SAF products and delivery options

D2.1

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Content

1. Executive summary

The aviation industry faces major challenges in procuring sustainable fuels, here referred to as SAF. This reporting is about what decisions and what circumstances need to be prepared for new fuel products to be used and what elements are important to take in consideration. The overall framework and conditions are crucial, and it has become more and more clear that this is a task that involves many actors within and outside the aviation sector and their effective collaboration.

For a decade, several raw materials, technologies, and methods have been approved, but the great breakthrough of SAF use has not yet been seen. Very limited quantities of SAF based on biooil, especially from used cooking oils have been on the market for some years, but limited availability, high prices, uncertain sustainability documentation and lack of willingness to invest in the technology have probably meant that a market breakthrough has been delayed. Of the global fuel consumption for aviation, it is estimated that less than 0.1% is SAF currently.

A review of the approved methods to produce sustainable fuels continues to show major challenges, but also that there are opportunities. Larger quantities are expected to be produced based on used cooking oils, but also that there are opportunities to utilize some of the large amounts of waste and residuals that are available in many places. Furthermore, several producers with the alcohol-to-jet pathway is expected to start production within a year or two. Over the past two years, PtX-based solutions have proven to be the most trusted in terms of sustainability. This requires access to large amounts of renewable energy, the production of hydrogen and the capture of carbon. Both in Denmark and in a number of countries, this technology is on its way to being ready for the establishment of the first industrial plants.

This development is in line with Danish governments objectives and is also in line with Danish Aviation's ambitions and plans. The construction of several PtX plants is under preparation, some of which have announced that they want to produce fuels for aviation. It is therefore a natural consequence that the ALIGHT WP2 about SAF supply line increases the involvement in these activities and includes the experiences from this in subsequent deliveries.

PtX or rather PtL produced SAF is expected by manufacturers to be introduced in the market around 2025. In considerable quantities probably not until the end of this decade.

Supplies of these fuels in the future are important to examine so that the whole supply line is prepared. New approved liquid fuels will not require modified physical measures, - unless decisions are made to target SAF separately in any given blend-in, or unblended. This can be actualized by the latest tests and measurements, which show that a significant part of the aircraft's climate impact arises in the form of non-CO2 effects at high altitudes from long-haul aircraft. A scheme that will, however, involve significant cost and changes in the fuel supply lines.

As a future CO2 payment system, SAF can be used in current logistical routes through a so-called mass balance system. Further in a broader setup, work is underway to establish a book

& claim system. A segregated supply system will be a very big challenge in the current state, but can, as mentioned, provide positive environmental benefits.

Other propellants should also be brought into play when we look into the not-so-distant future. Aircraft flying on other propellants are under development. In the second half of the current decade, the first smaller electric and hydrogen aircraft are expected to enter the market. In the ALIGHT project, work is being done with a future aircraft stand, and based on preliminary assessments and experience that it can take several years to finance and adapt the infrastructure to suit new variants of future aircraft.

2. Introduction

With the hard to abate nature of the aviation sector, Sustainable Aviation Fuel (SAF) is a pivotal component for its transition to climate neutral operations. Since the global aviation fuel system is basically exclusively designed for the use of kerosene-based aviation fuels and is hard to modify the benefit of current SAF approaches lies in its "drop-in" ability that allows to integrate it seamlessly (from a technical perspective) in existing fuel logistics and procedures. In the medium and long term, specifically tailored non-drop-in SAF or 100% SAF options could become central. With high potential carbon reduction spread over various technologies, SAF represent the most far-reaching solution to achieve emission reductions in the aviation sector for several years to come. IATA member airlines and the wider aviation industry are collectively committed to **ambitious emissions reduction goals**. Most recently, in November 2021, IATA committed the industry to reach zero carbon emissions globally by 2050. Many countries and individual airlines have, at various levels, established sub-targets and adopted initiatives and regulations that will contribute to achieving the overall climate targets. At general EU level, the content of the proposals in Fit for 55 and RED II (Renewable Energy Directive), has a clear goal of achieving noticeable emission restrictions.

The use of SAF is already a reality, even if it is still far away from the required large-scale usage as a commodity like todays fossil aviation fuels. Commercial flights have been carried out on SAF by more than 40 airlines and has thus demonstrated technical compliance with conventional jet fuel, i.e., more than 400.000 flights have flown on various amounts of blend-in SAF (Aviation benefits N/D). However, there are various barriers to using SAF on a regular basis, including challenges of operation and logistics as well as commercial barriers such as pricing, availability, and policy settings. The volumes being produced today are by far not enough to make a substantial impact on the environmental footprint from aviation activity. They cover less than 0,1% of global aviation fuel consumption, and prices between 2-5 times conventional jet fuel have been observed in recent years, sometimes even more – especially for SAF technologies lacking commercial maturity.

Practically all sustainable fuel used in aviation today is from biogenic sources, first and foremost HEFA from used cooking oils and waste oils, even though there are other drop-in fuels approved already. However, their commercial deployment and scale-up is still under development, like Power-to-Liquid (PtL) fuels or electrofuels. Other technologies expected to enter the market in 2023/24 are Alcohol-to-Jet (AtJ) and Biomass-to-liquid (BTL) based Fischer-Tropsch (FT) plant using municipal solid waste (MSW) as the main feedstock.

In the ALIGHT WP2 it is the estimated that an amount of 3.000 ton equivalent to 1 % of domestic aviation in Denmark is covered by SAF in CPH in 2022/23 and that nationally produced SAF is available at Rome Airport. In 2025 4 % of all aviation fuel uplifted at CPH is estimated to be covered by SAF (approx. 50,000 m^3) (NIRAS 2022).

Fuel for aircraft have a strict approval process, and with the first synthetic kerosene options as an alternative fuel to the traditional fossil aviation fuel being approved in 2009. Such alternative fuels must be approved by accredited organizations like the American Society for Testing and Materials (ASTM) which have since 2009 approved seven alternative pathways plus the option to co-process specific renewable feedstock (fat, oils, greases) and/or intermediates in conventional refineries.

While this deliverable focuses on the SAF supply line from the feedstock to production and delivery, the production of SAF must be seen as a holistic value chain. In such a perspective, sustainability is absolutely central and a key element for aviation stakeholders and is therefore naturally part of the assessment of possible solutions. The topic of sustainability is included in this report, but more in-depth descriptions of the topic of sustainability will be elaborated in depth in other parts of the ALIGHT project

Deliverable 2.1 is structured in three sections:

The first section presents the basics of alternatives to conventional aviation fuel and gives an insight to the different SAF products on the market. Although SAF is often mentioned under a single category the available and planned products differentiate significantly in both production method and environmental impact. It is therefore basically important to know how these products differ from one another and how their respective markets are developing.

The second section describes the decision process and circumstances developers must be aware of when engaging with the production of SAF. This section takes point of departure from CPH airport as the lighthouse and presents several projects in Europe as case examples. The cases all have a direct or indirect connection to CPH as potential point of delivery and demonstrates the steps needed to develop and scale up SAF production.

The third section highlights the logistics of SAF to CPH airport. With a point of departure from the storage facilities at Prøvestenen, the physical delivery of aviation fuel to CPH airport is described. Subsequently alternative deliveries, challenges, and purposes are discussed.

3. Section 1: Aviation fuel

Aviation fuel

ASTM international, American Society for Testing and Materials, is the leading fuel approving organization when it comes to the use of commercial aviation fuel. Due to the high safety philosophy in aviation, criteria for fuel are the highest in any transportation sector. Also, the English Defence Standard (DefStan) can approve new fuels. So far, civil aviation actors have used the ASTM approval. The testing and approving paradigm are a multi stakeholder and very resource and time heavy process. Previous experience has shown that it has taken several years for a new pathway to get through.

With only a very few SAF products available on the market on alternative fuels, both in terms of SAF options and volumes, the airline industry can, at the time of writing, utilize eight different ASTM approved production pathways.
All these alternative fuels can be added to the traditional A1 jet fuel as a drop-in fuel, with varying percentage of blending allowed, so far, however, maximum 50 % by volume blend-in depending on the chosen pathway. The 50% by volume was set due to the safety philosophy in aviation and a precautionary principle. In the following section each of the pathways will shortly be described. Since ASTM specifications are based on physical and chemical fuel properties in order to ensure technically reliable fuel use, sustainability is not a part of the ASTM approval and will together with challenges, potentials etc. be described at a later stage.

Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)

The Fischer-Tropsch (FT) pathway was approved as the first alternative pathway in 2009, with a maximum share of Synthetic Paraffinic Kerosene (SPK) or "neat SAF" in the blend of 50% by volume.

The pathway requires synthetic gases (syngas) – mainly a mixture of hydrogen and carbon monoxide – as an intermediate for the subsequent FT-synthesis. The syngas can be obtained from various carbon-containing sources like energy crops or wastes and residues such as municipal solid waste (MWS), forestry residues or agricultural waste. In addition, it can be produced via the electricity-based route based on renewable hydrogen and sustainably supplied carbon (e.g in the form of CO_2). Regarding fossil feedstocks it could also be obtained from natural gas, other similar gases, or coal. The feedstocks are gasified at high temperatures and the different chemical components separated, subsequently purified into a clean syngas which goes through the Fischer-Tropsch process. Here the syngas is converted to long hydrocarbon chains, via a reactor with either a cobalt or iron catalyst. The hydrocarbon product can then be cracked and isomerized into the desired hydrocarbon length and product.

Although this pathway was approved for alternative fuels in 2009, the Fischer-Tropsch process is far from new. The technology dates back to the 1930s when the conversion of coal to liquid fuel was the challenge.

Hydroprocessed esters and fatty acids – Synthetic paraffinic kerosene (HEFA-SPK)

The HEFA pathway was approved in 2011 as the second alternative fuel, with a maximum blend of 50% by volume.

With the HEFA pathway lipid feedstocks such as vegetable oil, animal fats, grease and various fatty acids and ester can be utilized. Through hydro processing, undesirable molecules and oxygen are removed and subsequently cracked down to the desirable hydrocarbon.

This pathway is the most matured technology on the market to produce SAF.

Hydroprocessed fermented sugars – Synthetic isoparaffins (HFS-SIP)

ASTM approved in 2014, with a maximum blend of 10% by volume.

The pathway utilizes mainly sugary feedstock, which is added to a modified yeast and through a fermentation turn the sugars into hydrocarbons. Subsequently, and similar to the HEFA pathway, the hydrocarbons are subjected to a hydroprocessing method and cracked to achieve the desired length of hydrocarbon.

Fischer-Tropsch synthetic paraffinic kerosene with aromatics (FT-SPK/A)

Being approved in 2015 and allowing a maximum blend of 50% by volume, the FT-SPK/A pathway is very similar to FT-SPK. It utilizes the same feedstock of syngas, that goes through the Fischer-Tropsch process, but this pathway adds alkylation of light aromatics to create aromatics in the jet fuel. The addition of aromatics makes the fuel closer to conventional fuel.

Aromatics are a chemical compound in the hydrocarbons, that are with a lower combustion capacity than the conventional straight hydrocarbon connections (n- or iso-alkanes) or cyclo-alkanes. The aromatics lubricate in the fueling system on the aircraft and support that there are no leaks during the flight, as they cause a certain behavior/swelling of sealing components. Therefore, there is still a mandate to have between 8,4% and 25% aromatics by volume in the total fuel on a plane (Sustainable aviation 2020). Most aromatics are burned during combustion, but it is important to note that on the ground the aromatics contribute to the particulate pollution which degrades air quality and can cause respiratory problems. Aromatics are also the cause of non-CO2 effects, which is responsible for large environmental impacts in the aviation sector.

Alcohol to jet - synthetic paraffinic kerosene (ATJ-SPK)

In 2016 the alcohol to jet pathway was ASTM approved, with a maximum blend of 30% by volume, which was subsequently increased to 50% by volume.

