SUSTAINABLE AVIATION

A SPATIAL PLANNING PERSPECTIVE ON SOURCING FEEDSTOCK FOR A METHANOL-TO-JET PRODUCTION TO COVER THE FUEL DEMAND AT CPH AIRPORT IN 2050

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Abstract:

The current state of climate change emphasises the need for new practices and technologies, to phase out conventional fossil fuels, which currently contribute significantly to climate change. As most sectors are able to directly electrify, some sectors, including the aviation sector, are currently unable to do so. As the demand for aviation continues to grow, where the sector currently accounts for 2-3 % of global emissions, it is important to uncover how this sector can reach climate neutrality. in light of this, international and regional plans have been proposed to replace fossil fuel with alternative fuels such as e-SAF. To assess the transition towards e-SAF the fuel demand at CPH Airport in 2050 has been estimated. This has enabled an estimation in domestic feedstock demand to produce e-SAF to cover the fuel demand at CPH Airport. Based on the sources of feedstock supply and expenses of the required technologies for e-SAF production, it is estimated that e-SAF will be more expensive than fossil fuel. However, by driving down the electricity price, the cost gap between e-SAF and fossil fuel is lowered significantly. Additional economic instruments such as CO_2 taxation and system integration of e-SAF production can ensure competitiveness of the e-SAF product. Despite the apparent opportunities of e-SAF, uncertainties and challenges remain regarding renewable power production, which risks jeopardising domestic e-SAF production to cover the fuel demand at CPH Airport.

Preface

This report is written with an equal contribution from both authors. The report has benefited from a close discourse with supervisor, Iva Ridjan Skov, who has given precise and concrete supervision regarding the direction of the project. In addition, the project has benefited from conversations with four key actors in the field of e-SAF. The four external key actors are as follows:

- Morten Poulsen - GrønAgenda
- Martin Hartvig - EnergiNet (Danish TSO)
- Peter Wiboe Holm - CPH Airport
- Thomas Bo Sørensen - DANVA

The key actors have each contributed with sector specific insights, as well as general thoughts regarding implementation of e-SAF and generally Power-to-X products in the Danish energy system.

In answering the research question, the data manipulation software, QGIS has given a geographic aspect to the report and enabled precise estimations. Additionally, Excel and EnergyPLAN have been utilised to perform calculations present in this report.

In relation to this report, the following appendices are attached:

- Appendix A* - Interview with Morten Poulsen
- Appendix B* - Interview with Martin Hartvig
- Appendix C* - Interview with Peter Wiboe Holm
- Appendix D* - Interview with Thomas Bo Sørensen
- Appendix E - Excel sheet with calculations
- Appendix F - EnergyPLAN output of e-SAF scenario for 2050
- Appendix G - EnergyPLAN output of fossil scenario for 2050

(* *Confidential*)

Abbreviations List

bio-SAF	Biomass-derived Sustainable Aviation Fuel(s)/bio-jet fuel(s)	ktonne	Kilotonne
CAPEX	Capital Expenditure(s)	Kerosene	Petroleum-derived hydrocarbon fuel commonly known as jet fuel
CO_2	Carbon Dioxide	kg	Kilogramme
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation	MEUR	Million Euros
CPH Airport	Copenhagen Airport	Mt	Megatonne
DAC	Direct Air Capture	MtJ	Methanol-to-Jet synthesis process
e-Diesel	Synthetically produced diesel	MW	Megawatt
e-Kerosene	Synthetically produced kerosene	MWh	Megawatt hour
e-SAF	Green hydrogen-derived synthetically produced Sustainable Aviation Fuel(s)	OPEX	Operating Expenditure(s)
EU	European Union	PJ	Petajoule
EU ETS	EU Emissions Trading System	PtL	Power-to-Liquid
FT	Fischer-Tropsch synthesis process	PtX	Power-to-X
GHG	Greenhouse Gas	PV	Photo Voltaic Panels
GW	Gigawatt	R&D	Research & Development
H_2	Hydrogen	RPK	Revenue Passenger Kilometres
HEFA	Hydroprocessed Esters and Fatty Acids	SAF	Sustainable Aviation Fuel(s)
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene	SIP	Synthesized Iso-Paraffinic Fuels
HVO	Hydrotreated Vegetable Oils	TJ	Terajoule
IATA	International Air Transport Association	TSO	Transmission System Operator
ICAO	International Civil Aviation Organisation	UN	United Nations

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Introduction 1

Denmark, as well as several other countries, is in the midst of an ongoing green transition in order to address climate change and limit global warming, as symbolised by adopting the *Paris Agreement*, the *European Climate Law*, as well the *Danish Climate Act* in recent years (UNFCCC, 2016; European Commission, 2020; The Danish Ministry of Climate, Energy and Utilities, 2020).

One of the main factors causing global warming is the utilisation and combustion of fossil fuels, which contributes significantly to global warming (IPCC, 2022).

The original political reason for addressing these practices was, however, not global warming, but the oil crises during the '70s and '90s, which exposed European countries to the dependence of fuel imports. The oil crises caused an economic downturn, as oil prices spiked. This affected the whole of the society, as transport, electricity generation and heating depended on oil imports. As a response, the political discourse changed, and energy policies began focusing on alternative, domestic production to limit the dependence on imported fuels. This resulted in explorations to uncover potential oil and gas reserves within the domestic borders, but also the widespread implementation of renewable energy in the energy systems. The path towards energy Independence later evolved into decreasing CO_2 emissions to mitigate climate change, as renewable energy holds the key to achieving a climate-neutral energy system while maintaining or increasing the energy supply. Additionally, electricity generation from renewable sources has, through development, enabled a much lower electricity price, which further incentivises the expansion of renewables. As of 2022 renewable electricity generation amounted to 51 % of the primary energy production in Denmark (The Danish Energy Agency, 2015, 2023).

