Producing 200 PJ of sustainable aviation fuel is, of course, a challenge. But with a pathway based on bio-methane, hydrogen and CO_2, all technologies in the supply chain needed to produce such jet fuel already exists even without any need for change of the current jet engine technology [2]. Technologies for jet fuel production based on bio-methane already exist in full scale in terms of the well-established gas-to-liquid, GTL technology. Some of the processes based on the feedstock of hydrogen and CO_2 exist only in smaller scale and need to be scaled-up, but many projects are presently ongoing and companies working in this field aiming at producing e.g. methane (electro-methane) or carbon monoxide or syngas from CO_2 and hydrogen. A full-scale production of jet fuel from bio-methane is, thus, already available for implementation, and a supplementing production based on CO_2 and hydrogen is judged to be so in a few years from now.

The reason for choosing a pathway based on feedstock of bio-methane, hydrogen and CO_2 is that this is judged to be the most feasible and sustainable pathway based on the criteria described in the next section.

1.3 Key sustainability criteria for future fuels

Using biomass as a feedstock is the most common for the very small-scale jet fuel production that exists at present. This is, however, challenged by both supply shortage and environmental concerns if scaled up. Already today, 1 million species are threatened with extinction [3] due to human impacts on nature, especially our occupation and cultivation of land. If simply applying biofuels as the alternative to fossil fuels, global biomass demand is likely to exceed the sustainable supply potential by far, and likely to cause even more damage to global biodiversity, climate and the environment [4]. The available global biomass potential is estimated at 100 – 300 EJ/year [5], [6], the demand for biomass by far exceeds this level, if biomass is singled out as the main substitute for fossil fuels.

Today, global fossil fuel consumption is around 500 EJ/year and expected to rise due both to a population increase and economic growth. In 15 years, around 3,5 billion people more are expected to enter the middle class, demanding more meat in their daily diet than today. In 2050, plastic production is projected to quadruple compared to 2016 [7], and aviation and sea transport is expected to double. If, thus, biomass is targeted as the main feedstock for plastic and for transport fuels, heat/cooling and power, the total demand for biomass will easily exceed 1000 EJ/year by 2050 [4].

In order to be both a reliable, feasible and competitive pathway for fuel supply, therefore, a set of criteria has to be met. We have identified the following:

- Cost efficiency – everything else equal, the most cost-effective pathway is preferred
- Area efficiency – and carbon efficiency. As availability of land area and carbon are key constraints, a key criterion is that the supply pathway is as efficient as possible in its conversion of carbon in the biomass to the essential fuels (and plastics) needed in society. Loss of carbon should be avoided
- Sufficiency – as biomass feedstocks are limited, it is a concern that a given pathway is sufficient, i.e. that it in a meaningful way can be scaled up and be a solution in large scale and on the long term. An implication of this is that the pathway should allow for a feasible assimilation of hydrogen into hydrocarbons in order to boost the hydrocarbon yield of biomass feedstocks
- Energy system integration – being storable, carbon containing fuels have a key role in supporting the balancing and integration of the energy system, i.e. not only provide transport fuels, but also support the balancing of the fluctuating renewable electricity production from wind and solar power. Further,

the inherent and unavoidable process heat from conversion processes should be utilized for heating and/or cooling purposes

- Agricultural system integration and soil quality – as biomass grow on soil, and as soil quality and soil carbon content are key concerns for a sustainable agriculture on the long term, it is a key criterion that the pathway supports good agricultural practices including returning nutrients and non-converted carbon back to soil
- Environmental efficiency – especially with respect to climate change and biodiversity

Figure 1 illustrates a generic fuel supply pathway, and the interactions of fuel production with the energy system and agricultural system.

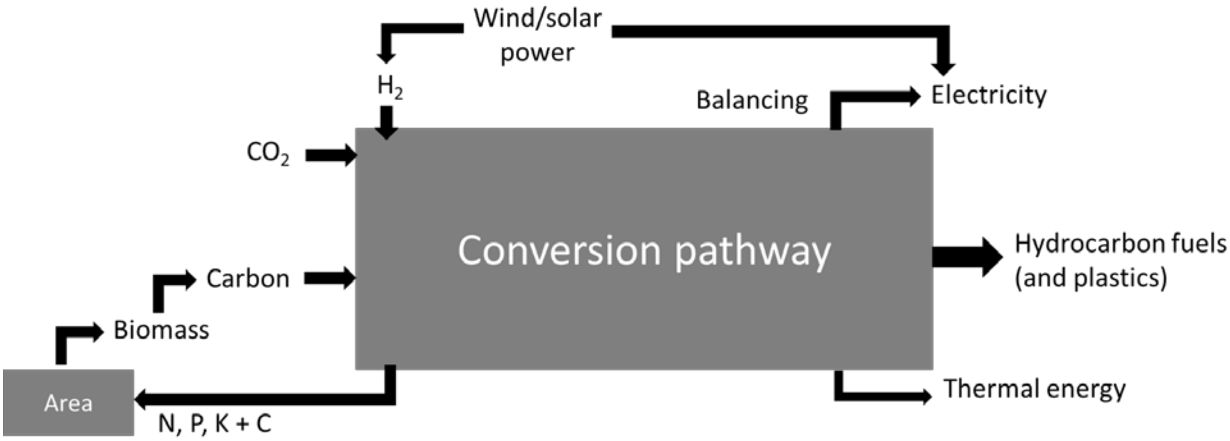


Figure 1: The integration and role of the fuel conversion pathway in the energy and agricultural systems

The characteristics and performance of the chosen supply chain can be described as:

- The technical readiness level, TRL is high for all technologies involved. If using only biogas or bio-methane as feedstock, TRL is 9 corresponding to mature, existing full-scale technology. In case of electro-methane, quite large-scale demonstration facilities are found several places in the world, and TRL is 8. For feedstocks of CO_2 and hydrogen, TRL is 7-8 for the syngas production, but expected to be ready by 2025, the same goes for carbon capture from waste and biomass incineration flue gas.
- Area efficiency is very high as only biomass residues and CO_2 are used as carbon sources, and carbon efficiency of the conversion of the initial carbon in the biomass (and CO_2) to carbon in the produced hydrocarbons/fuels is close to 100 %, because non-converted carbon from the biomass are taken back to soil, and because any CO_2 losses from conversion are captured and recycled.
- On the key criterion of sufficiency and scalability, this pathway is optimal, because of the high carbon efficiency and because the bio-carbon feedstock is easily supplemented by CO_2. In all, the pathway represents a fully sufficient supply for the whole energy system as well as plastic supply – as opposed to other emerging or existing green fuel supply approaches.
- The pathway allows for an ideal energy system integration, because the bio-methane is storable on the gas grid and the most cost-efficient and technically feasible way of balancing fluctuating wind/solar power by using gas turbines/motors as stand-by electricity production capacity. Finally, the combination of decentral and central production allows for an almost full use of the unavoidable process heat for district heating supply.

- The integration of the pathway into the agricultural system is also ideal. During anaerobic conversion in the biogas facility, the nitrogen content of the biomass is rendered more available for crop uptake allowing for better dosing, and both N, P and K can be better re-distributed among farmers. Further, non-converted carbon is left hard-degradable and returned to soil contributing to long term soil carbon content of the soil, and all-in-all the presence of wide-spread biogas facilities in the landscape have promising perspectives for professional agricultural management.

Finally, also the cost-efficiency of the pathway turns out to be very good, as described in subsequent sections.

2 Current initiatives in the Nordic Countries

This pre-feasibility study covers the possibility of producing sustainable jet fuel from hydrogen, CO_2 and bio-methane in the Nordic Countries. Several demonstration projects and research programs are already taking place in the Nordic countries which cover the possibilities to produce sustainable jet fuel and/or how to upscale the different technologies needed. The following section gives a short description of some of the activities.

The list of relevant projects and initiatives might be longer than covered here, as the timeline and budget of this project have not allowed for a fully exhaustive inventory. Each of the projects or initiatives identified in this report are rated according to their Technology Readiness Level (TRL) according to the specifications shown in Figure 2.

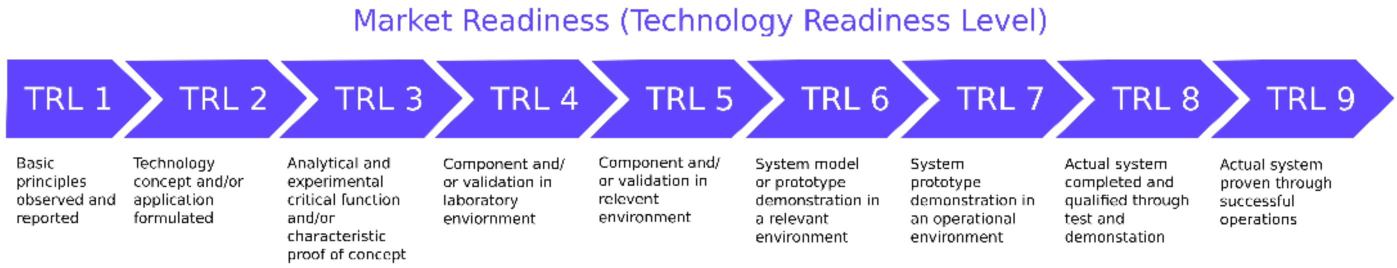


Figure 2: The TRL level specifications used in this report

2.1 Denmark

In Denmark, several projects are focused on either the specific technologies described in this pre-feasibility study or the whole process of making electro fuels. The project SYNFUEL at DTU started in 2015 and covers research on how to combine electrolysis and gasification of biomass in a way that produces more biofuel from the same amount of biomass [8]. The project is rated to TRL 2 and will be finished in 2019.

Power2Met is a project with several partners planning to build a pilot plant at Aalborg University that produces methanol [9]–[11]. Power2Met is rated to TRL 6.

The company Electrochaea has upscaled the biological process using biocatalysts (the microorganism archaea) to produce methane from CO_2 and hydrogen [12], [13]. Electrochaea has a demonstration plant located at BIOFOS waste water treatment at Avedøre Holme, and the technology is rated to TRL 8.

At University of Southern Denmark, SDU a project called eFuel is ongoing aiming at development and demonstration of the production of methane from CO_2 and hydrogen also using bio-catalysis by methanogenic microorganisms. The project is done in collaboration with DTU and the companies Nature Energy and Biogasclean as well as the regional business development organization Miljøforum Fyn. The project builds on a bio-trickling filter concept and aims at having a demo scale plant in operation by 2023 at TRL 8-9.

A report from the Danish TSO Energinet summarizes the potential for making Power-to-X (PtX) in Denmark before 2030, finding that PtX could be economically relevant on a short term. However, regulatory changes and system changes will be needed [14].

At DTU, a large concept project, Energy-X is addressing the systems and technologies to replace fossil fuels [15]. They are examining the whole system of carbon capture from biogas and flue gas, production of bio-methane, bio-methanol and bio-crude oil by PtX and utilization of all excess energies in the system to reduce costs.

The Danish demonstration facility GreenLab Skive is building a business park which will become a platform for various forms of energy storage including power-to-hydrogen, power-to-ammonia and other PtX technologies as well as methanization of biogas, thermal and electrical storage [16]. The different technologies in the business park are rated between TRL 4-7.

The Danish company Topsøe has a full scale technology ready, HydroFlex, for processing renewable feedstocks to existing refineries [17]. The technology is rated to TRL 8. Furthermore, Topsøe is building a demonstration plant to produce CO_2-neutral methanol from biogas and green electricity, located at Foulum, Denmark. The demonstration plant is scheduled to be fully operational in the beginning of 2022. The eSMR MethanolT technology will produce methanol from Topsøe's syngas eSMRT technology [18].

Carbon Capture and Storage or Utilization
Research and demonstrations of carbon capture and storage or utilization are taking place at the CERE Institute at the Technical University of Denmark [19].

Almost all new biogas plants in Denmark are upgrading the biogas to methane which is injected into the natural gas grid. Now they have started to recover CO_2 in contrast to diluting CO_2 directly into the air. In Esbjerg a CCU plant is planned to capture CO_2 from biogas [20] using amine absorption technology provided by Pentair – TRL 8-9.

Furthermore, Amager Resource Center together with Copenhagen Municipality are looking at the possibility of building a carbon capture plant for carbon storage or future utilization. A pilot plant will be delivered by Siemens [21] – TRL 8.

Production of hydrogen
The business park Hydrogen Valley in Hobro opened a hydrogen plant in 2018 and is now producing hydrogen from alkaline electrolysis [22]–[25] at TRL 9.

The company GreenHydrogen in Kolding produces smaller electrolysis units [26] at TRL 9.

Further, Topsøe manufactures solid oxide electrolyzer cells (SOEC) that use electricity to produce hydrogen from steam at high temperatures [27]. The technology is rated to TRL 7. Furthermore, Topsøe is looking into how to reduce CO_2-emissions from traditional steam methane reforming by using electric heating in smaller reactors [28].

2.2 Sweden

In 2017, the Swedish Government decided on an aviation strategy, and the Swedish Energy Agency allocated 34 million SEK to an innovation cluster called Fossilfria Flygtransporter 2045 (Fossil-free Air Transport 2045) [29]. A total of 11 research projects will examine how sustainable aviation fuel can be produced from biomass or PtX. Three of the eleven projects deal with jet fuel from bio-methane, CO_2 and hydrogen, as the rest of the projects deals with producing jet fuel from biomass such as wood chips and lignin.

The first project, a partnership between Research Institute of Sweden (RISE), SAS and Swedavia has the aim to gather actors from the entire value chain and develop a joint plan, both in terms of technical innovations and business models and services that will make it more interesting to invest in the production of bio-jet fuel [30].

The second project is from Chalmers Tekniska Högskola, where they are looking at the process of making methanol from hydrogen and CO_2 and then synthesize methanol to jet fuel. The hydrogen will be produced from electrolysis, and CO_2 will be captured from e.g. biomass combustion. The main focus for the research project is to develop and test various kinds of catalysts [30].

The third project is a research project at Lunds University, where they together with Kiram AB are developing a process for production of electrofuels that can be integrated with biofuels [30].

Furthermore, Chalmers Teksniska Högskola has examined the production costs of electro fuels for the transport sector [31]. The study covers methane, methanol, dimethyl ether, diesel and gasoline processes and show that the two most important factors affecting the production cost of all electrofuels are the capital costs of the electrolyzer and the electricity price, i.e. the hydrogen production cost.

IVL Swedish Environmental Research Institute (IVL), Jämtkraft, University of Lund, Chalmers University, NISA among others have been allocated funding from the Swedish Energy Agency to explore the possibility to start full scale production of fossil free jet fuel from the wood pellet combustion plant in Östersund. The project starts autumn 2019, the title of the project is: Large scale Bio-Electro-Jet fuel production integration at CHP-plant in Östersund, Sweden.[32], [33].

Also AkzoNobel Specialty is partnering with RISE, Södra and BillerudKorsnäs to explore the opportunities for producing chemicals, green hydrogen and electrofuels using renewable energy, supported be Swedish Energy Agency [34].

Carbon Capture and Storage or Utilization

An article from 2017 examines the possibility for producing electrofuels using CO_2 point sources. The focus in the article is mainly how many point sources there are, and where they are located. The conclusion is that there are good possibilities for setting up production of electrofuels near CO_2 point sources [35].

Carbon capture and utilization is already being used at a plant in Norrköping at Agroethanol, where 175.000 tons CO_2 are captured from biogas plants and used in sodas [36].

Stockholm Exergi has been granted around 400,000 EUR from the Swedish Energy Agency for a carbon capture test facility on a biomass fed combined heat and power plant [37].

In general, the potential for carbon capture and storage or utilization in Sweden is estimated to be high according to an ongoing investigation led by Statens Geotekniska Institut. The investigation is expected to be finalized in January 2020 [38].

Production of hydrogen

Preem and Vattenfall have released news to the press that they are planning to build Europe’s largest water electrolysis plant (20 MW) for the refinery sector. They want to use the hydrogen to produce fossil-free fuels. The power used for the electrolysis comes from hydro power [39].

The HYBRIT project funded by the Swedish Energy Agency, SSAB, LKAB and Vattenfall focuses on producing fossil-free steel which also involves a lot of water electrolysis [40].

St1 is building a new biorefinery in Gothenburg to produce jet fuel, naphtha and HVO-diesel, which will also include the production of hydrogen from water electrolysis [41].

2.3 Norway

In Norway many similar projects and discussions as in Sweden and Denmark are taking place. Nordic Blue Crude together with Sunfire and Climeworks aims to produce high quality synthetic fuels from water, $CO_{2,}$ and renewable electricity [42], [43]. The timeline of this is a demonstration plant of 20 MW established in 2022 and a full scale 200 MW facility in 2025.

Carbon Capture and Storage or Utilization
In 2013, a carbon capture project was initiated at Norcem Cement Plant in Brevik, and in Oslo, Fortum Oslo Varme are going to build a carbon capture and storage plant capturing CO_2 from the waste-incineration plant [44], [45]. The CCS plants are funded by the Norwegian Government [46].

At Mongstad Refinery [47], they have the world's largest technology center for development and testing of CO_2 capture technology. The facility started operation in 2013, and it is owned and operated by Gassnova (77.5%), Equinor (7.5%), Shell (7.5%) and Total (7.5%).

Technology Centre Mongstad (TCM) has a flexible amine plant and a chilled ammonia plant, with a combined CO_2 capture capacity of 100,000 tons per annum, from the refinery's two flue gas sources – which have a composition of 3.6 to 14% CO_2.

Production of hydrogen
The Norwegian company Nel builds small-size hydrogen generators [48]. TRL 9.

HydrogenPro also produces small and medium size electrolyzers, where a single cell block electrolyzer has the capacity range between 2 Nm^3/h and 600 Nm^3/h. The cell blocks can be connected [49]. TRL 9.

2.4 Finland

At the VTT Technical Research Centre of Finland and Lappeenranta University of Technology (LUT), a demo plant has been developed using carbon dioxide to produce renewable fuels and chemicals. The pilot plant with a production capacity of up to 80 liters of gasoline per day [50] is coupled to LUT's solar power plant in Lappeenranta. The aim of the project is to demonstrate the technical performance of the overall process and produce 200 L of fuels and other hydrocarbons for research purposes during the first campaign. The demo plant comprises four separate units: a solar power plant; equipment for separating carbon dioxide and water from the air; a section that uses electrolysis to produce hydrogen; and synthesis equipment for producing a crude-oil substitute from carbon dioxide and hydrogen. Pilot-scale plant units have been designed for distributed, small-scale production. Production capacity can be increased by adding more units [51]. The technology is rated to TRL 6.

Carbon Capture and Storage or Utilization
A report from 2016 covering the possibility for carbon capture and storage and utilization in Finland concludes that carbon capture and storage could profitably cover one-third of Finland's reduction of greenhouse gas emissions by 2050 [52]. Over 80% of carbon capture would relate to the combustion or processing of biomass (bio-CCS), the rest to carbon-intensive industry. According to the report, the utilization of carbon dioxide can turn out to be a usable method for producing carbon neutral fuels and other products with electricity [52].

