# Renewable Aviation e-SAF Catalogue and System Impacts

Skov, Iva Ridjan; Abid, Hamza

*Publication date:*
2024

*Document Version*
Publisher's PDF, also known as Version of record

*Citation for published version (APA):*
Skov, I. R., & Abid, H. (2024). *Renewable Aviation e-SAF Catalogue and System Impacts*.

# Renewable Aviation e-SAF Catalogue and System Impacts

Authors:

Iva Ridjan Skov

Hamza Abid

MISSION GREEN FUELS

AALBORG
UNIVERSITY
SUSTAINABLE ENERGY PLANNING

# Table of contents

# I. Sustainable aviation fuels

# I. Sustainable aviation fuels

## Demand for SAF fuels and current regulation

The transition of aviation to alternative propulsion technologies will be part of the solution to reduce $CO_2$ emissions in the sector. However, it is expected that the majority of the aviation demand in the future will still be met by jet fuels. Both electric and hydrogen-powered aircrafts are technologies that contribute to making aviation more sustainable. Currently, announced concepts for hydrogen are with +2000 nm and less than 200 passengers[1], while electricity is reserved for shorter flights. Sustainable aviation fuels (SAF) are seen as a long-term solution as they can be applied to all trip ranges.

According to Becken[2], bio-SAF can use up to 30% of the sustainable biomass in 2050, confirming the poor resource efficiency, and the availability of biomass used for some bio-SAF is very limited. Assurance of the use of sustainable biomass and accounting are of high importance. The EU trading system (EU ETS) already provides an incentive to use bio-SAF. According to the previous RED II Directive, as long as the SAF fuel complies with the sustainability criteria, it could be accounted towards a renewable energy target. However, this seems that this did not significantly influence the uptake of the SAF, according to the European Commission[3]. In 2020, only 0.05% of the fuel used in EU aviation was SAF[4]. Certified SAF fuels can be blended up to 50% with fossil counterparts; however, it is expected that this will increase to 100% in 2030. In 2022, the SAF demand worldwide covered only 0.15% of the total fuel demand[5] .

According to the ReFuelEU Aviation proposal, jet fuel suppliers are obliged to provide a blend of SAF (both advanced biofuels and e-fuels) in European airports. The aim is to provide a 2% blend in 2025, a 6% blend in 2030 and a 70% blend in 2050, with an indication of financial penalty for not complying with the regulation. E-SAF (Power-to-Liquid) has a specific sub-obligation of 1.2% in 2030, 5% in 2035 and 35% of SAF blends in 2050[6]. In the USA, the Sustainable Aviation Fuel Grand Challenge[4] has also been announced which should enable the supply of SAF by 2030 that can reduce emissions by 20%. The long-term goal is to supply 100% of the aviation fuel demand with SAF by 2050[7]. Furthermore, airlines have committed to reaching net-zero carbon emissions by 2050 in 2021. In 2022, the International Civil Aviation Organization (ICAO) has agreed upon the same goal.[7]

**OBJECTIVES**

- Give insights into EU regulation and SAF targets
- Give an overview of SAF's share in the jet fuel demand
- Give an overview of the SAF alternatives available on the market

The fuel suppliers failing to meet the SAF targets will be subjected to fines. The level of the penalties needs to be proportionate to the environmental damage and the damage created on the level playing field of the internal market inflicted by the non-compliance. SkyNRG analysis* indicates that penalties could be between €1,000€ to €6,000 per tonne of fuel. The revenue from the fines is encouraged to be used for investments in R&I in SAF, the production of SAF or mechanisms allowing the price differences between SAF and conventional aviation fuels to be bridged.

# I. Sustainable aviation fuels

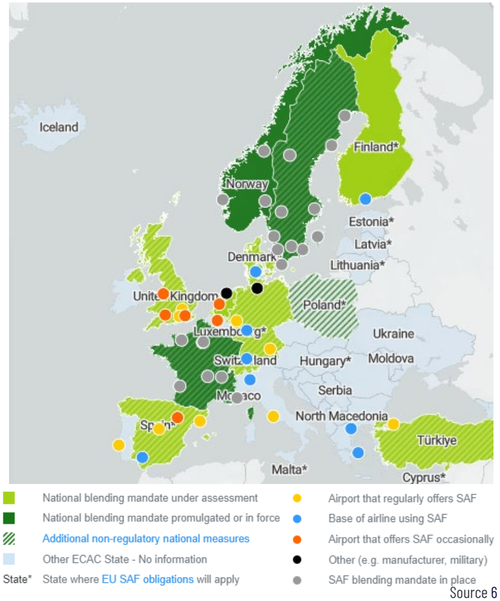
## Availability of SAF in the EU and targets

Meeting the EU mandates will require more than 2 million tonnes of SAF by 2030, while estimations for European-produced SAF correspond to only 10% of the mandate requirements according to EASA. The application of SAF is spread through EU airports and some countries already have national blending mandates in place. Some airports and airlines use SAF blends regularly, while other airports occasionally provide SAF. SAF is currently available in 13 European airports, but not in quantities for all users as they are reliant on the offtake agreements of airlines. According to ICAO, the number of SAF agreements by airlines is increasing, due to the growing interest and internal targets of airlines.

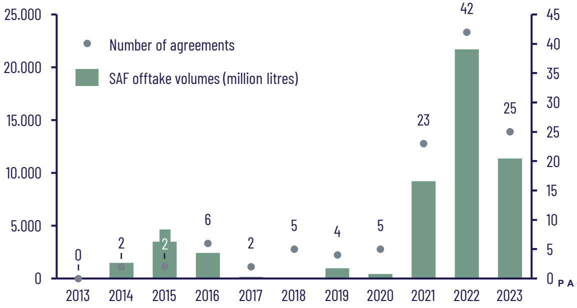
Sweden will be the first country that use blend-in SAF for all aircraft refuelling in one of its airports[6]. The Netherlands has governmental support for the use of biofuels for aviation and has been a large consumer of SAF due to this.

In May, the EU approved the final act on the Directive for aviation's contribution to emission reduction target[7]. This Directive introduces gradual phasing out of ETC allowances to full auctioning from 2026; however, 20 million allowances will be reserved until 2030 to support SAF. Furthermore, the reporting of non-CO$_2$ aviation effects in a monitoring, reporting and verification framework is introduced in the Directive and the details are currently under discussion as the tool for monitoring should be published in 2024.

In addition, EU ETS will continue to apply to flights within the EEA and departing flights to Switzerland and the United Kingdom and this decision will be reassessed in 2026.



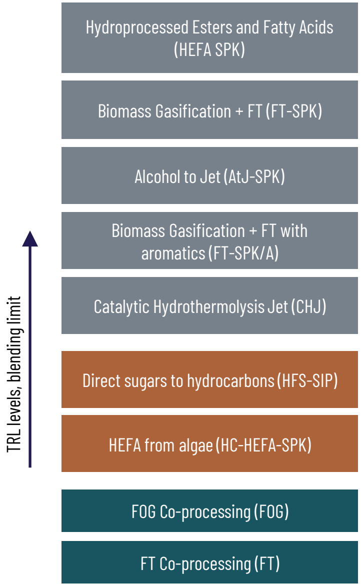
Source 6



Source: International Civil Aviation Organization

# I. Sustainable aviation fuels

## Approved pathways



Hydroprocessed Esters and Fatty Acids (HEFA SPK)

Biomass Gasification + FT (FT-SPK)

Alcohol to Jet (AtJ-SPK)

Biomass Gasification + FT with aromatics (FT-SPK/A)

Catalytic Hydrothermolysis Jet (CHJ)

Direct sugars to hydrocarbons (HFS-SIP)

HEFA from algae (HC-HEFA-SPK)

FOG Co-processing (FOG)

FT Co-processing (FT)

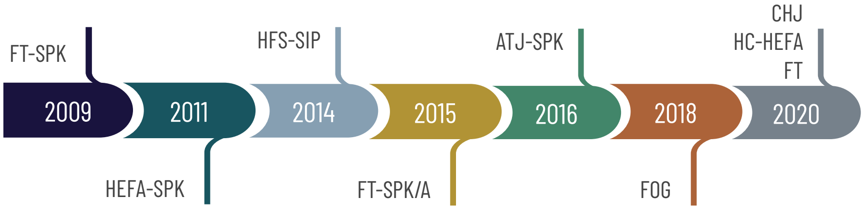
TRL levels, blending limit

Currently, nine approved SAF production pathways also include e-SAF pathways based on Fischer-Tropsch (FT) synthesis. The current alcohol-to-jet pathways, that were certified back in 2016, do not include methanol (as 1 carbon compound) as it allows individual use of ethanol and isobutanol and will with extension cover 2 to 5-carbon alcohols. Even though there are seven approved pathways, only two are used for regular civil aviation which are produced by fewer than 10 refineries worldwide[8].

Among the nine available pathways, five of the upper ones have a blending limit of up to 50% in the final product. The following two pathways permit a blending limit of up to 10% in the final product and the lowest two pathways have a limit of up to 5% in the final product.

According to Life Cycle Assessment (LCA), SAF pathways offer emission reductions in comparison to the fossil reference (89 g $CO_{2e}$/MJ) between 30-95%. Fischer-Tropsch routes seem to offer the highest emission reductions. E-jet pathways that are yet to be accounted for in the LCA comparison, such as methanol-to-jet, should offer up to 100% emission reductions. The current jet fuel standard allows for a maximum of 25% and a minimum of 8% due to safety considerations but results in emitting particles. SAFs typically have lower aromatic content, which can further contribute to the reduction of non-$CO_2$ climate emissions.

According to the SkyNRGs SAF market outlook[9], the SAF mandates up to 2030 are expected to primarily be met by HEFA pathways, followed by e-jet, alcohol-to-jet (AtJ) and biomass gasification + FT (Gas+FT) according to announced projects.



2009: FT-SPK

2011: HEFA-SPK

2014: HFS-SIP

2015: FT-SPK/A

2016: ATJ-SPK

2018: FOG

2020: CHJ, HC-HEFA, FT

# I. Sustainable aviation fuels

## Advancements in e-SAF via methanol-to-jet and Fischer-Tropsch route

Several key players in the industry have taken remarkable steps to pave the way for methanol-to-jet and Fischer-Tropsch pathways. These initiatives and projects highlight the innovation in the e-SAF pathways:

**Nacero USA's Methanol-to-Jet Fuel Complex:** Nacero USA has embarked on the development of a methanol-to-jet fuel complex supported by Topsoe's MTJet™ technology. It will be the largest commercial-scale facility in the US producing 30,000 metric tonnes per day (MTPD) of methanol.

**ExxonMobil's Methanol-to-Jet Technology:** announced in June 2022, ExxonMobil unveiled their Methanol-to-Jet technology efforts.

**Honeywell UOP's eFinning:** Honeywell announced their UOP eFinning producing e-SAF from e-methanol derived from green hydrogen and recycled $CO_2$. Their **HIF eSAF Project** is expected to be the world's largest e-SAF production facility**,** aiming to produce around 11,000 barrels of eSAF per day by the year 2030 and recycling approximately 2 million tons of captured $CO_2$.

**Metafuels Aerobrew and European Energy Methanol-to-Jet Collaboration:** European Energy and Metafuels have joined forces entering into a memorandum of understanding that targets the production of 10,000 litres/day of e-SAF at European Energy's current Power-to-X-sites in Denmark.