The current Russo-Ukraine war has meanwhile reignited the political interest for energy independence, as the EU and Denmark import substantial amounts of natural gas and oil from Russia. Although most sectors are technically able to transition from fuels to electricity, some sectors are currently not able to do so. One sector which is associated with significant challenges hereof is the aviation sector (European Union, 2023; Smed et al., 2022).

Additionally, the aviation sector accounts for about 3% of global CO_2-emissions, contributing significantly to global warming (Ritchie et al., 2019; IEA, 2019). Therefore, to enable the independence of imported fossil fuels and eliminate emissions within the sector, a sustainable and domestically produced alternative would be necessary to ensure independence from outside factors while mitigating climate change. The present project therefore delves into the challenges and possibilities for domestic sustainable fuel production to cover the fuel demand at the largest Danish airport by 2050.

Problem Analysis 2

This chapter presents the problem analysis, wherein the context and background for the scope of the present project is analysed and examined. The chapter is divided into the following sections: Introduction, Relevant Legislation & Targets, Sustainable Alternatives to Fossil Air Travel, and Feedstock Challenges and Opportunities for sustainable fuel alternatives for aviation.

2.1 Contextualisation

Greenhouse Gas Emissions (GHG-emissions) from human activities across trall sectors and industries conibute to the gradual warming of the globe, which leads to the earth's ecosystems reaching their respective tipping points. Consequently, all industries must swiftly transition from utilisation of fossil fuels towards sustainable pathways to reduce GHG emissions and thereby prevent irreversible damage to as many ecosystems as possible (IPCC, 2022).

Currently, the aviation sector accounts for approximately 3 % of the global GHG emission (Ritchie, 2020). Although this might seem insignificant, the sector is on course to account for a much larger share of emissions as other sectors gradually reduce their emissions through electrification, and the demand in the aviation sector increases (Bube et al., 2024). To express this numerically, CO_2 emissions from the aviation sector have increased at a rate of approximately 2.3 % per year since 1990, where it is anticipated that the emissions levels will surpass the current peak level observed in 2019 by 2025. Measures and changes are, therefore, needed to reduce emissions from the aviation sector to get on track with international and national pledges for GHG reduction and follow suit with other sectors (International Energy Agency, 2023).

For aviation, direct electrification and hydrogen pathways remain improbable on the global and regional scale in the near future, however, research in these pathways remains steadfast, as they can provide substantial reductions of GHG-emissions on short-haul flights (Bitossi et al., 2020; International Energy Agency, 2023). This thesis takes departure in the challenges of reducing emissions from medium- to long haul flights, where alternative modes of propulsion seem unlikely to substitute conventional jet engines.

The following sections delve into relevant legislation, technical possibilities for aviation to reduce GHG emissions, as well as the challenges associated with this transition from a Danish perspective.

2.2 Relevant Legislation & Targets

To govern aviation emissions, a legislative framework is a necessity, as the sector otherwise is encouraged to utilise fossil fuels as long as crude oil is associated with low costs. This section, therefore, describes relevant proposed and adopted legislative packages for the aviation sector on international, regional, and national arenas, as these are indicative of the development of the sector towards climate neutrality.

2.2.1 International Legislation

On an international level, the International Civil Aviation Organisation, known as ICAO, is the agency responsible for governing the aviation sector U.S. Mission to ICAO (nd). Established in 1947, the organisation operates within the United Nations. The Agency therefore encompasses all member states (ICAO, ndb). In addition, it encompasses the global aviation sector, including manufacturers, airlines and airports. The organisation works in close relation with regional aviation agencies, to ensure that minimum requirements for aviation security are met globally. Furthermore, ICAO formulates policies and standards for the sector (ICAO, nda).

In the wake of the Paris Agreement in 2015, ICAO put forth four initiatives to reduce emissions from aviation on a global scale, dubbed 'basket of measures'. These measures aim to reduce emissions significantly within the sector and aim to reach net-zero emissions by 2050. These include R&D in Aircraft Technologies, Operational Improvements for operators and airports, Implementation of Sustainable Aviation Fuels (SAF), and the CORSIA scheme, which is described in the following section(UNFCCC, 2018).

CORSIA

The most notable measure within the 'basket of measures' is the *CORSIA* scheme, as this enables the sector to reduce emissions without significant technical overhauls. CORSIA is the abbreviation for *Carbon Offsetting and Reduction Scheme for International Aviation.*

The CORSIA scheme mandates that every UN member state, excluding least developed countries, underdeveloped island states, and underdeveloped landlocked states, has to offset their remaining emissions from aviation, from 2027 to 2035 to maintain the sectors annual emissions at 2020-level (UNFCCC, 2018).

A critical aspect of CORSIA is monitoring offsets, as offsets historically have been associated with false claims (Anderson, 2012). Therefore CORSIA contains numerous requirements for offsets to ensure transparency (ICAO, 2019).

The emissions targets and measures put forward by ICAO must be supported by regional and national targets to be successfully enforced, hence the following section delves into regional and national targets and measures.

2.2.2 Regional Legislation

On a regional level, the EU has been one of the main drivers for the reduction of GHG emissions, where they define specific emissions reduction targets, principles, and measures for the aviation sector. These are described in depth in the following sections.

EU ETS

One major step in governing emissions from aviation, was the introduction of aviation emission in the *EU Emissions Trading System*, also known as *EU ETS*, in 2012. This means that operators operating within Europe have a certain amount of carbon allowances, where one allowance permits the operator to emit one tonne of CO_2e. Based on emissions history, a certain amount of allowances are allocated to each operator, after which they are free to buy or sell allowances to other operators to balance emissions accounting. Each year a certain number of allowances are surrendered based on emissions from the previous year, resulting in a smaller pool of allowances, driving up the cost of each allowance. This forces operators to reduce emissions, as sustainable pathways become more economically attractive than the cost of allowances. In addition, a penalty of 100 EUR per tonne of CO_2e emitted without allowances is applied. Only internal flights in the European Economic Area are included, meaning that substantial amounts of emissions deriving from airports within the European Economic Area remain unaccounted for (European Commission, nd).