2.5 Iceland

In Iceland, Carbon Recycling Int. produces methanol from CO_2 from geothermal energy [53], at TRL 9.

Furthermore, Climeworks are capturing CO_2 and storing it into basalt stones at demonstration scale, TRL 7-8 [54].

Also the company CarbFix has built a demonstration plant, where captured CO_2 comes into contact with basalt and turns into white chalky calcites that fill the pores of the rock. Currently they are demonstrating how this method can be applied world-wide [55], TRL 7-8.

3 Clarification of technology and investment costs

An overview of existing technologies and their estimated cost of investment have been made based on a search for projects and actors in the supply chain of fuels from methane, hydrogen and CO_2.

3.1 Available technologies

Three overall pathways have been identified for producing jet fuel from methane, CO_2 and hydrogen:

1. Producing a synthesis gas (syngas) which is synthesized through the Fischer-Tropsch (FT) process to liquid hydrocarbons with different carbon chain lengths, e.g. kerosene. This pathway, in turn, has three different routes to producing the syngas:
    1.1. Steam reforming, partial oxidation, and catalytic partial oxidation of methane to syngas [56]
    1.2. Reverse-Water-Gas-Shift of CO_2 and hydrogen into syngas
    1.3. Electro-chemical conversion of CO_2 and electricity into a syngas e.g. through co-electrolysis

2. Producing alcohols which is then processed through dehydration, oligomerization and hydrogenation to form liquid hydrocarbons with different carbon chain lengths, e.g. kerosene. The alcohols can be produced through various ways, e.g.:
    2.1. Fermentation
    2.2. Chemical conversion

3. Producing ethylene via Oxidative Coupling of Methane (OCM) which is then polymerized and hydrogenated to form liquid hydrocarbons with different carbon chain lengths, e.g. kerosene

The methane feedstock can be produced from:

1. Anaerobic digestion of e.g. agricultural residues, manure, and organic household waste
2. Chemical conversion of CO_2 and hydrogen trough e.g. the Sabatier process
3. Biological conversion of CO_2 and hydrogen through methanogenic microorganisms (archaea)

The CO_2 feedstock can be captured from:

1. Point sources such as biogas, fermentation, cement production, biomass-fired power plants etc.
2. Directly from the air with Direct Air Capture (DAC)

The hydrogen feedstock can be produced as:

1) Green hydrogen, i.e. made from water electrolysis powered by renewable electricity sources
2) Blue hydrogen, i.e. made from natural gas with CCS, where the natural gas is cracked into hydrogen and CO_2, the CO_2 pumped back into the natural gas reservoir, and the hydrogen subsequently pipelined for further distribution and use

All these different pathways and underlying variants give a wide range of possible combinations and configurations of a potential crude oil production (named 'syn-crude') and subsequent jet fuel production. The optimal whole-chain pathway/solution depends on the concrete case, the geographical distribution of the feedstocks, location in question, the existing infrastructure, etc.

The only pathway that is implemented in large-scale today with existing facilities that produce kerosene and other long chained hydrocarbons is the FT-pathway. The syngas used today is produced from many sources and methane is one of them, though from natural gas today i.e. fossil-methane. These big *Gas-To-Liquids* (GTL) facilities could as well use bio-methane if it were available. An overview of GTL plants can be found in Table 2, where economic, technology, and ownership data are also found.

Table 2: Overview of full-scale Gas-To-Liquids plants already existing or under construction

	Mossel Bay	**Shell's Bintulu**	**Oryx GTL**	**Pearl GTL**	**Escravos GTL**	**Oltin yo'l GTL**
Owner	PetroSa	Shell (72%), Mitsubishi (14%), Sarawak state (7%), PETRONAS (7%)	Sasol (49%) and Qatar Petroleum (51%)	Shell and Qatar Petroleum	Chevron Nigeria Limited (75%) Nigerian National Petroleum Company (25%)	Uzbekneftegaz (44,5%), Sasol (44,5%) and Petronas (11%)
Location	South Africa	Malaysia	Qatar	Qatar	Nigeria	Uzbekistan
Main technology provider	Sasol	Shell	Sasol	Shell	Sasol, Chervon, Topsøe	Sasol, Chervon, Topsøe,
Production capacity	45,000 bpd	14.700 bpd	34.000 bpd	260.000 bpd where of 140.000 bpd GTL capacity	33.000 bpd	37.000 bpd
Investment cost	-	1 billion USD	1.2 billion USD	18-19 billion USD	10 billion USD	3.2 billion USD
Investment cost per capacity	-	68.000 USD/bpd 0.87 mill. EUR/MW	35.000 USD/bpd 0.45 mill. EUR/MW	71.000 USD/bpd 0.91 mill. EUR/MW	303.000 USD/bpd 3.87 mill. EUR/MW	86.000 USD/bpd 1.10 mill. EUR/MW
Conversion efficiency	-	45 %	-	80 %	-	50-55 %
Products	Kerosene, gasoline, diesel, lubricants, wax, chemicals	Naphtha, kerosene, diesel, paraffins, lubricants, wax	Naphtha, diesel	Naphtha, kerosene, diesel, paraffins, lubricants	-	Diesel, kerosene, naphtha, LPG
Operation time	-	98 %	80-90 %	-	-	-
Production start	1992	1993	2006	2011	2013	2020
Other	Does not operate at full capacity due to gas delivery issues	Originally 12.500 bpd at 850 million USD. Upgraded to 14.700 bpd around year 2000. Only 40% of the products are fuels; the other 60% are specialty chemicals and waxes	-	Shell's Pearl GTL converts about 1.4 bcfd of dry gas into 140,000 bpd of diesel and other hydrocarbons while the upstream gas processing plant separates 160,000 bpd of valuable liquids (LPG, condensates) from the produced wet gas. [57]	Big delays. Originally 1.7 billion USD for 33.000 bpd equivalent to 52.000 USD per bpd	Still under construction
Sources	[58], [59]	[59]–[61]	[59], [62]	[59], [63]	[59], [64], [65]	[59], [66]–[68]

All the facilities listed in Table 2 are large scale facilities, and the two main technology providers are Shell and Sasol, who through these plants have demonstrated that they can deliver the necessary technology in large scale. For smaller scale GTL, a lot is presently happening, led for instance by the Global Gas Flaring Reduction Partnership (GGFR), which is an initiative financed by the World Bank. The goal for the partnership is to end routine gas flaring by 2030, also at the smaller scale sites, and instead put the gas to productive use [69]. The flared gas is natural gas which in some cases is an unwanted co-product of oil extraction.

Often the gas is flared because it is uneconomically to ship the gas, but this might be changing if the gas is turned into a liquid. In small scale, a lot of technology providers have a range of different solutions which could also be used to turn bio-methane into a liquid hydrocarbon e.g. kerosene or methanol for further processing. The GGFR partnership operates with four sizes of GTL facilities as seen from Table 3, where feed-rates and approximated financial information can be found as well.

Table 3: The Global Gas Flaring Reduction Partnerships definitions of world scale, small-scale, mini, and micro GTL facilities [70]

	Micro-GTL	Mini-GTL	Small-Scale	World scale
Gas feed-rate	>2.8k m^3 per day	>28k m^3 per day	>280k m^3 per day	>2.8 million m^3 per day
Lower heating value	0.1 TJ per day	1 TJ per day	10 TJ per day	100 TJ per day
	~0.04 PJ/year	~0.35 PJ/year	~3.5 PJ/year	~35 PJ/year
Higher heating value	0.11 TJ per day	1.1 TJ per day	11 TJ per day	110 TJ per day
Investment cost	>$1MM	>$10MM	>$100MM	>$500MM
Product make	>10 bpd	>100 bpd	>1000 bpd	>10,000 bpd
Capacity cost	>100,000 USD/bpd	>100,000 USD/bpd	>100,000 USD/bpd	>50,000 USD/bpd
	Unattended "machine", modular	Moveable, modular	Stationary, 20+ years life	Stationary, 20+ years

The capital expenses (CAPEX) for small scale GTL-FT have dropped in price lately and are now expected to be around 100,000 USD per barrel per day(bpd) capacity. And claims are that the price can be lowered 10 % to 30 % more [57].

A lot of companies have developed or are developing solutions for the Micro-GTL, Mini-GTL, and small-scale ranges. A list of these companies can be seen in Table 4 where the main products are also listed. A more in-depth description of the companies and their technologies can be found in [71] or at the companies webpages listed in Table 4.

Table 4: An overview of companies working with or providing GTL-technology smaller than world scale facilities. Status: 1 = commercial i.e. low risk, short time to commercialization, 2 = ready for commercial i.e. low risk, long time to commercialization, 3 = mini-GTL i.e. high risk, short time to commercialization, 4 = not ready i.e. high risk, long time to commercialization. Direct FT stops the hydrocarbon chain growth before it turns into wax, POX is partial oxidation of methane, OP is oxidative Pyrolysis and MSA is methane sulfonation. The words; target, good, maybe, and no refer to the companies' ability in delivering and scope of plant sizes. Data and table from [57]

Company	**Website**	**Technology**	**Status**	**Micro-GTL**	**Mini-GTL**	**Small-scale**
	www.etc...	Product		2.8k m3 per day	28k m3 per day	280k m3 per day
Greyrock	Greyrock.com	direct FT/diesel+	1	maybe	target	good
Velocys	Velocys.com	FT/diesel+	1	good	target	good
CompactGTL	Compactgtl.com	FT/diesel+	1	no	maybe	target
SGC Energia	Sgcenergia.com	FT/diesel+	1	no	good	target
Oberon Fuels	Oberonfuels.com	DME/MeOH	2	target	good	no
Aum Energy	Aumenergy.com	DME	2	no	target	maybe
EFT	Emfueltech.com	FT/diesel+	2	no	target	good
Primus Green Energy	Primusge.com	MeOH, gasoline	2	maybe	target	target
TIGAS	Topsoe.com	gasoline	2	no	good	target
Proton ventures	Protonventures.com	Ammonia	3	target	maybe	no
GasTechno	Gastechno.com	POX/MeOH+	3	target	good	no
R3Sciences	r3sciences.com	MeOH	3	target	no	no
Maverick Synfuels	Mavericksynfuels.com	MeOH+	3	target	good	no
Infra Technology	Infratechnology.ru	direct FT/diesel+	3	target	target	no
Verdis	Verdisfuels.com	direct FT/diesel+	4	target	good	no
Biofuels Power	Biofuels.com	FT/diesel+	4	no	target	no
Greenway IE	Greenwaygtl.com	FT/diesel+	4	no	target	good
Siluria	Siluria.com	OCM/ethylene, gasoline	4	?	?	?
Gas2	gas-2.com	FT/diesel+	4	?	?	?
Methion	Methion.com	MSA/methanol+	4	target	target	target
Synfuels	Synfuels.com	OP/ethylene, gasoline	4	no	no	target

The data in Table 4 also gives an indication of the maturity of the three main pathways. The FT-pathway is well established, the alcohol/methanol pathway is ready for commercial and OCM/ethylene pathway is still immature, though Siluria is moving fast and are now collaborating with Linde to scale up the process [72].

When the aim is to produce kerosene within a short timeframe the most interesting companies seems to include Greyrock, Velocys, CompactsGTL, SGC Energia, Shell and Sasol. A collaboration between these very promising actors and others is of course also a solution and is already happening in the Altalto Immingham Project where Velocys, Shell, and British Airways are developing a commercial waste to jet fuel project in the United Kingdom [73], [74].

The pathways discussed above all started with methane, but CO_2 and hydrogen(electricity) are also two feedstocks that can be used to produce either methane, alcohols or a syngas for further processing into jet fuel. Some of the technology holders of such technologies using CO2 and hydrogen(electricity) are Sunfire, OPUS-12, Hydrogenics, Electrochaea, Hydrogen Pro, NEL Hydrogen, Inventys, Climeworks, Carbon Engineering, Topsøe, Lanzatech, Gevo, Honeywell UOP, Swedish Biofuels, Byogy and many more. The first companies are active in the area of capturing, producing and/or converting CO_2 and hydrogen into fuels. The companies mentioned from Haldor Topsøe and after are all active in alcohol to jet.

3.2 Elaborating on the Fischer-Tropsch pathway

The first used FT reactors started out in very small scale a few barrels per day (bpd) and have since developed in size. Commercial reactors have today been built with capacities of 1500 bpd or higher. In 1955, Sasol opened a plant with a 1500 bpd reactor, in 1980 and 1982 the reactors used had grown to 6500 bpd [56]. The FT-reactor used at Shell's Bintulu plant in 1993 were at 3000 bpd. Also, in 1993, Sasol commissioned another FT-reactor type with a capacity of 2500 bpd. There is a push to increase the reactor sizes and some are today at 10,000 bpd [56].The challenge with FT-reactors seems to be getting them up in scale, not down in scale, i.e. small scale reactors are not a technical challenge.

When combining carbon and hydrogen into longer chains to form kerosene, it is almost impossible only to reach the kerosene range no matter the process. To get an idea of how the distribution of products could be a more in-depth analysis of the FT-pathway is presented here.

The refining of FT syn-crudes at conventional refineries seems to require adaptations at the conventional refinery, but these adaptations have not been covered very much in literature. But even so, FT syn-crudes seem to require less complex refineries than conventional oil refineries. Even less complex if the syn-crude comes from Low-Temperature-Fishcer-Tropsch (LTFT) compared to High-Temperature-Fischer-Tropsch (HTFT) [75]. The LTFT process operates at 170-230 °C and the HTFT process at 250-340 °C [76].

The feed material does not determine the type of FT technology or the syn-crude compositions. The feed material only influences the gasifier type and once the feed has been converted to syngas, the gas loop can be configured to suit the FT technology [75]. For a fossil fuel based GTL-FT process, the refinery cost is typically less than 15% of the total capital cost [75].

Jet fuel from a FT process does not require much refining to achieve specification. The basic steps involved in producing maximum jet fuel from syn-crude are [75]:

1. Adjust the chain length distribution to maximize kerosene.
2. Synthesize appropriate kerosene range aromatics.
3. Skeletally isomerize the linear hydrocarbons to lower their freezing point.
4. Hydrogenate the syn-crude to reduce the olefin and oxygenate content.

In Table 5, the product ranges from refining a HTFT and a LTFT with maximum jet fuel production for an on-specification jet fuel while still keeping the motor-gasoline on specification can be found.

Table 5: Overview of the refinery production from a High-Temperature-Fischer-Tropsch (HTFT) crude and from a Low-Temperature-Fischer-Tropsch (LTFT) crude with a flow rate of 500 ton per hour of C2 and heavier. Roughly equivalent to a 100,000 bpd crude oil refinery [75].

Product	Refinery production							
	HTFT				LTFT			
	Kg/h	M3/h	bpd	Vol%	Kg/h	M3/h	bpd	Vol%
Liquid fuels								
Motor-gasoline	98,880	131	19,742	22.4	101,328	137	20,641	23.0
Excess fuel ethanol	17,624	22	3,351	3.8	2,272	3	432	0.5
Jet fuel	302,863	389	58,650	66.5	355,912	455	68,720	76.5
Diesel fuel	0	0	0	0.0	0	0	0	0.0
LPG	23,563	42	6,410	7.3	0	0	0	0.0
Other Products								
Fuel gas	32,612				26,781			
Unrecovered organics	14,894				15,634			
Hydrogen	281				-3,243			
Water	9,277				1,315			
Sum	500,000	584	88,152	100	500,000	595	89,793	100

The reforming of methane to syngas in large scale often happens through the reactions listed here:

Partial oxidation:

$$2\,CH_4 + O_2 \rightarrow 2\,CO + 4\,H_2 \qquad (1)$$

Steam reforming

$$CH_4 + H_2O \leftrightarrow CO + 3\,H_2 \qquad (2)$$

If the start products are hydrogen and CO_2, the reversed water-gas shift (RWGS) reaction can be used

$$CO + H_2O \ \leftrightarrow CO_2 + H_2 \qquad (3)$$

A company that starts from CO_2 and hydrogen is Sunfire, actually they start from electricity, water, and CO_2. They have the RWGS reaction to go from CO_2 and hydrogen to syngas, but they are also providing a co-electrolysis solution that today is successfully running where electricity, water and CO_2 is transformed into a syngas. The integration between the co-electrolysis and the FT-process will be demonstrated in Karlsruhe starting end of August 2019 [43]. Some specification for Sunfire's Power-to-liquids can be seen in Table 6.

If Sunfire's technology is chosen around 6,000 MW nominal capacity of Sunfire units, then running 6,000 hours a year will produce a bit less than 85 PJ of FT-products whereof around 50 PJ could be jet fuel which is around what Denmark is projected to demand in 2030, the same goes for Norway (around 55 PJ), Sweden (around 45 PJ) and Finland (around 40 PJ). Producing 85 PJ of FT-products would require around 36 TWh of electricity and a bit more than 8 million tons of CO_2.

For the 2050 projections taking all the Nordic countries together, the numbers are around 26,000 MW nominal capacity of Sunfire units running 6,000 hours a year that will produce around 365 PJ of FT-products where of 220 PJ could be jet fuel. This would require approximately 155 TWh of electricity and around 36 million tons of CO_2. The electricity production in the Nordic countries were around 415 TWh in 2016 [77].

Table 6: Specification of Sunfire's Power-to-Liquids technology, by Sunfire

Power Output	250 kW up to several MW equivalent to 600 liters/d up to several thousand liters/d
Pressure	Max. 80 bar
Temperature	Max. 1,000 °C
Efficiency	Approx. 70%
Carbon utilization	Min. 95%
GHG mitigation	Min. 85%

3.3 GTL conversion pathway scenarios

Taking the FT-pathway gives a lot of flexibility since all three feedstocks, that we are looking at, can be used by the same conversion technology and fits into the same overall pathway. The pathway can be established ‘tomorrow’ with existing GTL technology building on bio-methane feedstock, in 2-3 years be supplemented by electro-methane feedstocks, and at the same time or soon after being further supplemented by hydrogen and CO_2 feedstocks, all entering the FT-synthesis after conversion to syngas. This gives a lot of flexibility and robustness. Figure 3 below illustrates an example of a conversion pathway scenario.