**CAC's Methanol-to-Jet Fuel Technology:** CAC's innovative approach to SAF production is a multi-stage process, including Methanol-to-Olefins (MtO), Olefins-to-Jet fuel (OtJ), and hydrofinishing. These stages result in primary SAF products, such as kerosene, while also producing valuable by-products like diesel, gasoline, LPG, fuel gas, and water.

**Project SAFari - Fraunhofer's Pilot Plant:** Fraunhofer's Project SAFari aims at the development of a tailormade pilot plant dedicated to producing sustainable aviation fuels based on methanol as a part of a research-based 6-year project ending in 2028.

**Construction of the First U.S. Commercial E-SAF Plant:** The construction of the first U.S. commercial e-SAF plant in Moses Lake Washington with scheduled operation by mid-2024 targeting the production of 40,000 gallons of SAF a year with a potential output of 1 million gallons.

**Arcadia eFuels:** has announced the production of 66,000 MT of e-jet in Vordingborg in 2026, which is more than what is needed to cover the Danish domestic green aviation mandate in 2030.

**Nordic Electrofuels:** has received a EUR 40 million grant for building 10 million litres of e-SAF plant in Norway at Herøya Industrial Park, Porsgrunn.

**Atmosfair:** inaugurated in 2021 a plant in Werle in Emsland producing e-SAF from $CO_2$ from biogas and delivering 336 gallons of jet fuel to Hamburg airport.

**Uniper and Sasol ecoFT:** SkyFuelH2 project to begin construction in 2025 to deliver e-SAF as early as in 2028 in Sollefteå municipality in Sweden.

**Vattenfall, SAS & Shell:** 80,000 tonnes of e-SAF around 2030 near Forsmark on Sweden to cover 25% of the SAS global demand for SAF.

# II. PtX pathway principles to e-jet

# II. PtX pathway principles

## Mapping of e- SAF pathways

There is a wide range of literature on the production of synthetic jet fuels. Jet fuels like most synthetic fuels can be made via electricity only, biogenic only, or a mix of the two, i.e., bio-electro. The biogenic-only pathways involve the production of bio-based jet fuel, via Hydrothermal liquefaction, direct sugar to hydrocarbons or Hydro-ester-fatty-acid (HEFA) hydroprocessing. These processes require little or no hydrogen, and the only electricity utilised is for the fuel synthesis. In outlining the pathways, this report only focuses on Power-to-liquid-based jet fuel (e-jet) production pathways where electricity (power) is converted with or without the use of biomass to jet fuels.

Both electro-only and bio-electro pathways have the following two major constituents as their setup:

1. Source of Hydrogen
2. Source of $CO_2$

For renewable-based jet fuel production, the sources of hydrogen are either low-temperature electrolysers (Alkaline, PEM) or high-temperature electrolysers (SOEC). The classification is based on the operating temperatures, with low-temperature electrolysers operating at around 100 °C and high temperatures operating at around 700-1000 °C . Both low and high-temperature electrolysers each come with their own pros and cons. The most relevant and significant advantage of low-temperature electrolysers is that they are relatively well-developed and represent a more readily commercially available technology. However, recently SOECs have gained attraction owing to their high electricity to $H_2$ conversion efficiencies over their low-temperature counterparts. They are also expected to be better suited for power-to-jet pathways, as they can integrate up to 20 % of their input demand via heat integration from other fuel synthesis processes. However, SOECs are also more expensive and not yet commercially available on a large scale. This unavailability of SOECs on a commercial scale also causes uncertainty in the cost estimates, as we will discuss in the later part of the report.

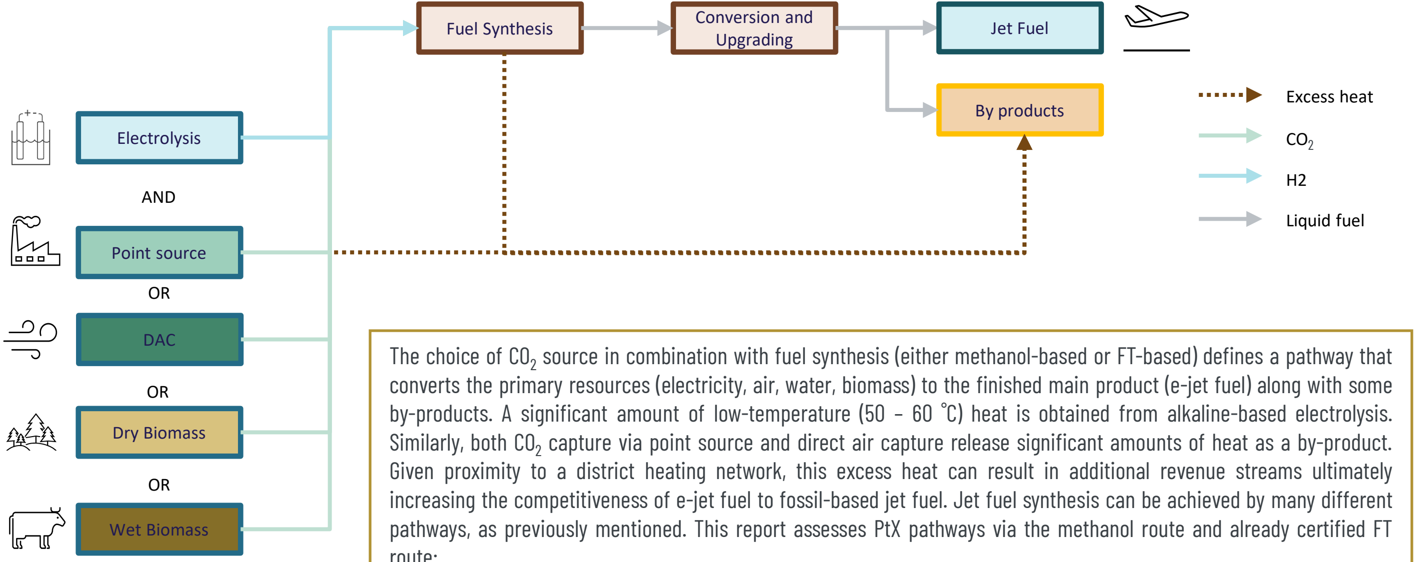
**OBJECTIVES**

Mapping of e-SAF pathways
- Fischer-Tropsch e-jet fuels
- Methanol-to-jet

For renewable-based $CO_2$ production, three major sources are possible, namely direct air capture, point source capture from existing industrial processes, and biogenic production. Direct air capture involves the separation of $CO_2$ directly from the air by utilising heat and electricity as inputs. Biogenic production of $CO_2$ is the process of obtaining $CO_2$ or CO, either as part of a syngas or a biogas directly from biomass via intermediate processes such as biomass gasification or anaerobic digestion. Biomass gasification of dry biomass such as straw, wood etc, generates a mixture of $H_2$ and $CO_2$ (syngas) – a direct input for FT or methanol synthesis - whereas anaerobic digestion of wet biomass such as slurry, manure etc. generates biogas, which can be upgraded to biomethane by methanation. The e-biomethane produced from anaerobic digestion can then be converted to syngas ($CO+H_2$) via steam methane reforming or partial oxidation.

# II. PtX pathway principles

## Mapping of e- SAF pathways



The choice of $CO_2$ source in combination with fuel synthesis (either methanol-based or FT-based) defines a pathway that converts the primary resources (electricity, air, water, biomass) to the finished main product (e-jet fuel) along with some by-products. A significant amount of low-temperature (50 – 60 °C) heat is obtained from alkaline-based electrolysis. Similarly, both $CO_2$ capture via point source and direct air capture release significant amounts of heat as a by-product. Given proximity to a district heating network, this excess heat can result in additional revenue streams ultimately increasing the competitiveness of e-jet fuel to fossil-based jet fuel. Jet fuel synthesis can be achieved by many different pathways, as previously mentioned. This report assesses PtX pathways via the methanol route and already certified FT route:

1. e-SAF production via Methanol synthesis
2. e-SAF production via Fischer Tropsch (FT) synthesis

Both pathways involve the production of intermediate products, i.e., methanol and FT liquids that can be upgraded (converted) to jet fuel. Furthermore, pathways build on the existing industrial experience of large-scale gas-to-liquid or coal-to-liquid conversion. Hence, for renewable jet fuel production, these can be adapted to utilise power and $CO_2$ to establish renewable fuel production pathways. FT process can be adapted to produce a certain type of fuel. According to Winther Mortensen et al [9], a jet fuel output of 76 % is possible with low-temperature FT synthesis, with the remaining by-products such as naphtha and FT-diesel, while Topsøe[10] is reporting 82%. While the literature is scarce on the exact by-product fraction of methanol-to-jet, it is expected to be somewhat similar to methanol-to-gasoline, yielding around 74 % jet fuel and the remaining volume in by-products such as LPG equivalent and fuel gas.

# II. PtX pathway principles

## Fischer – Tropsch and methanol-based e- jet fuels

The FT pathway requires carbon monoxide and hydrogen to generate a crude FT fuel product in an exothermic reaction. The temperature of the heat release ranges around 250 – 300 °C, which is an important feature of the reaction. This crude product is then converted to well-established industrial processes such as hydrocracking, isomerization and distillation. The production of carbon monoxide from carbon dioxide takes place via a reverse water gas shift reaction. $H_2$ can be produced either via low-temperature electrolysers or high temperatures. If high-temperature electrolysers are employed and proper heat integration is possible by placing $H_2$ production and fuel synthesis in close proximity, part of the excess heat can be utilised as input to the high-temperature SOEC electrolyser, reducing the electricity demand for $H_2$ production. Similarly, excess process heat can also be used for direct air capture or point source capture for $CO_2$ capture. In this way, the overall power to fuel efficiency of the pathway can be increased. An important characteristic of FT-based jet fuels is that several types of FT-based synthetic jet fuels such as FT-SPK (Fischer Tropsch synthetic paraffinic kerosene) have been approved as direct drop-in jet fuels by ASTM international with up to 50 % blend with conventional jet fuels.

Fischer Tropsch-based e-SAF fuels

Methanol-based e-SAF fuels

The methanol-based pathways, as the name suggests, use methanol as an intermediate, which in itself is a valuable product for many industrial applications such as pharmaceuticals, chemical solvents, de-icing etc. An important distinction from the FT pathway is that for methanol production both $CO_2$ and CO can be used. Hence, a reverse water gas shift reaction is not required. Methanol synthesis like FT synthesis is also an exothermic reaction where the excess heat can be utilised for either $H_2$ production or $CO_2$ capture. Jet fuel conversion from methanol requires many subsequent processes, such as olefin synthesis, oligomerization and hydrotreating. While methanol synthesis and subsequent processes are mature, methanol-based jet fuel production still lacks ASTM approval for direct drop-in use.