The pathway uses either ethanol or isobutanol as the intermediate feedstock for the actual AtJ-syntheses. There is no regulation on where the alcohol can come from if it fits the chemical composition of either isobutanol or ethanol it can be utilized. Commonly its collected from fermentation processes of starch, sugars, or cellulosic biomass. However, all C2-C4 alcohols are to be approved in the future.

Another potential acquisition of feedstock is conversion of hydrogen and carbons via an organism that can convert the molecules.

The alcohols used as intermediates are then first dehydrated, then oligomerized, hydrogenated and finally fractionated to end up with a synthetic kerosene fraction that can be upgraded to ASTM compliant jet fuel.

Catalytic hydrothermolysis synthesized kerosene (CH-SK/CHJ)

Approved in 2020 with a maximum blend of 50% by volume.

This pathway uses vegetable oil, animal fats, grease and various fatty acids and ester, like the HEFA pathway.

The pathway differs in the production process where the feedstock is subjected to hydrothermal conversion with a combination of either hydrotreating, hydrocracking or hydro isomerization and other conventional refinery processes.

Hydroprocessed hydrocarbons, esters, and fatty acids synthetic paraffinic kerosene (HHC-SPK or HC-HEFA-SPK).

Approved in 2020, due to fast-track approval with a maximum blend of 10% by volume.

This process is very similar to HEFA but enables algae feedstock to be utilized. The feedstock is hydroprocessed to saturate the hydrocarbon and all oxygen is removed and refined to the desired hydrocarbon.

Co-processing. FT-biocrude and lipid feedstocks up to 5% by volume of lipid feedstock in petroleum refinery processes.

Sustainable aviation fuel

In the seven pathways described above (including the co-processing pathways) it is important to mention that the ASTM or Def Stan approval does not include sustainability criteria. Thus, isolated from further consideration and sustainability criteria, the alternative pathways cannot be defined as a sustainable fuel.

With the sustainability aspect on fuels, it is possible to help mitigate negative environmental impacts from the aviation industry and in the process engage in the developing green economy on a global scale. SAF will play a key role in reducing GHG-emissions, which has gained a lot of attention in order to achieve climate goals globally as well as on national level. However, SAF contains other and equally important development aspects like the reduction of particulate matter (PM) and sulphur (SO_X), compared to conventional jet fuel. Reducing these emissions could improve local air quality and areas with a high traffic volume, such as airports.

Several studies have shown that the neat SAF component can also have a higher gravimetric energy density than conventional jet fuel (approx.1%). This could mean better fuel performance by SAF and an improved fuel efficiency respectively.

Furthermore, in recent studies conducted by NASA and DLR, there are indications that the use of SAF can reduce contrail cloudiness (Voigt et al 2021), mainly because SAF contains fewer aromatics, which leads to less soot particles from the combustion outlet. This is especially applicable for long haul flights, as they are for a longer time in the higher altitudes– i.e., in atmospheric conditions where the probability of cloud formation is higher when carbon hydrate fuels like jet fuel are combusted, and therefore are responsible for most non-CO2-emissions in aviation (Eurocontrol, 2021).

An additional exciting perspective is that several of the well-known and upcoming SAFs seem to be able to be produced regionally. This can result in reduced fluctuations in supplies and prices and not least attract investment and job development.

Several more points about the positive impacts of SAF could be made, but in here lies a challenge in the definition of SAF, since no unified definition has been agreed upon. In the short history of SAF we have already seen a rapid development of criteria to be met for organizations to accept a product as SAF. Several certification schemes and regulations have risen to create standards and show the way to more environmentally friendly production methods.

This topic will be further developed in D2.2 (Guidance on sustainability criteria and best practice framework) and D3.3 (Broader environmental benefits).

The SAF market

To understand the SAF market a global list of SAF producers was initially and mainly created from public sources available. Producers, partners, location of production, starting year of production, pathways, feedstock, capacity, sustainability certifications, GHG reduction in percentage and price should be covered by the datasheet (Global SAF list: https://nisa.dk/sustainableaviation/saf/saf-producers). The Global SAF list presents the current and immediate producers on the market, where presently only very few producers are realistically capable of producing and delivering large batches or continuous production of SAF on a global scale, at least in a short time perspective, one to four years.

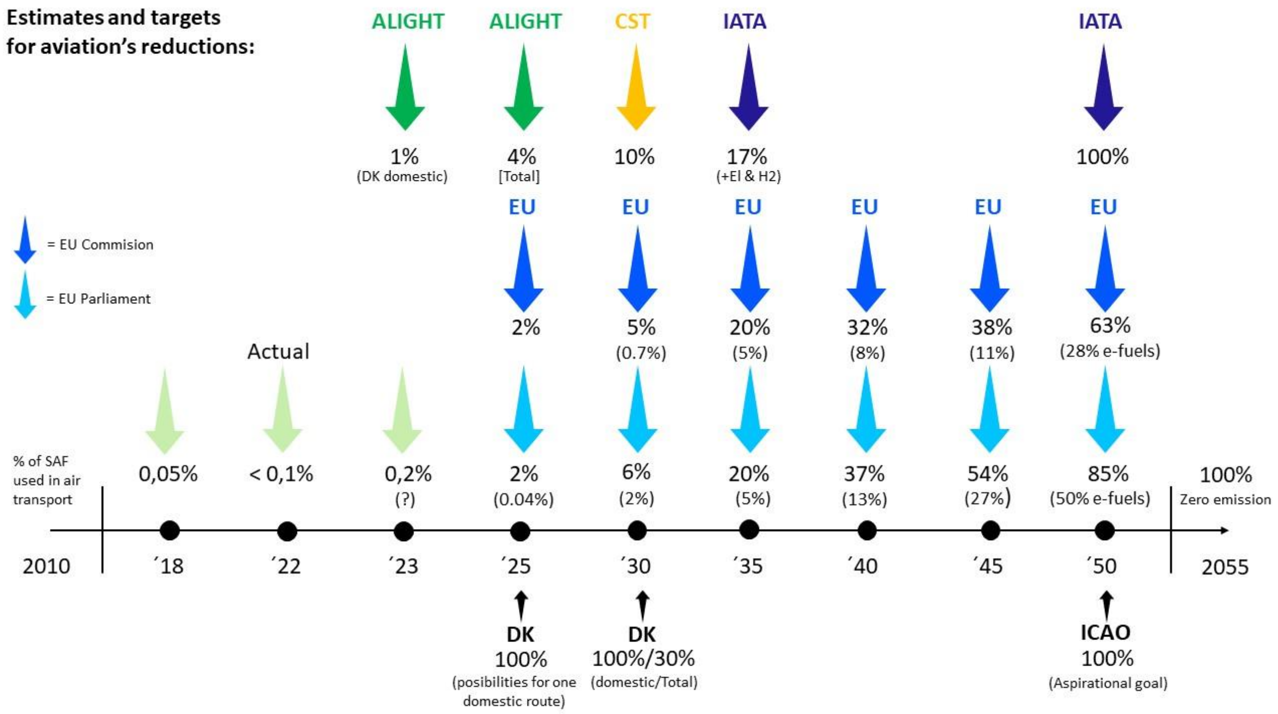
At the time of writing only two SAF producers can perform a continuous production, World Energy in California, and Neste in Finland. Both companies engaged with a HEFA pathway, based primarily on used cooking oil (UCO), other waste oils and fats. In the coming years few more producers are to scale up with similar and other organic materials as their primary feedstock, making biofuels the most immediate available SAF both technological and commercial.

Through the preparation of the Global SAF list, it became apparent that a lot of new producers announced that they will be on the market before quite long. Between 2022-2024 approximately 12-14 new producers plan to enter the market. Several of the potential upcoming producers have produced batches of SAF and made single or few deliveries trying to engage in the market. In Europe most clearly expressed through the refineries ENI, Repsol and Total.

Most producers, until 2024, will be HEFA dominated, as a result of the matured technology of biofuel production and, so far, the relatively easy access to feedstocks although limited. In the subsequent years it is expected to see an increase in other ASTM approved pathways, such as Alcohol to jet (AtJ), Fischer Tropsch on MSW, biomass to liquid (BtL) and Power to liquid (PtL).

Gaining a specific insight to the number of producers is rather difficult and scarcely public information at this time. To understand the development of the market post-2024, we must therefore investigate the technological development and expectation of market development from other perspectives.

Besides the Global SAF list, we have through media, scientific literature, network meetings, reports and dialogues with producers and developers gained an insight to the potentials and challenges of the various markets. This also includes the access to feedstock, renewable energy, technology solutions, socioeconomic analysis, conditions in value chains that must be met, and much more.
Well in line with the assumptions in the start-up of the ALIGHT project, we will in the medium and long term probably see a movement towards SAF produced based on MSW, ATJ and even more likely a SAF supply based on hydrogen and carbon capture technologies. (e-fuels/PtX or PtL) This will be presented in following sections.



The biofuel markets

The biofuel market is the most matured market regarding SAF, with HEFA being the dominant pathway. The maturity is enabled by other sectors like road transport having invested large sums in facilities that could produce biobased fuels to reduce the emissions within transportation. With operational experience and an established sector, some few producers are transitioning into SAF consequently expanding a market with high demand.

Although biofuels seem both mature and available, various studies points toward several difficulties of a continuous production and enabling larger parts of the transportation sector impossible to fully transition into zero emissions within these pathways.

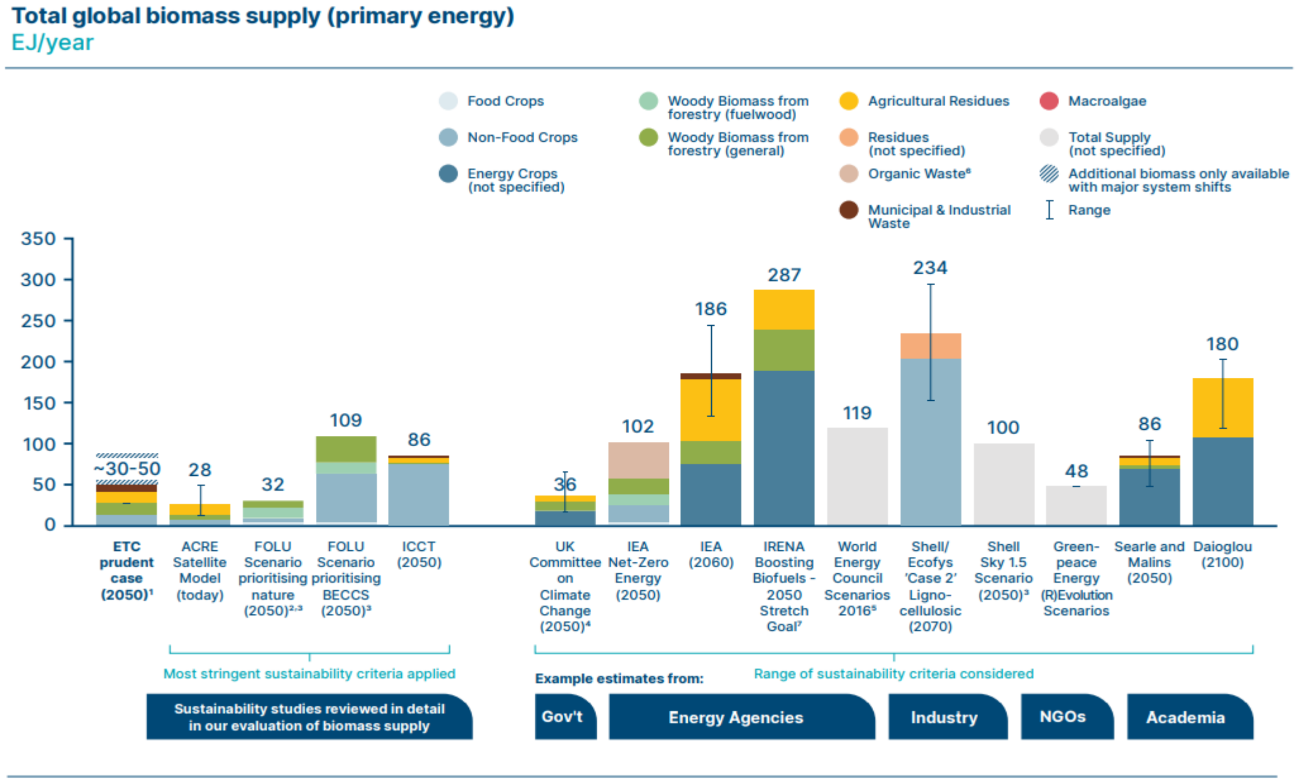
Developing the sustainable framework

First can be mentioned that the sustainability criteria have had a significant and important development in the past years. Leading airlines and their organizations have for some years made it clear that sustainability is a prerequisite for the introduction and use of new fuels. If this is not met, the media, the public and many customers will raise or increase the criticism of aviation as a climate burden. The perception of which feedstocks can be sustainable and under what circumstances, has taken huge leaps with organizations like RSB and ISCC, who through data collection and a continuous framework development has pushed the boundaries for sustainability. For instance, with UCO it's difficult to differentiate between the sources of oils included. Products like palm oil have several times been proven having a negative impact on the environment, due to cuts in rainforests, and therefore been excluded from being sustainable certified for the use in SAF. The question of the use of residuals has been part of this position.