REfuelEU Aviation

As part of the Fit for 55 package, *RefuelEU Aviation* is the legislative package for the European aviation sector. The package was adopted in October 2023 with the primary purpose of reducing GHG emissions and increasing the demand for SAF in the aviation sector, thus aligning this sector with the targets of the EU's Climate Law (European Union, 2023).

The package mandates a gradual increase of the minimum share of SAF in fuel blends for aircraft operators at airports in Europe. From 2025, operators are required to use a minimum share of 2 % of SAF in fuel blends, which gradually increases to 70 % in 2050 (European Union, 2023). As SAF includes both biofuels (bio-SAF) and synthetic fuels (e-SAF), a sub-mandate for e-SAF minimum shares in fuel blends is also applied. This is included as a supplement to the overall SAF targets, as it would ensure that the production and utilisation of bio-jet fuels are restricted due to its associations with Land Use Change (European Union, 2023).

The criteria for eligible varieties of SAF are defined by the *Renewable Energy Directive II*, hence the targets of RefuelEU Aviation are designed to comply with that (European Union, 2023; European Commission, 2023).

An overview of the specific targets is listed in the table below.

Table 2.1. Overview of minimum share of SAF and e-SAF in fuel blends from 2025-2050 (European Union, 2023).

Fuel Blend %	2025	2030	2035	2040	2045	2050
Minimum Share of SAF	2 %	6 %	20 %	34 %	42 %	70 %
Minimum Share of e-SAF	-	1.2-2.0 %	5 %	10 %	15 %	35 %

In addition to fuel blend targets, provisions to avoid fuel tankering practices are also included in the legislative package, as operators tend to overfuel at airports with lower fuel prices. The rationale behind this objective is that flying with excess fuel leads to increased emissions and fuel consumption due to heavier takeoff- and landing weights. In addition, it also ensures that flights departing from EU airports are filled with fuels that conform with the minimum SAF and e-SAF blend shares presented above (European Union, 2023).

2.2.3 National Legislation

An equivalent ambition to reduce GHG emissions from the aviation sector is also present on the Danish national level, as international and regional legislation functions as the framework for national legislation.

Danish PtX Strategy & Agreement

This ambition is reflected in the *Danish Power-to-X Strategy*, and the subsequent agreement ratifying the strategy. In this agreement, a target for hydrogen electrolysis capacity has been set, which is 4-6 GW before the year 2030. From this capacity, Power-to-X products such as Green Hydrogen, Methanol, e-SAF, Ammonia, and so forth can be produced, which entails that Denmark is indirectly committed to the e-SAF pathway for reducing emissions in the aviation sector (The Danish Government, 2022a).

Despite a capacity target being set, there is no exact distribution defined between the production of the above-mentioned PtX products in the agreement. Instead, it has been decided from a political standpoint that the distribution is dictated by market conditions. Therefore, it is up to each project partner to determine the course of their projects in terms of what should be produced (The Danish Government, 2022a).

As of March 2024, an extensive list of PtX projects has been announced, which, if realised, accumulate to an expected production capacity of 17.8 GW in 2030. From this, it is claimed that the aviation sector will be able to absorb approximately 1.2 GW of the total capacity, which translates to 2̃36.000 tonnes of e-SAF (Brintbranchen, 2024).

2.3 Sustainable Alternatives to Fossil Air Travel

The general trend across sectors is to electrify as much as possible, to enable high efficiency and eliminate emissions. In the transport sector, this is ideally achieved through rechargeable batteries, however, it is currently only possible to transition to batteries in aviation to a limited extent (Edelenbosch et al., 2022; Gray et al., 2021). The next best alternative, utilisation of green hydrogen through fuel cells or combustion, is also associated with uncertainties regarding R&D (Gray et al., 2021). There are currently concepts and interest in the field of hydrogen and electric propulsion, which suggests that commercial hydrogen aircraft for short- and medium-haul flights could be implemented before 2040, however, it is still riddled with uncertainties (Airbus, 2024; Reed, 2021). The general expectation in aviation is that battery- and hydrogen-propelled planes will replace a portion of the current fleet on short- and medium-haul flights towards 2050, while conventional propulsion will remain on long-haul flights (Gray et al., 2021; Bergero et al., 2023). central reasons behind this come down to the technical properties of batteries, hydrogen and conventional jet fuel, which are delved into in the following sections.

2.3.1 Technical Barriers for Other Modes of Propulsion

Compared to the remaining transport sector, the aviation sector is currently limited to long-chain hydrocarbon fuels. This can by in large be pertained to the energy needs for aircraft during take-off and landing, combined with longer routes relative to road and rail transport (Hepperle, 2012).

For planes to take off, they need a fuel with low weight relative to its energy content (Hepperle, 2012). This is dubbed 'gravimetric energy density'. Furthermore, they require a fuel with low volume relative to its energy content to contain the fuel in as small an area as possible, making room for passengers and goods. This is dubbed 'volumetric energy density'.