# III. Comparison of e-SAF pathways

# III. Comparison of e-SAF pathways

Cross–comparison of 8 e-SAF pathways

| Pathway no | $CO_2$ source | Main process |
|---|---|---|
| 1 | Point source capture | Methanol based |
| 2 | Direct air capture | Methanol based |
| 3 | Anaerobic digestion | Methanol based |
| 4 | Biomass gasification | Methanol based |
| 5 | Point source capture | FT based |
| 6 | Direct air capture | FT based |
| 7 | Anaerobic digestion | FT based |
| 8 | Biomass gasification | FT based |

**OBJECTIVES**

Cross-comparison of pathways in terms of:

- Energy Efficiency
- Resources
- Costs

Different pathways will have different efficiencies and costs associated with them. In this report, eight different sustainable e-SAF pathways are compared as shown above. The first four are methanol-based and the latter use FT synthesis as the main hydrogen-to-fuel conversion process. All of these eight pathways are compared in terms of the energy efficiency of the entire pathway, the primary resources and their associated costs. The results are analysed for the projected domestic aviation fuel demand in 2030 for Denmark, here assumed to be 400 GWh. It is worth noting that it is not necessarily feasible that the methanol-to-jet pathway will be a mature technology in 2030, but the demand is used as a proxy to illustrate the pathways. However, it is expected that this route will be available by 2035.

- The **energy efficiency** here corresponds to the ratio of the output jet fuel to the total energy input, i.e., electricity or biomass
- **Resources** compared here are; direct electricity consumption for electrolysis, $CO_2$ capture and other processes, and indirect electricity consumption for heat input such as needed for direct air capture and point source capture
- The **costs** are annual costs that include both the capital cost of investments as well as fixed and variable operation and maintenance costs over the lifetime of the installed components

# III. Comparison e-jet pathways

Overview of results presented

The pathways are compared, as previously mentioned, in terms of energy efficiency, resource utilisation, and costs. In these pathways, certain parameters are varied to observe the impact of changes. Firstly, literature-based scenarios grounded in reported data are presented, followed by expected technology development scenarios where methanol and Fischer-Tropsch technologies reach technological maturity and undergo further developments. Scenarios for pathways are also presented for alkaline electrolysis and Solid Oxide Electrolysis Cells (SOEC). The impact of electricity price levels is tested to evaluate the price sensitivity of pathways to changing electricity prices. Details on the assumptions are presented at the end of the report. The objective of the comparison is to illustrate the availability of technology within the timeframe spanning from 2030 to 2035.

1. **Energy efficiency and resources**
   - Literature-based scenario with alkaline electrolysis
   - Expected technology development scenario with alkaline electrolysis
   - Literature-based scenario with SOEC
   - Expected technology development scenario with SOEC
2. **Cost comparison**
   - Literature-based scenario with alkaline electrolysis
   - Expected technology development scenario with alkaline electrolysis
   - Literature-based scenario with SOEC
   - Expected technology development scenario with SOEC
3. **Break-even price of electricity**
   - For point source pathway with and without by-product revenues for two price levels of fossil jet
4. **Impact of $H_2$ demand on efficiency**
   - For point source pathway

# III. Comparison e-jet pathways

## Literature-based scenario energy efficiency and resources – low-temperature alkaline electrolysis

This figure on the right shows the resource energy consumption on the left axis (GWh) and the overall pathway efficiency on the right (%) for the eight pathways based on literature data. The hydrogen in this case comes from a **low-temperature alkaline electrolysis** without heat integration.

It is visible from the figure that there is a significant variation in efficiencies between different pathways, with methanol-based pathways being more efficient overall due to slightly lower requirements for hydrogen-per-jet and $CO_2$ -to-jet fuel.

The choice of $CO_2$ greatly influences the overall efficiency. In general, $CO_2$ extracted via biomass gasification from dry biomass with the production of syngas is the most efficient pathway. Direct air capture is the most inefficient form of $CO_2$ utilisation due to the very high heat input demands for the separation of $CO_2$ from the air.

The availability of biomass is crucial when deciding between the preferred pathways as well as availability of the green $CO_2$ for the point sources.

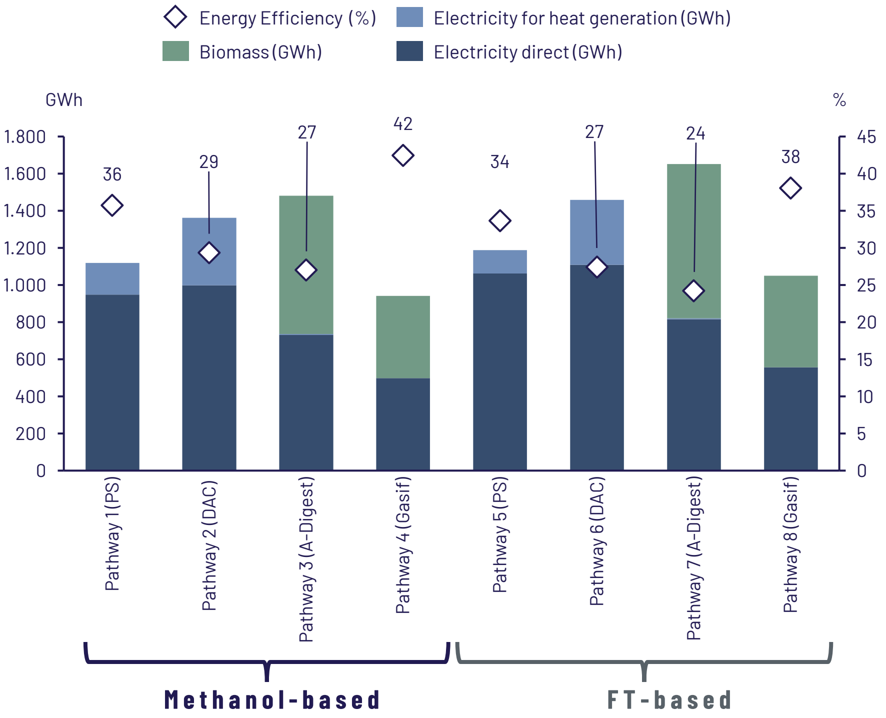


Figure 1. Overview of the energy efficiency and resources for 8 pathways. Methanol-based pathways assume an $H_2$/jet fuel ratio of 1.6 while FT-based pathways assume 1.7. The carbon-to-jet ratio for methanol-based pathways is 0.34 tonnes of $CO_2$/MWh e-SAF, while for FT-based pathways the ratio is 0.39 tonnes of $CO_2$/MWh e-SAF. Jet fuel selectivity is 74% for methanol-based and 82% for FT. An alkaline electrolysis efficiency of 68% was assumed.

# III. Comparison e-jet pathways

## Expected technology development scenario energy efficiency and resources – low-temperature alkaline electrolysis

This figure on the right shows the results for the expected technology development scenario for the eight pathways. The hydrogen in this case comes from a low-temperature alkaline electrolysis, without heat integration.

In comparison to previous results, it is visible that the overall efficiency of pathways increases. However, the trend of the efficiency relations remains the same. Both routes are showing the same results due to the expected future technology developments, where the technology maturity of methanol-to-jet reaches the level of the FT pathway.

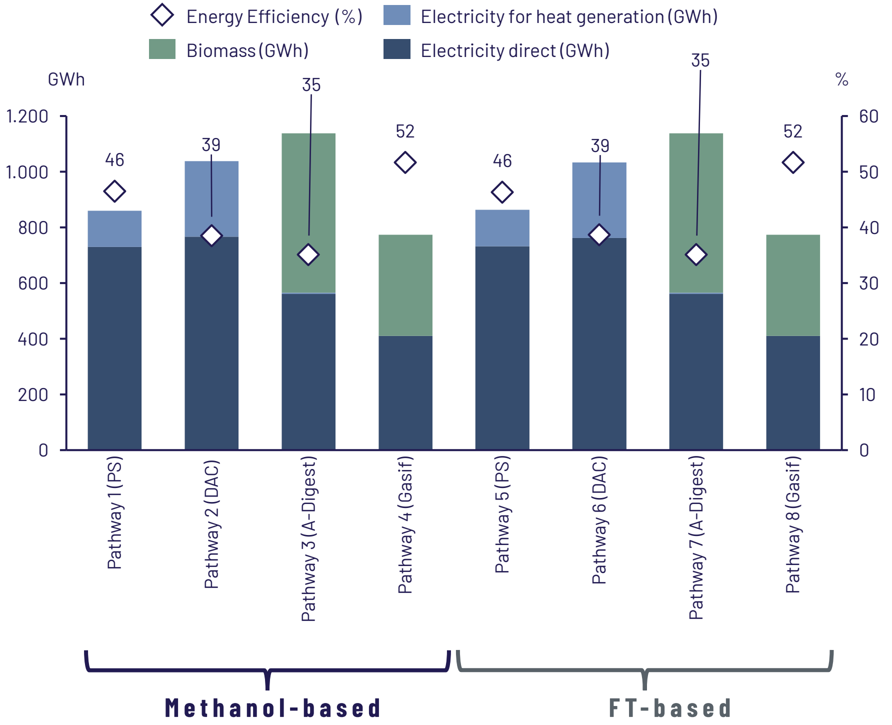


Figure 2. Overview of the energy efficiency and resources for 8 pathways. Both methanol-based and FT-based pathways assume an $H_2$/jet fuel ratio of 1.2 and jet fuel selectivity of 90%, with a carbon-to-jet ratio of 0.25 tonnes of $CO_2$/MWh. An alkaline electrolysis efficiency of 68% was assumed. Also, similar levels of heat and electricity input for the two processes is assumed.

# III. Comparison e-jet pathways

## Literature-based scenario energy efficiency and resources – high-temperature electrolysis SOEC

As mentioned before, high-temperature SOEC-based electrolysers are an emerging electrolysis technology with the potential benefit of integrating excess heat from a fuel synthesis process that can increase the overall efficiency of the pathway. The graph here shows the energy efficiencies and resource consumptions of the different pathways with hydrogen production using **high-temperature SOEC electrolysis.**

We can observe that the overall energy efficiency of the pathways predominantly dependent on hydrogen (Pathways 1,2,5 and 6) increases by around 10 %. This is because of the reduced electricity demand needed for both hydrogen and heat generation for the different processes. Since the main input for point source carbon capture and direct air capture is heat, much of the electricity needed for heat generation can be provided via heat integration. The use of high-temperature electrolysis changes the dynamics of the process efficiency between point-source pathways and biomass gasification pathways.

It is important to note that such levels of heat integration require the co-location of all production processes in close proximity, including electrolysis, fuel synthesis and CO$_2$ capture, and a dedicated infrastructure for heat integration, which poses certain challenges.