The development of political pressure and regulations has also had a great impact. Going from first generation (1G) biofuels to what is commonly known as second generation (2G) biofuels or advanced biofuels (such as SAF that is produced based on sustainable biomass feedstocks, e.g., MSW, straw, or forestry residues), the criteria for what constitutes a sustainable feedstock has accordingly been developed.

Availability

As a part of the sustainability development, a parallel important discussion is the availability of renewable feedstock – especially biomass. Reports from various sources highlights different quantities available of sustainable biomass. Ranging from 32 EJ to 287 EJ, the span of estimates varies due to both different sustainability criteria as well as uncertainties and different assumptions of parameters and data.



Overview of different biomass availability estimates (ETC Bioreport 2021, P. 24) - Aviation is assumed to have a need for 25 EJ In 2050 (twice as much as 2019)

The demand for bio feedstock from several sectors is increasing and puts pressure on producers to procure raw material for the quantity needed. This risk driving prices up on for example UCO to the point where it has a higher worth than the factual price. Thus, increasing the risk of interfering with direct food supply, or perhaps palm oils, which is in violation of the sustainability criteria. In other cases, it could lead to price gouging and directly affect biofuel and SAF prices.

Analysts and public information, as well as information from few producers, points towards between 2-5 times the price of conventional fossil fuels. It is very difficult to create a concrete overview of prices. With today's limited supply, the price is pushed up, existing and future producers have to struggle for access to the raw materials, which in turn also will affect the price in an upward direction. Energy for the production processes fluctuates but will probably be upward for a long period of time as access to renewable energy is an increasing requirement. This also affects the price of hydrogen, which is an important component in all SAF production processes and to largest extent to produce PtX based SAF.

Key points:

- Most mature SAF products
- Limits to sustainable feedstock.
- Increased competition for limited resources.

Municipal solid waste, Alcohol, and syngas

Although this category to some extend overlaps with the two others (biofuel and PtX), certain technological and feedstock characteristic must be seen as a separate development on the market.

Waste as a resource

Municipal solid waste has for a long time posed environmental and resource challenges. In many countries depositing waste in landfills, is still the main practice. Another way of waste management is waste incineration to support the community with heating and energy. Such solutions can solve landfill problems but could also cause large amounts of GHG into the atmosphere. New technologies are currently being deployed on the market to mitigate this effect via filtering and carbon capture.

As of today, waste is an abundant resource with a continuous production rate and low utilization rate. Although concepts like circular economy, simplified products and waste incineration technologies will mitigate the amount of waste we cannot environmentally handle, MSW is still a large sustainability issue.

Waste have also proved to be a valuable resource in the fuel production sector. By admitting waste to high temperatures (pyrolysis), followed by a gasification process and turns the feedstock into a syngas, which can then be converted to hydrocarbon through FT-synthesis.

On the market, few SAF producers are engaged with ATJ as a pathway and MSW as feedstock. At the time of writing seven companies has announced their ambitions to enter the market between 2021-2026, of which 2 have produced small SAF batches already, Lanzatech and Velocys.

At this point there is little evidence that MSW, ATJ and syngas will be available for large scale in the immediate future. However, this category carries great potential to scale up and become a viable supplement to biofuels for the aviation industry to reach its climate goals.

The price range is estimated to be 3-5 times higher than conventional jetfuel. Other technologies also have plans for the utilization of waste resources, based on liquefaction- and/or catalytic methods and technologies.

Key points:

- Good synergy with other sectors
- Large potential for feedstock supply
- Will be available on the market within few years
- In competition with many waste sorting- and recycling technologies and expansions

PtX

Power to X (PtX) is in the early stages of development and market availability. PtX is a conceptual process where renewable electricity and a broad variety of chemicals are turned into products. The underlying importance with this concept is the potential in using electricity of renewable origin to produce hydrogen and provide carbon, to substitute fossil-based production. In huge dimensions this can potentially lead to unlimited and clean feedstocks for fuel production, in a short term limited only by the availability of renewable electricity and CO2 capture technologies.

Although the basic concept of PtX has both been theoretically and practically proven, no industrial scale facility has yet been constructed. Nevertheless, a small-scale plant has been built in Germany and on November 4, 2021, the Swiss NGO Atmosfair inaugurated the world's first production plant for manufacturing synthetic fuel for aircraft (power-to-liquid = PtL) from water, CO_2, and renewable electricity in Werlte/Emsland in northern Germany. The e-fuel will be transported from Emsland to Hamburg, where it is processed into specification compliant Jet A1 kerosene. The first customer is the Lufthansa Group, which is thus buying completely CO_2-neutral kerosene based on electricity for the first time. Lufthansa Cargo and Kühne+Nagel have made a joint commitment to support the production plant in Werlte/Emsland in Germany by purchasing the equivalent of 20 tons or 25,000 liters annually.

Another small-scale project has been completed in the US, where the startup company Twelve in cooperation with Emerging fuels has produced a small amount of SAF delivered to the United States Airforce. At this point there is no further production of SAF planned at Twelve (Business wire 2021).

Lately over 220 PtX projects have either been completed or planned in Europe so far (Wulf et al. 2020), and it must be assumed that on a global level this figure is even higher. The application of PtX attends to many different industrial purposes, from chemical production to liquid fuels, with aviation having interest in the latter. The European Commission funded 56 projects on this topic within the Horizon 2020 Framework Program, and five of them dealt on aviation as final utilization of the produced fuel, i.e., KEROGREEN, ENABLEH2, EcoFuel, TAKE-OFF and 4airCRAFT (Marzi et al 2022). To narrow the definition of PtX to liquid fuels several terms have progressed on the market, though the two most dominant are Electro fuels (E-fuel) and Power-to-Liquid (PtL).

PtL is in high demand by land-, sea- and air transportation, due to its high GHG-emission reduction and potential high quantity output. For aviation, PtL can only utilize either an ATJ or FT pathway. The two former sectors are less restrictive on the production methods, which create a greater flexibility for suppliers to create PtL plants.

Maritime transportation is currently looking into the shift onto methanol and ammonia as a viable production pathway of fuel. Using methanol as an intermediate to produce synthetic kerosene could potentially also be a viable path in aviation but would need to be approved by either ASTM or DEF STAN. Steps towards investigation the potentials of methanol have been taken but cannot at this time be disclosed.

The potentials in PtL are high but challenged by many variables and complications. Thus, PtL as a viable means to produce SAF on commercial scale is expected to break through post 2030. In the following sections we will break down the vital parts of PtL development that will affect the market development.

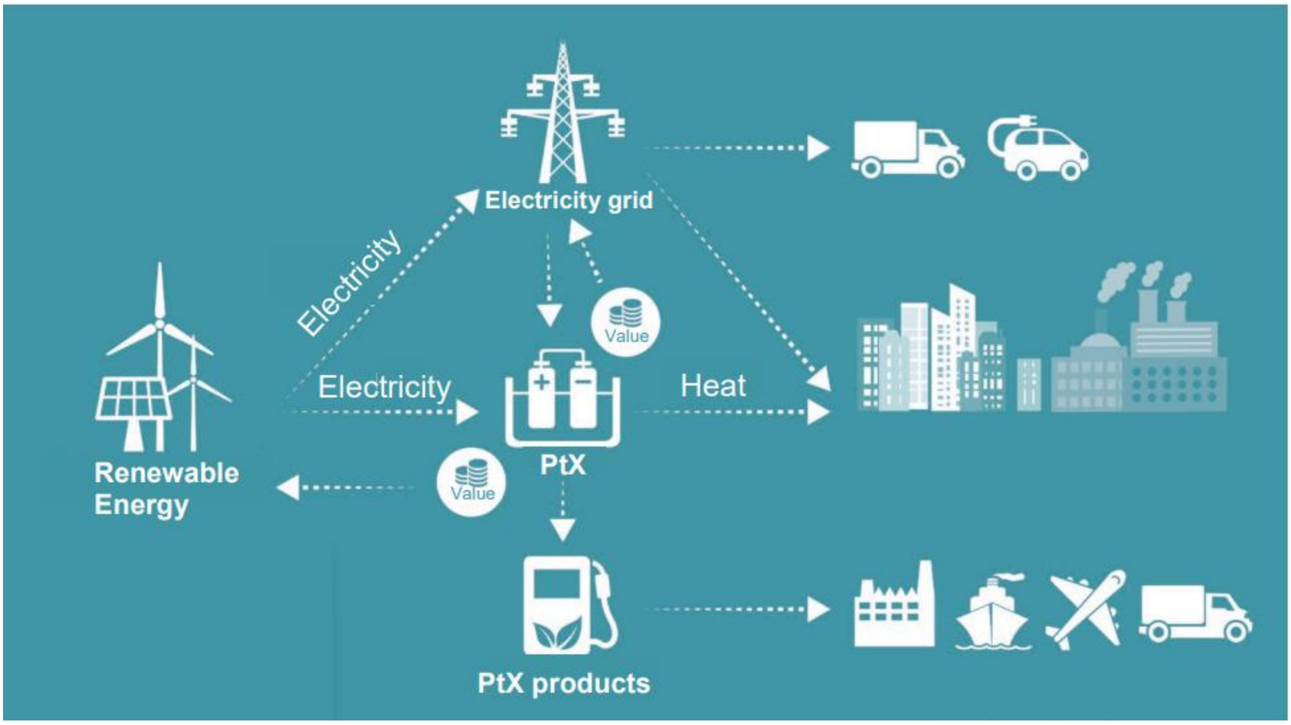


Figure: PtX can create value for electricity supply, the electricity grid, provide heat for district heating and produce sustainable fuels (Danish ministry of climate, energy and supply 2021, P. 39)

Renewable energy and electrolysis - Hydrogen

One of the general premises for PtX is the scaling of renewable electricity (RE). Although we still have a long way to go to replace fossil fuel energy with RE, major steps with wind-, solar-, geothermal- and hydropower technologies is pushing the RE agenda significantly. In 2020 the world record for RE-capacity was set with an addition of 260 GW (IRENA 2021). The continuation of this trend is essential to make a sustainable hydrogen product, which is a vital part of the sustainable hydrocarbon production.

Hydrogen serves two purposes. The first as being an energy storage enabler. By converting energy to hydrogen, it is possible to store energy much longer and potentially reverse the effect and utilize the hydrogen as an energy source. This however has been deemed as an ineffective process (Wulf et al 2020) and such leads us to the second purpose. Hydrogen is a vital component of a lot of products, and through electrolysis with renewable electricity and water as a feedstock, a sustainable source of hydrogen can be made - also called green hydrogen.

This current production of hydrogen can be acquired as either “grey” or “blue” hydrogen, which is both evaluated as a significant less sustainable source of hydrogen than green. In the development of PtL we must acknowledge, that there might be transitionary phases, where grey or blue hydrogen partly can be the only viable means of producing hydrocarbons. To what extend and how this affects sustainability criteria, certifications, GHG emissions will be investigated, developed, and further described.