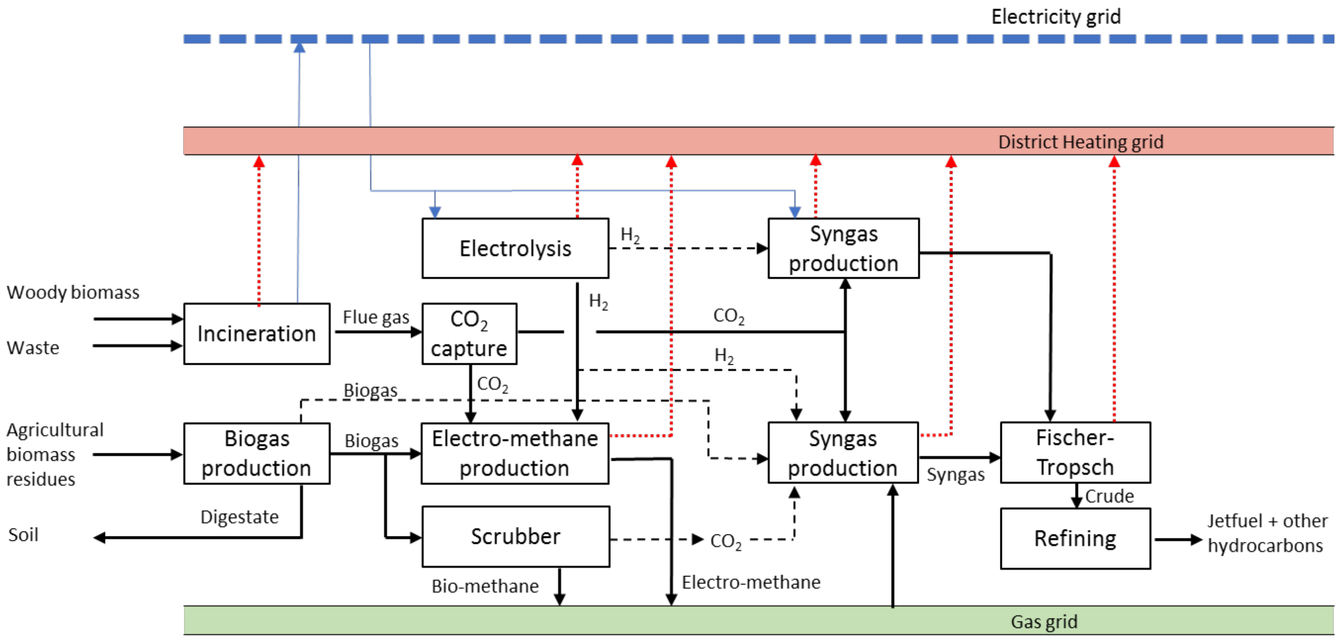
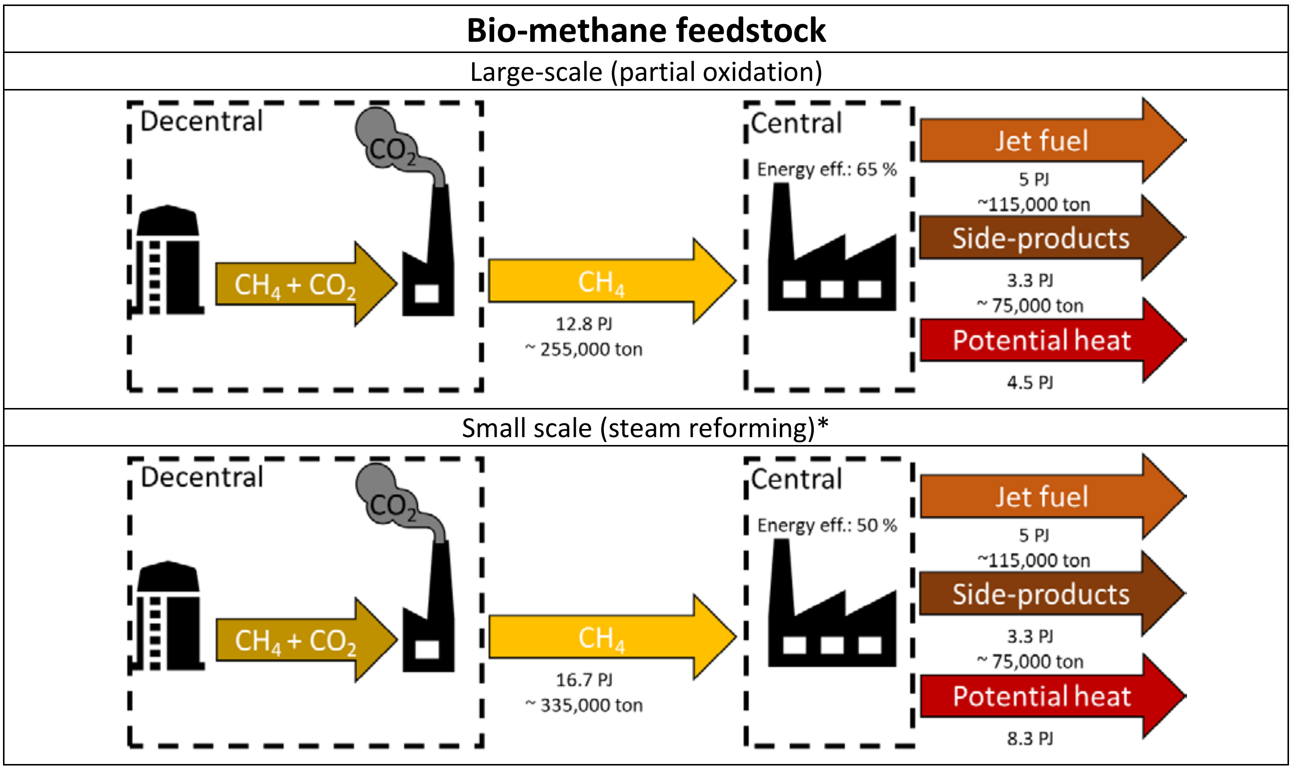


Figure 3: The studied supply chain of jet fuel based on renewable and waste-based feedstocks of biogas, bio-methane, electro-methane, CO_2 and hydrogen. Interactions with the key grids of electricity, gas and district heating are shown. Black arrows are mass flows, red arrows heat flows, and blue arrows electricity flows. Dotted lines represent potential alternatives or supplements to bold lines. The syngas production from CO_2 (upper syngas box) may run on both CO_2 and hydrogen inputs or be a co-electrolysis based on only electricity, CO_2 and steam inputs

Many variants of the FT-pathway exist in the following three scenario variants are illustrated. The process flow diagrams are shown with a 65 % and a 50 % conversion efficiency defined as the liquid hydrocarbon output divided by the energy input. The high conversion efficiency represents a larger scale facility where partial oxidation is economical to build, and the lower conversion efficiency represents a smaller scale facility applying steam reforming. The pure electrofuel plant, something similar to Sunfire’s technology, is only shown with 65 % conversion efficiency as the technology is more modular.

Table 7. In the "Decentral" box, anaerobic digestors are producing biogas which is then stripped from CO_2 in the upgrading facility and the, now, natural gas quality methane is injected into the gas grid. At the central facility, the methane is turned into jet fuel, side-products and heat. The setup for the biogas facilities is common and the GTL facilities can also be built today. The energy efficiency at the GTL plant is for a large-scale facility around 65 % and for a smaller scale around 50 %. The scale is here determined by when it pays off to run a partial oxidation of methane instead of a steam reforming, which has not been calculated. More detailed economic data can be found in Appendix 1 and 2.

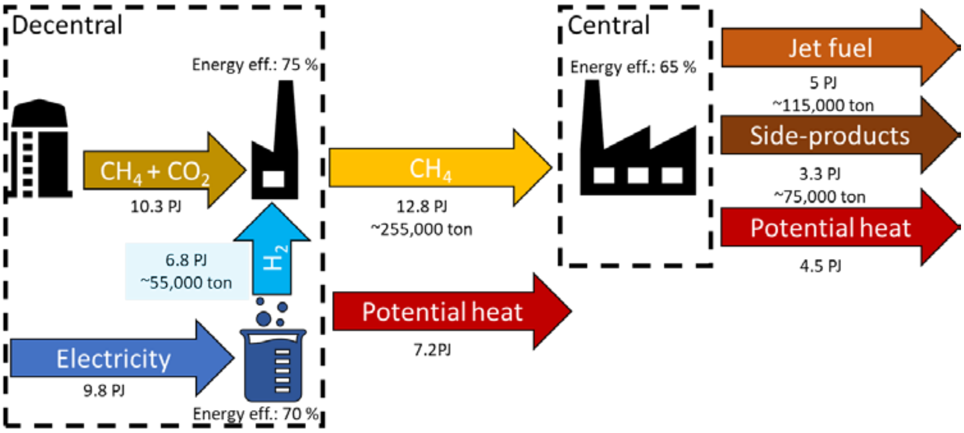


**Steam reforming gives a hydrogen surplus which is not shown on its own, but included in the potential heat flow. This hydrogen may be recovered and fed back to a CO_2 methanation unit, which will significantly increase the energy conversion efficiency*

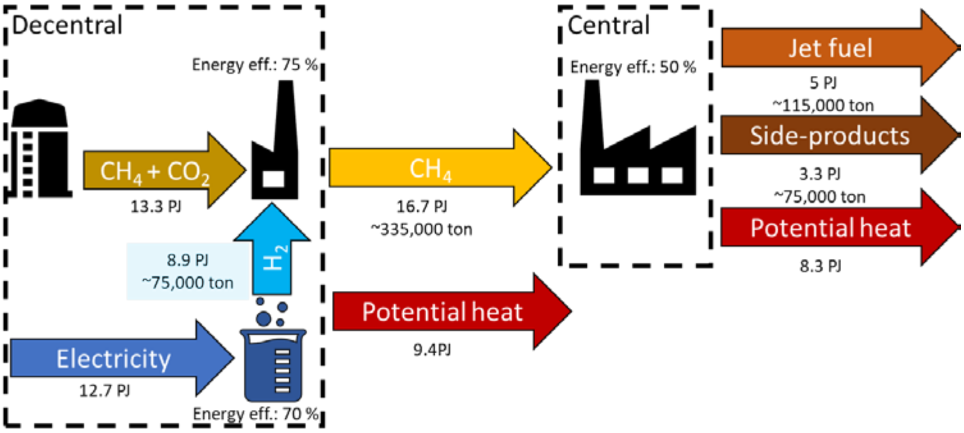
Table 8. In this setup the CO_2 at the biogas plants is upgraded with hydrogen into electro-methane and then injected into the gas grid. This also boosts the biogas potential. The rest follows the same procedure as above where only bio-methane was used. The energy efficiency at the GTL plant is for a large-scale facility around 65 % and for a smaller scale around 50 %. The scale is here determined by when it pays off to run a partial oxidation of methane instead of a steam reforming, which has not been calculated. More detailed economic data can be found in Appendix 1 and 2.

Bio- and electro-methane feedstock

Large-scale (partial oxidation)



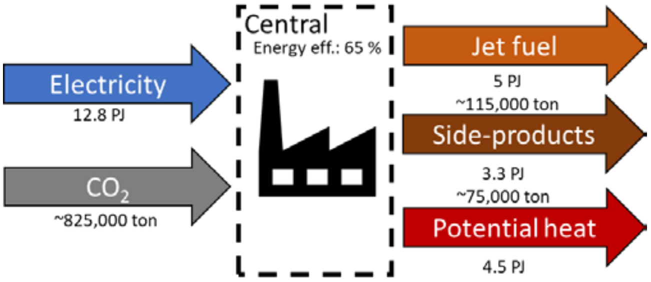
Small scale (steam reforming)*



**Steam reforming gives a hydrogen surplus which is not shown on its own, but included in potential heat. See comment on hydrogen recycling in note for Table 7*

Table 9. In this scenario, CO_2 from any source is converted into a syngas by either co-electrolysis or reverse-water-gas-shift with hydrogen. The syngas is then fed to an FT-reactor and refined into fuel. Same procedure as above except syngas is not produced from methane. The energy efficiency is set to 65% for both small and large scale as the technology is more modular. More detailed economic data can be found in Appendix 1.

Pure electrofuel



The quantity of heat displayed is the theoretical potential, not the actual recovered heat, see more details in the later economic feasibility assessment. The heat is envisioned to be sold for district heating.

A combination of the different setups shown in Table 7-9 is also possible to give more flexibility when operating the plant.

The illustrations are only shown for the FT-pathway, but the alcohol (methanol) pathway seems to have the same costs as the FT-pathway when the starting point is CO_2 and hydrogen [78].

3.4 Operating the plant

The operation of the plant depends on the feedstock inputs almost independently of the pathway. If the jet fuel facility is based on methane or other storable products, the plant will run continuously because the feedstock price is not that volatile. If the facility, on the other hand, is using CO_2 and electricity as the inputs the plant would start and stop more often, since electricity prices are quite volatile.

A hybrid between a methane feedstock and a pure electrofuel plant could therefore prove to be beneficial. Syngas could be produced from CO_2 and electricity when the electricity prices are not too high, and when the electricity prices are high, methane or another storable feedstock can be converted to syngas and fed to the reactor. This can give a continuous production of reactor feedstock (syngas) for almost all hours of the year. In this way, “power” plants would no more produce CO_2, but consume it, and if the plants are centrally located, where power plants were located before, the electricity infrastructure is most likely ready for large scale electrolysis, and it would be easier to co-optimize all the energy flows from the different processes, when they are centralized at one location with access to the electricity grid, the gas grid and the district heating grid.

Another thing to have in mind is whether the plant should produce a crude for later refining at a refinery or have a refining unit included in the setup. This is the topic of the next section.

3.5 Products and processing – what are the options?

Two types of conventional jet fuel exist which is Jet A and Jet A-1. USA is the only place where Jet A is used as defined by ASTM D1655 [79], the rest of the world has standardized on Jet A-1 as aviation turbine fuel which must meet the DEF STAN 91-91 [80]. The main difference between Jet A and Jet A-1 is the lower freezing point of Jet A-1 that makes it more suitable for long international flights [75].

Sustainable Aviation Fuels (SAF) should also be certified before use and they must have drop-in quality. Today, no SAF has been certified for more than 50 % blending with conventional jet fuel [81] even though it is possible to produce SAF that is 100 % on specification with conventional jet fuel properties [75]. Synthetic jet fuels must live up to other standards than conventional jet fuel. Synthetic jet fuels should live up to the ASTM D7566 requirements [82].

As mentioned earlier, jet fuel is not the only product coming from any of the pathways. Depending on the process design, a lot of other products can arise or at least the building blocks for these products including gasoline, diesel, naphtha, ship fuel, waxes, lubricants, and a range of other petrochemicals which can be used in plastics, fertilizers, packaging, clothing, digital devices, medical equipment, detergents, tires, etc. Petrochemicals are also found in solar panels, wind turbine blades, batteries, thermal insulation for buildings, and electric vehicle parts [83].

To obtain all these fractions of products, a refining or separation process should take place since all the pathways give a mix of hydrocarbon length. One way of doing this is by a straight run distillation where the products afterwards have to be blended with conventional fuels. Another option is to co-process the products at an existing refinery. At present, most fuels that include a bio-derived component are only blends, but there are already investigations dealing with possible co-processing [75].

An overview of all the Nordic refineries can be found in Table 10. From this Table, it can be seen that only four refineries in the Nordic countries produce jet fuel, with the biggest facilities being in Norway and Finland and a smaller facility in Denmark. The refinery in Fredericia, Denmark, has stated that it is possible to co-refine a FT-crude at their refinery. They do not expect big challenges if the FT-crude can be approved by i.e. passing the so-called Bocle test.

Table 10: Overview of the Nordic refineries and their current capability to produce jet fuel

Refineries in the Nordic countries	**Jet fuel**	**Total capacity**	**Country**	**Ref.**
Fredericia Refinery (Shell)	100,000 ton	68,000 bpd	Denmark	[84]
Kalundborg Refinery (Equinor)	No	110,000 bpd	Denmark	[85]
Porvoo Refinery (Neste)	Yes	206,000 bpd	Finland	[86]
Naantali Refinery (Neste)	No	58,000 bpd	Finland	[87]
Slagen Refinery (ExxonMobil)	Yes	110,000 bpd	Norway	[88], [89]
Mongstad Refinery (Equinor)	Yes	200,000 bpd	Norway	[47]
Gothenburg Refinery (ST1)	No	78,000 bpd	Sweden	[90]
Nynäshamn Refinery (Nynas)	No	90,000 bpd	Sweden	[91]
Gothenburg Refinery (Preem)	No	125,000 bpd	Sweden	[92]
Lysekil refinery (Preem)	No	220,000 bpd	Sweden	[93]

The greenhouse gas emissions from the products depends on how the different feedstocks i.e. methane, CO_2, and hydrogen/electricity are produced, but also the assumptions made on the surrounding energy and construction system. A life cycle assessment of CCU can be found in [94].

4 Projection of available feedstocks towards 2025

4.1 Bio-methane

The most current production levels of biogas, bio-methane, and the potential levels can be seen in Table 11. As shown in the Table, Denmark and Sweden are seen to have the highest biogas production. These two countries are also the countries upgrading the highest amount of biogas to bio-methane. According to the latest estimate, the Danish production for 2019 is expected to be around 18 PJ of biogas produced with approximately 11 PJ upgraded to bio-methane. Thus, Denmark and Sweden are the most attractive countries for a GTL facility with a bio-methane feedstock. Both Denmark and Sweden also have a large amount of district heating grids to make use of the process heat and both countries have gas grids, with the Danish gas transmission grid being a lot larger than the Swedish.

Table 11. Current and potential future levels of biogas production excl. forestry. For Norway, Sweden, and Finland, including forestry products could significantly increase the potential, but would most likely not be through anaerobic digestion [95]–[97]

Year	**Biogas – 2017**	**Bio-methane**	**Potential**
Unit	*Petajoule*	*Petajoule*	*Petajoule*
Denmark	11.2	4.5	80
Sweden	7.4	4.8	50
Norway	3.6	1.4	8
Finland	3.5	0.4	15
Iceland	0.1	0.1	-
Total	**25.8**	**11.2**	**157**

The potentials for Norway, Finland, and Iceland are relatively small. This could change if forestry residues from Norway and Finland were turned into methane and included in the numbers.

For a GTL facility based on bio-methane, an adequate amount of bio-methane should be available to make a good case. This is also the biggest obstacle for this pathway. Today, most biogas production is subsidized through different schemes and tax exemptions, but if these subsidies are removed this could be a threat to this pathway.

The bio-methane price estimates for a Danish biogas plant can be seen in Table 12 to give an indication of the price level and what the current and potential future Danish subsidy scheme could look like.

Table 12: Bio-methane price estimates at a Danish biogas plant

Year	Un-subsidized biomethane	Subsidized biomethane
	(EUR/GJ)	(EUR/GJ)
2018	22.76	10.04
2023	18.07	9.37
2030	16.06	8.03

4.2 Carbon dioxide

Carbon dioxide can be captured from biogas, fermentation processes, cement production, iron and steel production, incineration plants (like waste incineration plants or CHP plants or boilers running on wood chips or pellets) and directly from the air. For a renewable jet fuel, all the carbon dioxide sources should originate from sustainable biomass supply or recycled carbon from industrial sources. This criterion excludes all oil, gas and coal-based carbon dioxide emissions, if we are to meet the targets of the Paris agreement. Waste incineration is in this perspective a grey zone since some of the emissions are still fossil based, but this is gradually changing towards biogenic emissions.