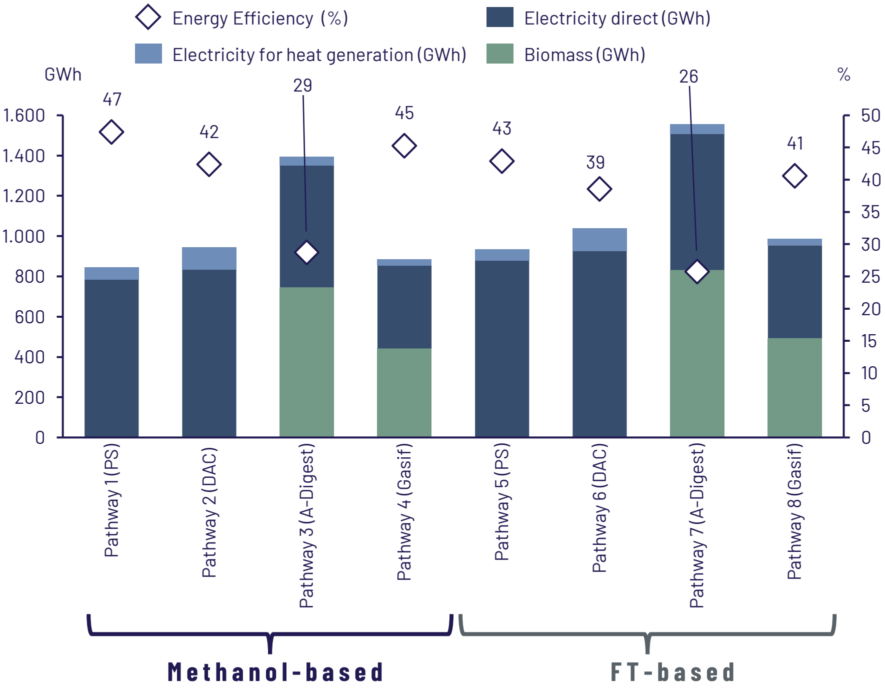


Figure 3. Overview of the energy efficiency and resources for 8 pathways. Methanol-based pathways assume an $H_2$/jet fuel ratio of 1.6 while FT-based pathways assume 1.7. The carbon-to-jet ratio for methanol-based pathways is 0.34 tonnesof $CO_2$/MWh e-SAF while for FT-based pathways the ratio is 0.39 tonnes of $CO_2$/MWh e-SAF. Jet fuel selectivity is 74% for methanol-based and 82% for FT. SOEC efficiency of 80 % was assumed.

# III. Comparison e-jet pathways

## Expected technology-based scenario energy efficiency and resources – high-temperature electrolysis SOEC

Similar to low-temperature alkaline-based electrolysers, the graph on the right shows the results for the expected technology development scenario for the eight pathways utilizing **high-temperature solid oxide electrolyser cells.**

This scenario showcases the advances in the development of methanol-to-jet and FT-to-jet processes. As seen previously, the overall efficiency of the pathways increased for all the pathways and both fuel production processes are expected to be at similar jet fuel production efficiency levels in the future.

It is visible that Pathway 1 becomes more efficient than Pathway 4. This is due to the reduction in electricity consumption for hydrogen production directly related to the higher efficiency of SOEC as well as that around 20% of the input can be provided as excess heat available from fuel synthesis if co-located.

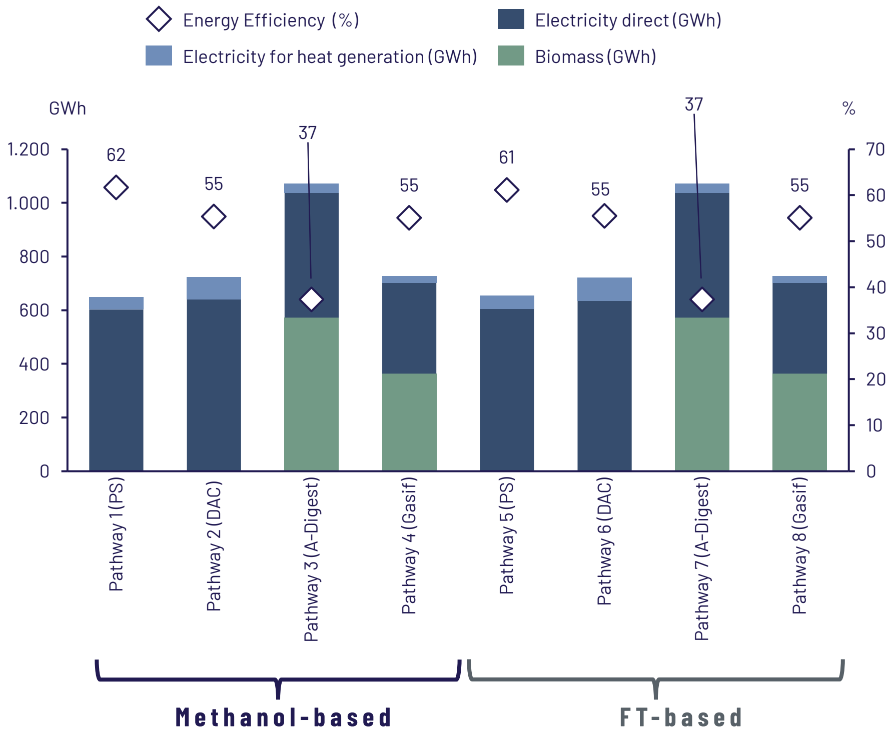


Figure 3. Overview of the energy efficiency and resources for 8 pathways. Methanol-based pathways assume an $H_2$/jet fuel ratio of 1.6 while FT-based pathways assume 1.7. The carbon-to-jet ratio for methanol-based pathways is 0.34 tonnes of $CO_2$/MWh e-SAF while for FT-based pathways ratio is 0.39 tonnes of $CO_2$/MWh e-SAF. Jet fuel selectivity is 74% for methanol-based and 82% for FT. SOEC efficiency of 80 % was assumed.

# III. Comparison e-jet pathways

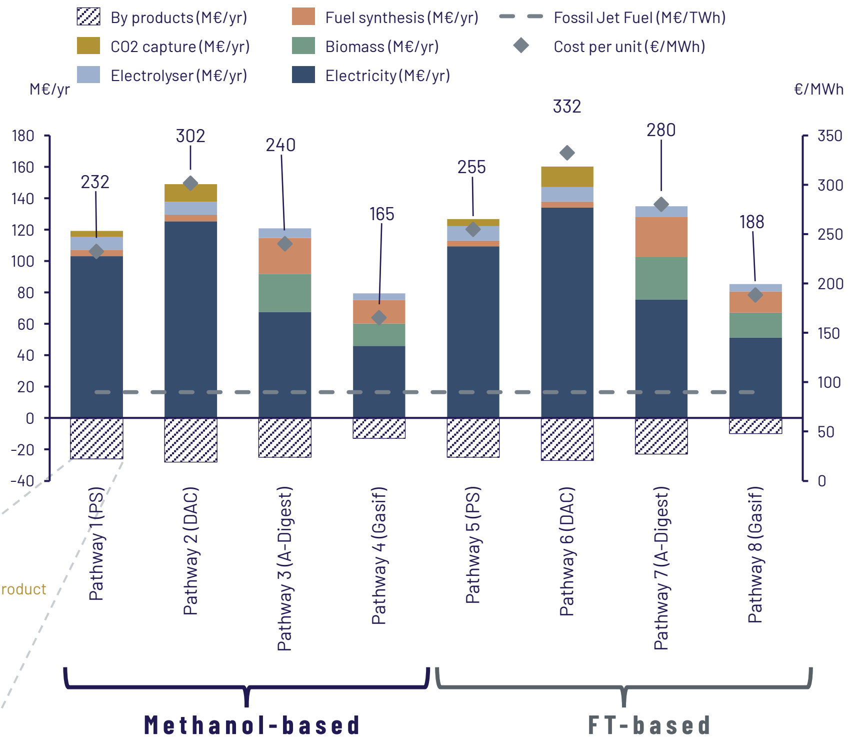
## Literature-based scenario annual costs and cost per unit – low-temperature alkaline electrolysis / high electricity price

The figure here illustrates the annual cost breakdown of different components for each pathway on the left (M€/yr) and the cost per unit of e-SAF on the right (M€/TWh). The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Hydrogen is produced using **low-temperature alkaline electrolysis**. The electricity price assumed here is **92 €/MWh** (Danish electricity price for industrial consumers incl. taxes).

Revenues account for the realisation of all revenue streams, though it may not necessarily be feasible to realise.

It is visible that the electricity price is the dominant factor in the cost per unit of fuel, which is closely linked to the high demand for electricity for individual pathways. The biomass gasification pathway has the lowest costs when high electricity prices are used due to the lowest fraction of electricity demand in comparison to other pathways. With the assumed reduction of capital costs of alkaline electrolysers to around 450 €/kWe in 2030, the share of electrolysers in the overall costs is rather low.

However, it is visible that with the assumed high electricity costs, even the least expensive Pathway 4 is almost twice as expensive than the historically high fossil jet fuel price of (90 €/MWh). The revenues from by-products such as naphtha, FT diesel and excess heat improve the overall economy of the pathways. The majority of the revenue is generated by selling excess heat to the district heating network.



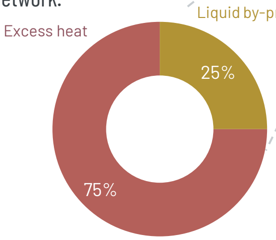


Figure 4. Overview of the annual cost and cost per unit of fuel for a case of alkaline electrolysis and high electricity price including revenue streams from by-products. Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

## Literature-based scenario annual costs and cost per unit – low-temperature alkaline electrolysis / low electricity price

The figure here illustrates the annual cost breakdown with the electricity price of **30 €/MWh**, that represents an estimate of the levelized cost of electricity for offshore wind, with a direct connection via a substation and a capacity factor of 51 %. Hydrogen is produced using **low-temperature alkaline electrolysis**.

By using a lower price of electricity instead of the previous high price, it is visible that Pathway 1, which involves point source and methanol-based jet fuel production, emerges as the most cost-effective option, particularly when electricity prices are as low as 30 €/MWh. This cost is even lower than the high-end estimate for fossil-based jet fuel on a per-unit basis.

This highlights the substantial impact of electricity prices on the unit cost of e-jet fuel. It is important to note that revenue streams from by-products, such as excess heat, play a significant role in reducing the per-unit price of e-jet fuel. For example, if we were to exclude the revenue from by-products in Pathway 1, the per-unit price of e-jet fuel would increase to approximately 125 M€/TWh, compared to the current figure of 59 M€/TWh.

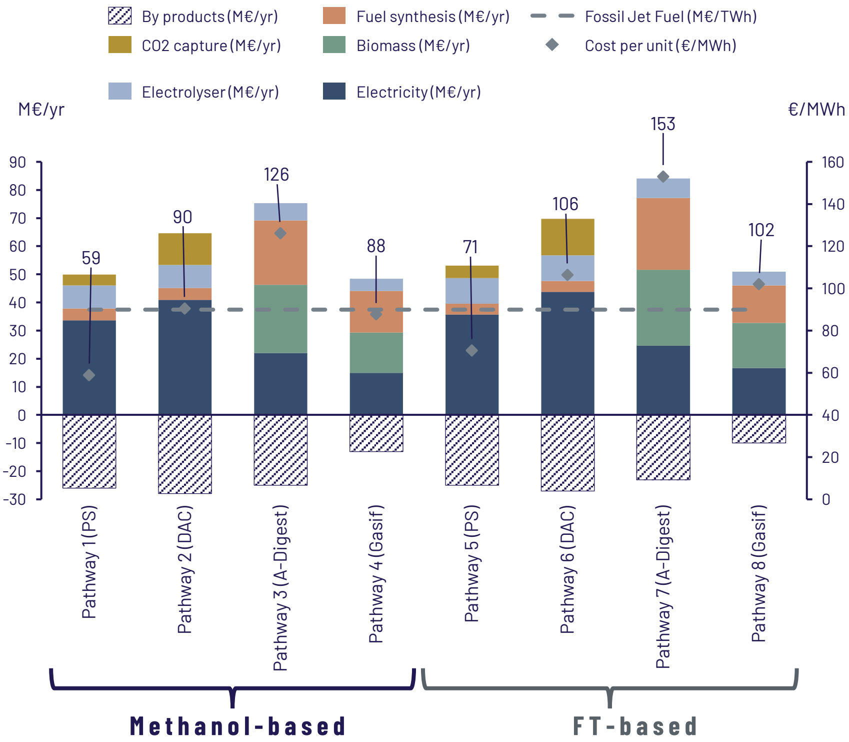


Figure 5. Overview of the annual cost and cost per unit of fuel for a case of alkaline electrolysis and low electricity price including revenue streams from by-products. The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

Expected technology development scenario annual costs and cost per unit – low-temperature alkaline electrolysis / high electricity price

In the case of expected technology development, the annual cost breakdown for e-SAF is illustrated on the right for **low-temperature alkaline electrolysis** and a **high** electricity price of **92 €/MWh.**

It can be noted that the price is reduced across all pathways and that trends reflect the efficiency trends and share of electricity in the production process, again highlighting the large effect of electricity costs on the end fuel price. Even with the utilisation of all by-products, all pathways are still up to 3 times more expensive than the high fossil jet fuel reference. This is primarily due to the electricity costs.