Figure 2.1 illustrates the volumetric and gravimetric energy densities of various fuels, including batteries, hydrocarbon chain fuels, and non-carbon fuels:

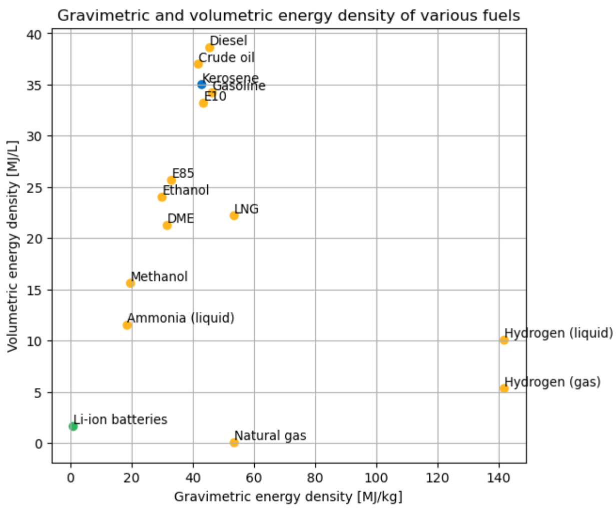

Figure 2.1. Gravimetric and volumetric energy density of various fuels (Data from (Yin et al., 2018; Bitossi et al., 2020)).

As shown in Figure 2.1, the volumetric and gravimetric energy density of Lithium-ion batteries are low relative to conventional fuels derived from refining crude oil, which all have similar characteristics regarding energy density. Interesting to note is that liquid hydrogen has a high volumetric energy density and a low volumetric energy density, which indicates that a much larger fuel tank and changes to airframes would be required for this fuel to be utilised in aviation. Lithium-ion batteries (marked with green), along with other batteries, are currently characterised by a low volumetric and gravimetric energy density relative to hydro carbon fuels. If utilised in aviation, this would result in a heavy aircraft per carried load, resulting in higher energy consumption during take-off and landing, making less room for passengers and goods (Bitossi et al., 2020). Kerosene, marked by blue in Figure 2.1, has a fairly high volumetric and gravimetric energy density (Bitossi et al., 2020). Other traits include a low freezing point, which enables utilisation in high altitudes making it ideal for aviation.

As hydrogen is characterised by a low volumetric energy density and batteries currently are characterised by low volumetric and gravimetric energy density, they are unlikely to widely replace kerosene in aviation. Although research in battery- and hydrogen propelled aviation suggests that shorter routes can be replaced by these technologies in the near future, as short-haul flights eliminate the need for larger fuel tanks for H_2 storage and large batteries (Bitossi et al., 2020).

Another barrier for replacing kerosene is the level of dependence, built up over the years. Since every aircraft refills at airports and most large airports have centralised fuelling systems, every aircraft utilises the same fuel (Hromádka and Cíger, 2015). It would be inconvenient to shift partially to other fuel compounds, as this necessitates major infrastructural changes to fuel pipe systems in most major airports. Furthermore, jet engines have been perfected to combust jet fuel to a degree which has reduced the risk of failure and accidents dramatically (Panish Shia Ravipudi, 2023). It would be unacceptable for the sector to shift to another fuel without assuring the same level of safety. Therefore, it requires many years worth of research into other fuel compounds for aviation before they are deemed eligible for commercial aviation (Courtin and Hansman, 2018).

The remaining pathways for aviation to reach climate neutrality are through production of jet fuels that do no contain fossil crude oil. These are delved into in the following sections.

2.3.2 Sustainable Pathways for Jet Fuel Production

As mentioned in the section above, it is difficult to transition away from conventional jet fuel, as alternatives such as battery-electric and hydrogen do not offer the same capabilities. One potential pathway is *Sustainable Aviation Fuels*, as this pathway offers a climate-neutral mode of propulsion without the need for major changes in equipment and operations (Bitossi et al., 2020).

Bio-SAF & e-SAF

Sustainable Aviation Fuels, known as SAF, enable the utilisation of the existing aviation fleet and fuelling infrastructure, as the chemical compound of SAF is similar to conventional jet fuel. The term includes a variety of drop-in fuels with characteristics that vary slightly in comparison to conventional jet fuel. The common denominator of SAF is that they are produced through the utilisation of sustainable feedstocks instead of fossil feedstocks (Bitossi et al., 2020). SAF can be divided into two main groups, namely *bio-SAF* and *electro-SAF*, also known as *e-SAF* (Bitossi et al., 2020).

Bio-SAF includes fuels such as HEFA, HEFA-SPK, HVO, and SIP, which differentiate depending on the production process and feedstock. The typical feedstock for production are energy crops, unwanted vegetable- and animal fats, and other types of residues (Mayeres et al., 2023). Although these fuels can be considered climate-neutral, wide-scale use should be limited due to the risk of direct and indirect changes in land use, which can lead to scarcity in food and feed for food production, biodiversity loss, emissions from peat lands, etc. (European Commission, 2023; IPCC, 2022).

E-SAF differs from bio-SAF in that the fuel is produced through various chemical syntheses. Common for all e-SAF pathways is the production of hydrogen through electrolysis. Furthermore, the process requires carbon to synthesise kerosene, which can be extracted from biogenic sources or directly from ambient air in the form of CO_2. Currently, the Fischer-Tropsch synthesis and Methanol-to-Jet seem to be the most promising technologies to synthesise e-SAF (Bitossi et al., 2020; Skov and Abid, 2024).

These processes are in general associated with less negative impact than the production of bio-SAF, as renewable electricity and water for electrolysis are expected to be abundantly available, unlike land area for fuel production. In addition, a large electrolysis plant can act as a balancing factor in an energy system based on fluctuating energy sources. Currently, e-SAF is associated with significantly higher investment and operating costs than bio-SAF, however as R&D improves the e-SAF pathways, the gap is expected to decrease significantly. Policies such as ReFuelEU Aviation can act as a catalyst in this regard as the framework mandates a certain share of e-SAF in the European Economic Area, increasing towards 2050(European Commission, 2023; Mayeres et al., 2023).

As e-SAF pathways provide a cleaner end product and as the general focus within the European aviation sector shifts towards these pathways, the present report is delimited to e-SAF.