To cover the Nordic demand for jet fuel in 2050, around 36 million tons of CO_2 is needed, if CO_2 were the only carbon source, and around 60 % of the product fraction was turned into jet fuel [75]. In Sweden the forestry industry e.g. pulp and paper emits more than 22 million tons of biogenic CO_2 per year [98], and CHP plants around 10 million tons of biogenic CO_2 per year [98]. A similar number for the CHP plants can be found in Denmark [99] which is already more than enough to cover the carbon demand for jet fuel in the Nordic countries. In a European context more than 9,000 point-sources of CO_2 at high concentration, emitting more than 1.5 billion tons of CO_2 per year exists [100]. Not all sources are biogenic.

On top of these numbers comes the carbon from biogas which if upgraded with hydrogen could boost the biogas potentials in Table 11 significantly. Furthermore, cement production from all the Nordic countries is also emitting a couple of million tons of CO_2 per year that could be captured and utilized. The biogenic CO_2 potential for Norway and Iceland seems to be small, but Finland, Denmark, and Sweden alone have more than enough biogenic point source CO_2 to cover the demand for carbon feedstock for the Nordic jet fuel production.

Direct Air Capture (DAC) is also a potential source of carbon dioxide which mostly requires heat at around 100 °C and some renewable electricity, which makes Iceland an ideal location for this type of plants. But also, locations at district heating grids will be attractive, as the thermal heat needed for DAC can, then, first derive from the process heat of the jet fuel production and subsequently be reused for district heating, thus requiring no extra heat supply. Other areas with excess or surplus heat around 100 °C could also be of interest in relation to direct air capture. The price for the CO_2 ranges from 10 EUR/ton from fermentation [101], to 40 EUR/ton for iron and steel [101], a bit less than 70 EUR/ton for cement [101] and DAC at around 200 EUR/ton, projected to fall to less than 100 EUR/ton [102] and presumably even lower. Projections for DAC costs go all the way down to around 30 EUR/ton, when the thermal energy is either provided as free waste heat [103] and/or recyclable into district heating.

Concerns are being raised about DAC because of the energy needed to extract the CO_2 from the air [100]. In many cases, it would most likely be the most optimal to use concentrated point sources, but if the alternative is a concentrated fossil-based point-source of CO_2 or DAC based on surplus heat and renewable electricity, then the biggest CO_2 reduction comes from using the DAC as the fossil-based point-source is then not given an initiative to continue production.

4.3 Hydrogen

Hydrogen can be produced from electrolysis, where water is split into its two components i.e. oxygen and hydrogen by applying electricity to the water. Since electricity is the input to electrolysis, the amount of renewable hydrogen that can be produced is basically limited by the willingness to put up wind turbines and solar panels, and the potential for geothermal power and hydroelectric power.

For this reason, the amount of hydrogen that can be delivered is mainly an economic question, but this is also in practice a limiting barrier for large-scale hydrogen production. What could help the implementation of large-scale hydrogen production was a flexible transmission *tariff.* The tariff could depend on time and/or location. The transmission tariff could be changed in a way to ensure that when the production from fluctuating energy sources is high, the transmission tariff would be very low or zero, and when the electricity production from the fluctuating sources is low the transmission tariffs would be higher. This will also encourage more flexible consumption of electricity, and it could be done without losing money for the transmission system operator. Locating the facility at more optimal sites for the electricity grid could also be awarded with a lower tariff.

Changing the *tax* would not help a lot since, at least in Denmark, the tax for electricity used in industrial processes such as for electrolysis is quite low, only 0.054 EUR cents/kWh. Transmission tariffs make up the major regulative cost element.

Another regulatory instrument could be to accept the use of power purchasing agreements or green certificates for electricity while fossil energy is still a part of the electricity mix, this way the hydrogen can be made a 100 % renewable already today and enter in EU's double counting schemes.

In Table 13, the hydrogen prices at different electricity prices can be found for an alkaline electrolyzer. As shown, a small change in the electricity price has a big impact on the hydrogen price.

Table 13: Overview of cost data for an alkaline electrolyzer with data based on expectations of 2020 and a lifetime of the electrolyzer of 25 years. Multiply the numbers in the table with 0.12 to get the values in EUR/kg [104]

Alkaline – 2020 – 25 years life time										
Operating hours	6000									
CAPEX (EUR/GJ)	1.7									
Financing – annuity 5 % IR (EUR/GJ)	1.4									
Fixed O&M (EUR/GJ)	2.2									
Total fixed cost (EUR/GJ)	5.3									
Electricity price (EUR/kWh)	*0.01*	*0.02*	*0.03*	*0.04*	*0.05*	*0.06*	*0.07*	*0.08*	*0.09*	*0.10*
OPEX (EUR/GJ)	4.4	8.7	13.1	17.5	21.8	26.2	30.6	34.9	39.3	43.7
Total cost of hydrogen (EUR/GJ)	9.7	14.0	18.4	22.8	27.1	31.5	35.9	40.2	44.6	49.0

5 Scenarios and business cases

To determine whether a jet fuel plant is economically viable, many parameters must be estimated e.g. investment cost, operation and maintenance cost, feedstock prices, product selling prices and so on. For each of the pathway scenarios shown in Chapter 4, five business cases have been made for each with varying assumptions on cost, price of side-products, and heat sales prices. The cases are a base case, a worse and a better case, and a worst and best case. Most assumptions are based on data from already existing facilities as found in Ramberg et. al [105].

5.1 Assumptions behind business case calculations

All scenarios are set to produce 5 PJ of jet fuel per year, which approximately can cover 10 % of the Danish jet fuel demand in 2050 or 2-3 % of the Nordic demand in 2050. Further, this scale means that the process heat from the jet fuel production matches well the district heating supply from one of the remaining coal-fired power plants in Denmark, implying that the jet fuel factory can replace the heat produced from coal in the district heating supply. The input and output fractions are in line with the process flow diagrams shown in Table 7 to Table 9. For all cases the lifetime is set to 25 years, and the utilization rate is set to 93 % of the year, which means that producing 5 PJ of jet fuel a year gives a plant size of around 4,000 bpd (barrels per day).

The capacity cost is set to vary from case to case assuming 100,000 EUR/bpd as the base case, 275,000 EUR/bpd as the worst case and 50,000 EUR/bpd for the best case. The capacity costs for the better and worse case are the same as the base case. The capacity cost should be multiplied with the plant size to give the total investment cost for the plant. The capacity cost is 10 % higher for the bio- and electro-methane feedstock scenarios as electrolyzers and methanation reactors should be built at the biogas facilities, refer to Appendix 1 and 2 for details on all the base cases.

The financing cost is estimated assuming an annuity loan with an interest rate of 5 % for all cases. The operation and maintenance cost (O&M) is for all cases set to 5 % of the capital cost and the variable O&M is set to 4.5 EUR/bbl.

The assumption on the bio-methane price is ranging from around 18 EUR/GJ in the worst, worse, and base case to around 16 EUR/GJ in the better and best cases in line with the expected future cost of bio-methane from key biogas producers on the Danish market. The CO_2 price is ranging from 180 EUR/ton for the worst case representing a Climeworks DAC-facility, to 90 EUR/ton for the worse, base, and better cases representing carbon capture from flue gas or the target for DAC, and down to 25 EUR/ton for the best case representing either CO_2 from biogas or the company Inventys' estimate for flue gas capture.

The electricity cost differs between the central and decentral facilities due to transmission tariffs being included for both, but distribution tariffs only being added at the decentral facilities and not at the central facilities. The transmission tariff is around 0.01 EUR/kWh almost equivalent to the distribution tariffs for large electricity consumers [106], [107]. The electricity price varies from 0.05 EUR/kWh equivalent to the bid for the offshore windfarm Krieger's Flak between Denmark and Germany [108], over 0.03 EUR/kWh for the better case, and down to 0.02 EUR/kWh for the best case in line with prices and expectations for both photovoltaic power and onshore wind turbines from the International Energy Agency [109], [110] for 2020. This is equivalent to hydrogen prices for the central facilities starting at 31.5 EUR/GJ for the worst, worse, and base case, over 22.8 EUR/GJ for the better case, and down to 18.4 EUR/GJ for the best case. The equivalent numbers for the decentral facilities i.e. hydrogen for electro-methane are 35.9 EUR/GJ, 27.1 EUR/GJ, and 22.8 EUR/GJ.

The selling prices for the co-products of the process concerns the price of heat and liquid side-products. The resulting selling price for the jet fuel is determined as the price that makes the incomes balance the expenses, which can result in jet fuel selling prices lower than the side-products or even negative if the expenses are low. Optimizing the plant for jet fuel in such cases where side-products sell for more is not optimal, but it indicates a potential profit or cheaper side-products.

The heat price is set to around 10 EUR/GJ, which approximate the willingness to pay from the large Danish district heating companies, when buying heat from facilities that they have not co-financed. The number is lower for co-financing, but then the risk is also spread and the investment cost for the other investors is reduced. The heat utilization is assumed to be 0 % in the worst case, 60% in the worse case, 90 % in the base case, 95 % in the better case, and ends at 100 % in the best case.

The sales price for the side-products have for the worst case been set to the fossil gasoline prices around 12 EUR/GJ [111], for the worse side-products have been set to 25 % more than the bio-methane price indicating the price of bio-LNG, which is around 22 EUR/GJ equivalent to Used Cooking Oil Methyl Ester (UCOME) [112], and for the base, better, and best case the price is set to around 38 EUR/GJ equivalent to the judged true production cost of 2. generation bioethanol [113], a product that from a sustainability perspective is equivalent to or worse than the fuel produced from bio-methane, CO_2, and hydrogen/electricity. The market for selling the side-products at the sales prices of UCOME, bio-LNG or 2. generation bioethanol is governed by the EU legislation on mandatory blending of renewable and low carbon fuels into fossil fuels, which implies that prices can be set to those of competing green alternatives.

As mentioned earlier, depending on the chosen technology and the configurations of this technology, other petrochemicals and waxes could also be side-products from the process. These products are in some instances very high value products and could give an extra income to the facility, but since it is very dependent on the technology pathway, potential higher side-product prices have not been assessed.

5.2 Business case calculations for the base case

Table 14 contains on overview of the base case scenario for GTL with a bio-methane feedstock. The other base case scenario overviews can be found in Appendix 1 (for the 65 % conversion efficiency) and Appendix 2 (for the 50 % conversion efficiency, which does not include the pure electrofuel plant due to the more modular character of this plant).

The graph in Figure 4, then, illustrates the breakdown on cost factors as well as assumed sales revenue from side-products and process heat for all scenario variants. The resulting sales prices for the jet fuel fraction are found as the price that makes costs and revenues balance. The jet fuel price is shown as a bold black line in each of the bars. Finally, the range of fossil fuel prices is shown as the lower and upper limits. All prices are at factory, i.e. distribution costs from factory to airport or customer are not included.

From Figure 4 it is evident, that with the base case assumptions, many of the scenarios are estimated to lead to prices similar to the upper range of fossil jet fuel prices or only slightly higher. Moreover, the price estimates are significantly lower than prices of green jet fuel presently found on the market. This is somewhat surprising. The key reason for this is the assumed sales price of the side-products that is set to the production cost of 2. generation bioethanol. If the assumption is that these side-products can be sold at this price due to the mandatory blending target from the EU, then jet fuel made from pure bio-methane can be sold at the high fossil fuel price still keeping an investment interest rate of 5 % on the capital investment. The following section 5.3 shows, then, the sensitivity to this result from varying assumptions.

Table 14: Overview of inputs and results of the base case for GTL with a bio-methane feedstock and 65% conversion efficiency of methane into jet fuel and other hydrocarbon side-products. The base case inputs and results for all other scenarios can be found in Appendix 1 and 2

Lifetime	25	Resulting jet fuel price: 24.27 EUR/GJ ≈ 0.85 EUR/l ≈ 1.04 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capacity cost (EUR/bpd)	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	313.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Price - EUR/GJ
Methane	5,798.66	12.8	18.12
Total expenses over lifetime	**7,186.55**		
Output			
Heat	1,019.30	4.1	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**4,153.19**		
Jet fuel	3,033.36	5.0	**24.27**
Total balance over lifetime	**0.00**		

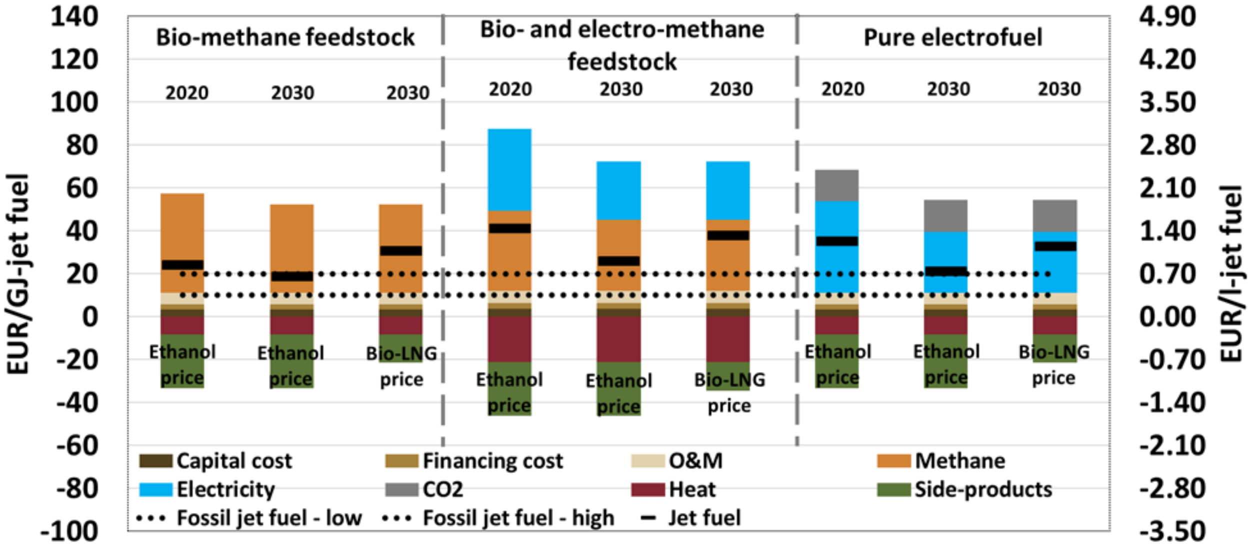


Figure 4: Jet fuel prices for three setups shown with assumptions for 2020 and for 2030. Ethanol price and bio-LNG price refers to the selling prices of the side-products. For 2020 the side-products are sold at the same price as 2. generation bioethanol. Bio-methane is assumed to drop to 16.11 EUR/GJ in 2020, and the electricity price is set to 0.03 EUR/kWh plus 0.01 EUR/kWh for transmission. Methane-to-liquid and power-to-liquid conversion efficiencies are set to 65 % (see Table 7-9 for specification of this).

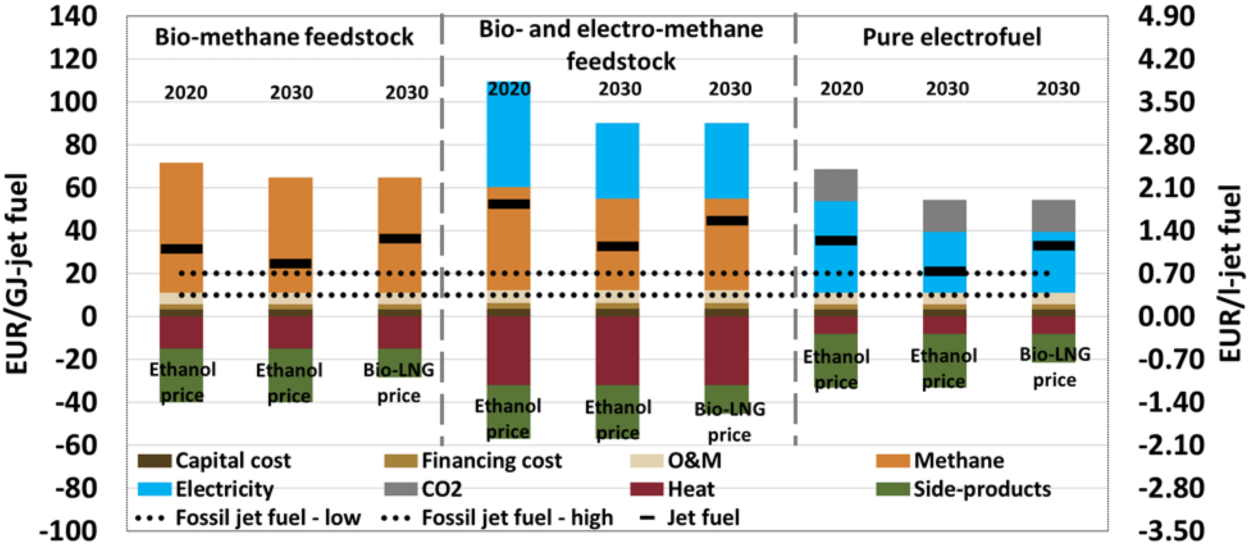


Figure 5: Jet fuel prices for three setups shown with assumptions for 2020 and for 2030. Ethanol price and bio-LNG price refers to the selling prices of the side-products. For 2020 the side-products are sold at the same price as 2. generation bioethanol. Bio-methane is assumed to drop to 16.11 EUR/GJ in 2020, and the electricity price is set to 0.03 EUR/kWh plus 0.01 EUR/kWh for transmission. Methane-to-liquid conversion efficiency is set to 50 % and power-to-liquid conversion efficiency is set to 65 % (see Table 7-9 for specification of this).

It is our judgement that within the airline industry in the Nordic countries there is widespread recognition that future sustainable aviation fuel prices will be higher than the conventional fossil fuels used today. How much higher, an acceptable surplus price is, is difficult to estimate, as it depends on many different factors. However, what is certain is that the tendency by airlines to increase their overall cost structure through a substantial fuel price premium (fuel costs comprise on average 20 – 25 % of the total operating cost of an airline) are their expectations of market response. The early SAF-adapters are very sensitive to the risk of the market (passengers) ignoring the green initiatives.

Today, and up till now, the very limited available volumes of SAF are at prices between 3 and 4 times higher than fossil fuels. These limited quantities are sold to a wide range of companies, but as long as they make up only a very limited part of the airlines total fuel costs, such prices are not a deterrent. But as quantities increase to 3 %, 10 %, 30 %, 50 % or more the airlines willingness to pay is reduced unless other initiatives are in place.

The overall pointers from this pre-feasibility study are very positive for the prospects of the green transition of aviation, since it is indicated that the additional cost of the synthetic jet fuel can be kept within a reasonable range. The indicated price levels, although mainly based on bio-methane and electricity in the most promising pathways, seems to be within a competitive range. This provides a very promising outlook for further work.