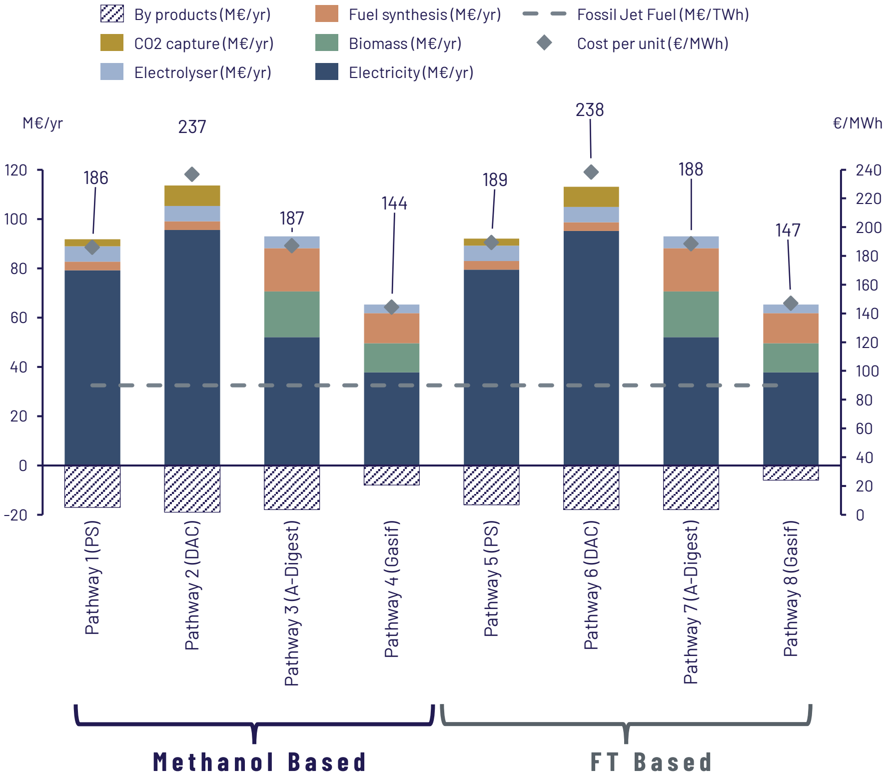


Figure 6. Overview of the annual cost and cost per unit of fuel for a case of alkaline electrolysis and high electricity price including revenue streams from by-products for the expected technology development scenario. The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

Expected technology development scenario annual costs and cost per unit – low-temperature alkaline electrolysis / low electricity price

In the case of expected technology development, the annual cost breakdown for e-SAF is illustrated on the right for **low-temperature alkaline electrolysis** and a **high** electricity price of **30 €/MWh.**

Once more, certain pathways experience a reduction of fuel price to a level lower than the historically high fossil jet fuel price of 90 €/MWh, if the revenues from by-products are accounted for. On the contrary, the prices of fuels can rise to levels surpassing those of fossil alternatives. For example, in Pathway 1, the price would increase to 96 €/MWh.

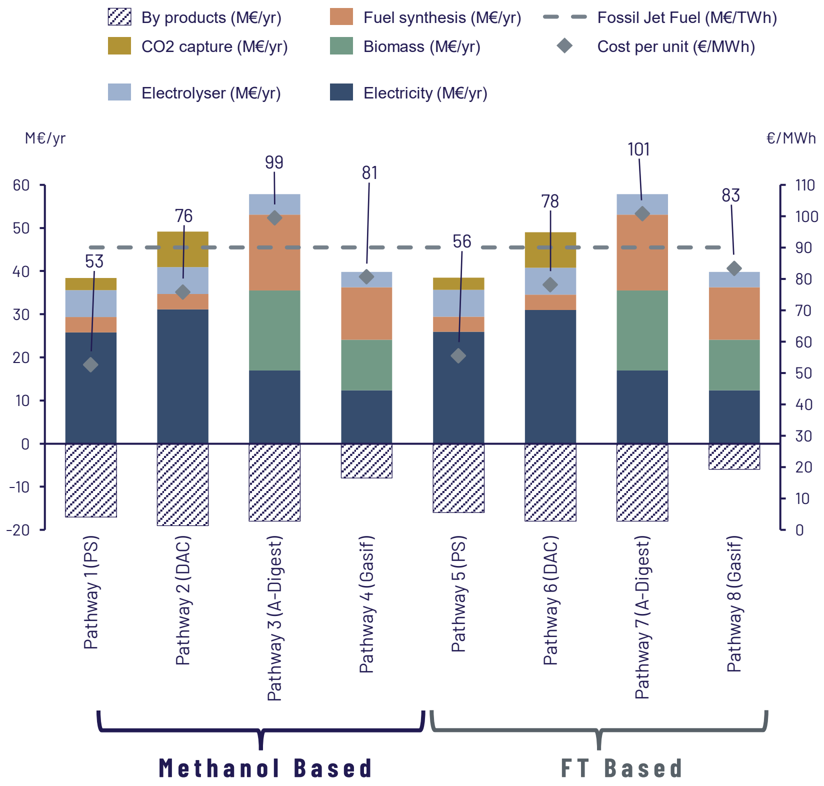


Figure 7. Overview of the annual cost and cost per unit of fuel for a case of alkaline electrolysis and low electricity price including revenue streams from by-products for an expected technology development scenario. The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

Literature-based scenario annual costs and cost per unit – high-temperature electrolysis SOEC and low electricity costs

The use of high-temperature electrolysers enables higher levels of heat integration and increases the efficiency of the pathways as illustrated previously. However, due to the higher CAPEX costs (675 €/kW) compared to alkaline, e-SAF production costs via SOECs are still 1.5 times higher than via low-temperature electrolysers.

Along with high investment costs, a low lifetime of the SOEC cell stack greatly reduces their cost competitiveness with low-temperature electrolysers. The lifetime of the current SOEC cell stack is about 30,000-40,000 hours, which is almost half of the lifetime of AEC, i.e., 85,000 hours.

This, along with the reported high cost of SOEC electrolysers, no large-scale deployment and small-scale production, indicates that SOECs will not significantly contribute to e-SAF production in the immediate future.

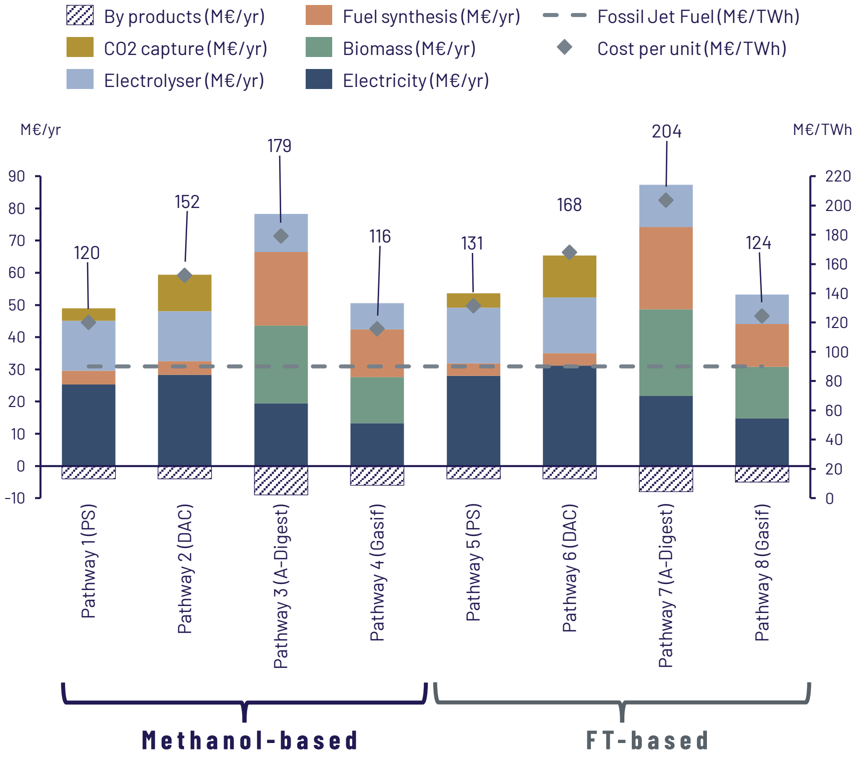


Figure 8. Overview of the annual cost and cost per unit of fuel for a case of SOEC electrolysis (675€/kWe) and low electricity price (30 €/MWh) including revenue streams from by-products for an expected technology development scenario. The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

Expected technology development scenario annual costs and cost per unit – high-temperature electrolysis SOEC and low electricity costs

This figure shows the cost breakdown with the expected technology development scenario and utilizing high-temperature electrolysis SOEC with a low electricity cost of 30 €/MWh.

As expected, the cost per unit production will be reduced in the future due to technological advancements in the fuel production processes. However, the cost of fuel production remains higher than the high-cost point of fossil-based jet fuel accounting for the income from the by-products. However, the cost reduction is significant, making high-temperature electrolysis competitive with low-temperature electrolysis at the locations where by-products cannot be utilised and only in cases where high-temperature electrolysis is co-located with fuel synthesis.

Here we can also note that the cost of electrolysers constitutes a much larger portion of the overall costs when compared with the alkaline-based electrolysers.