The general consensus regarding e-SAF is that it eventually represents the largest share. This is evident as the RefuelEU Aviation initiative mandates a blend of e-SAF at 35 % in 2050. Currently, this share of SAF blend is not approved for any pathway and at the present moment only few pathways have been approved. The reasons behind the current caps for fuel blends are delved into in the following section.

Fuel Blends

Even though it is technically possible to utilise a fuel blend with 100 % SAF, it is not yet approved by the governing body for fuel standards, ATSM International, at this moment in time. Currently, it is approved to utilise fuel blends with up to 50 % SAF, when utilising Fischer-Tropsch-derived fuels, whereas Methanol-to-Jet fuels currently are being processed for approval (Skov and Abid, 2024; Bube et al., 2024).

SAFs require approval, as their chemical compounds vary slightly from fossil-derived jet fuel. Although both fuel types mainly consist of long hydrocarbon chains, conventional jet fuel also has a fossil-derived aromatic content between 8 and 25 % which ensures that the characteristics of the fuel remain unchanged, depending on temperature and pressure (Stauffer, 2023). In addition, aromatics naturally create seals, which prevents fuel leakage (Stauffer, 2023). Currently, it is not possible to produce e-SAF with equivalent aromatic content to conventional jet fuel since the aromatic component must derive from sustainable sources for the fuel to be classified as sustainable. Although it is technically possible to synthesise the aromatic components sustainably, it has not yet been approved for aviation (Skov and Abid, 2024; Stauffer, 2023).

2.4 Feedstock Challenges and Opportunities for e-SAF

As mentioned above, e-SAF requires sustainably sourced hydrogen and CO_2. For sustainable hydrogen production, different electrolysis technologies can be utilised, all utilising the same principle in terms of separating water through an electric current. The required feedstock for electrolysis is low-conductivity water and electricity.

To source these feedstock sustainably, an array of challenges arise, although it can also bring opportunities. The following sections delve into the possibilities and challenges regarding sourcing and utilising each feedstock.

2.4.1 Future demands for feedstock

The general expectation is that the future cross-sectoral demand for renewable hydrogen will be limited to processes that are unable to transition to direct electrification leaving behind only a few sectors that are unable to transition. These sectors will then determine the production capacities of renewable hydrogen production. For CO_2, it is currently only utilised to a limited extent across sectors, although, as fossil fuels are phased out, the demand for sustainably derived CO_2 is expected to increase dramatically entailing an increase in the cost of biogenic CO_2, presenting a potential challenge for sourcing renewable CO_2 for the aviation sector.

The opportunities and challenges regarding each feedstock are further delved into in the following sections.

Potentials and Challenges regarding production of Renewable Electricity for Hydrogen Production

The main input in the production process of electrolysis is, as the name indicates, electricity. Currently, most energy systems produce electricity through centralised power production plants, however renewable technologies such as wind turbines and solar panels have proven to be significantly more competitive in peak production hours than conventional power production, while in addition being sustainable and abundantly available (The Danish Energy Agency, 2024d,e).

A core challenge regarding renewable power generation is their fluctuating characteristics, which ignore the electricity demand at that certain moment in time. In this regard, electrolysis plants might prove to be beneficial, as they would introduce balancing characteristics between renewable electricity production and demand. This would entail that electrolysis plants have a surplus capacity, which is only utilised to a limited extent (The Danish Energy Agency, 2024e,d).

Despite electrolysis plants offering balancing characteristics to the energy system, the fluctuating nature of renewable technologies does pose a challenge for e-SAF production. This stems from the fact that both Power-to-Methanol and FT plants have been designed to operate at a continuous rate rather than at a dynamic rate, as they have been intended for fossil energy sources, which are reliably available. When renewable energy is to be used instead, the fluctuating characteristics can result in frequent start-ups and shutdowns of the plants if the electricity supply is below the minimum operating capacity of the plant. As a result, this will negatively impact the efficiency of the system and the operating costs, since cold start-ups extend for 2-3 days (The Danish Energy Agency, 2024e).

For this reason, a stable renewable electricity production with a large capacity is a necessity for e-SAF production to operate efficiently, to which green hydrogen storage would be needed to balance supply variations (The Danish Energy Agency, 2024e).

Another smaller, but still significant challenge is to source water with low conductivity. This is covered in the following section.

Water for the production of hydrogen through electrolysis

The second input in producing hydrogen is water, and a hydrogen electrolysis plant requires substantial amounts of de-ionised water, with a conductivity below 1 μScm^{-1}, as this enables efficient production of hydrogen (H_2) through electrolysis (Becker et al., 2023).

The process of de-ionising water is associated with higher costs if the water contains more impurities, why cleaner sources of water input are preferred (Simoes et al., 2021). One challenge, which occurs when utilising cleaner sources of water, is that it might conflict with other interests. Utilising water from less clean sources is, however, associated with higher costs in the treatment phase (Simoes et al., 2021).

The challenge is therefore to uncover a sufficiently cost-effective pathway to de-ionised water, that avoids conflicts of interest with other sectors.

Limitations of biogenic CO_2 and other pathways for sustainable CO_2-sourcing

To process hydrogen to methanol, and subsequently to e-SAF, carbon is required. Similar to electricity for hydrogen production, the carbon source must also be sustainably sourced for e-SAF to be classified as sustainable, which limits the feedstock options to biogenic and non-fossil CO_2 (The Danish Energy Agency, 2024e,b).

Given that it is not possible to utilise fossil CO_2, abundances of CO_2 can, therefore, not be utilised for this purpose. Despite this, the production of e-SAF enables the utilisation of biogenic CO_2 that otherwise would have been considered waste.