Industry and Carbon capture - Carbon

The second vital part of hydrocarbons is the acquisition of sustainably supplied carbon. This can come from many sources, ranging from organic material, syngas, industries, and direct air capture (DAC). Biogenic CO2 can, for example, be obtained from biogas production or bioethanol production, and potentially also from (waste) wood combustion plants. To capture CO2 from the atmosphere, DAC plants can be used; this requires the use of electricity and heat from renewable sources.

DAC has in recent years been through intensive development, and in September 2021 the world’s first medium-scale DAC facility became operational in Iceland. The facility demonstrates the capacity and slowly maturing technology to CC directly from the atmosphere and either store or utilize the carbon. Through carbon capture utilization (CCU) PtL is the only technology that can reach 98%-100% GHG emission reduction (in some cases negative), or with carbon capture storage (CCS) can achieve negative emission effect. The technology is still maturing and currently cost around 1200 USD per tons of CO2 capture (Datacenter 2021).

Sustainability criteria and certifications are not yet developed, but both EU and international certification organizations working on the matter. NISA and ALIGHT WP2 closely follow the developments at the regulatory level in the EU, - and NISA participates in the RSB working group for the development of a PtX platform.

Key points:

- PtL is so far the only technology that could offer close to a 100% GHG emission reduction, if combined with green Hydrogen and CCU. If combined with CCS and renewable resource inputs, PtL can reach negative emissions.
- Synergizes well with several sectors within heating, transport, chemical- and industrial production, so called sector couplings.
- Technologies are still maturing, and only pilot scale production exist. Both Norwegian and Danish PtX producers are striving for a production start-up in 2024-25. A large number of analyzes point out that large scale production of PtL will not come until after 2030.
- Best overall economic picture is obtained by effective sector couplings and utilization of all synergy effects in connection with the entire production process.

New propulsions for future aircraft

The development of electric aircraft, hydrogen aircraft and hybrid are also on its way. Whether it is the direct use of electricity for aircraft or indirectly to produce hydrogen for aircraft, a considerable expansion of power production and power supply must be planned. Several versions of electric aircraft in a size up to 19 seats are estimated to enter the market within the next 4-5 years.

A critical element in that development is that new aircraft with propellants are not yet a part of the infrastructure at the airports. Therefore, one of the tasks in ALIGHT WP5 is named "Aircraft stand of the future". As a first initiative in this work WP2 and WP5 together with Danish Aviation and Naviair arranged the conference "Future aviation and air mobility", April 5th 2022 in Copenhagen. The conference intended to present and create a basis for the further work of planning infrastructure, increased power supply, charging facilities and arranging the stands of the future, which is led by ALIGHT WP5 Task5.

It will probably take some years before aircraft with these new fuels and propellants have a significant volume, but to keep up with this development, airports need to plan well in advance. Extensive infrastructural adjustments can take several years. EVTOL (Electric Vertical Take Off and Landing) is also included in this work. Furthermore, it has become part of the task to create a general overview of relevant developments, new initiatives and new opportunities within the sector that includes new propellants.

Deloitte has examined the decarbonization initiatives that exist for the aviation sector in a time perspective to 2050 (see table below). Factors complicating the adoption of new technologies could be named "infrastructure lock-in". Today's infrastructure is built around uplifting liquid fuel into an aircraft. Any other technology will be a challenge. The aviation sector cannot afford to wait if it wants to decarbonize and achieve climate neutral air transportation in time. It is necessary to increase the use of SAF and at the same time prepare for the slightly longer-term future by finding solutions for the integration of the newer technologies, Deloitte points out in the analysis.

Decarbonisation option	Description	Sector perspective on decarbonisation impact before 2050	Applicability	Sentiment (before 2050 perspective)
Efficiency gains	Design and operations improvements to reduce fuel burn	55% 35% 10%	All flights	Important option but **impact diminishing over time**
Sustainable Aviation Fuels (SAF)	Fuels from sustainable resources to substitute fossil-based kerosene	78% 20% 2%	All flights	**Main decarbonisation option** in the next 30 years; ability to **use with existing aircraft**
Offsets	Investment in out-of-sector emission reductions or removal	50% 29% 21%	All flights	Important to bridge the timing gap as other options are scaled up
Hydrogen	Combustion of (low-emission) hydrogen and/or conversion to electricity through fuel cell	14% 32% 55%	Short- / medium-haul	Requires cryogenic storage and new airframe designs. **Long time** to develop, ensure safety, certify and deploy at scale
Battery	Electric propulsion with zero emissions if charged with green electricity	12% 14% 73%	Short-haul	Because of battery weight and size, only applicable on **very short-haul routes**
Behavioural change	Reduction of demand resulting from remote working and modal shift	15% 25% 60%	All flights	**Any behavioural change** likely to be outpaced by **overall population and economic growth**

■ Major impact ■ Moderate impact ■ Limited impact

Sources: Deloitte analysis

(Shell 2021, P. 14)

4. Section 2: Decisions and circumstances surrounding the establishment of a production facility

In recent years a few new SAF producers have entered the market, primarily with HEFA solutions. The companies typically have a point of departure from the conventional fuel industry and is transitioning through available technologies. HEFA products currently available from 2-4 manufacturers globally and covers a wide range of feedstocks, where used cooking oils makes up by far the most. The products offer a 40-84% emission reduction (CST 2021, Atmosfair 2022) and is on the market with limited quantities.

While today almost all sustainable fuel used in aviation is from the HEFA pathway, there are other drop-in fuels under development, especially the so-called power-to-liquid (PtL) or electrofuels.

In this section, WP2 have chosen to focus on the production of SAF based on PtX, which with the lighthouse concept is expected to be established in the regional vicinity of CPH, and as well as the following: 1. Can be expected to have a decisive impact on future sustainable aviation, 2. expected categorized as the most sustainable kerosene product, 3. Creating the least problematic long-term access to feedstocks, 4. No other types of SAF with a significant volume, are considered to be established in the regional vicinity of CPH, 5. Is in sync with the EU RefuelEurope Aviation long-term goals of an increasing share of PtL.

With reference to 3 or 4 forerunners in the Nordics, the new technologies, such as PtX (preferable as PtL - in this section also named as e-fuels), are arriving the market within a few years, and enables the highest reduction in emissions, with potentially in the long run huge and increased quantities of supply. This is highly desirable for aviation and will significantly support the international goal of achieving net zero in 2050 (IATA 2022). Therefore, this section will focus on the establishment of PtL facilities, as these are pivotal in the transition of sustainable aviation fuel.

PtL faces large challenges, and there is a huge need for investigating what possibilities and challenges connected to the development. This is happening on a large scale among the development companies involved, authorities, energy suppliers and researchers. Through NISA, WP2 has become involved in this with several activities. Mention may be made of participation in the Danish Innovation Fund's grant to investigate whether methanol can be converted into jet fuel, participation in the advisory board in the EU-supported project Take-off, and active participation in the recommendation report "PtX aviation fuels for green conversion of aviation" initiated by Green Power Denmark with support from a number of actors involved in the entire value chain for sustainable aviation.

Introduction to cases:

In the following section we will present five PtL producers which will serve as case examples to demonstrate the variations in E-fuels production.

The first case is Green Fuels for Denmark (GFDK). The project is established as a consortium of partners ranging from technology providers from front-end to back-end solutions and to potential buyers of the final products.

Green Fuels for Denmark are planning a large-scale production of sustainable fuels for a big part of the transport sectors. The ambition is a CO_2-reduction of 850,000 tons by 2030. The project is led by a partnership of Orsted, SAS, Copenhagen Airports, Maersk, DFDS and DSV. NEL, Topsoe and Everfuel are partners and COWI are knowledge partner. Also, the project is supported by Molslinjen, the City of Copenhagen and the Capital Region of Denmark. The plan is a 1,300 MW plant in 2030 that will be able to supply green fuels, primarily jet fuel, that can substitute approximately 30% of the total jet fuel consumption at Copenhagen Airport i.e., for both domestic and international flights. GFDK has an ambition to produce the first smaller amount of SAF in 2025.

With the direct involvement of aviation, this setup is supposed to lead to the best possible conditions for future access to SAF. We will have the primary focus on how the preparations, decisions, assumptions, and developments in the GFDK project progress. This applies to the entire supply chain, energy supply, hydrogen production, and how the important synergy effects and sector couplings are developed in collaboration with other stakeholders. All this also incorporates SAF production as an integral part of national energy policy.

GFDK will build and operate a large-scale PtX plant with the primary purpose of producing e-fuels for a wide range of actors from aviation, maritime and heavy land transport.
A crucial aspect of GFDK is the project's focus on the production of methanol as a fuel. This can be used in several places in heavy transport and for other purposes, but it is not approved as one of the possible pathways for production of jet fuel. Whether it can be converted to kerosene in the long term will be investigated in a two-and-a-half-year subproject led by Topsoe, which must build up all the technical facilities that are a prerequisite for being able to assess it sufficiently. NISA, and therefor also ALIGHT WP2, and CPH are involved in this

GFDK "subproject", which is planned for completion ultimo 2024. The goal for the methanol-to jet project is to investigate whether methanol can achieve ASTM approval as a valid new pathway for aviation jetfuel.

The second case is Nordic Electrofuel based in Norway. They plan to start production at the end of 2024 at the chemical- and fuel production area at Herøya, Porsgrunn in Norway. NISA and ALIGHT have been in contact with the company for months and followed the preparation processes closely. Nordic Electrofuel production plant will include all the production value chain except for the back-end. The plan is that the final production step (the final refining process) will take place at a refinery in Germany.

The third case is Arcadia Efuels. The company has announced that they will build a PtL facility in Vordingborg, Denmark. They will begin production will be in 2024. Arcadia will construct and own the entire production value chain of E-fuel and at this point, Arcadia differs from Nordic Electrofuel, otherwise the technology and processes are relatively identical. The facility will produce hydrogen from an electrolyzer supplied by RE from domestic sources. Carbon is sources either from biogenic carbon capture technology or direct air capture, or a combination of the two sources.

The feedstocks are then put through an electrified reverse water gas shift (RWGS) to create the feedstock for their low temperature FT-process. Finally, the product is hydroprocessed into E-fuel and E-diesel, or a combination of both.

The fourth case Fairfuel is a non-profit daughter company of Germany based Atmosfair. They have proclaimed to be ready to start the first production in mid-2022 producing PtL SAF through a FT pathway. This is a small plant that will serve as a demo- and inspiration facility for the construction of full-scale plants. The process starts with a hydrogen production through a PEM-electrolyzer supplied by RE. 2,3% of the carbon is supplied by DAC and the rest by biogas. The hydrogen and carbon are then processed through a FT facility and subsequently produced into kerosene at a refinery in Germany.

The fifth case Norsk E-fuels is a consortium consisting of Sunfire, Climeworks, Valinor and Paul Worth. The company represents a broad set of competences from RE, technology providers, construction experts and finance.
The electrolyzer consist of primary alkaline with a combination of SOEC, supplied by RE. The carbon is supplied from DAC and point source from waste gas processes. From there the feedstock is processed through RWSG, FT and a refinery to the final product. Noticeably the facility contains an integrated heat recovery system, utilizing produced heat to reduce energy input. The facility is expected to be operating in 2026.

Technological:
The maturity level of technology is often described by the technological readiness level (TRL). The underlying scale, range from 1 (basic principles observed) to 9 (actual system proven in

operational environment). Several SAF production technologies are already commercially available, with HEFA reaching TRL 8-9.

Other technologies like PtL can generally be found at TRL 3-5. However, this TRL rather describes the entire fuel production pathway, which is sometimes also described by the so-called Fuel Readiness Leve (FRL). Various components of the PtL route already have a significantly higher TRL than 3-5 (e.g., water electrolysis). A technically challenging component of the PtL route is the large-scale implementation of the reverse water gas shift (RWGS) reaction. This means that the technology has moved from an experimental phase and is entering the development phase and therefore a viable option to deploy commercially once fully developed.