The aviation industry faces many development paths for its green transition. A key aspect is how to bring the many thoughts and ideas into a true operational state. Aviation cannot solve this alone. It requires close and solution-centered cooperation among relevant actors, i.e. politicians, scientists, investors, and industrial players within synthesis, refining etc.

As mentioned earlier, sustainable fuels will most likely come at higher prices and for the early adapters this will add to their business and market risk if the market neglects the initiative. This may be a threat for further development since it may inhibit airlines in entering SAF supply contracts. If it's an option, for example, to link such future additional costs for SAF to the decisions on the EU and ICAO market-based systems, it may have a far greater perspective. A solution could also be to consider the possibilities in a Nordic fund or platform for implementing and operationalize SAF well knowing that already established taxes could be brought into play and included and thus offset. These are issues that need to be further discussed and clarified in a setup that can be used in the further decision-making processes on establishing SAF production facilities in the Nordic countries.

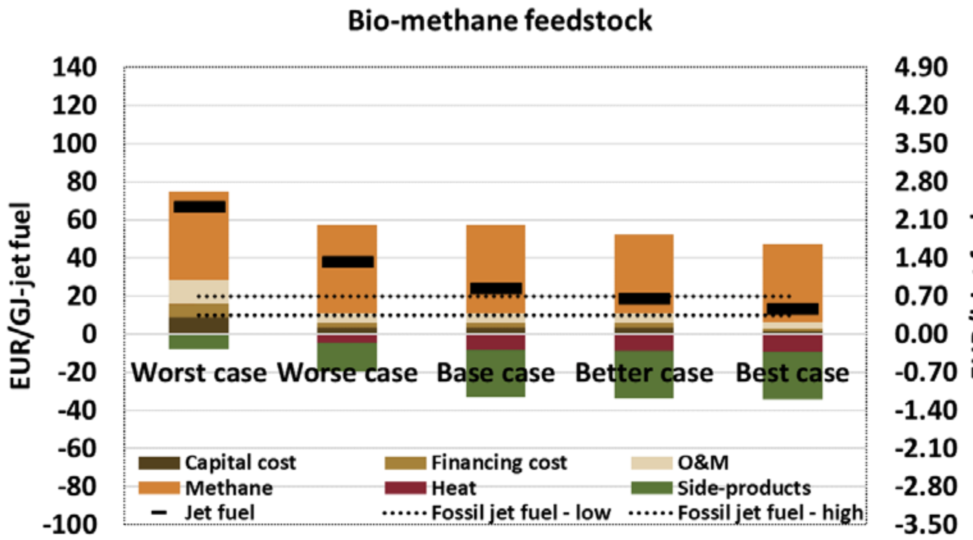
This must also include commitments to purchase the sustainable fuels for a number of years. This can help producers and investors and perhaps also the political level to implement the necessary conditions.

5.3 Sensitivity analysis on the business case calculations

Variations of the assumptions are done as described earlier in this chapter and illustrated in Table 15 for the GTL plant with a bio-methane feedstock and 65 % methane-to-liquids conversion efficiency. As evident from Table 15, a relatively low investment rate together with the expected future bio-methane price and high degree of heat utilization will lead to very low jet fuel production costs when the side-products can be sold at the true production cost of 2. generation bioethanol. In the same way as illustrated in Table 15, sensitivity analyses are done for all scenarios and covering both assumptions on 65 % conversion efficiency, refer to Appendix 1, and 50 % conversion efficiency, refer to Appendix 2.

Table 15: Sensitivity analysis with varying calculation assumptions for the bio-methane feedstock scenario

Case:	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	3.90	1.42	1.42	1.42	0.71
Methane (EUR/GJ)	18.12	18.12	18.12	16.11	16.11
CO2 (EUR/ton)	n/a	n/a	n/a	n/a	n/a
Electricity (EUR/kWh)	n/a	n/a	n/a	n/a	n/a
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**66.82**	**38.01**	**24.27**	**18.67**	**13.28**
Jet fuel (EUR/l)	*2.34*	*1.33*	*0.85*	*0.65*	*0.46*
Jet fuel (EUR/kg)	*2.87*	*1.63*	*1.04*	*0.80*	*0.57*



6 Framework conditions for moving forward

6.1 Electrofuels and the EU

At the regulatory level, it is important to have a clear understanding of how e-fuels are included in European legislation. As e-fuels get increasing attention, both in the individual states and in the EU, pressure must be put on getting all relevant aspects clarified, including whether it is implemented in the new Renewable Energy Directive, REDII. From what we can read in REDII, there is nothing which could hinder the production and use of e-fuels. The carbon source is not mentioned in REDII, thus the interpretation is that the carbon source is not regulated, which means that there are no barriers using any of the feedstocks targeted in our Nordic GTL approach. On the other hand, it may be necessary to clarify whether feedstocks used are renewable in order to live up to the directive's objective of using advanced biofuels, because only renewable raw materials can be considered under the term advanced biofuels. Therefore, the unresolved questions are whether biogas, hydrogen and CO_2 are to be considered as renewable resources, or whether there are parts of EU legislation and directives that should still be adapted to encourage the development that will occur in the field of e-fuels.

6.2 The political interest and opportunity

The political attention and sense of urgency of the actions targeted by the Paris agreement has become stronger in the past few years. The greenhouse gas emission budget corresponding to a 1.5 degree C temperature increase is projected to be exceeded 5-10 years from now in a business-as-usual scenario and the 2 degree C budget 15-20 years from now. This urgency is becoming acknowledged by political decision makers in the Nordic countries and many other countries, significantly encouraged by voters, and especially the young generation has sent a clear mandate to decision makers. For the same reason, the present Danish government has decided on a 70 % reduction in greenhouse gas emission by 2030 – an unprecedented strong reduction target. Such a reduction is not achievable without efficient measures for green fuel supply, especially for longer distance aviation and sea transport.

Further, the Nordic countries aim to be world leaders in green transition, and a main election slogan of the new Danish Prime Minister in the Danish 2019 election was that Denmark should regain its position as a 'World leading superpower in green transition'. Accordingly, the Danish Ministry for Climate, Energy and Utilities is being reorganized gaining more power, and it has been decided to develop and pass a new mandatory Climate Act securing that Denmark reaches its ambitious targets.

Finally, three coal-fired power plants remain in operation in Denmark, but they will all phase out the coal use, two by 2025 or before and one by 2028 or before. The loss of heat from these three coal plants equals the process heat from a jet fuel factory, if designed for the co-produced heat. In other words, replacing the coal produced heat with respect to its district heating supply. To sum up, timing has never been better for building the first factory of the first truly green and sufficient jet fuel production pathway.

However, as part of a subsequent more detailed feasibility analysis, the following questions should be considered:

- Will politicians be willing to support – with subsidies or tax exemptions - the first bio-methane and/or power-to-fuels plant on e.g. 5 PJ per year of jet fuel output?
- What is the political interest to have the plant located at specific locations?
- Could such a political interest result in financing or contribute to support other sources of financing?

- What are the opinions of various stakeholders – the agricultural sector, the biogas sector, the industry sector, the energy sector, the hydrogen sector, etc., etc.

6.3 Establishing a supply chain and a consortium of stakeholders

It is technically possible to establish a jet fuel facility that uses bio-methane, CO_2 and/or hydrogen to showcase that technologies are available to drive the green transition in aviation. When the facility is built the customers will be there. Politicians taking their climate pledges seriously would demand sustainable jet fuel for their flights. The same goes with green companies and universities.

It is a big task to initiate such a project, but there are several stakeholders that could be willing to participate. Some of them are listed in Table 16.

When PtX is developed, the renewable energy companies will also be able to hedge the electricity price e.g. companies such as Ørsted or Vattenfall could be very important stakeholders due to their wide range of business areas.

The Defense sector in Nordic countries have been added to the list of stakeholders because a bio-methane GTL-facility could be a way to an even more secure source of fuels than oil especially in the long run and this could have a strategic value. It could be argued that some of the defense budget should be used this way to secure independence of fuel imports.

The Global Gas Flaring Reduction partnership [114] is willing to facilitate contact to the GTL technology providers. Contacts have already been established with the German company Sunfire who could be a potential supplier of the PtX-pathway and their project could run simultaneously with the Norwegian project at Nordic Blue Crude [42].

Throughout the duration of the project – and even before startup – we have had contact with several actors and technology and feedstock providers within the jet fuel supply chain. Key questions were;

- Which stakeholders could be willing and interested in progressing the production of aviation fuels from bio-methane, hydrogen, and CO_2?
- Which potential investors could find this project attractive enough to invest?
- What types of financing models can be possible?
- Who are the technology providers and who could take part in such a consortium?
- Who are the customers for the jet fuel and the side-products?
- Who can/will be partner in developing an actual plant and what is the investment cost for such a development partner?

Table 16: Potential stakeholders in the supply chain. The customers above the punctured line are all airlines, whereas the customers below the punctured line could be potential customers for the side-products of the jet fuel production. See Appendix 3 for a gross list of projects and stakeholders related to the pathway

Potential investors	Feedstock providers	Technology providers/producers	Customers	Other stakeholders
Maersk Holding Ørsted Equinor Shell Preem ExxonMobil Nature Energy Municipalities Pension funds Danish Defense Fjernvarme Fyn The Green Investment Fund Airports …etc.	Vestas Siemens Ørsted Vattenfall Nature Energy EON Aalborg Portland Climeworks Carbon Engineering Global thermostat Nel Steel/ore plants Agriculture Forestry Waste collectors ARC and other incineration plants …etc.	Sunfire Greyrock Siluria Nature Energy Biogasclean Electrohaea Topsøe Hydrogen Pro Opus 12 Shell Sasol …etc.	SAS Norwegian DAT Sun-Air Thomas Cook Widerøe Finnair Iceland Air Air Greenland Bra Alsie …etc. ------------------------- Maersk BASF LEGO Borealis National/Nordic Defense …etc.	Copenhagen Airports Swedavia Finavia Isavia Avinor …etc.

During this project, as well as in previous research and project activities, we have been in contact with stakeholders of the entire supply and demand chain of these pathways. In the front end of the chain, we have had dialogues with agricultural organizations and companies, and we acknowledge that the agricultural sector has a strong interest in being a key future supplier of not only feed and food, but also feedstocks for energy in a co-optimized approach to both cropping scheme innovations, biomass refining and value addition.

Also, at the final stage of this supply chain, waste incineration companies are increasingly considering carbon capture since many municipalities have set targets for greenhouse gas emissions and even overall targets of becoming CO_2 neutral. For some municipalities, for instance Copenhagen, the target of becoming CO_2 neutral is as early as 2025. For this reason, Amager Resource Center, has decided to apply carbon capture and are about to establish a pilot scale plant. Stockholm Exergi will install a carbon capture test facility at its biomass-fired KVV8 unit [37]. Several companies develop large scale carbon capture technologies. One of them, Siemens plan to be able to capture carbon in large scale from both waste incineration and biomass incineration by 2025.

The Danish biogas producer and technology developer, Nature Energy is today the largest producer of bio-methane delivered to the gas grid. They will in the near future include pretreated straw as feedstock, thereby increasing the overall biogas potential considerably. One such recent pretreatment innovation is the development of a process to de-wax straw, thereby making it hydrophilic and easier to mix and degrade. According to Nature Energy, it is realistic to supply more than 10 PJ/year of bio-methane for a jet fuel factory by 2025. Furthermore, Nature Energy is running several projects on biogas methanation, expected to be operating at full scale by 2023. The Swiss company Electrochaea has started larger scale methanation at a 20 MW bio-methane facility in Switzerland.

The German company Sunfire expects to install a 20 MW co-electrolysis unit for syngas production by 2022 and further expand this into a 200 MW facility by 2025. Sunfire also has a similar project running in Norway. Shell and several other companies already have facilities suitable for GTL production.

Danish district heating companies are presently looking for future green heat supply technologies, and several have expressed their interest in establishing "green fuel factories". The third largest Danish district heating company, District Heating Funen, are keen to understand the business case for this fuel production pathway and are prepared to pay around 10 Euro per GJ of heat. District Heating Funen plans to phase out their coal-use by 2025 or before.

Finally, Nordic aviation companies like SAS and others have already expressed their interest in purchasing jet fuels from this supply pathway at the prices indicated in this report. The plastic industry states an interest in the possibility of purchasing green plastic feedstocks from this pathway. The German BASF has expressed interest in purchasing green feedstocks for further polymerization into plastics.

The Figure below illustrates examples of key stakeholders with whom we have communicated and who have all expressed their preliminary interest in pursuing the possibilities.

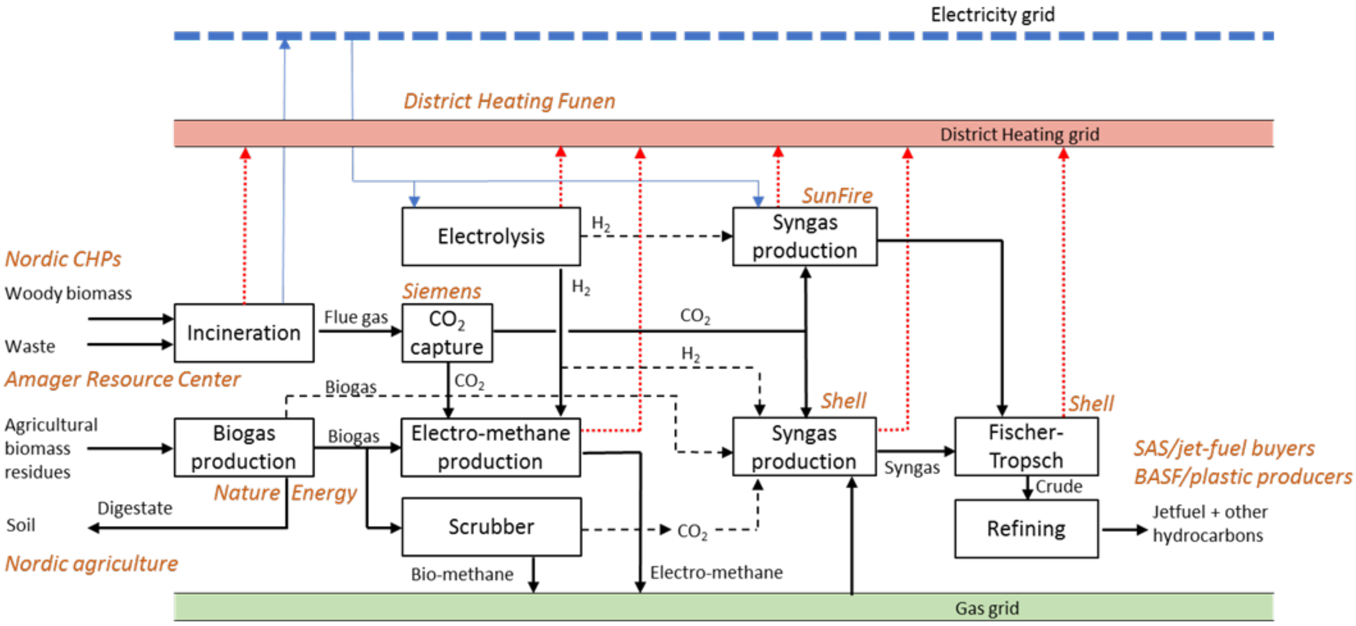


Figure 6: Examples of key stakeholders in the studied supply and demand chain who have expressed a strong interest in the pathway. The Figure is only meant to illustrate concrete examples of interested and capable actors in the supply-demand chain, no pre-selection of suppliers lies herein

6.4 Potential locations

The location of the jet fuel facility will influence which pathway that is most suitable. For regions and islands without gas-grids, it could be beneficial to take the methanol pathway because it is easier to transport liquid methanol to a central facility and it gives the flexibility to use the methanol as a fuel on the spot. On the other hand, if a gas grid is available, it could be attractive to use this and then go via the FT-pathway at a central location.

The opportunities are very different in the Nordic countries. Thus, there is a need to dig deeper into circumstances prevailing at different sites. To exemplify, we decided to look at possible locations in Denmark.

The Danish gas Transmission System Operator (TSO), Energinet is also testing the injection of up to 15 % hydrogen into the gas grid [115], which gives more flexibility of the location of the different plant components. Below are a few possible jet fuel plant locations in Denmark.

6.4.1 Replacing the coal fired power plant in Odense

Fynsværket, a coal fired power plant in Odense, Denmark, will phase-out coal by 2025 or before. The district heating company is currently looking at means to cover the lost heat. They are currently looking at biomass, heat pumps and natural gas. Given that there will be considerable volumes of excess heat from a jet fuel production plant, it could be an attractive replacement for coal. Fynsværket may, thus, be willing to host a facility and offtake the heat. Furthermore, there is an 800 MW gas pipe right at the gate of the power plant that could be used by the GTL plant. Additionally, there is a high-voltage transmission line connection to the plant.

If the FT-pathway is chosen, the plant could operate on bio-methane in the beginning or, in case the bio-methane supply becomes inadequate, even use natural gas as a supplement in the start-up phase. When the electro-methane technology matures and electro-methane is injected into the gas grid, the plant can start to operate on this as well. By capturing the CO_2 from the nearby straw incinerator or the waste incineration facility, the process can be optimized and hydrogen from a centralized electrolysis facility can be included to form a syngas. Looking further ahead, some of the excess heat could potentially be used for DAC of CO_2 and any waste heat can be reused for district heating. It would, thus, be possible to show and demonstrate a lot of configurations and synergies between the configurations while producing around 5 PJ of aviation fuel annually. The maximum size of the plant would be determined by the heat demand in the district heating grid of Odense.

6.4.2 The Nine Islets in Hvidovre

In and around Copenhagen, a lot of infrastructure and construction work takes place (including subway metro train) resulting in a lot of soil being permanently relocated. The Municipality of Hvidovre in Greater Copenhagen has an idea of using the soil to create nine new islets in the sea off the shore of the municipality. The idea is to centralize all existing wastewater treatment plants on one of these islets. This new facility is going to produce a lot of biogas which could be fed into a GTL plant located on one of the islets.

There could be multiple benefits of placing a jet fuel plant on one of the islets. First, it is relatively close to the huge district heating grid of Greater Copenhagen, so the size of the plant can be large while still having the option to utilize the excess heat. Second, the islets will be accessible by ship. Third, the location is close to a big biomass power plant where CO_2 can be obtained from the flue gas. Fourth, if the distillation or refining of jet fuel takes place at the GTL plant the distance to Copenhagen airport is relatively small.

6.4.3 The “Petrol Island” in Copenhagen

Close to Copenhagen Airport, CPH, a large fuel storage facility named the ‘Petrol Island’ is located. This is also close to the waste incineration facility Amager Resource Center, ARC, and also next to Øresund, the Sound between Denmark and Sweden. Power from off-shore wind turbines can be brought on-shore. The Petrol Island could potentially offer electricity free of (or with low) grid tariffs and easy transport of feedstocks by ship and produced fuels shipped by pipelines.