A significant challenge is, however, that this type of CO_2 would also become a hot commodity for other sectors, which are in the same process of moving towards sustainability. This indicates a potential cost increase of non-fossil CO_2, due to resource scarcity. A major issue is, therefore, that biogenic and non-fossil CO_2 is at risk of becoming such a sought-after resource that emitters actively produce CO_2 to sell it. This creates a lock-in effect, resulting in Indirect and Direct Land Use Change (ILUC and LUC), as CO_2 as a commodity enables a company to stay economically afloat. It is therefore important that the production of biogenic CO_2 is carefully regulated and that CO_2 is considered a by-product of existing activities (The Danish Energy Agency, 2024b; Mayeres et al., 2023; The Danish Energy Agency, 2021b).

Non-fossil CO_2 captured directly from the ambient air is insofar an infinite resource, but a low technology readiness level and appertaining high operating costs currently prevent widespread adaption of this technology. For this technology to become relevant, the cost of production must decrease significantly for economically sustainable e-SAF production (The Danish Energy Agency, 2024b).

The central limitation for biogenic and non-fossil CO_2 is, thus, that this resource will be sought-after by several sectors within the foreseeable future, which will lead to resource scarcity and increased prices. As a result, the cost of producing e-SAF would increase substantially, as to why a reasonably cost-effective pathway to source biogenic and non-fossil CO_2 is a necessity. In addition, to ensure the sustainability of biogenic CO_2-production it is a necessity to regulate the future biogenic CO_2-production market (Mayeres et al., 2023).

2.4.2 Economic Challenges

In regards to the production of e-SAF, one of the main challenges is driving down the cost of feedstock for production, as these have a substantial impact on the cost of the final product. According to Skov and Abid (2024), the cost of electricity is considered the most influential factor, although as CO_2 becomes a more sought-after commodity, it is likely to have a substantial impact on the final cost of e-SAF, as the demand for CO_2 reaches the supply (Mayeres et al., 2023).

As the capacity of renewable electricity production is planned to be further expanded, the cost of electricity is expected to decrease, due to the lower production cost of renewable sources compared to conventional power plants and the larger supply (The Danish Government, 2022b; Cevik and Ninomiya, 2022). Although to drive down the cost of electricity, it is important that an array of technologies are utilised. This is the case as each renewable electricity production technology is unable to reach a stable production on its own, although they are able to support each other in their respective periods of high production. In a Danish context, the relevant technologies include renewable electricity production technologies, regional electricity trading systems, electricity storage technologies, and sector coupling opportunities.

As hard-to-abate sectors transition towards renewable fuel alternatives, the aviation sector is expected to compete with said industries in regards to biogenic CO_2 and green hydrogen demand, notably the agricultural-, shipping-, plastic-, and metal industries, which could entail resource scarcity for e-SAF production. The cross-sectoral transition away from fossil fuel entails that biogenic CO_2 might become a coveted commodity, thereby increasing the price, and thus making the price for e-SAF even higher. Therefore, it is important to rely on multiple sources of CO_2, as the price and availability can change quickly (Mayeres et al., 2023; Cui and Chen, 2024).

2.5 Chapter Summary

As specified in Section 2.3.2, the most suitable pathways for sustainable aviation are through the production of synthetically produced aviation fuels. Although a share of the current fleet is expected to be replaced by alternative modes of propulsion, namely battery-driven and hydrogen-driven propulsion, it is still expected that fuels with similar characteristics as conventional jet fuel will be necessary to cover the future demands for longer routes.

As mentioned in Section 2.3.2, bio-derived fuels are associated with high risks of Indirect Land Use Change as well as agricultural lock-in effects. Therefore, further analyses are limited to the production of synthetically produced fuels, with the exception of sourcing biogenic carbon as feedstock for fuel production.

Synthetically produced sustainable aviation fuels, dubbed e-SAF, are associated with a relatively high cost, by in large due to the cost of feedstock, namely carbon from non-fossil CO_2 and renewable electricity, as mentioned in Section 2.4.2.

The challenge, therefore, remains to drive down the cost of these feedstock to enable a swift transition away from the present utilisation of fossil aviation fuels.

In the context of this report, it is therefore sought to estimate the future supply and demand for the required feedstock for e-SAF production, as well as identifying potential policy changes to foster the utilisation of e-SAF. The year, 2050 has been chosen as the year of interest, as the EU has set ambitious targets regarding climate neutrality before the end of 2050. It is, therefore, interesting to analyse the opportunities and challenges regarding climate neutrality for the aviation sector at that point in time.

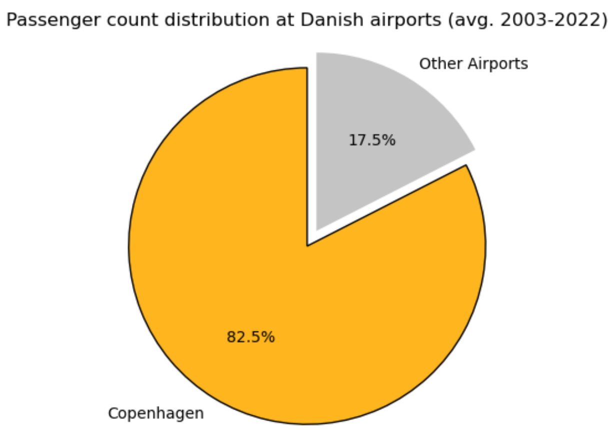

Figure 2.2. Average distribution of passengers at Danish airports during 2003-2022 (The Danish Civil Aviation and Railway Authority, 2024).

To accomplish this, CPH Airport is selected as a case for implementation of e-SAF, as it stands as the leading airport in Denmark and functions as a hub for the Nordic countries concerning regional and international flights when compared to the smaller airports, whose primary activity instead is centred around domestic flights.