The development of said technology is not so straight forward. PtL consist of several technologies that individually has been proven and is commercially driven as hydrogen production, clean energy, or point source capture etc. The challenge for the PtL production is combining these into one value chain and streamline the production process to achieve efficiency throughout and reduce production costs and subsequently scale-up the technology on a system level.

Companies such as Nordic Electrofuel currently do not have the capacity to engage with the entire value chain on their own. Although they provide a business model for the E-fuel product, the front-end production processes are planned taking place in Norway with the production of a synthetic crude, and after that transport it to Germany for the back-end production and final distribution of E-fuel.
As well Arcadia, Norsk E-fuels and GFDK have planned to include front – and back end into their production facilities.

A number of additional and extremely crucial factors that will determine market opportunities and pricing are the extent to which a PtL plant can enter into synergy with the need for other energy developments. Sector coupling is part of this. The greater financial interaction that can be established on the input side with the capture and use of carbonaceous exhaust gases, utilization of renewable energy at the right times, including the possibility of storage and other sectors' need for hydrogen will be crucial. The same on the process side where, for example, methane gas can be utilized in the district heating system, which can also be an option with support of power production and surplus heat from parts of the production processes.

Opportunities for sector couplings for heat production are of course most obvious where there is a need for district heating and where interconnections are otherwise possible.

When we initially mentioned that the production of SAF is also part of the countries' energy policy, this is probably best expressed in the challenges of ensuring access to renewable energy to the necessary extent. PtL produced SAF in countries with a large share of renewable energy will be in an advantageous position in terms of achieving the largest share of sustainability in energy input. At present, very few countries are close to 100% renewable electricity generation. In Denmark, the political goal is to achieve it by 2030 at the latest. As with many other large projects, SAF produced from PtL, like many other sustainable products, must be calculated, decided, and assessed as being sufficiently effective in their contributions to the climate goals and at the same time be the socially and economically correct decisions.

The issue of storage of captured carbon is also an element that will play a role in the development of plants that must utilize the carbon. The degree of sustainability of PtX-made SAF may depend on this. While there is great political attention around storage, one can very easily sense the contours of the conflicts in the political interests of the two directions. Immediately, storage will contribute the most to CO_2 reduction, and at the same time, the use of the captured CO_2 is a prerequisite for aviation to achieve its ambitions for climate-neutral fuel.

Frontend: Hydrogen and CO2

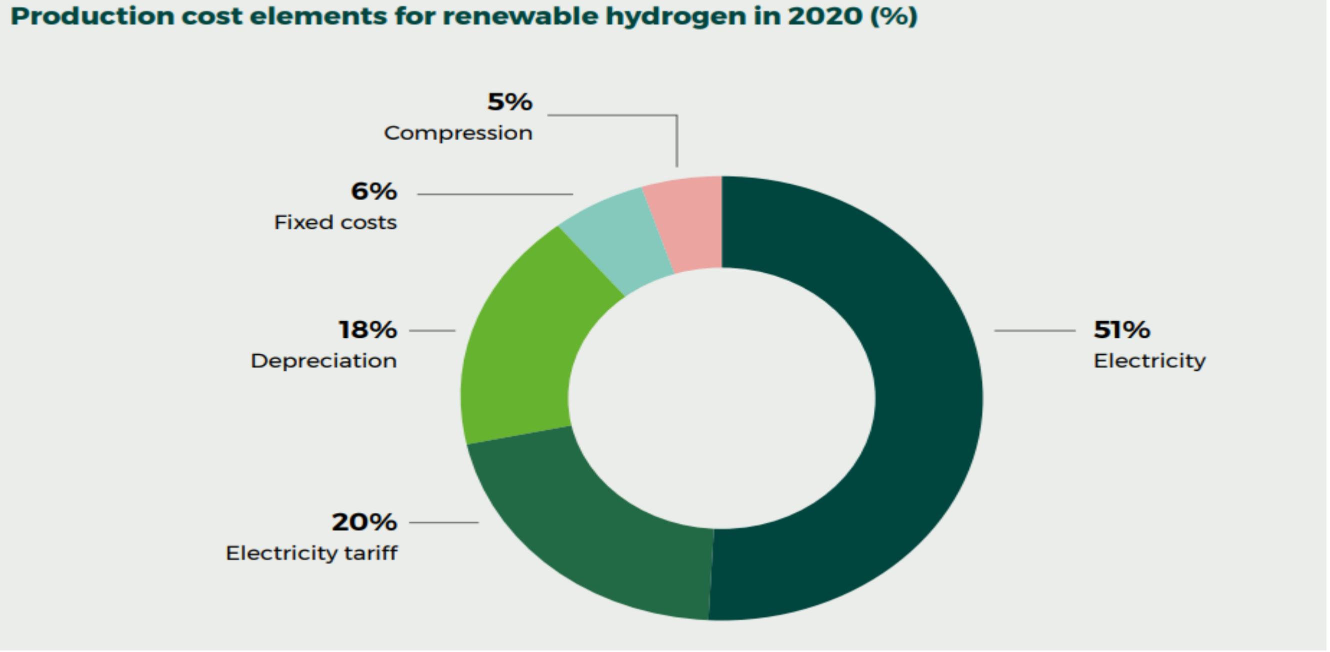
The front-end of PtL consists of hydrogen production and long-term access to carbon in the form of CO and/or CO_2. This creates the foundation for further production, since PtX offers a wide variety of products depending on possibilities of application and consumer demand.

On the current market three type of electrolyzer exists: Alkaline (AEL), Proton exchange membrane (PEM) and Solid oxide electrolyzer cell (SOEC). Each of the technologies provide different benefits and challenges, for example is Alkaline the cheapest but less efficient than the other two (Jensen et al 2020). PEM is currently the most popular technology but contains iridium which can become a bottleneck when the industry scales up. The selection of electrolyzers are often an assessment of the economic impact and efficiency of the given product.

In GFDK Topsoe is a key player in the project, that together with other participants in the project represent market leading providers of the electrolyzer technology. They aim to enable the project to push cost of Hydrogen production down to a competitive level. Through applying and continuous developing the SOEC-technology, GFDK have the potential of significantly reducing the production cost of Hydrogen, which is of the highest production costs in the value chain, mainly because of the volume of renewable energy.

Arcadia purchases their electrolyzer from an external company and expect a mix between alkaline and PEM to the first production facility.

Producing hydrogen requires large portions of power which must be made from RE as a precondition for the fuel to be sustainable. RE is also the largest cost of running an electrolyzer as seen below.



(Danish energy 2020, P.11)

All the cases have a direct engagement with purchasing RE due to their geographically positioning in the Nordic countries. Denmark and Norway have in the past decade invested heavily into RE, which the PtX developments can greatly benefit from.

The choice of carbon depends on the availability and price for the different point sources from heavy industries biogenic plants or DAC. All the mentioned cases use point sourcing as their primary carbon access.

Carbon is typically captured from other industries, making the feedstock depending on other businesses to continue their activities and provide CO2 at affordable prices. In this context, having access to a mix of sources can be crucial, as the availability of a single source cannot be predicted. At the same time, it must be noted that certain point sources may be questionable either for reasons of sustainability or because they are expected to perform significant emission reductions and therefore less interesting for investments in DAC equipment.

Due to the geopolitical situation in Europe, a political ambition of independence from Russian gas has led to the potential of a significant increase of biogas in Denmark and other countries. This provides a benefit of producing carbon from Biogenic sources, although numbers of availability, timeframes and price remains scarce and is therefore difficult to predict a realistic impact (biogas 2022).

Although DAC is technological available, the prices are currently too high. Long term DAC can scale up and become affordable to integrate into a PtX supply chain but is in large volumes estimated not to become viable before post-2030. In our cases only very little DAC volumes is planned and only in minor scale, due to the current prices and availability.

The Danish Energy Agency has calculated the production cost of PtX and compared with the price of fossil fuel and SAF from 2G biofuel/advanced biofuels.

Seen In a development perspective after the current decade, the price is expected to be about the double of fossil fuel, even without an expected increasing price of fossil fuel considered, and lower than 2G biofuels.

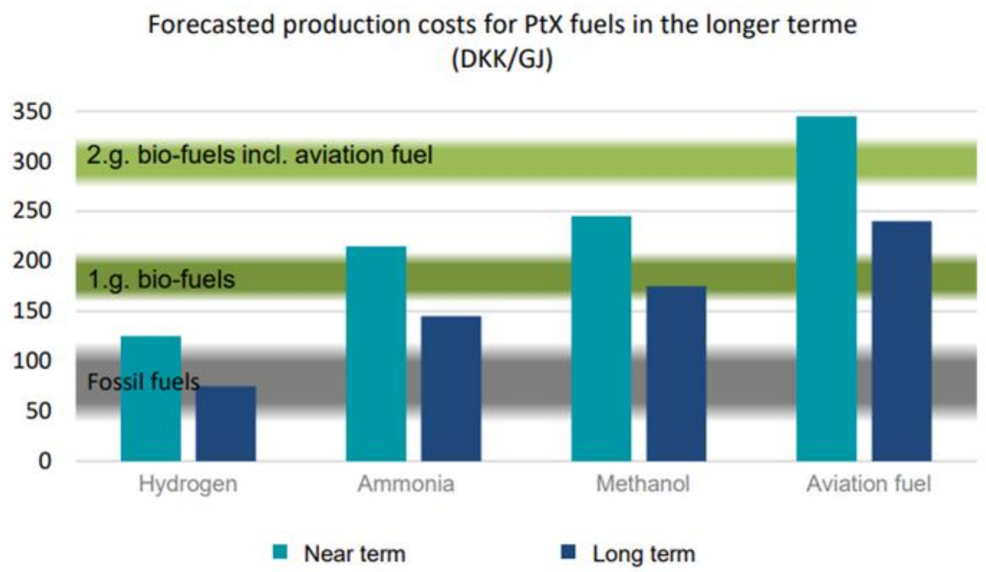


Figure 8. Forecasted production costs over this decade (near term) and the long term following upscaling of production, technology development, improved framework conditions and implementation of supporting infrastructure for each of the four PtX fuels. Ranges for market prices of fossil fuels and biofuels are also shown, where ILUC effects are not factored in.
Source: The Danish Energy Agency

(Note: 1 Danish krone equals 0,13 Euro. Danish Ministry of climate, energy and supply 2021, p. 31)

Back end: From gasses to fuel

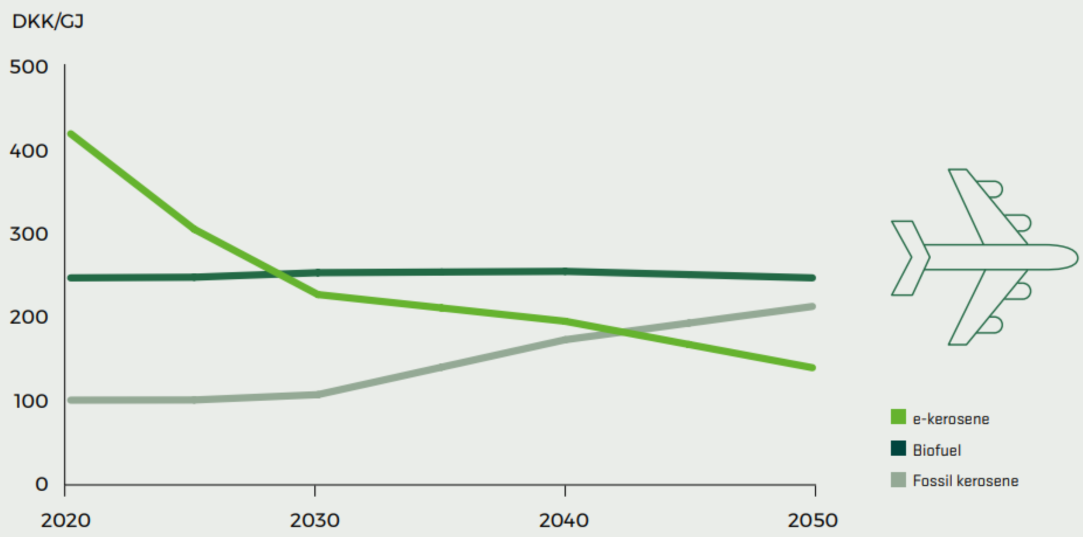
The back-end of PtL processes are the part of the value chain that determines what type of product comes out of production. In relation to aviation very few options are available. Fischer-Tropscsh and ATJ are the two only approved ASTM-methods that works in a PtL con-texts. This presents a challenge since both are difficult to implement as a flexible or cost-effi-cient method to the PtL value chain.