7 Conclusion

To conclude, we find the outcome of this pre-feasibility assessment promising. Key stakeholders in all parts of the supply and demand chain have expressed an interest in exploring the possibilities including embarking on a more in-depth feasibility study. Our recommendation is that such an analysis should be initiated with the aim of providing sufficient decision support for establishing a consortium and detailing possible ownership and investment models.

Our ambition has been to present this pre-feasibility assessment in a clear and concise manner in order to capture input and comments. We offer this as a possible comparison for any other emerging fuel pathway to compare with. Finally, we encourage other technology developers and solution providers to apply the same concrete and quantifiable sustainability criteria. See the overview in Table 17 below for details on sustainability criteria.

Table 17: Characterization and quantification of the performance of the studied jet fuel supply pathway on the key sustainability criteria of technical, economic and environmental feasibility

Sustainability criterion	Performance according to pre-feasibility assessment
Cost-efficiency – economic feasibility	
From biogas and bio-methane	0.7 – 1.1 EUR/L jet fuel in the period 2025 and onwards
From bio- and electro-methane	0.9 – 1.4 EUR/L jet fuel in the period 2027 and onwards
From CO_2 and electricity	0.7 – 1.2 EUR/L jet fuel in the period 2030 and onwards
Fuel feasibility & accreditation	
ASTM and DEF STAN compliance	Technically compliant with ASTM and DEF STAN requirements
Technical readiness level of technologies in the supply chain	
From biogas and bio-methane	TRL 9 for the whole supply chain
From electro-methane	TRL 8 for electro-methane production, TRL 9 for the rest
From CO_2 and hydrogen	TRL 8 for carbon capture from waste & biomass flue gas, TRL 7-8 for syngas production, TRL 9 for the rest
System level efficiency and feasibility	
Area and carbon efficiency	No land use and close to 100 % carbon efficiency
Sufficiency	Up to around 200 EJ/year of hydrocarbons globally using only sustainable biomass. Supplemented with direct air capture (DAC) of CO_2, the pathway is fully sufficient
Energy system integration	Most cost-efficient balancing of fluctuating electricity of all. Most cost-efficient sources of CO_2 for assimilating electricity & hydrogen into fuel supply. Almost full utilization of process heat
Agricultural system integration	Improved plant availability of N. Full N, P and K recycling and better re-distribution among farmers. Full return of hard-degradable carbon to agricultural soils for soil-carbon maintenance
Environmental feasibility	
Climate change	Negative carbon footprint for biogas and bio-methane feedstock. Around zero carbon footprint for other feedstocks. In both cases excluding the stratospheric water vapor and other high altitude emission impacts
Biodiversity	No land use implies low biodiversity impact
Soil quality	Good agricultural soil quality management with respect to N, P, K and C

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Appendix 1. Base case scenarios and sensitivity analyses for a jet fuel factory with 65 % conversion efficiency

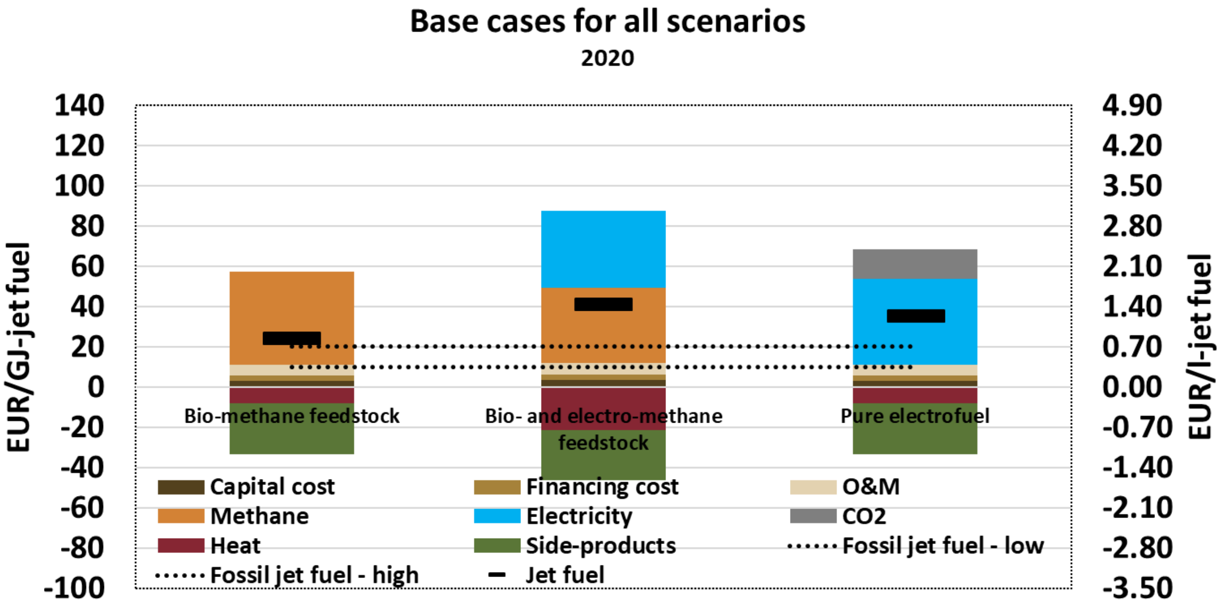


Figure 7: Economic estimates for all base case scenarios with assumptions for 2020. Assumptions for each scenario are shown in the tables below. All costs/prices are normalized to sold jet fuel per GJ

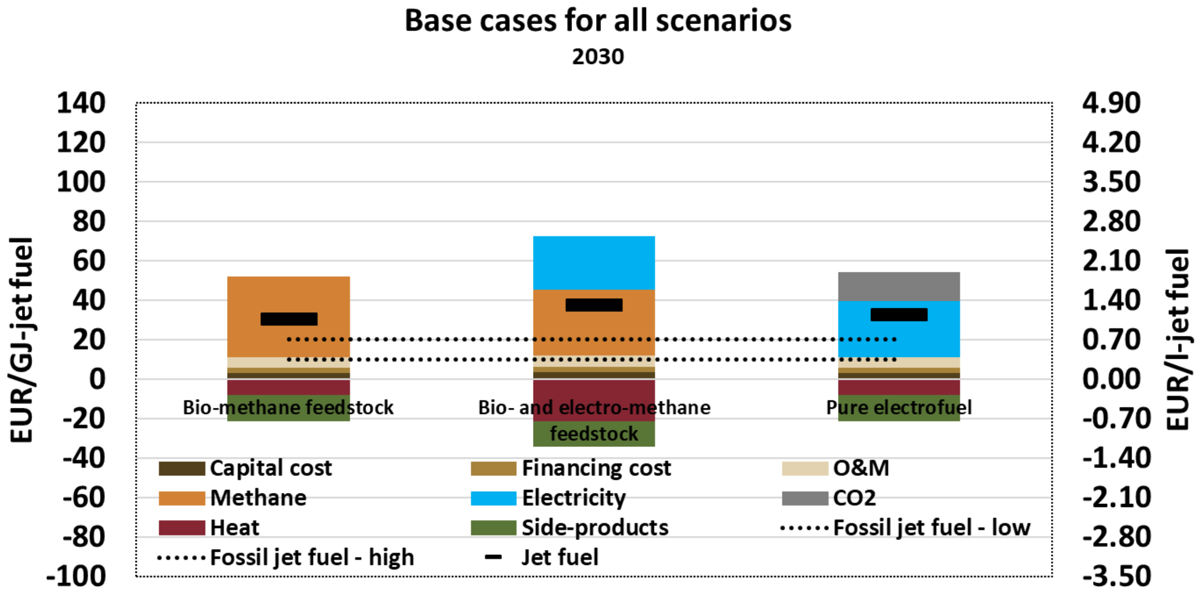
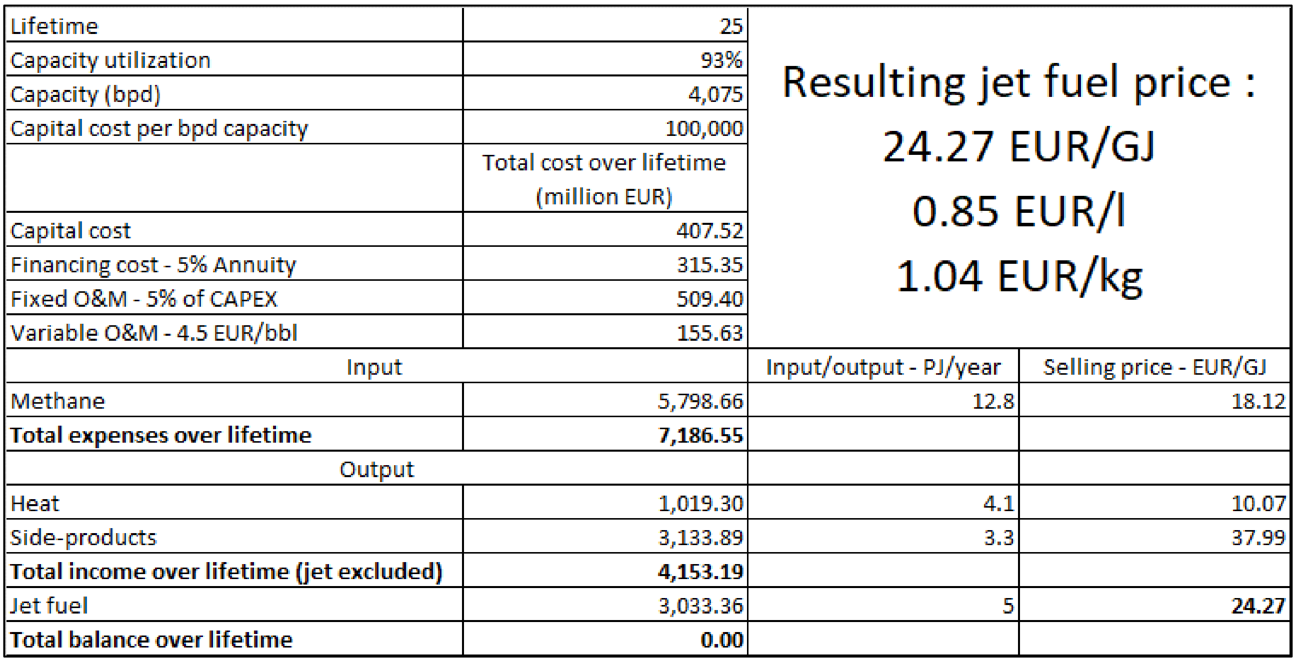


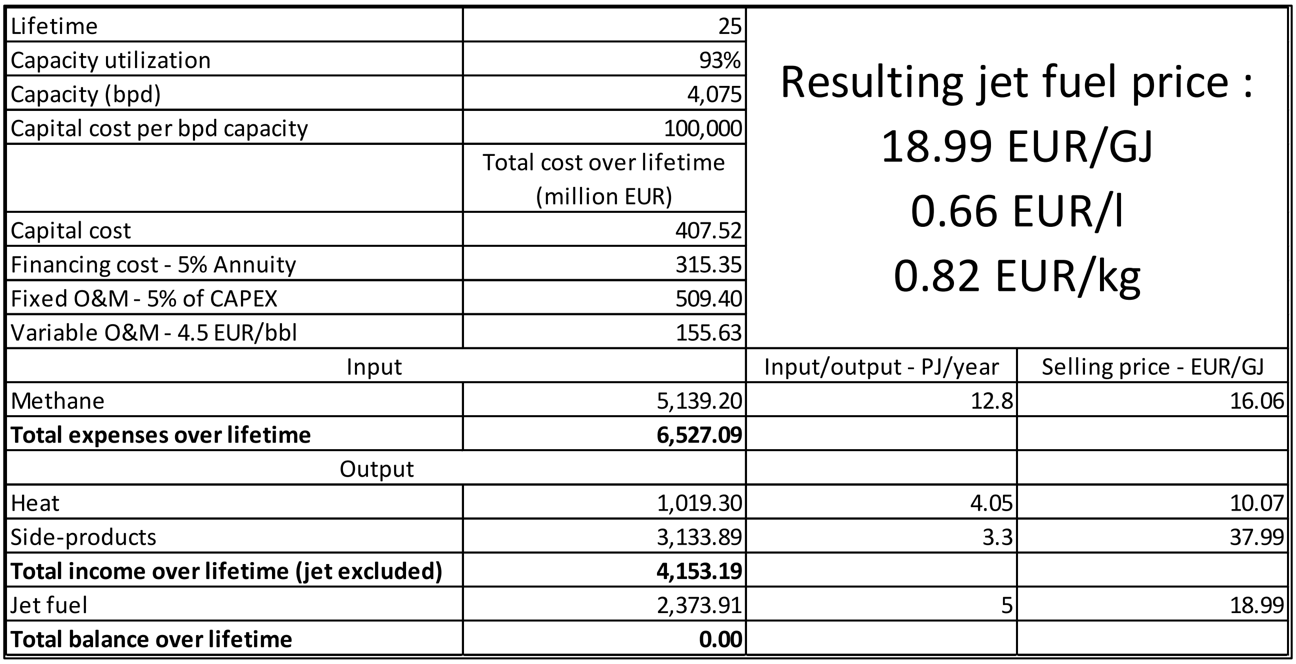
Figure 8: Economic estimates for all base case scenarios with assumptions for 2030. Assumptions for each scenario are shown in the tables below. All costs/prices are normalized to sold jet fuel per GJ

Table 18: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2020 assumptions and 2. generation bioethanol as the price of the side products*



Lifetime	25	Resulting jet fuel price : 24.27 EUR/GJ 0.85 EUR/l 1.04 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	5,798.66	12.8	18.12
Total expenses over lifetime	**7,186.55**		
Output			
Heat	1,019.30	4.1	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**4,153.19**		
Jet fuel	3,033.36	5	**24.27**
Total balance over lifetime	**0.00**		

Table 19: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2030 assumptions and 2. generation bioethanol as the price of the side products*



Lifetime	25	Resulting jet fuel price : 18.99 EUR/GJ 0.66 EUR/l 0.82 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	5,139.20	12.8	16.06
Total expenses over lifetime	**6,527.09**		
Output			
Heat	1,019.30	4.05	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**4,153.19**		
Jet fuel	2,373.91	5	18.99
Total balance over lifetime	**0.00**		

Table 20: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2030 assumptions and bio-LNG as the price of the side products*

Lifetime	25	Resulting jet fuel price : 30.81 EUR/GJ 1.08 EUR/l 1.32 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
Total cost over lifetime (million			
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	5,139.20	12.8	16.06
Total expenses over lifetime	**6,527.09**		
Output			
Heat	1,019.30	4.05	10.07
Side-products	1,656.19	3.3	20.08
Total income over lifetime (jet excluded)	**2,675.48**		
Jet fuel	3,851.61	5	30.81
Total balance over lifetime	**0.00**		

Table 21: Sensitivity analysis with varying calculation assumptions for the ***bio-methane feedstock*** *scenario.*

	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	3.90	1.42	1.42	1.42	0.71
Methane (EUR/GJ)	18.12	18.12	18.12	16.11	16.11
CO2 (EUR/ton)	n/a	n/a	n/a	n/a	n/a
Electricity (EUR/kWh)	n/a	n/a	n/a	n/a	n/a
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**66.82**	**38.01**	**24.27**	**18.67**	**13.28**
Jet fuel (EUR/l)	2.34	1.33	0.85	0.65	0.46
Jet fuel (EUR/kg)	2.87	1.63	1.04	0.80	0.57