As seen in Figure 2.2, this amounts to CPH Airport handling 82.5 % of air passengers in Denmark on average during the last 20 years, emphasising its importance for Danish air travel, domestically and internationally (The Danish Civil Aviation and Railway Authority, 2024; Statistics Denmark, 2020). For this reason, CPH Airport is the largest facilitator of jet fuel in Denmark currently and is expected to become a central hub for sustainable aviation fuel in the foreseeable future, hence this report utilises CPH Airport as a case.

Research Question 3

As identified in the Problem Analysis, the central problem regarding e-SAF production is to source the necessary feedstock for production. In relation to this report, CPH Airport has been chosen as a case to analyse the feedstock challenges and opportunities towards 2050.

The central question that this report seeks to answer is therefore:

How can e-SAF production through Methanol-to-Jet cover the fuel demand at CPH Airport towards 2050, and how should feedstock for production be sourced responsibly to meet the demands?

To answer the research question, the following analyses are performed:

- Analysis 1: Fuel & Feedstock Demand Mapping Analysis
- Analysis 2: Feedstock Sourcing Analysis
- Analysis Results: Cost Evaluation

The analyses are followed by a discussion where uncertainties, dynamics, mechanisms, and alternative pathways for a climate-neutral aviation sector are discussed, taking departure in interviews with key actors within the field.

3.1 Scope & Delimitation

As described above, the scope of this project is to assess how an e-SAF production utilising the Methanol-to-Jet pathway can be realised with emphasis on feedstock availability in order to cover the fuel demand at CPH Airport in 2050 with domestic fuel production.

The project is generally performed from a macro perspective concerning domestic feedstock availability relative to the location of CPH Airport. For this reason, the project is mostly concerned with the availability and capacity of suitable sources in Denmark but is delimited from delving further into factors such as specific locations and local factors and conditions in the vicinity of feedstock concentrations. Local factors that might be relevant when determining the specific locations for production include distance to settlements, protected areas, areas of cultural importance, and more are important to include when determining the specific location for production. The project, therefore, follows a rational planning approach rather than a relational approach.

As Methanol-to-Jet is determined to be the ideal pathway for replacing fossil jet fuel, the project is naturally delimited from delving further into potential pathways such as bio-SAF, battery electric, and direct hydrogen. e-SAF is, however, frequently compared to the fossil jet fuel pathway, since it is the reference scenario.

Methodology 4

This chapter presents the methodology for this project. The chapter is divided into the following sections: Conceptual Clarification, Methods, and Analytical Framework, which explains how concepts and methods are utilised in each analysis.

For each element, a definition, utilisation, and reflections are presented.

4.1 Conceptual Framework

This section describes the concepts utilised in this project, which provides the foundation for understanding and analysing the project's problem field.

4.1.1 Rational Planning

The concept of *Rational Planning* can be described as a linear planning approach, whose purpose is to enable informed and objective decision-making based on the analysis of data and factual evidence (Rydin, 2021).

Rational Planning can, thus, be described as a top-down approach, where the planner, or officials, are the sole actor, who makes data-driven planning decisions for the common good. Rational Planning is, therefore, particularly well-suited for making planning strategies at larger levels such as international, regional, and national, whereas concepts such as *Relational Planning* are better suited for local planning, where there is a larger emphasis on the relationship between human actors and material elements (Rydin, 2021).

Adaptation

In the context of this project, Rational Planning has been the overarching approach to address and assess the problem.

This applies to the analysis framework, which predominantly relies on projections and information from technology catalogues, academic articles, and expert opinions from interviews. Projections and information from these sources are considered as objective and impartial as possible, which, therefore, should facilitate the identification of the most optimal solutions from a financial standpoint.

It is, however, acknowledged that Rational Planning does not cover individual agendas, social aspects, and softer values to the same extent as the concepts of Rational Choice and Relational Planning, hence elements from these concepts are included in sections, where these areas are the focal points.

4.1.2 Spatial Planning

The concept of *Spatial Planning* is essential in planning, as it provides a coherent framework for managing the multi-faceted difficulties within this activity. Planning activities include among others infrastructure development, urban development, environmental conservation, and disaster risk reduction, meaning that spatial planning must take economic, social, and environmental aspects into consideration during decision-making (Stead and Nadin, 2008; Yamagata and Yang, 2020).

Spatial Planning can, thus, be described as a holistic approach to systematically organise resources within a given area - both from a macro- and micro perspective. The primary aim is to optimise land use, meaning that land mass and infrastructure must be efficiently allocated for the right sectors and purposes. The interconnectedness across different sectors is, therefore, of utmost importance, as the planning within one sector must align with the policies of other affected sectors. At its core, Spatial Planning essentially functions as a guide for decision-makers, whilst the largest hurdle is to navigate through intricate trade-offs to cater to the development of multiple sectors at once (Stead and Nadin, 2008; Yamagata and Yang, 2020).

Despite Spatial Planning's greatest strength, which lies in how holistic it is, this is also its greatest weakness for various reasons. Firstly, spatial planning involves multiple sectors, which means that bureaucratic hurdles and existing interests for instance can hinder the implementation of the most optimal solutions. Secondly, data limitations or inaccurate data can result in flawed analyses and modelling, which can introduce bias, as it leads to assumptions and simplifications. This emphasises the importance of accurate and comprehensive data collection in each country, as it can negatively impact decision-making (Stead and Nadin, 2008; Yamagata and Yang, 2020).

Adaptation

In this project, Spatial Planning functions as an extension of the concept of Rational Planning and is utilised for analysing the geographical dimension of e-SAF production in Denmark centred around CPH Airport as the provider. This includes a mapping of the current fuel demand, available feedstocks, announced projects, and existing feedstock infrastructure.

4.1.3 Sustainable Business Model

As businesses move towards sustainability, new sources of revenues might be necessary to stay economically afloat. This is especially true for aviation, as Sustainable Aviation Fuels are associated with much higher CAPEX and OPEX than fossil jet fuel. Economic sustainability in regards to SAF would require multiple new revenue streams, which can be realised and supported through new partnerships, technical breakthroughs and policy measures nationally, regionally and globally.