GFDK is researching and developing a methanol-to-jet pathway to produce aviation fuel. Methanol is a versatile product that can be transformed into the transport sector except for aviation, and a variety of other products. The cost of methanol production from hydrogen and carbon is relatively cheap in comparison with other feedstock and therefore gives the investors incentive to engage because of the broad application.

Methanol is currently not ASTM approved as an alternative source of aviation fuel. This presents one of the largest challenges of the methanol-to-jet project. An ASTM approval takes significant amount of both investments, tests, and involvement of a wide range of participants. The undertaking is also time consuming and can take years to be completed and finally approved. The process can eventually be somewhat accelerated by engaging the process with a European Clearing House, that coordinates and execute the many processes involved with approval. EU currently has no Clearing House, but EASA has presented a framework that could be beneficial for such a collaboration (EASA 2019). At this point GFDK has not engaged directly with a clearing house. An issue that NISA and ALIGHT WP2 will try to pursue and also bringing the proposal to an international level so that the greatest possible interest in this development is ensured.

Arcadia, Atmosfair, Norsk eFuels and Nordic electrofuel are all planning to produce E-fuel in accordance with the ASTM approved FT pathway. FT has been used for decades and is still being used to process fossil crude oil and coal. Natural gas is also converted into road and marine fuel at FT plants in Qatar and Malaysia. Shell is a partner in both plants. With a large knowledge and experiences related to the FT technologies, this technology choice would bring a direct production value chain to aviation and ensure the necessary framework for SAF production

Expected price trends for various types of aviation fuel



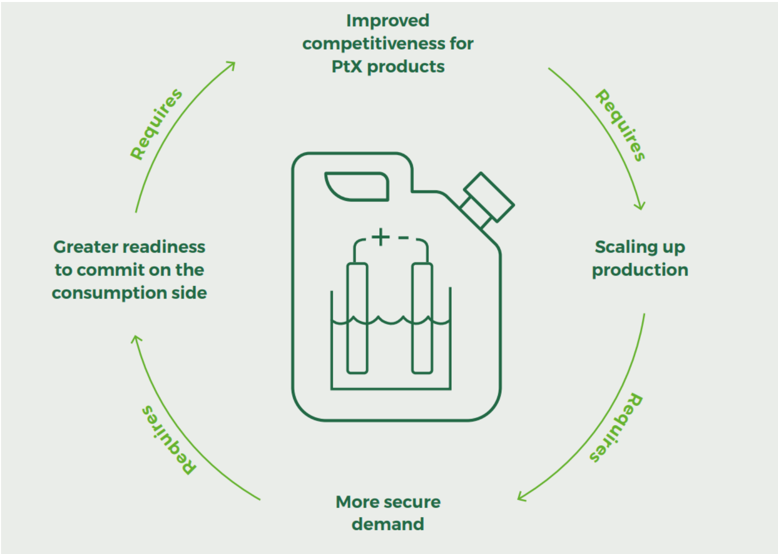
NOTE: There are major uncertainties associated with the price of e-kerosene. This analysis shows a high and low estimate for the e-kerosene price. Carbon emission allowances are expected to increase the price of fossil kerosene after 2030.

SOURCE: Hydrogen Council, Danish Energy, Bain & Company analysis.

(Note: 1 Danish krone equals 0,13 Euro. Danish energy 2020, P. 61.)

Business:

The preference of fossil fuel as a primary resource in the fuel industry, has developed an incredible efficiency and reduced cost to an absolute minimum. Entry on the market with new technologies and value chains contain large risks that must be addressed to ensure a stable financial progression. With PtL not being available in commercial scale so far, many project



are under way. Up until 2020 approximately 220 PtX demonstration plants in Europe have been created, with the majority having a strong focus on the front end. Only 22% of the 220 projects includes a back-end processing part with methanation and 6% with methanol (Wulf et al 2020).

The success of establishing demonstration plants and providing data on hydrogen and CO2 production has led the technology into the developing phase, where a network of investors and technology providers needs to push PtL into a commercial/industrialized state.

This phase creates what Danish energy calls the PtX paradox. "*PtX products will only become competitive when production is sufficiently industrialized and scaled up. Production will only begin to be industrialized and scaled up once there is a guaranteed demand – i.e., when consumers demand or commit to purchasing the products. We call this the PtX paradox.*" (Danish Energy 2020, P26. Figure: P.27).

Since PtX/PtL is in an uncertain startup phase competing with other production pathways, the new investments are inherently risky. For PtL to become competitive, or commercial attractive for the aviation sector, it needs to industrialize and utilize economies of scale to be a long-term SAF solution.

In today's projects that aim to scale up and create a business model around it, we typically see a collaboration of actors engaging in strategic partnerships. Norske E-fuel consist of Sunfire (technology provider, electrolyzer), Climeworks (CO2 capture technology provider), Paul Wurth (Plant builder), Valinor (investment company) and Lux-airport (support, aviation). A similar collaboration can be found in GFDK with Topsoe (technology provider, electrolyzer), Orsted (RE provider), SAS (buyer, aviation), Copenhagen Airport (support, aviation), Maersk (buyer, maritime), DFDS (buyer, maritime) and DSV (buyer, land heavy transport).

These two projects demonstrate a strong network on front end and potential buyers/off take is represented directly in the project. This constellation ensures a functional production of the core components in PtL, though the lack of specialized back-end competences is often not as integrated. This poses a challenge because of the few pathways approved to produce E-fuels from PtL. This must be seen in the light that other industries demand for PtX might be cheaper to produce and more flexible to purchase products from.

Arcadia, Fairfuel and Nordic electrofuel has specialized their PtL production towards aviation and integrated FT into the production facility. Although this reduces the flexibility to offset a wide variety of products, the specialization gives investors and collaboration partners a clear road map with the entire value chain accounted for. Aviation is going to be reliant on kerosene products to reduce its emission in both near- and long-term future, and therefore guarantees an existing market for future products (with reference to ReFuelEU Aviation, CST, EASA, IATA). The companies demonstrate that through the available technologies E-fuels can be engaged without a large network of technology providers. For example, Arcadia have made an agreement with Shell to purchase the total quantity of produced SAF.

An interesting perspective to the investment of PtL is also the potential of hydrogen airplanes in the future. As both production and infrastructure scale up, the logistics will enable hydrogen airplanes to easier gain access to the aviation industry than if the industry would solely develop this on their own. Hydrogen airplanes are expected to enter the market no before 2030 (CST 2020, Airbus 2021).

The cost of the finished E-fuel product is a central challenge to engage in the competitive SAF market. Development and scaling of PtL is still an ongoing task to reduce cost and benefit from both technological learning and economies of scale. Current prices on E-fuels are not available, but indications from several reports estimates from 2-6x the price on conventional fossil fuel (CST 2020, Mortensen et. Al 2019, Agergaard et al 2021, Wolcott et al 2021). The span is affected by a variety of circumstances from capital venture to fluctuating cost of energy (for example with the current conflict in Ukraine leading to rising energy prices), and the extent of synergies, sector couplings etc. that can be established in connection with the facilities
As pointed out several times the reduction of operational cost is pivotal to become competitive. Beyond efficiency the industry looks to political frameworks to help push the agenda, which will be described in the following section.

Political:
The industrial development of E-fuels is vital to achieve the political ambition of combating climate change. Political landscapes from global to local is working to enable competitive frameworks to help push industries, with varies tools from tariffs, taxes, regulations, promotions etc.

ICAO recently launched CORSIA. It is an offset scheme which will become mandatory for all ICAO's members in 2027. CORSIA is manly focused on a polluter pays principle so the offset will compensate for each airline's emissions. Airlines can reduce the need to off-set their emissions by purchasing SAF. The incentive is to increase the demand for sustainable solutions, dominated by SAF. The program is under development and will first become mandatory from 2027, giving the industry time to transition partly into SAF.

In Europe regulations such as the proposal package Fit for 55 is centered around creating a fair market with forced developments. For example, the ReFuelEurope Aviation suggests a blending mandate, with an increase of synthetic fuels from 2025 to 2050. This regulation will ensure generating a market to de-risk investments into PtL.

Other proposals within Fit for 55 is tightening the provisions of the EU Emissions Trading Scheme (EU ETS) for intra-European flights and the introduction of tax on fossil kerosene based on the energy content introduced linearly in a transition period of 10 years from 2023, corresponding to the minimum tax rates for road transport fuels. With an increasing economic pressure on fossil fuels, PtL can in the long term become a financially viable alternative. This could decrease risk of investment in PtL technologies, due to long-term economic benefits and market security.

In the Danish prime minister's new year speech 2022 an ambition to provide CO_2-neutral flights on one domestic destination in 2025 and the whole domestic in 2030 was presented. The political ambition sparked intensive debate on what type of SAF should be used or other technical solution would be preferred to achieve the ambitious goal. As a direct consequence of this GFDK proceeded to move their timeline to deliver the first SAF products from 2027 to 2025 (Ørsted 2022). The PtX solution was directly mentioned in the speech and have had an increased attention.

Merely a month after the speech the Danish government presented a public tender on 1,25 billion DKKR (approx. 170 million euro) to produce sustainable fuels for transportation on land, sea, and air (Energy supply 2022). The primary focus of the tender is increasing the capacity for electrolyzers, which is a core component of PtX. This pushes the agenda for PtX even further than previously and is in line with the Danish PtX-strategy launched in (Danish ministry of climate, energy, and supply 2021).

The political ambition, public tender and industrial development is in line with the EU ambition set in the proposal Fit-for-55. Denmark and other Nordic countries have a unique positioning in developing synthetic fuels with previously heavy investments into renewable energy and actions like this can help push the boundaries and cost efficiency for synthetic fuels.

PtX is depended on significant increase of RE in the coming years, thus the continuous work with upscaling RE is pivotal to the success of E-fuels. Political processes of establishing RE is resource- and time consuming to meet both demand of the average household and industry alike. If political and administrative improvements are not made to this process, the availability of RE risk a bottleneck to meet the high demand.

As demonstrated above the connection between the political landscape and industrial development closely affects one another. With political priority and attention, the reassurance for

fuel producers and their investors is pivotal for the ambitious engagement with synthetic fuel.
There is a strong connection between different sectors, and all must work together to achieve the ambition of PtX as a large-scale industry. Although numerous processes are already taking place, the need to fast track processes are present and can have a direct impact on the scaling opportunities.

The many proposals, decisions and initiatives play a major role in ALIGHT WP2's work with SAF solutions, on which recommendations are to be submitted in the project process and so on. In ongoing reports and deliverables, the development processes will be updated.

Societal

With PtX on the rise as a promising technology, there is a great need for a societal commitment and prioritization for all the new challenges, but also opportunities. Amongst a few can be mentioned upgrading the electric grid to safely handle and transport the planned RE, increasing storage and transportation for hydrogen, working cross-sector to optimize utilization of products and biproducts (such as heat) and in general create a broad industrial cooperation.

It is clearer than ever before that aviation cannot be seen as a sector that has to find its own solutions. Aviation is highly dependent on a strong cooperation with other sectors to engage not only in the direct development of SAF, but also in the circumstances enabling large scale production.