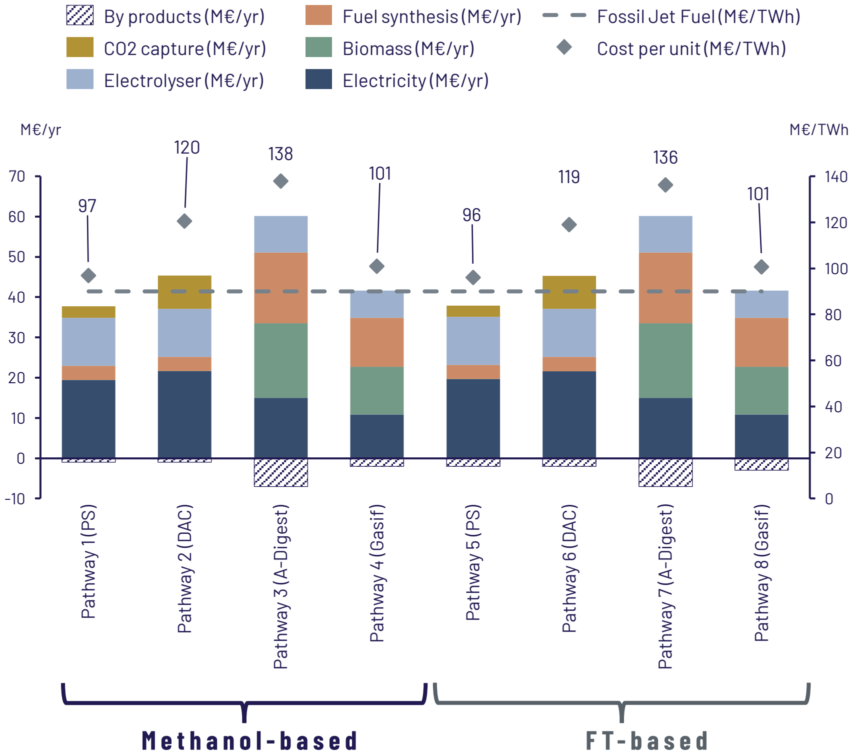


Figure 8. Overview of the annual cost and cost per unit of fuel for a case of SOEC electrolysis (675€/kWe) and low electricity price (30 €/MWh) including revenue streams from by-products for an expected technology development scenario. The dotted line serves as a high reference point value for fossil jet fuel (90 €/MWh). Biomass costs are assumed to be 9 €/GJ.

# III. Comparison e-jet pathways

## Breakeven electricity price for point source pathways with expected technology developments

As highlighted before, the electricity price is the critical element when it comes to the cost competitiveness of e-SAF with fossil-based jet fuel. We have seen that even for a low electricity price of 30 €/MWh, e-SAF produced via alkaline electrolysers and point source $CO_2$ (Pathway 1), has electricity costs corresponding to 70 % of their total annual cost. Hence, it is worthwhile to consider the breakeven electricity price at which e-SAF can become cost-competitive with fossil-based jet fuel.

It can be noted that, in case that the price of fossil jet fuel remains at relatively high levels, such as 90 €/MWh, e-jet fuel could become competitive with an electricity price of 27– 47 €/MWh. The revenue streams from selling by-products such as excess heat and liquid by-products, play an important role in the price competitiveness of e-jet fuel.

For the other pathways utilising DAC and biogenic CO2, the breakeven electricity price is even higher. This implies that under the current conditions, for these pathways to be cost-competitive with fossil jet fuels, electricity prices continuously need to be lower than 20 €/MWh, which is not deemed realistic. Hence, in addition to low electricity prices and the utilisation of by-product revenue streams, a carbon tax on fossil-based jet fuels becomes important for the cost competitiveness of e-SAF.

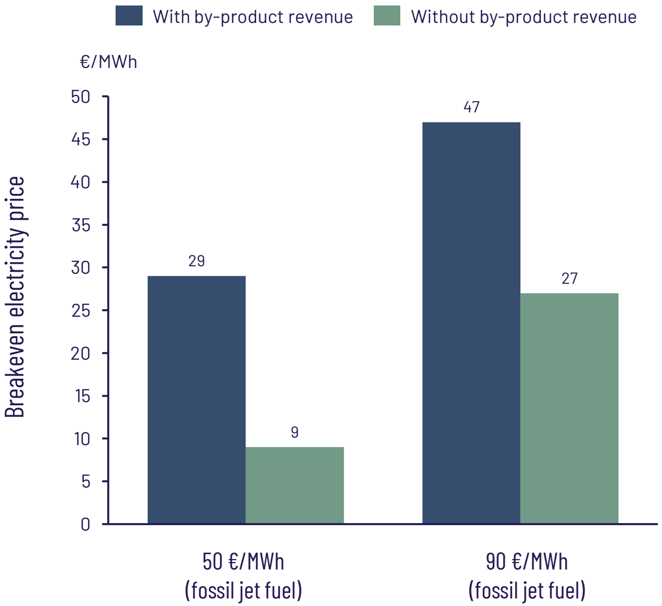


Figure 9. Breakeven electricity price for a point source pathway with and without by-product revenues for 2 fossil jet fuels price levels.

# III. Sensitivity analysis

## Fuel production efficiency as a function of H2/JF ratio for Pathway 1 (PS)

The impact of the hydrogen utilisation rate on the overall pathway efficiency is significant as previously highlighted. It is visible from the figure that the efficiency decreases exponentially with the increase in hydrogen demand per unit of jet fuel.

As the production of electrolytic hydrogen is an energy-intensive process, it has a noticeable impact on the overall efficiency of the e-SAF.

Process improvements in the future need to focus on reducing hydrogen demand per fuel production unit, which can significantly improve the overall efficiencies of the e-SAF pathways.

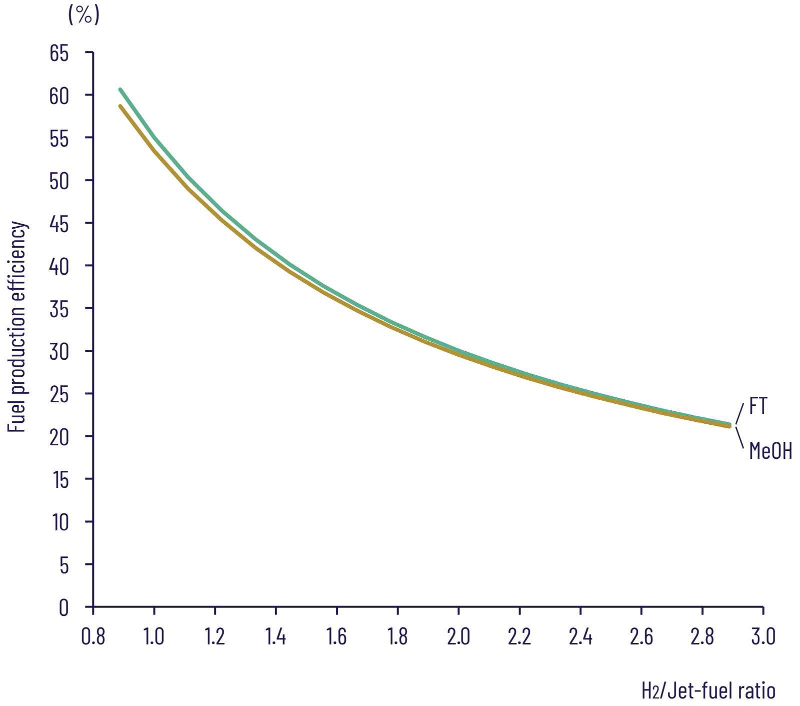


Figure 10. Impact of hydrogen to jet-fuel ratio on fuel production efficiency.

# V. Comparison e-jet pathways

## Challenges and Barriers

From the analysis, certain e-SAF fuel pathways seem like a promising solution for the decarbonisation of the aviation sector. However, in practice, there are a few associated challenges and barriers that need to be addressed:

**Low-cost renewable electricity:** The cost of electricity, primarily for hydrogen production, is the most dominant factor in the e-SAF production. It is imperative to have an abundance of large-scale renewable electricity to make e-SAF competitive and the electricity price development and regulation around it are the most important elements for making e-SAF competitive with fossil jet fuel.

**$CO_2$ availability:** An imperative for producing e-jet is the availability of $CO_2$ either from point sources (biobased due to the regulatory framework for green fuels) or directly through biomass. In the future energy systems with a high share of variable renewables, the operation rates of biomass power plants and combined heat and power plants will not be on the same level as today, and the availability of point source $CO_2$ could become the bottleneck for production of e-SAF and the need for DAC will increase.  Furthermore, these $CO_2$ sources are also under competition from other forms of CCU (plastics etc.) and CCS (achieving negative emissions).

**Biomass availability:** It is visible from the results that biomass gasification-based e-SAF pathways are the least energy and resource-intensive. However, the availability of sustainable biomass such as wood chips or straw etc. in sufficient amounts is essential for the success of biogenic e-SAF pathways.

**Heat integration:** Excess heat is an important by-product of the overall e-SAF pathways. This is especially significant for pathways with point sources and direct air capture of $CO_2$. And since heat integration makes up the bulk of the by-product revenue for e-SAF pathways, this greatly helps improve the overall competitiveness of e-SAF pathways with fossil-based jet fuels. However, in practice, such heat integration demands proximity to the district heating network and co-location of electrolysis and fuel synthesis in the case of high-temperature electrolysis. This requires high levels of contextual infrastructure planning and collaboration among the stakeholders.

**Methanol-to-Jet conversion:** Currently, the literature on methanol-to-jet fuel conversion is scarce, and though jet fuel from methanol is expected to achieve similar efficiency rates as Fischer-Tropsch production pathways, more proof-of-concept plants in form of industrial demonstrations are needed for large-scale take-up of methanol to jet fuel production. Similarly, pending ASTM approval is also an important barrier to the market success of methanol-based pathways.

**FT – Jet fuel production:** The Fischer-Tropsch process has a high level of maturity due to its use in existing industrial coal-to-liquid (CtL) and gas-to-liquid (GtL) plants. The FT process requires CO as a source of carbon rather than $CO_2$. For e-SAF, this needs to be provided either via syngas production (CO+ $H_2$) in the case of biomass gasification or conversion of $CO_2$ to CO via reverse water shift (RWGS).  Since CtL and GtL industrial processes also obtain their CO from gasification rather than RWGS, large-scale demonstration of RWGS is still lacking and requires further industrial demonstration.

# IV. Energy system impacts

# IV. Energy system impacts

## System level effects for future energy systems – case of Denmark 2045

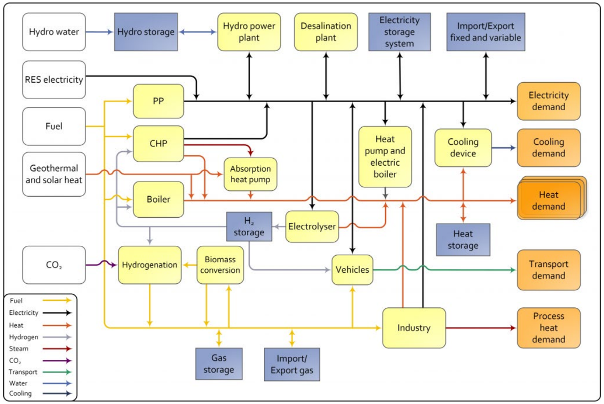
While the cross-comparison of e-SAF pathways highlights specific technological differences and nuances in terms of efficiencies, economy and available by-products, it is important to analyse the system effects of integrating these pathways into the larger energy system. Hereby e-SAF pathways are analysed in the hour-by-hour energy system modelling tool EnergyPLAN, where interactions and their impacts of them can be captured. The outcomes of this analysis can highlight the differences in energy supply needed and the impact on biomass demand. The pathways have been integrated into the energy system model of Denmark for 2045, adapted from Lund et al. 2022[11] to capture the impacts of the expected technological developments in e-SAF routes. The 2045 model represents a fully decarbonized model of Denmark that has 100% renewable energy supply.