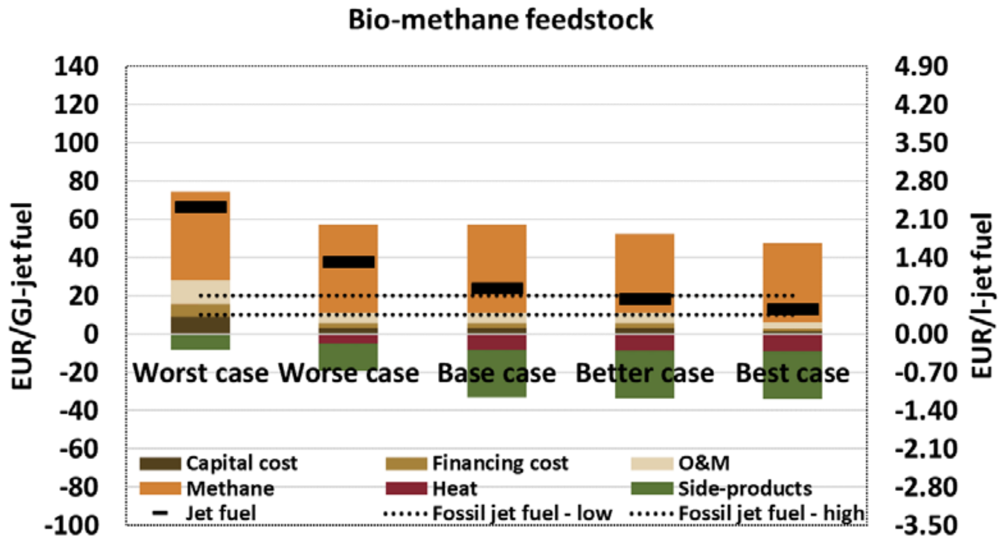
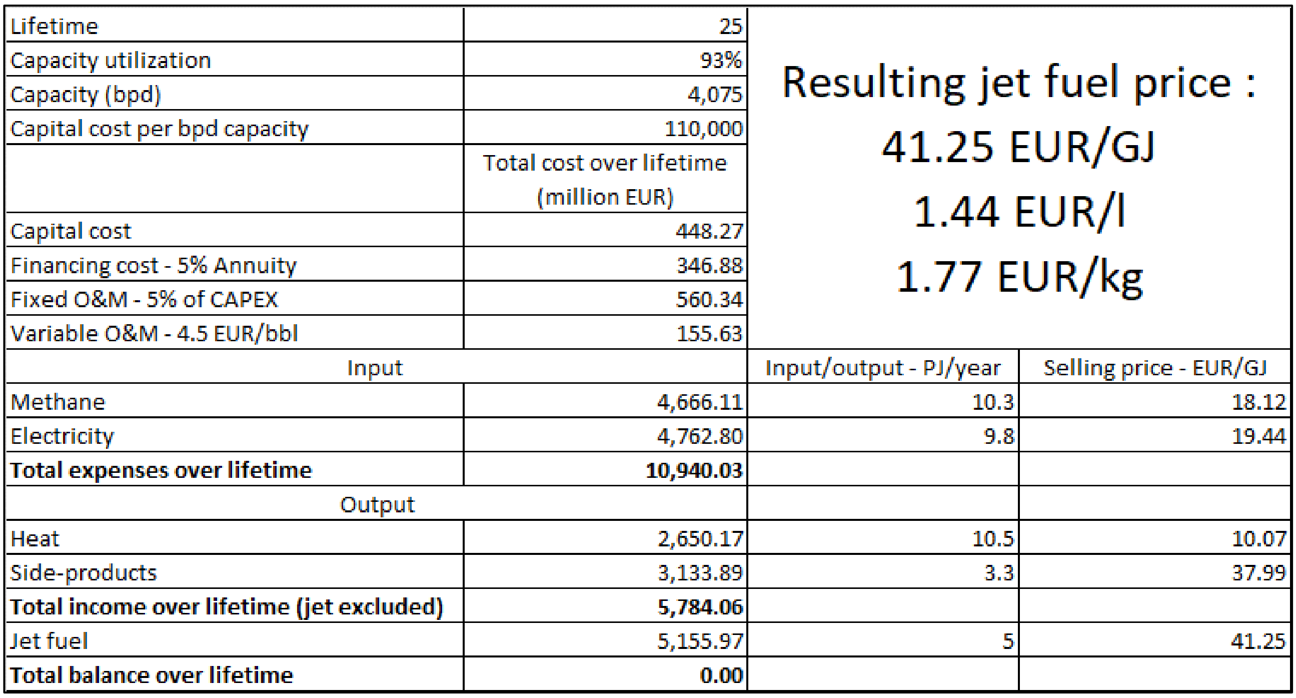
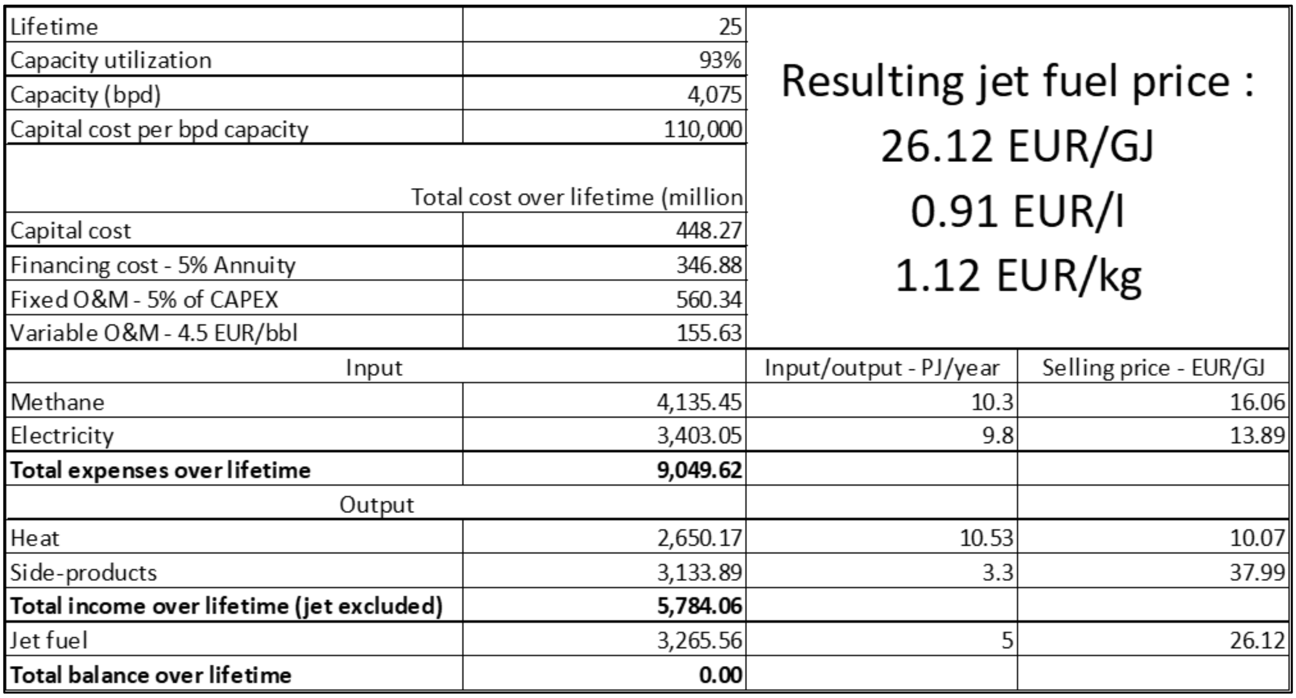


*Table 22: Overview of inputs and results of the base case for GTL with a **bio- and electro-methane feedstock**, 2020 assumptions and 2. generation bioethanol as the price of the side products*



Lifetime	25	Resulting jet fuel price : 41.25 EUR/GJ 1.44 EUR/l 1.77 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million EUR)		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	4,666.11	10.3	18.12
Electricity	4,762.80	9.8	19.44
Total expenses over lifetime	**10,940.03**		
Output			
Heat	2,650.17	10.5	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**5,784.06**		
Jet fuel	5,155.97	5	41.25
Total balance over lifetime	**0.00**		

*Table 23: Overview of inputs and results of the base case for GTL with a **bio- and electro-methane feedstock**, 2030 assumptions and 2. generation bioethanol as the price of the side products*



Lifetime	25	Resulting jet fuel price : 26.12 EUR/GJ 0.91 EUR/l 1.12 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	4,135.45	10.3	16.06
Electricity	3,403.05	9.8	13.89
Total expenses over lifetime	**9,049.62**		
Output			
Heat	2,650.17	10.53	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**5,784.06**		
Jet fuel	3,265.56	5	26.12
Total balance over lifetime	**0.00**		

*Table 24: Overview of inputs and results of the base case for GTL with a **bio- and electro-methane feedstock**, 2030 assumptions and bio-LNG as the price of the side products*

Lifetime	25	Resulting jet fuel price : 37.95 EUR/GJ 1.33 EUR/l 1.63 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million EUR)		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	4,135.45	10.3	16.06
Electricity	3,403.05	9.8	13.89
Total expenses over lifetime	**9,049.62**		
Output			
Heat	2,650.17	10.53	10.07
Side-products	1,656.19	3.3	20.08
Total income over lifetime (jet excluded)	**4,306.36**		
Jet fuel	4,743.27	5	37.95
Total balance over lifetime	**0.00**		

Table 25: Sensitivity analysis with varying calculation assumptions for a ***bio- and electro-methane feedstock*** *scenario*

	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	4.28	1.56	1.56	1.56	0.78
Methane (EUR/GJ)	18.12	18.12	18.12	16.11	16.11
CO2 (EUR/ton)	n/a	n/a	n/a	n/a	n/a
Electricity (EUR/kWh)	0.07	0.07	0.07	0.05	0.04
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**98.58**	**60.79**	**41.25**	**25.05**	**-9.07**
Jet fuel (EUR/l)	3.45	2.13	1.44	0.88	-0.32
Jet fuel (EUR/kg)	4.24	2.61	1.77	1.08	-0.39

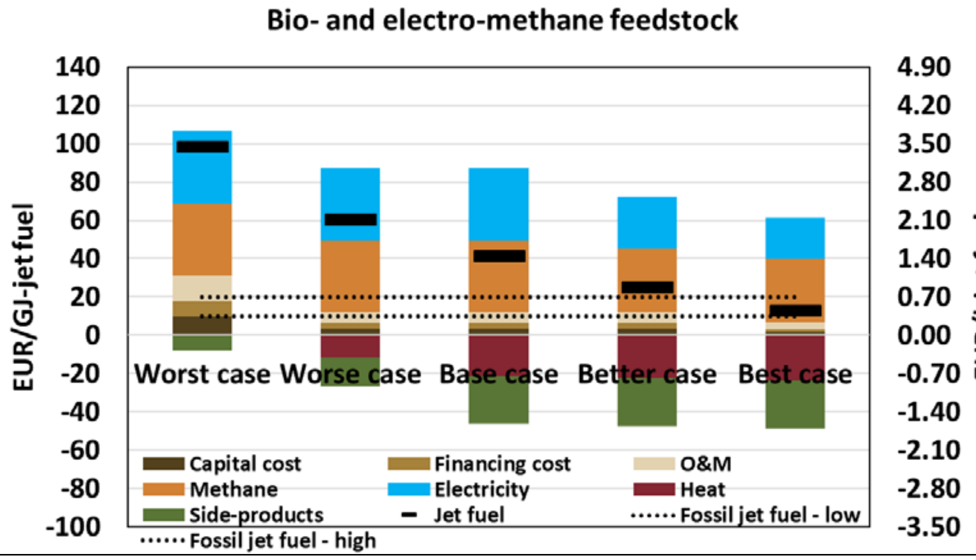


Table 26: Overview of inputs and results of the base case for a ***pure electrofuel*** *plant, 2020 assumptions and 2. generation bioethanol as the price of the side products*

Lifetime	25	Resulting jet fuel price : 35.40 EUR/GJ 1.24 EUR/l 1.52 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Electricity	5,334.40	12.80	16.67
CO2 (million EUR, kt, EUR/ton)	1856.25	825	90
Total expenses over lifetime	**8,578.54**		
Output			
Heat	1,019.30	4.1	10.07
Gasoline	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**4,153.19**		
Jet fuel	4,425.36	5	35.40
Total balance over lifetime	**0.00**		

Table 27: Overview of inputs and results of the base case for a ***pure electrofuel*** *plant, 2030 assumptions and 2. generation bioethanol as the price of the side products*

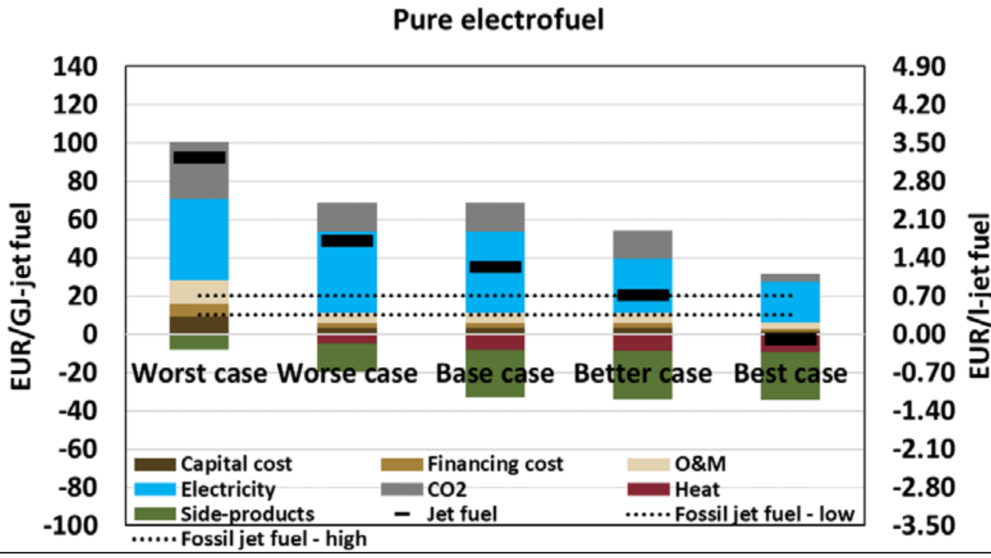
Lifetime	25	Resulting jet fuel price : 21.17 EUR/GJ 0.74 EUR/l 0.91 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Electricity	3,555.20	12.8	11.11
CO2 (million EUR, kt, EUR/ton)	1856.25	825	90
Total expenses over lifetime	**6,799.34**		
Output			
Heat	1,019.30	4.05	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**4,153.19**		
Jet fuel	2,646.16	5	21.17
Total balance over lifetime	**0.00**		

*Table 28: Overview of inputs and results of the base case for a **pure electrofuel** plant, 2030 assumptions and bio-LNG as the price of the side products*

Lifetime	25	Resulting jet fuel price : 32.99 EUR/GJ 1.15 EUR/l 1.42 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Electricity	3,555.20	12.8	11.11
CO2 (million EUR, kt, EUR/ton)	1856.25	825	90
Total expenses over lifetime	**6,799.34**		
Output			
Heat	1,019.30	4.05	10.07
Side-products	1,656.19	3.3	20.08
Total income over lifetime (jet excluded)	**2,675.48**		
Jet fuel	4,123.86	5	32.99
Total balance over lifetime	**0.00**		

Table 29: Sensitivity analysis with varying calculation assumptions for a ***pure electrofuel*** *plant*

	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	3.90	1.42	1.42	1.42	0.71
Methane (EUR/GJ)	n/a	n/a	n/a	n/a	n/a
CO2 (EUR/ton)	180.00	90.00	90.00	90.00	25.00
Electricity (EUR/kWh)	0.06	0.06	0.06	0.04	0.03
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**92.81**	**49.15**	**35.40**	**20.72**	**-2.51**
Jet fuel (EUR/l)	3.25	1.72	1.24	0.73	-0.09
Jet fuel (EUR/kg)	3.99	2.11	1.52	0.89	-0.11



Appendix 2. Base case scenarios for a jet fuel factory with 50 % efficiency except the pure electrofuel plant which is the same as in Appendix 1

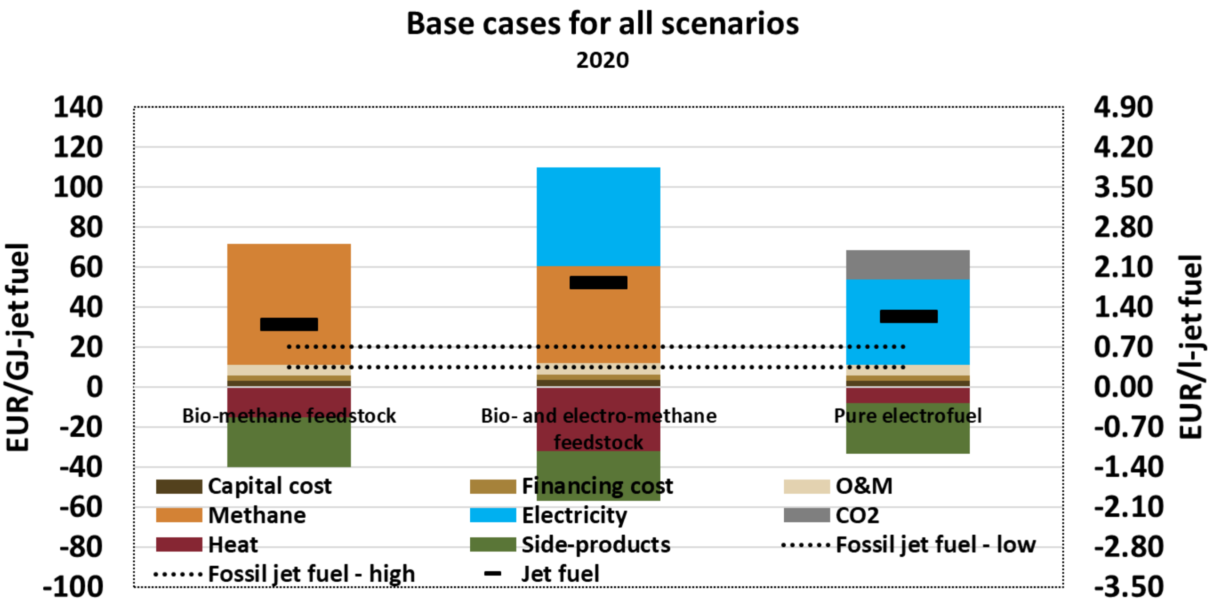


Figure 9: Economic estimates for all base case scenarios with assumptions for 2020. Assumptions for each scenario are shown in the tables below. All costs/prices are normalized to sold jet fuel per GJ

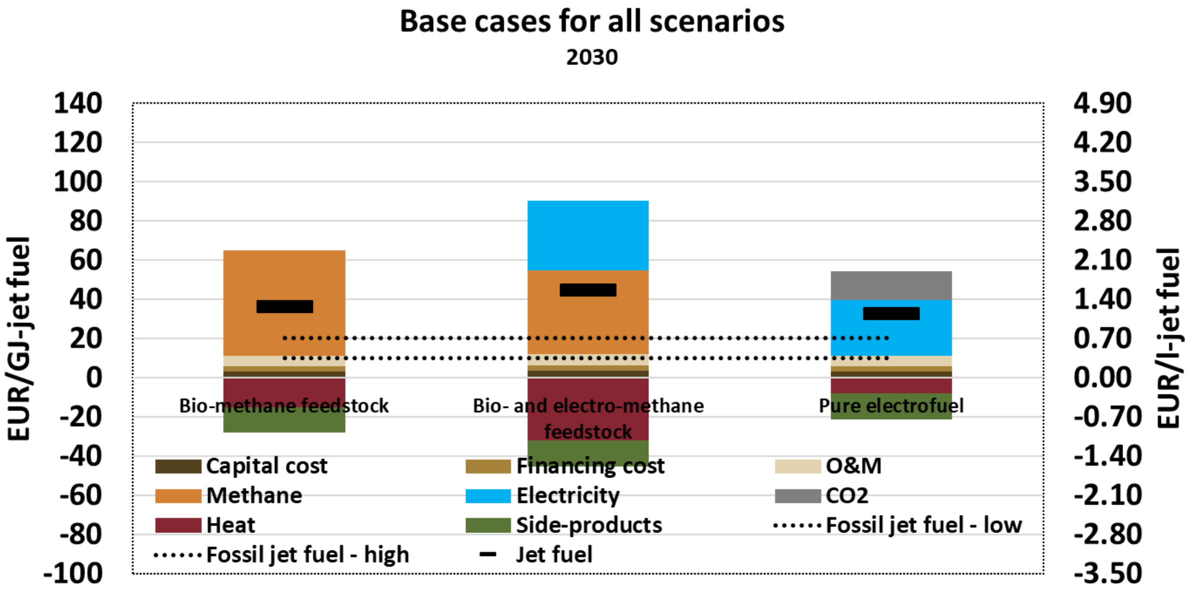


Figure 10: Economic estimates for all base case scenarios with assumptions for 2030. Assumptions for each scenario are shown in the tables below. All costs/prices are normalized to sold jet fuel per GJ