With the recent policy proposals and increased focus on the sustainable transition, aviation is an integral part of societal development. It is therefore crucial that aviation is involved in broad networks to engage with progression in a mutual beneficial cooperation. The perspectives in a societal investment in PtX also provide good opportunities for gaining experience and knowledge that can be transferred to other areas, other sectors and other countries.

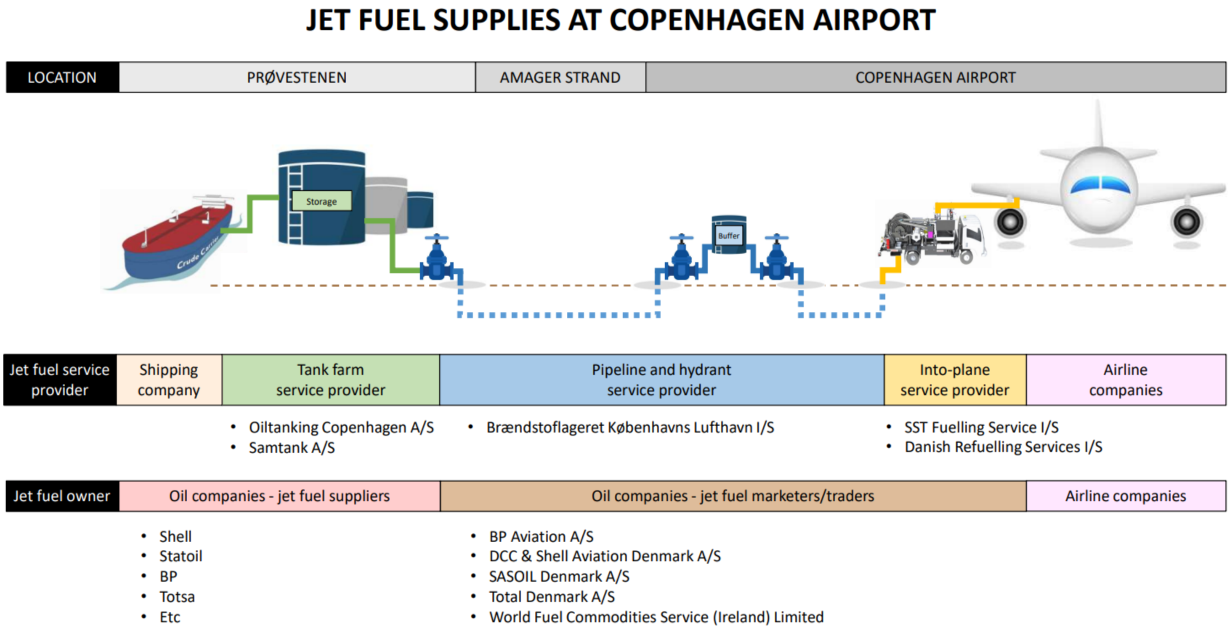
With this, it is an obvious task for WP2 to follow the development and to go much deeper into the real future possibilities for PtX-based SAF to be developed, produced and delivered to Copenhagen Airport and others. The technology and the many complex elements it consists of are in a vigorous development, actors who are to build the facilities are ready, the political support is present to an extent that has not been present before, - and the end-users, airlines and airports have long supported the development of PtX solutions and will increasingly do so in the future. In the present ALIGHT project, WP2 will closely follow and describe the decision-making processes and the circumstances it entails to establish the facilities and start production of PtX based SAF.

5. Section 2: Logistics

This section is about the logistics of providing fuel to Copenhagen Airport. Subsequent three delivery methods will be presented and shortly discussed.

Copenhagen:

The picture below is a visualization of the fuel delivery process from the fuel arriving at storage facility "Prøvestenen" all the way through pipelines to the airport and to the aircraft via the hydrant system at Copenhagen Airport.



Source: BKL

Copenhagen Airport is supplied with jetfuel A-1 through BKL I/S as the fuel operator and storage handler.

The jet fuel is first delivered at Prøvestenen, 6,8 km. from Copenhagen Airport. It arrives by seaside at the storage facility, in large tankers that can carry large quantity.

After arrival at Prøvestenen, a vigorous testing paradigm is carried out by an external authorized company (an independent surveyor). The testing is to ensure the high quality of hydrocarbons is identical with the ASTM regulations. In the case a ship has several separated storage tanks on board, each of the compartments must be approved by-the surveyor before being offloaded.

From the jetty the jet fuel goes through one of two single and product dedicated pipelines entering the storage facility and distributed to various storage tanks.

From the storage facility the jet fuel is pumped through a large pipeline to the airport. At the airport it goes through a filtering and quality check process to ensure there is no water or dirt in the fuel and that the quality of the fuel is in accordance with the specifications. Then it is stored in one of four tanks inside the airport, from where it is distributed through the hydrant piping system to the individual aircraft stands and airplanes.

The entire process of storage handling and delivery upstream of Airport is compliant with the EI/JIG 1530 standard, which sets the standard for managing fuel (JIG/Energy Institute 2019, 2nd. Edition). In the airport there is no difference in handling SAF vs. conventional fuels, as the relevant operating standard covers both fuel types.

ALIGHT WP3 plans to perform tests of the airport's air quality on the ground using SAF. This will involve a direct filling of the aircraft on which the exhaust is to be measured. Work is being done to plan which measurements and tests are to be performed and what this will entail. Separate tank-vehicle capacity for transport and storage is investigated. Similarly, action procedures, safety and quality controls and procedures must be organized and described. The established working group under WP3 is currently discussing with SAS to make aircraft and crew available for the performance of measurements and tests. The scope and how SAF deliveries from the selected manufacturer and supplier are to be organized are also discussed.

Alternative logistics:

Mass balance

As described in chapter 3, the preferable way of delivery is through conventional logistical routes. The benefit of most SAF is the comparability as a blend in fuel and therefore poses a reduced challenge in physically delivering of SAF. Such a system where SAF is blended with conventional fuel and utilizes existing pipelines is called a mass balance system (however, this mass balance is about tracking physical fuel volumes and percentages, which is why it should not be directly confused with a general mass balance concept for the reporting and accounting of SAF or the tracking and reporting of sustainable SAF attributes (environmental documentation)).

However, it still involves several challenges to replace ordinary fuel with SAF. First, we must be aware of volumes and percentages in the mass balance and adequately monitoring by fuel operators. Currently no SAF can exceed 50 vol % within the blend and several options even have a lower blending limit.

A mass balance system must also be able to track the product attributes to document and transfer attributes to the purchaser of the fuel. In the future this will have an impact on the financial benefits and environmental documentation due to emission savings. At this point it is not clear who is responsible for managing such a system in Copenhagen Airport.

Today's practice will be that the supplier delivers a preblended product, or an unmixed product at the fuel operators' facility at the storage tanks outside the airport, where a standard quality check is conducted to ensure compliance with ASTM and EI/JIG 1530 standards. The received SAF, mixed or unmixed, will be blended with the fossil fuel and from there the fuel is handled in the same way as any other fuel.

Though it is safe to assume that any SAF made from each of the producers will be transported to an established facility where the blending activity can take place, since none of the production plants includes blending facilities.

Having access to the sea for a producer enables easy and efficient modes of transportation. The blend-in potential makes it possible to utilize existing logistical practices, with a challenge of ensuring the right documentation along the way.

Segregated delivery

A direct physical delivery of SAF to individual aircrafts is an option but this will require major restructuring and requires analyzes of which airports and which flights will achieve the most positive results.

By segregating the delivery of SAF to specific aircrafts, especially long-haul flights, it could be possible to design delivery to target high emission flights and achieve even greater emissions reductions than an evenly distributed SAF percentage. Which are commonly referred to as non-CO2 effects.

Practically however, segregated delivery poses significant challenges. With CPH airport as an example: The current design of logistics to the airport does not allow for SAF to be isolated in the hydrant system. An alternative could be to deliver by truck. Currently, CPH only has two trucks, operated by a third party, each with the capacity of approx. 24.000 liter, to put into perspective a long-haul flight can contain 60.000-90.000 liters of fuel. Within the existing framework, a fuel supply system based on truck deliveries in continuous supply in larger quantities will be a very big challenge. To create a segregated hydrant system will also be a big challenge, both regarding infrastructure and budget.

Other airports may be able to find a solution with a segregated system more easily, depending on many infrastructural factors. The biggest opportunity will be the construction of new airports, and of course looking at all the traffic conditions.

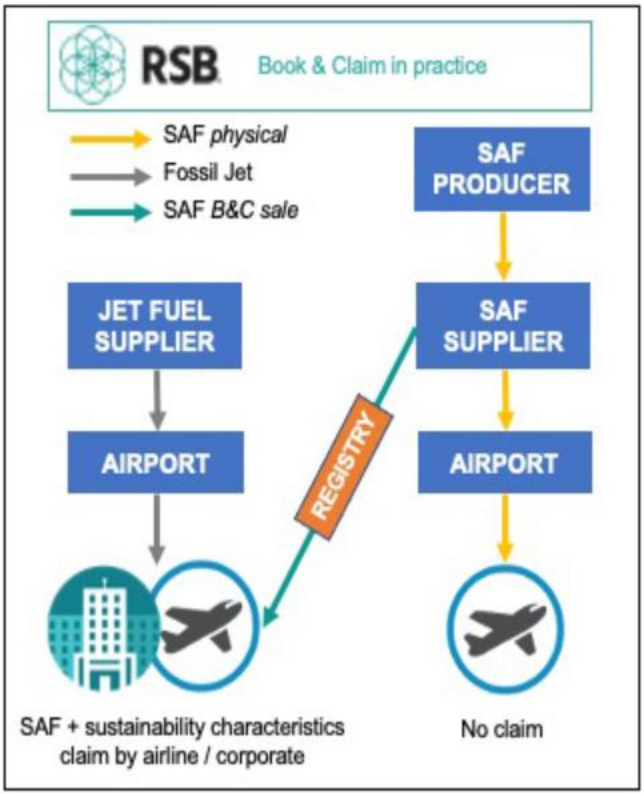
The commissioning of a future 100% SAF will be a completely new and epoch-making measure, that requires ASTM approval of the SAF products, approval of certain aircraft for the use of 100% SAF and an upscaled production that in addition to being extensive is also allowed and prioritized use for the said purpose. It is possible to investigate whether some airports may be more suitable for establishing separate fuel systems. Other solutions with separate tanks on the ground and the possibility of refilling SAF in separate tanks in the aircraft may also be included in future assessments.

Fueling aircrafts with 100% SAF can bring environmental benefits by reducing the combustion of aromatics. "*Uptake of sustainable aviation fuels, that typically have lower aromatic concentrations and lower sulphur content, will contribute to reducing the non-CO2 climate impacts. A further reduction of the aromatic and sulphur content in aviation fuels could reduce contrail cirrus formation, improve air quality in and around airports, and increase the quality of the* *fuel for the benefit of airlines, both through high energy density and lower maintenance costs due to lower soot levels".* (European parliament 2022, amendment 25).

Book and claim

A recent initiative to accommodate the high demand on SAF, several companies and organizations have developed book and claim systems, with more on the way.

Book and claim are a certificate system where the ownership of specific attributes of a product is disconnected from the physical flow (e.g., sustainability properties of SAF are decoupled from the physical SAF product and transferred onto tradeable certificates). This means that a company can procure a product and claim the environmental benefits, while the actual product is delivered physically elsewhere in the world. In this case, the physical product is relieved of its certified attributes and is handled in the same way as other conventional products (i.e., in the case of SAF, like conventional jet fuel).



The transnational nature of aviation can make it difficult to ensure SAF is fueled at a specific aircraft, since SAF might not be available at certain airports during the market ramp-up phase. Book and claim can support a continuous delivery between a procurer and supplier, despite logistical and geographical challenges. Furthermore, the system can reduce climate impact even further by potentially reducing transportation of SAF. In contrast, however, there is the influence of non-CO2 effects. To reduce these, it may be necessary to be able to control the physical input flow of SAF ex-ante or at least to be able to trace it. Book and Claim as a chain of custody model for SAF does not allow this without more ado. In the future, it will therefore be necessary to compare the various advantages of Book and Claim with the various disadvantages and to compare them fairly with other chain of custody approaches.