These pathways are analysed as extreme cases and the forecasted Danish aviation fuel demand for 2045 of 10.15 TWh is met by each of these. The demand reflects not only the Danish domestic aviation fuel demand but also 50% of the international aviation demand and 100% of the Danish transit demand in other countries. The Danish reference model has e-fuels integrated in the system and only jet-fuel production has been investigated.

The four pathways have been compared to the reference model in terms of primary energy supply, renewable energy integration and electrolysis. The analysis also included reflections on the availability of CO2 and biomass consumption per capita to give indications on the feasibility of choosing some of the pathways.

Energy PLAN

Advanced energy
system analysis
computer model



# IV. Energy system impacts

## System level effects for future energy systems – case of Denmark 2045

The system effects of implementing different pathways in the Danish energy system scenario for 2045 are illustrated on the right. All e-SAF scenarios are technology-insensible concerning FT-to-jet or Methanol-to-jet route due to minor differences between the technologies in the future.

The results reflect the differences between the efficiencies that have previously been highlighted for different pathways resulting in the highest primary energy supply for the direct air capture and biogas-based pathways. The elevated energy consumption in the DAC pathway and the substantial biomass demand for the biogas pathway are the primary reasons for this.

The gasification pathway results in the lowest system costs and the lowest primary energy supply. However, this pathway has a higher biomass demand than the reference case, which raises the question of biomass availability and sustainability. The point source pathway reduces the biomass demand within the system but has the highest electricity demand from solar and wind apart from DAC.

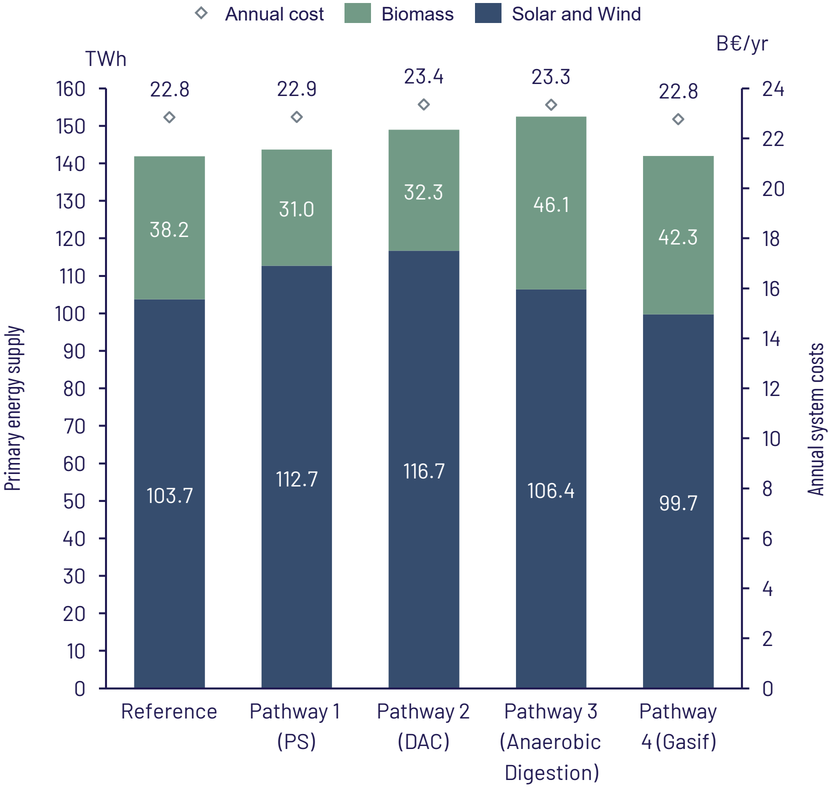


Figure 11. Primary energy supply and annual system cost results for 4 e-SAF pathways on the overall Danish energy system in 2045

AALBORG UNIVERSITY

# IV. Energy system impacts

## System level effects for future energy systems – renewable energy capacities

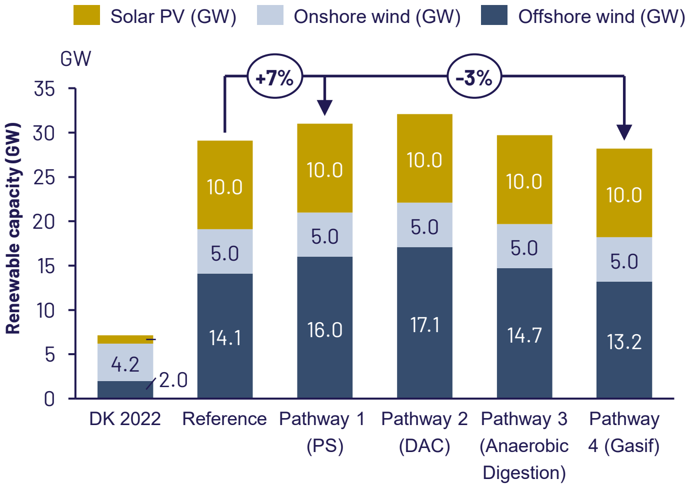
The figure on the right depicts the main renewable capacities that are needed in the overall energy system to meet the demand. If compared to the capacities installed in the system in 2022, it is visible that there is a high need for large expansions of renewable energy in Denmark to fully transition to 100% renewable supply.

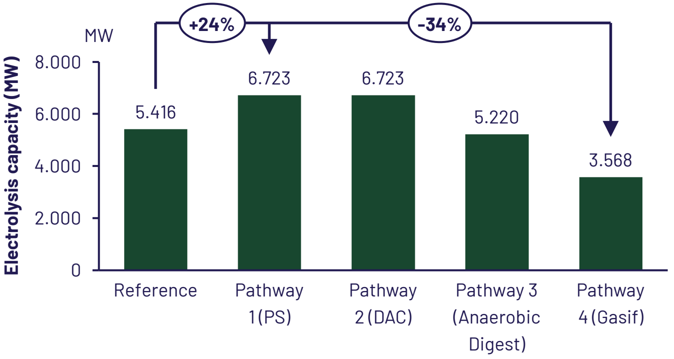
Meeting the jet-fuel demand with some of the pathways (pathway 1-3) increases the need for renewable capacities. The variations between the capacities are reflected on offshore wind installations as these were varied to maintain the transparency between the scenarios.

Due to the efficiency trends, the point source pathways and DAC require the highest renewable installed capacities. An increase of 7% in the needed capacities can be seen for the point source pathway, while the gasification pathway requires 3% fewer offshore installations resulting in 13 GW.

The pathways also vary in the needed electrolysis capacity related to the hydrogen-to-fuel ratio. If a biomass gasification pathway is chosen, the electrolysis capacity can be reduced by almost 50% in comparison to the point source pathway.

This leads to the question of the availability of $CO_2$ and biomass, as these can give indications of whether it is possible to use these pathways to such a large extent.





AALBORG UNIVERSITY

# IV. Energy system impacts

## System level effects for future energy systems – CO2 availability and biomass demand per capita

The availability of CO2 for producing e-SAF via the point source pathway is crucial. To meet the Danish aviation demand 3.6 Mt of CO2 is needed. As illustrated in the figure, in the reference scenario, 1.4 Mt is used for e-fuel production, but it is expected that 5.6 Mt of CO2 is available for capture of which almost 3 Mt is expected to come from the industrial sector. It appears that there might be a sufficient supply of CO2 available, suggesting the feasibility of employing the point source pathway to mitigate the impact of increased biomass demand for the biomass gasification pathway.

If applied, the biomass gasification pathway will result in an increased biomass demand of 25 GJ/capita. According to Lund et al. 2022,[12] Denmark should limit itself to the Danish share of sustainable biomass (26 GJ/capita) which is on the high end of the global estimates of 10-30 GJ/capita.

It is, however, not expected that one of the pathways will be chosen to meet the total aviation demand, and therefore the integration of the different pathways will result in a more balanced approach to CO2 utilisation and biomass demand.

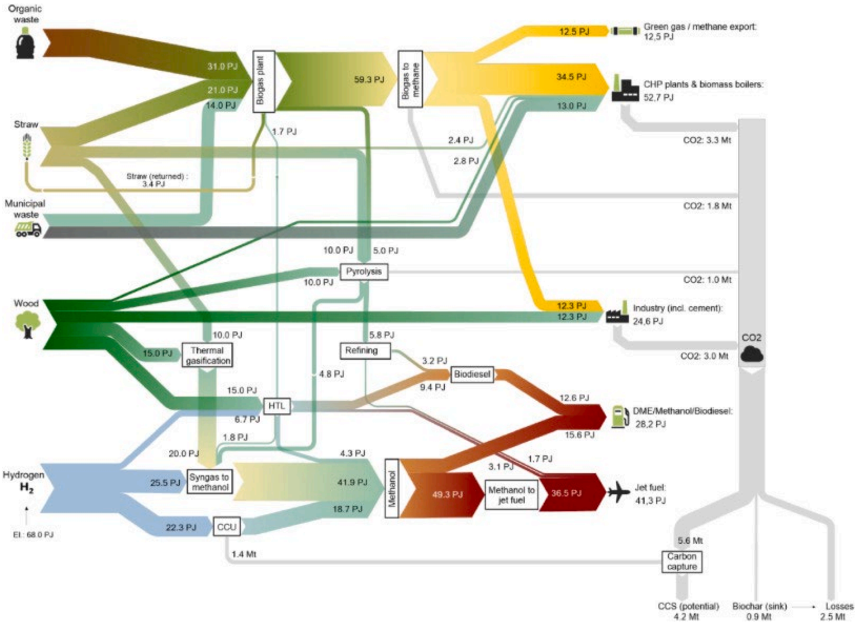


Figure 12. Biomass and CO2 balance in IDA's Climate Response scenario of Denmark year 2045[12], depicting a biomass demand of 23 GJ/capita

# V. Conclusion and future perspectives

# V. Conclusion and future perspectives

The cost of electricity is the main determining factor of the price-competitiveness of e-SAF with fossil-based jet fuel. Storing electricity in the form of fuels requires significant reductions in electricity prices to make these pathways competitive with fossil alternatives or increase the prices of fossil fuel alternatives. The analysis indicates that it is possible for e-SAF produced via electricity sourced from dedicated offshore wind plants (LCOE of 30 €/MWh) to become cost-competitive with their fossil counterparts.

The choice of $CO_2$ source greatly influences the energy efficiency and resource consumption of the e-SAF pathways but also highlights the potential issues of $CO_2$ and future biomass availability in the future that can be used for jet fuel production. It is worth highlighting the fact that the biomass consumption in the e-SAF pathways is significantly lower than for bio-SAF. The hydrogen share in the production process has a significant impact on the efficiency of the pathways and hereby also the costs.

Utilising revenue streams from by-products, and hereby to a large extent utilising excess heat, can benefit the price reduction but is also highly dependent on the possibility of connecting to the district heating network. This influences the infrastructure planning process and the decision on which electrolysis technology is more suitable. However, when using high-temperature electrolysis, the co-location of electrolysis and fuel synthesis is necessary to harvest the improvements in the efficiency that can be achieved by synergies of heat integration within the process. . It should be noted, though, that the high cost of the SOECs influences the competitiveness of this technology and its role in near-term investments in e-jet production.