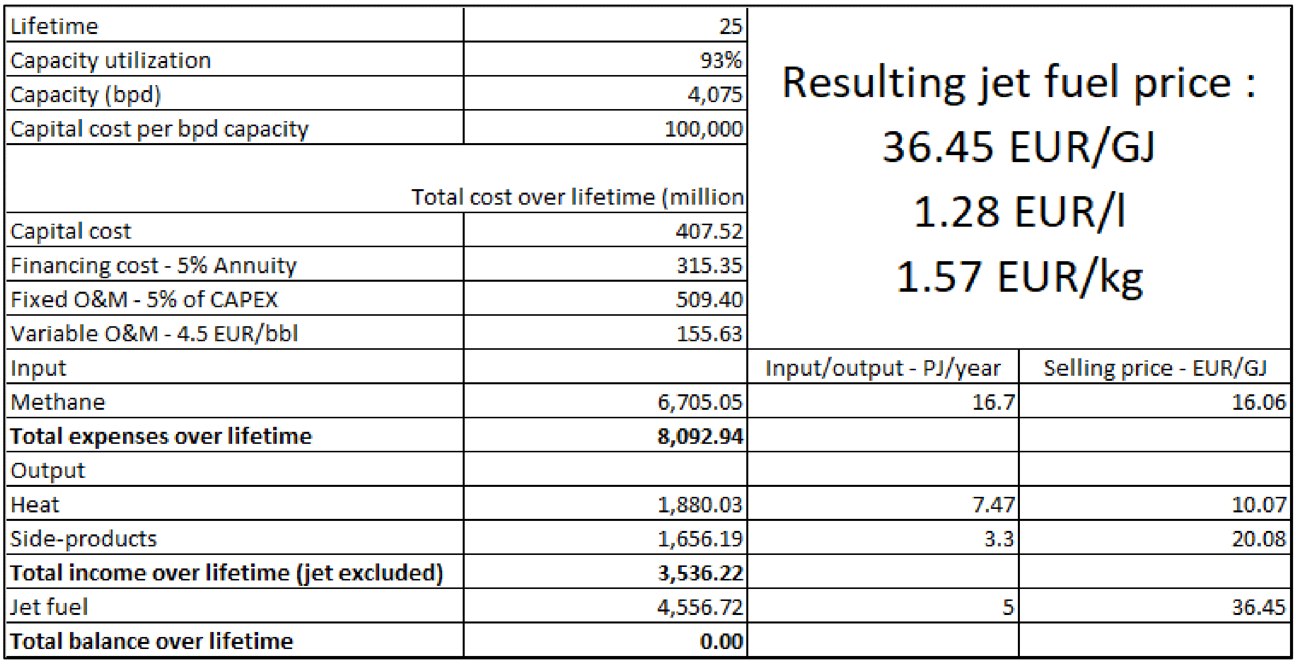
Table 30: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2020 assumptions and 2. generation bioethanol as the price of the side products*

Lifetime	25	Resulting jet fuel price : 31.52 EUR/GJ 1.10 EUR/l 1.36 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	7,565.44	16.7	18.12
Total expenses over lifetime	**8,953.33**		
Output			
Heat	1,880.03	7.5	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**5,013.93**		
Jet fuel	3,939.40	5	**31.52**
Total balance over lifetime	**0.00**		

Table 31: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2030 assumptions and 2. generation bioethanol as the price of the side products*

Lifetime	25	Resulting jet fuel price : 24.63 EUR/GJ 0.86 EUR/l 1.06 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million EUR)		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	6,705.05	16.7	16.06
Total expenses over lifetime	**8,092.94**		
Output			
Heat	1,880.03	7.47	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**5,013.93**		
Jet fuel	3,079.02	5	24.63
Total balance over lifetime	**0.00**		

Table 32: Overview of inputs and results of the base case for GTL with a ***bio-methane feedstock****, 2030 assumptions and bio-LNG as the price of the side products*



Lifetime	25	Resulting jet fuel price : 36.45 EUR/GJ 1.28 EUR/l 1.57 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	100,000		
	Total cost over lifetime (million		
Capital cost	407.52		
Financing cost - 5% Annuity	315.35		
Fixed O&M - 5% of CAPEX	509.40		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	6,705.05	16.7	16.06
Total expenses over lifetime	**8,092.94**		
Output			
Heat	1,880.03	7.47	10.07
Side-products	1,656.19	3.3	20.08
Total income over lifetime (jet excluded)	**3,536.22**		
Jet fuel	4,556.72	5	36.45
Total balance over lifetime	**0.00**		

*Table 33: Sensitivity analysis with varying calculation assumptions for the **bio-methane feedstock** scenario.*

	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	3.90	1.42	1.42	1.42	0.71
Methane (EUR/GJ)	18.12	18.12	18.12	16.11	16.11
CO2 (EUR/ton)	n/a	n/a	n/a	n/a	n/a
Electricity (EUR/kWh)	n/a	n/a	n/a	n/a	n/a
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**80.96**	**48.32**	**31.52**	**23.96**	**18.20**
Jet fuel (EUR/l)	2.83	1.69	1.10	0.84	0.64
Jet fuel (EUR/kg)	3.48	2.08	1.36	1.03	0.78

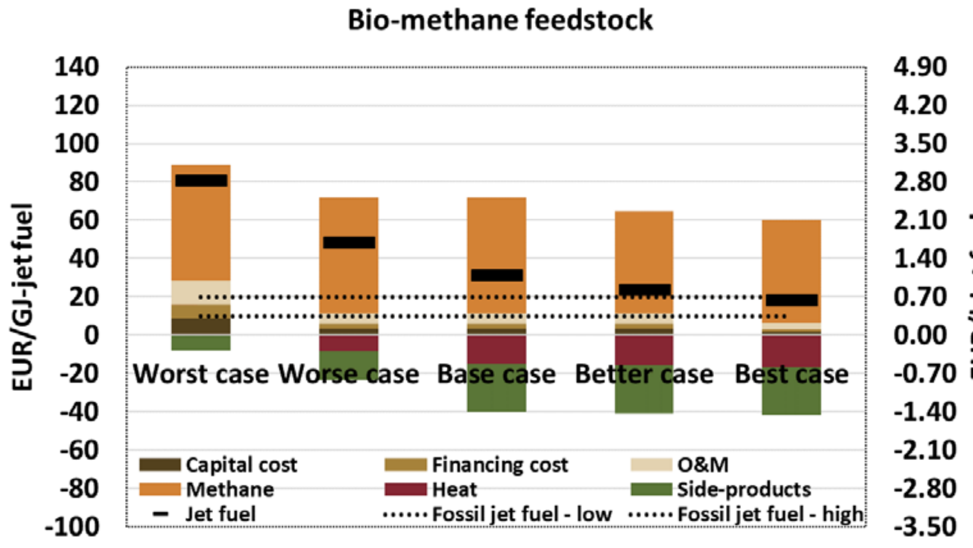


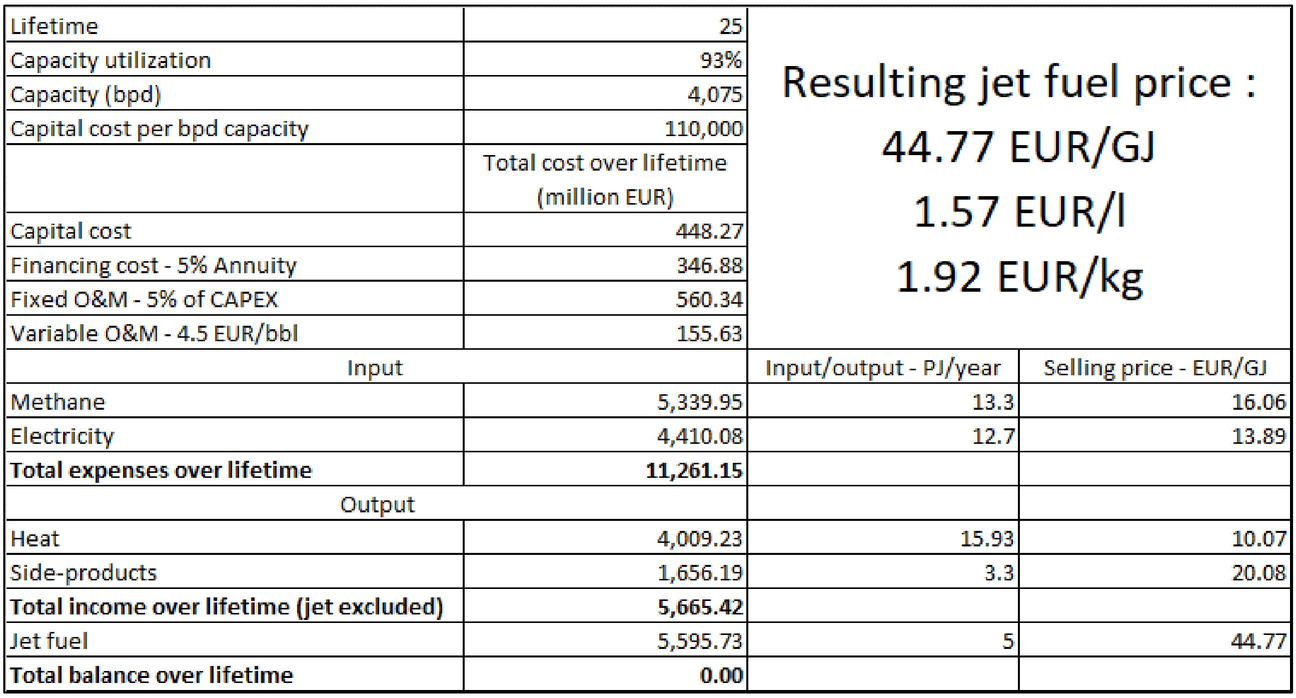
Table 34: Overview of inputs and results of the base case for GTL with a ***bio- and electro-methane feedstock****, 2020 assumptions and 2. generation bioethanol as the price of the side products*

Lifetime	25	Resulting jet fuel price : 52.52 EUR/GJ 1.84 EUR/l 2.26 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million EUR)		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	6,025.17	13.3	18.12
Electricity	6,172.20	12.7	19.44
Total expenses over lifetime	**13,708.49**		
Output			
Heat	4,009.23	15.9	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**7,143.12**		
Jet fuel	6,565.37	5	52.52
Total balance over lifetime	**0.00**		

Table 35: Overview of inputs and results of the base case for GTL with a ***bio- and electro-methane feedstock****, 2030 assumptions and 2. generation bioethanol as the price of the side products*

Lifetime	25	Resulting jet fuel price : 32.94 EUR/GJ 1.15 EUR/l 1.42 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	5,339.95	13.3	16.06
Electricity	4,410.08	12.7	13.89
Total expenses over lifetime	**11,261.15**		
Output			
Heat	4,009.23	15.93	10.07
Side-products	3,133.89	3.3	37.99
Total income over lifetime (jet excluded)	**7,143.12**		
Jet fuel	4,118.03	5	32.94
Total balance over lifetime	**0.00**		

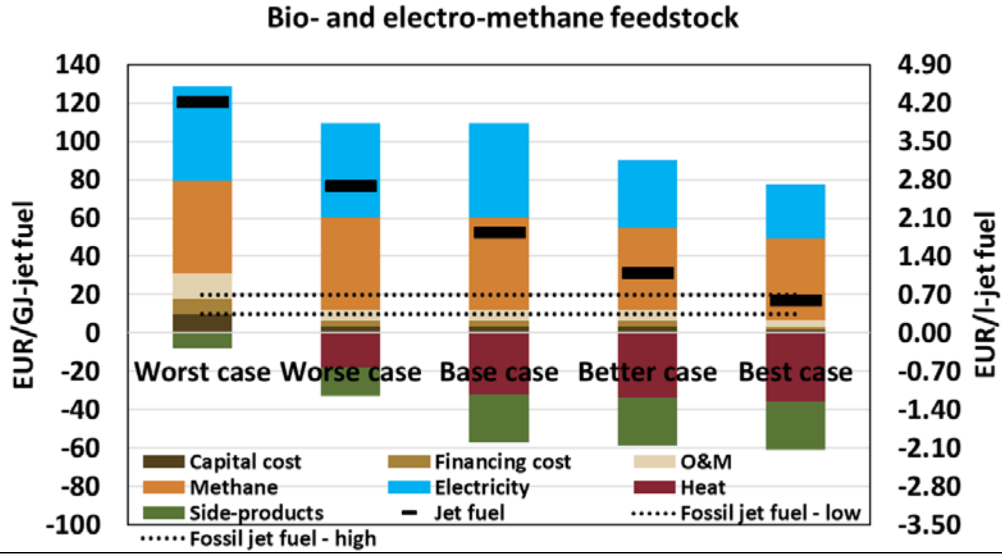
Table 36: Overview of inputs and results of the base case for GTL with a ***bio- and electro-methane feedstock****, 2030 assumptions and bio-LNG as the price of the side products*



Lifetime	25	Resulting jet fuel price : 44.77 EUR/GJ 1.57 EUR/l 1.92 EUR/kg	
Capacity utilization	93%		
Capacity (bpd)	4,075		
Capital cost per bpd capacity	110,000		
	Total cost over lifetime (million EUR)		
Capital cost	448.27		
Financing cost - 5% Annuity	346.88		
Fixed O&M - 5% of CAPEX	560.34		
Variable O&M - 4.5 EUR/bbl	155.63		
Input		Input/output - PJ/year	Selling price - EUR/GJ
Methane	5,339.95	13.3	16.06
Electricity	4,410.08	12.7	13.89
Total expenses over lifetime	**11,261.15**		
Output			
Heat	4,009.23	15.93	10.07
Side-products	1,656.19	3.3	20.08
Total income over lifetime (jet excluded)	**5,665.42**		
Jet fuel	5,595.73	5	44.77
Total balance over lifetime	**0.00**		

Table 37: Sensitivity analysis with varying calculation assumptions for a ***bio- and electro-methane feedstock*** *scenario*

	Worst	Worse	Base	Better	Best
Expenses					
Capacity cost (Million EUR/MW)	4.28	1.56	1.56	1.56	0.78
Methane (EUR/GJ)	18.12	18.12	18.12	16.11	16.11
CO2 (EUR/ton)	n/a	n/a	n/a	n/a	n/a
Electricity (EUR/kWh)	0.07	0.07	0.07	0.05	0.04
Sales prices (at factory)					
Heat utilization (%)	0	60	90	95	100
Side-products (EUR/GJ)	12.00	22.65	37.99	37.99	37.99
Jet fuel (EUR/GJ)	**120.72**	**76.90**	**52.52**	**31.30**	**-9.07**
Jet fuel (EUR/l)	4.23	2.69	1.84	1.10	-0.32
Jet fuel (EUR/kg)	5.19	3.31	2.26	1.35	-0.39



Appendix 3. Gross list of projects and stakeholders

Projects/sources/ stakeholders:	Links:
Nordic Blue Crude	Will produce high quality, carbon neutral, synthetic fuels and other fossil replacement products, based on water, carbon dioxide and renewable power https://www.nordicbluecrude.no/ https://www.sunfire.de/en/company/news/detail/breakthrough-for-power-to-x-sunfire-puts-first-co-electrolysis-into-operation-and-starts-scaling https://bioenergyinternational.com/biofuels-oils/sunfire-build-8-000-tonne-per-annum-power-liquid-facility-norway
LanzaTech (ethanol to jet)	http://www.lanzatech.com/virgin-atlantic-lanzatech-celebrate-revolutionary-sustainable-fuel-project-takes-flight/
Synfuel at DTU	https://energiforskning.dk/da/project/synfuel-baeredygtige-syntetiske-braendstoffer-fremstillet-ved-gasifikation-af-biomasse-og
KEROSyN100 from the refinery in Heide:	https://trendsandtravel.dk/tyskere-vil-flyve-paa-kunstigt-benzin/ https://www.uni-bremen.de/de/ https://www.heiderefinery.com/en/ https://www.hamburg-airport.de/de/ https://www.lufthansa.com/dk/en/homepage
SkyNRG	http://skynrg.com/ http://skynrg.com/technology-section/
Preem and Vattenfall -20MW electrolysis:	https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2019/preem-and-vattenfall-deepen-partnership-for-the-production-of-fossil-free-fuel-on-a-large-scale
Sunfire	https://www.greencarcongress.com/2019/01/20190116-sunfire.html https://www.youtube.com/watch?v=D055qqVNc1E
Hydrogen Valley in Hobro, Denmark	http://hydrogenvalley.dk/ https://www.dr.dk/nyheder/viden/teknologi/teknologien-rykker-snart-saetter-flere-anlaeg-sol-og-vind-paa-flaske
Carbon Capture possibilities in Sweden:	http://www.mynewsdesk.com/se/svebio/pressreleases/stor-potential-foer-bio-ccs-i-sverige-38-orter-med-baest-foerutsaettningar-2864383?utm_campaign=send_list https://www.researchgate.net/publication/314966911_The_Potential_for_Electrofuels_Production_in_Sweden_Utilizing_Fossil_and_Biogenic_CO2_Point_Sources
Chalmers University of Technology	Electrofuels for the transportation sector: A review of production costs? https://www.iea-etsap.org/workshop/gothenburgh_june2018/22-180618%20Brynolf%20Production%20cost%20of%20electrofuels%20ETSAP.pdf https://www.ncbi.nlm.nih.gov/pubmed/30633863
Aalborg University and partners	https://www.et.aau.dk/research-programmes/electro-fuels https://house-of-energy.dk/wp-content/uploads/2019/01/Produktion-af-CO2-neutralt-br%C3%A6ndstof-fra-sol-og-vindenergi.-S%C3%B8ren-Knudsen-K%C3%A6r-AAU.pdf http://www.biopress.dk/PDF/electrofuels-kan-blive-fremtidens-diesel-og-flybraendstof
AkzoNobel	https://www.nouryon.com/news-and-events/news-overview/2018/mar/akzonobel-specialty-chemicals-joins-partnership-to-explore-opportunities-for-green-hydrogen-and-electrofuels-in-sweden/

Global Gas Flaring Reduction Partnership	http://www.worldbank.org/en/programs/gasflaringreduction http://www.worldbank.org/en/programs/gasflaringreduction#5
X company	Fuels from carbon dioxide from seawater https://x.company/projects/foghorn/
Projects on Iceland	https://qz.com/1100221/the-worlds-first-negative-emissions-plant-has-opened-in-iceland-turning-carbon-dioxide-into-stone/ http://www.carbonrecycling.is
Nordic Energy Research	https://www.nordicenergy.org/article/nordic-leadership-in-sustainable-aviation-fuels-policies-technology-options-research-needs-and-markets/ https://www.nordicenergy.org/wp-content/uploads/2015/11/CO2-Electrofuels.pdf
DTU	https://www.energy-x.eu/dtu/
Two German projects	https://www.ptj.de/co2plus https://www.uni-kassel.de/einrichtungen/en/cesr/research/projects/active/co2plus.html¨
EU and IEA	http://artfuelsforum.eu/wp-content/uploads/2017/12/ART_Fuels_Forum_Position_Paper_PtX_Dec_2017.pdf https://www.iea.org/workshops/joint-workshop-by-the-iea-and-the-european-commission-on-electrofuels.html https://www.theicct.org/sites/default/files/publications/Electrofuels_Decarbonization_EU_20180920.pdf
Certificates	www.CertifHy.eu https://static1.squarespace.com/static/56926c502399a318016c5ed8/t/5a9ea88824a6940b3d5ad91c/1520347273679/ISCC+PLUS+2018+certificate+Carbon+Recycling+International.pdf

Reports:

Sustainable Jet Fuel for Aviation: Nordic perspectives on the use of advanced sustainable jet fuel for aviation
https://www.nordicenergy.org/publications/sustainable-jet-fuel-for-aviation-nordic-perspectives-on-the-use-of-advanced-sustainable-jet-fuel-for-aviation/

Carbon Neutral Aviation in the Netherlands:
https://s3-eu-west-1.amazonaws.com/static.quintel.com/publications/Carbon_Neutral_Aviation.pdf

UK's Committee on Climate Change
https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

Fischer-Tropsch refining
https://repository.up.ac.za/bitstream/handle/2263/26754/Complete.pdf?sequence=10