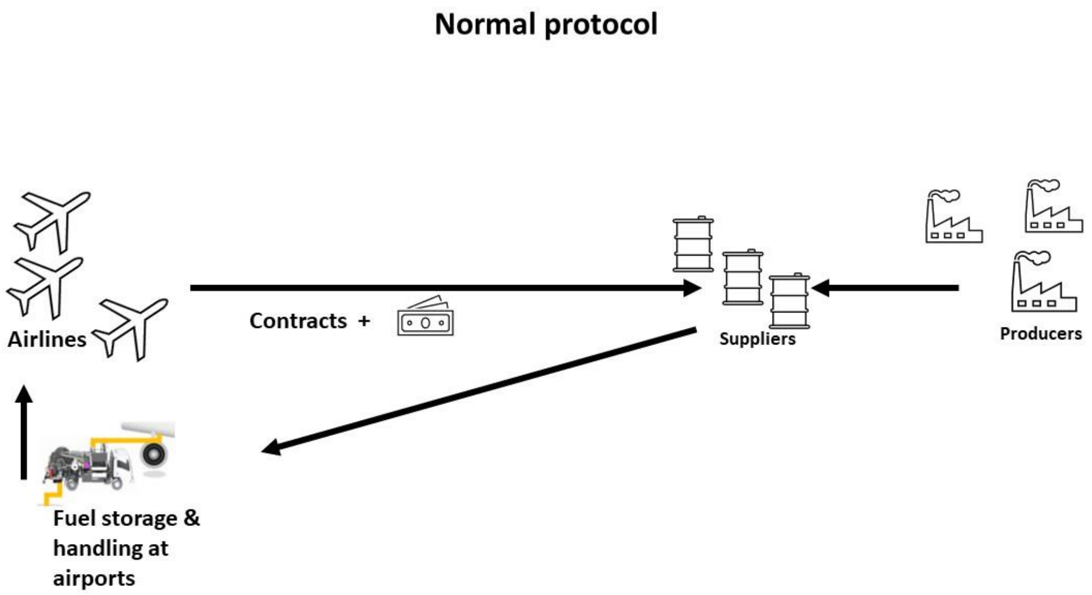
The environmental benefits can be transferred digitally to whomever owns the actual product and can through ownership alone reduce their GHG-emissions. This can also lead to financial benefits if data is compatible/recognized with other systems such as ETS schemes, offset schemes or similar GHG-protocol systems.

The system does have several challenges when it comes to the actual accounting. Since all book and claim systems within aviation is relatively new, the industry needs to gain experience when transferring data and avoid double/multiple issuing, selling, counting, or claiming. This challenge increases with other newly initiated GHG-protocol focused systems interacting with one another such as CORSIA, the CST SAF framework, SABA, and regional regulations such as EU Fit for 55.

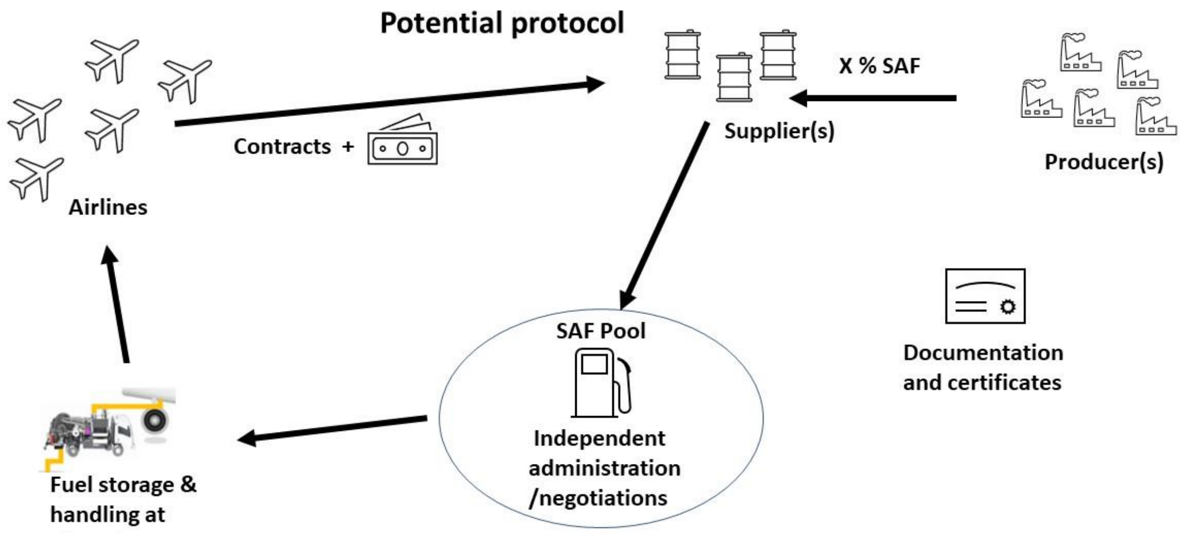
Book and claim approaches are a common practice in several sectors, for example the trading of renewable electricity in Europe or biomethane in Germany. From an environmental point of view, it does not matter where the emission reduction takes place, due to the nature of the climate's interconnectedness – yet this does only count for the CO_2-effects, but neither for non-CO2-effects nor local pollutant emissions.

5.2.4 Who will be end users

Agreements on the supply of SAF will, with current rules and contractual conditions, be a matter between one or more fuel suppliers and one or several airlines. A key question is how many and to what extent such agreements are entered into. Another question is how it can be handled in practice. Assuming a supply through existing pipelines and hydrant systems, the blend-in SAF will be refueled on all aircraft. However, a presumed additional price for SAF will only have to be paid by those who choose to enter into agreements in this regard. To promote as broad a participation as possible, a model should be established that encourages participation in the scheme. The more companies that participate, the larger quantities of SAF must be delivered. It may therefore be an idea to look at one or more models that make it interesting for as many companies as possible to participate. A crucial element can be to establish a model that generates a more attractive price than the one the airlines can achieve individually. It could be created through the establishment of a major customer agreement that all airlines at the airport are given the opportunity to participate in. WP2 has taken the initiative to try to create a model that both ensures a more attractive price and can ensure the largest possible use of SAF.



Figure, simplified, shows the ordinary fuel process flow at the airport



Figure, simplified, shows how a process flow can look like with the establishment of a SAF Pool

The model includes joint access to requisition SAF without undermining the airlines' right to enter into their own contracts with fuel suppliers and manufacturers. The possibilities must be explored to establish a SAF "Pool" facilitated by the airport, offered to all users (airlines) and executed through existing contractual agreements. The proposal has been discussed with the participants in the work package as well as with some other actors. Many matters must be examined, - including the practical, legal and contractual conditions for participation etc. We consider a SAF "Pool" to be an interesting concept for many airports, first and foremost the participants in ALIGHT and thus in a wider EU perspective. As there is no other known setup for a common access to the future SAF deliveries, with a concrete realization, the proposal can become a significant contribution to the SAF part of ALIGHT.

This will be reported in subsequent deliveries. We must, of course, consider that the above model may be made redundant, or must be set up differently, if significant changes occur, it could be a considerably changed prioritization of non-CO_2 efforts and it could be if the EU decides on a mandatory blend-in model which, as ReFuelEurope has proposed, must be required of the fuel suppliers to carry out. In later stages, this should be developed in relation to regulatory changes, including what consequences or opportunities it provides for such a SAF Pool.

6. Conclusions

Since 2011 the possibilities for producing SAF products have expanded to seven pathways, though production, technological readiness level and scale remains a challenge. Mature technologies, such as HEFA, can deliver a portion of the demand in the short term, but have high sustainability concerns connected and cannot cover the entirety of the market, especially not in the long term. With several new producers entering the market within the next couple of years, SAF is expected to increase in supply with HEFA as the dominant pathway in the short term.

Mid- and long term we look to new technologies such as PtX, which is promising on both feedstock availability and can live up to high sustainability demands. These technologies are still under development and needs intensive investment and scaling to be a viable option for mid- and long term SAF supply.

Although the SAF market is slowly growing, proposed regulation such as Fit-for-55 aims to push the market even further. With ReFuelEurope's proposed blending mandate, Europe guaranties a steady growing market for both biofuels and synthetic fuels alike. This push is important to attract and by that de-risk investments into SAF. Through several articles and interviews this has been pointed out as one of the most important steps to push forward the SAF agenda. This has also made local governments increase their attention to SAF production and recently Denmark announced the ambition to fly domestic on SAF within this decade.
As a direct consequence of the political push several PtX SAF producers have sharpened their timeline and ambitiously aims to produce SAF within the next 3-5 years in the Nordics. Other

SAF producers in Europe and USA has also communicated they will enter the market within the same timeframe.

Although SAF is dedicated to the aviation industry there is a strong connection to the societal development. To produce SAF from PtX we need to increase the production of renewable electricity, green hydrogen, and carbon capture utilization. This is a societal matter, and we therefore see new cross-sector networks included in the new SAF production companies and their associations to other sectors to ensure the entire supply chain is represented or included into decision making processes.

The logistical supply of SAF can utilize current logistical infrastructure with a mass balance system, which significantly benefits the industry. Thus, many established logistical practices can continue almost in a business as usual and be considered part of the sustainable transition. In this regard the largest challenge remains within the administrative system of ensuring an effective mass balance monitoring system and appoint responsible facilitators.
Segregated delivery is a big challenge at the current state, due to the already efficient hydrant piping system. This generally applies to most airports in the EU and will be subject for investigation at a later point in WP2. An important note is that a segregated delivery option for long haul flights could contribute with positive environmental benefits in the future, - because long haul flights operating on high amount of SAF, preferable 100 % neat SAF, could avoid creating contrails, that are responsible for significant emissions within the aviation industry. There is increasing attention directed at fossil fuels content of sulfur and aromatics, which cause the formation of non-CO2 effects. New research results show that these impacts on the climate are at least as great as the CO2 effects and therefore as important to reduce.

D2.1 has focused on the immediate circumstances to engage with SAF production. D2.2 (Guidance on sustainability criteria and best practice framework) will dive deeper into the environmental and regulatory aspects. As part of the conclusion, it should also be mentioned that all significant aspects regarding D2.1 "Report on the decision process and other circumstances involved to establish a production facility and identification of possible alternative delivery options" will be followed up and reported later in the ALIGHT project. In the meantime, updates will be made on the NISA/ALIGHT WP2 website, see ALIGHT timeline at:
https://www.nisa.dk/alight/timeline-wp2

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Table a, next page:

Annex 16 Vol IV defines a conversion process as a type of technology used to convert a feedstock into aviation fuel.

As of October 2021, 9 conversion processes for SAF production have been approved by the ASTM International.

In order to be used in commercial flights, a sustainable aviation fuel (SAF) has to comply with ASTM D4054

Ref ICAO, https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

ASTM reference	Conversion process	Abbreviation	Possible Feedstocks	Blending ratio by volume	Commercialization proposals / Projects
ASTM D7566 Annex 1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	FT	Coal, natural gas, biomass	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
ASTM D7566 Annex 2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	Bio-oils, animal fat, recycled oils	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
ASTM D7566 Annex 3	Synthesized iso-paraffins from hydroprocessed fermented sugars	SIP	Biomass used for sugar production	10%	Amyris, Total
ASTM D7566 Annex 4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%	Sasol
ASTM D7566 Annex 5	Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	Biomass from ethanol or isobutanol production	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
ASTM D7566 Annex 6	Catalytic hydrothermolysis jet fuel	CHJ	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%	Applied Research Associates (ARA)
ASTM D7566 Annex 7	Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids	HC-HEFA-SPK	Algae	10%	IHI Corporation
ASTM D1655 Annex A1	co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	co-processed HEFA	Fats, oils, and greases (FOG) co-processed with petroleum	5%	
ASTM D1655 Annex A1	co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery	co-processed FT	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%	Fulcrum