Due to the technological developments, it is expected that the efficiency of both FT and methanol-jet routes will be rather aligned. The flexibility of the methanol route seems to be able to provide additional benefits to the overall implementation. The methanol route is applicable to the smaller scale production sites (decentralisation) and could also enable the utilisation of by-products and minimise the need for additional infrastructure such as for hydrogen or $CO_2$. With methanol as a median product that can be transported but also used directly it offers a more versatile value chain.

Even though e-SAF is included in the EU regulation, the promotion of higher blends for e-SAF could minimise biomass needs and sustainability issues of bio-SAF pathways.

# V. Data, assumptions and references

# V. Data and Assumptions

| | | | |
|---|---|---|---|
| **Jet fuel upgrading** | | | |
| Methanol to Jet (%) | 74 % | [1], [2] | Assumed state of the art |
| FT fuel to jet fuel (%) | 82 % | [3] | Assumed state of the art |
| Methanol Production | | | |
| Output heat (MWh/MWh total input) | 0,2 | [4] | Steam temperature of 50 -100 C |
| Input H2 (MWh H2/MWh methanol) | 1,2 | [4] | |
| Input CO2 (ton/MWh Methanol) | 0,25 | [4] | |
| Input Electricity (MWh/MWh methanol) | 0,02 | [4] | |
| Input heat (MWh/MWh methanol) | 0,1 | [4] | Input steam temperature of 184 C |
| Capital costs (M€/MW) | 0,8 | [5] | Authors assume similar cost for both FT to jet and methanol to jet synthesis |
| Lifetime (years) | 30 | | |
| Discount rate (%) | 3 | | |
| Fixed O and M (% of capex) | 3 % | [4] | |
| **FT Production** | | | |
| Output heat (MWh/MWh total input) | 0,2 | [4] | Output temperatures of 220-250 C |
| Input H2 (MWh H2/MWh FT fuel) | 1,4 | [5] | |
| Input CO2 (ton/MWh FT fuel) | 0,3 | [4] | |
| Input Electricity (MWh/MWh FT fuel) | 0,007 | [4] | |
| Capital costs (M€/MW) | 0,8 | [5] | Authors assume similar cost for both FT to jet and methanol to jet synthesis |
| Fixed O and M (% of capex) | 3 % | [4] | |
| **Point Source Capture** | | | |
| Output heat (MWh/ton CO2) | 0,72 | [6] | Post combustion carbon capture, large scale biomass plant (100 MW thermal). Heat output temperature of 60 C |
| Input electricity (MWh/ton CO2) | 0,025 | [6] | |
| Input heat (MWh/ton CO2) | 0,72 | [6] | Almost similar output and input heat but input heat temperature range from 130-150 C |
| Capital costs (M€/ton CO2/hr) | 2,3 | [6] | |
| Fixed O and M (% of capex) | 3 | [6] | |
| Lifetime (years) | 25 | [6] | |
| **Direct Air Capture** | | | |
| Output heat (MWh/ton CO2) | 1 | [6] | Output heat temperature of 50 |
| Input electricity (MWh/ton CO2) | 0,32 | [6] | |
| Input heat (MWh/ton CO2) | 2 | [6] | Input heat temperature of 100 |
| Capital costs (M€/ton CO2/hr) | 6 | [6] | |
| Lifetime (years) | 20 | [6] | |
| Fixed O and M (% of capex) | 4 | [6] | |
| **High temperature water electrolysis (SOEC)** | | | |
| Input electricity (MWh/MWh output) | 1 | [4] | SOEC 1 MW plant, input needed when heat input available |
| Input electricity (MWh/MWh output) | 1,25 | [4] | SOEC 1 MW plant, input needed when no heat input available |
| Input heat (MWh/MWh output) | 0,25 | [4] | SOEC 1 MW plant; input heat temperature of 130 -150 C |
| Capital costs (€/kWe) | 675 | | Based on industrial input; assumed 1,5 times the capex of AEC |
| Stack lifetime (hrs) | 30,000-<br>40,000 | | Based on industrial input |
| Stack replacement cost (% of capex) | 20 | [4] | |
| Technical plant lifetime (years) | 20 | [4] | |
| Fixed O and M (% of capex) | 2 | [5] | Assumed similar to AEC |
| Operating hours | 4468 | | Based on electricity generation by offshore wind |

# V. Data and Assumptions

| | | | |
|---|---|---|---|
| **Low temp water electrolysis (Alkaline)** | | | |
| Input electricity (MWh/MWh output) | 1,5 | [4] | |
| Output heat (MWh/MWh output) | 0,24 | [4] | Recoverable heat of 50 – 60 C |
| Capital costs (€/kWe) | 450 | [4] | |
| Stack lifetime (hrs) | 85000 | | Based on industrial input |
| Stack replacement cost (% of capex) | 30 | [4] | |
| Technical lifetime (years) | 30 | [4] | |
| Fixed O and M (% of capex) | 2 % | [5] | |
| Operating hours | 4468 | | Based on electricity generation by offshore wind |
| **Anaerobic Digestion** | | | |
| Output biogas per input (GJ/tonnes) | 0,8 | [4] | |
| Energy content wet biomass LHV (MJ/kg) | 11,42 | [7] | |
| Input electricity (KWh/tonne biomass) | 8 | [4] | |
| Input heat (KWh/tonne biomass) | 18,6 | [4] | |
| Capital costs (M€/MW output) | 1,54 | [4] | |
| O and M (% of capex) | 7 | [4] | |
| Lifetime (years) | 20 | [4] | |
| **Biomass Gasification** | | | |
| Syngas to methanol ratio (MWh/MWh) | 0,73 | [8] | |
| Syngas to FT ratio (MWh/MWh) | 0,6 | [9] | |
| Gasifier efficiency (%) | 77 | [4] | |
| Hydrogen to methanol ratio (MWh/MWh) | 0,61 | [8] | For upgrading the H2/CO ratio of syngas for methanol synthesis |
| Hydrogen to FT ratio (MWh/MWh) | 0,74 | [8] | For upgrading the H2/CO ratio of syngas for FT synthesis |
| Energy content dry biomass LHV (MJ/kg) | 21 | [2] [9] | Dry wood |
| Capital costs (M€/MW output) | 2,92 | [4] | Values for methanol production from biomass gasification. Similar costs are assumed for FT production from biomass gasification |
| O and M (M€/TWh/yr) | 0,039 | [4] | |
| Lifetime (years) | 20 | [4] | |
| Operating hours | 8585 | [4] | |
| Costs of dry biomass (€/GJ) | 9 | [10][11] | |
| **Methanation** | | | |
| Output heat (MWh/MWh input) | 0,1 | [4] | |
| Output methane (MWh/MWh input) | 0,89 | [4] | |
| Input biogas (MWh/MWh total input) | 0,53 | [4] | |
| Input hydrogen (MWh/MWh total input) | 0,46 | [4] | |
| Capital costs (M€/MW output) | 0,76 | [4] | |
| O and M (M€/MW output/yr) | 0,03 | [4] | |
| Lifetime (years) | 25 | [4] | |

# V. Data and Assumptions

| | | | |
|---|---|---|---|
| **Partial Oxidation + Jet Fuel Production** | | | |
| Process efficiency (%) | 65 % | [12] | Values for overall partial oxidation and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| Output heat (% of output) | 50 % | [12] | Values for overall partial oxidation and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| Input Methane (TWh/TWh jet fuel) | 2,56 | [12] | Values for overall partial oxidation and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| **Steam Reforming + Jet Fuel Production** | | | |
| Process efficiency (%) | 50 % | [12] | Values for overall steam reforming and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| Output heat (% of output) | 50 % | [12] | Values for overall steam reforming and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| Input Methane (TWh/TWh jet fuel) | 3,34 | [12] | Values for overall steam reforming and jet fuel production combined via FT synthesis. Similar values for methanol synthesis are assumed |
| **Electricity** | | | |
| Cost of electricity - grid (M€/TWh) | 92 | [13] | Non household electricity price including taxes avg for past 5 years, for consumers with consumption between 20,000-70,000 MWh |
| Cost of electricity – offshore wind (M€/TWh) | 30 | [10] | Estimated cost of electricity production from offshore wind in Denmark |
| **By product potential market price** | | | |
| Low temp DH (M€/TWh) | 53 | [14] | By product of low temp electrolysis, fuel synthesis and carbon capture processes.<br>DEA 2024 price cap of surplus excess heat price of 110 DKK/GJ |
| Naptha (M€/TWh) | 31 | [9] | By product of FT – jet fuel conversion |
| LPG equivalent (M€/TWh) | 43 | [9] | By product of methanol - jet conversion |
| Oxygen (€/tonne) | 50 | [1] | By-product from electrolysis |

# V. References

[1] M. Grahn et al., “Review of electrofuel feasibility - Cost and environmental impact,” Prog. Energy, vol. 4, no. 3, pp. 0–28, 2022, doi: 10.1088/2516-1083/ac7937.

[2] A. D. Korberg, B. V. Mathiesen, L. R. Clausen, and I. R. Skov, “The role of biomass gasification in low-carbon energy and transport systems,” Smart Energy, vol. 1, 2021, doi: 10.1016/j.segy.2021.100006.

[3] TOPOSE, “Technology for converting CO2 and renewable energy to synthetic fuels - White Paper.”

[4] Danish Energy Agency, “Page 1 | 259 - Technology Data for Renewable Fuels,” pp. 1–259, 2017, [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

[5] F. E. Agora Energiewende, “The future cost of electricity based synthetic fuels,” 2018.

[6] Energistyrelsen Danish Energy Agency, “Page 1 | 151 - Technology Data for Carbon Capture, Transport and Storage,” pp. 1–151, 2021.

[7] “Livestock and poultry environmental learning community.” https://lpelc.org/what-is-the-energy-value-btu-lb-of-livestock-manure-our-manure-source-is-dairy-solids-that-are-separated-from-the-slurry-at-about-60-moisture-we-want-to-reduce-that-moisture-further-and-burn-the-f/ (accessed Aug. 11, 2023).

[8] L. R. Clausen, “Integrated torrefaction vs. external torrefaction - A thermodynamic analysis for the case of a thermochemical biorefinery,” Energy, vol. 77, pp. 597–607, 2014, doi: 10.1016/j.energy.2014.09.042.

[9] M. Hillestad et al., “Improving carbon efficiency and profitability of the biomass to liquid process with hydrogen from renewable power,” Fuel, vol. 234, no. June, pp. 1431–1451, 2018, doi: 10.1016/j.fuel.2018.08.004.

[10] “IDAs Klimasvar 2045-Sådan bliver vi klimaneutrale KORT FORTALT.”

[11] IRENA, Biofuels for Aviation. 2017.

[12] A. Winter Mortensen, W. Henrik, K. Dalgas Rasmussen, S. Sandermann Justesen, E. Wormslev, and M. Porsgaard, Nordic GTL: A pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO2. 2019.

[13] “Energy prices - Statistics Denmark.” https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/energiforbrug-og-energipriser/energipriser (accessed Oct. 09, 2023).

[14] “Nyt prisloft for overskudsvarme | Forsyningstilsynet.” https://forsyningstilsynet.dk/nyheder/2023/nov/nyt-prisloft-for-overskudsvarme (accessed Jan. 04, 2024)