Components to the Sustainable Business Model (SBM) are shown in the following table:

Table 4.1. Components of Sustainable Business Model (Trapp et al., 2022).

Component	Description
Value proposition	Includes the products/services a firm offers to generate benefits for its costumer segments, stakeholders and the natural environment.
Value creation & delivery	Describes the various aspects necessary to provide the value proposition sustainably, including key activities, resources and partners.
Value capture	Covers both revenue model, i.e. how to appropriate value for the firm from the value proposition and cost structure incurred through the value creation component.

As shown in Table 4.1, the Value proposition encompasses all revenue streams, both economically, socially and environmentally. This deviates from conventional business models, which is limited to economic growth (Bocken et al., 2014). The *Value creation & delivery* component enables the value proposition, through partnerships, partnerships and resources. Lastly, the *Value capture* component revolves around defining value for the specific firm. This aspect is especially relevant in the context of sustainability, as conventional revenue streams can be insufficient, with higher CAPEX and OPEX of sustainable pathways.

An especially interesting addition to SBM is sector-coupling, where the sector in question achieves a higher share of sustainability and realises new revenue streams through cross-sectoral partnerships. This is covered in depth in the following section.

Sector-Coupling

Sustainable production in hard-to-abate sectors is associated with a much higher OPEX and CAPEX than conventional production through fossil materials. Therefore, it is necessary to create new revenue streams to enable a continuation of growth in the sector, as they transition towards sustainable production.

To uncover other potential revenue streams in a future system, it is highly likely that it would be necessary to analyse other sectors which currently are unrelated to the sector in question. This could prove to be beneficial to the society as a whole, as it further decouples GHG-emissions from economic growth (Vogel and Hickel, 2023).

In the context of the present paper, the following definition from Trapp et al. (2022) is utilised:

> [...]*the union of at least two different sectors* [...]*involving the substitution of non-renewable activities with renewable alternatives to establish fully renewable energy systems.*
>
> (Trapp et al., 2022)

Central to the definition is that sector coupling is the transition from conventional practices towards sustainable practices entailing fully renewable energy systems.

Revenue streams, which enable other sectors to reach a higher share of sustainability would be inherently good as the total emitted CO_2 is decreased.

Adaptation

In the context of this report, Sustainable Business Model and Sector-Coupling are utilised to identify potential revenue streams for Aviation, outside of the transport sector. As SAF is projected to be 2-5 times more expensive than conventional jet fuel, there is a need to uncover alternative revenue streams. Although a multitude of potential revenue streams can be realised, interviewees have provided knowledge on the most central possible revenue streams in regard to SAF. This is further covered in Section 4.2.1.

4.2 Methodological Framework

This section describes the methods utilised in this project, which provides the foundation for data collection and modelling in the present thesis.

4.2.1 Semi-Structured Interview

A *Semi-Structured Interview* is an interview form, which is conducted based on a semi-fixed structure. This structure is established by an interview guide sent prior to the interview, which predefines the scope and contents of the interview (Kvale and Brinkmann, 2009).

This structure allows one to gain additional knowledge and more nuanced answers than with a fixed structure since it enables further questioning, which facilitates the exploring of other related peripheral topics that were not included originally (Kvale and Brinkmann, 2009).

Utilisation

For this project, three interviews have been performed. The purpose of the interviews is to gain an understanding of different facets of this project's problem field, which is achieved through interviewing actors, each representing separate segments of the planning process.

An overview of interviewees, position, purpose and date is displayed in Table 4.2.

Table 4.2. Overview of interviewee's and the purpose of the interviews.

Interviewee	Workplace & Position	Purpose	Date
Morten Poulsen	Grøn Agenda → Freelance	To gain a better understanding on infrastructure, opportunities, and challenges relative to e-SAF production in Denmark	9/4-2024
Martin Hartvig	Energinet → Senior Engineer, System Perspective	To gain a better understanding on infrastructure, opportunites, and challenges relative to e-SAF production in Denmark	10/4-2024
Peter Wiboe Holm	CPH Airport → Sustainability Advisor	To gain a better understanding of CPH Airport's strategies and role as a facilitator in the transition to e-SAF	16/4-2024
Thomas Bo Sørensen	DANVA → Head of Department for Data Utilisation	To gain a better understanding on the utilisation and regulation of wastewater and seawater relative to e-SAF production in Denmark	21/5-2024

After performing the interviews, they have been transcribed, where little to no details have been omitted, as this allows for detailed analysis and interpretation of the contents of the interviews. To further streamline the utilisation of the interviews, they have been coded to organise contents and information by topic. The gained information has subsequently been used in the project's analyses and discussion (Brinkmann and Tanggaard, 2015).

To accumulate additional information or to clarify the gained information, a written correspondence has been ongoing after conducting the original interviews.

Reflections

To gather as much information as possible, the interviewees have been carefully chosen, as they represent different segments directly or indirectly involved in the e-SAF, and/or Power-to-X, planning process in Denmark. As a result, potential bias in the project is eliminated, as perspectives from experts from different fields with differing interests are included, which provides a much more nuanced overview of the topic.

4.2.2 Literature Review

A *Literature Review* is a selective review of relevant, existing academic literature within a specific field of research, meaning that it is not an exhaustive review of the broader topic, but a review of relevant literature that directly implicates the research. To avoid becoming a "[...] *a prisoner of the theoretical or methodological perspectives*" within a particular field, literature reviews should, however, be coupled with a review of peripheral fields to obtain alternative perspectives (Maxwell, 2006, p. 29).

The aim of a literature review is, thus, to gain an understanding of the state of the art for the specific field of research, which can be utilised in multiple ways. Firstly, the obtained information can help uncover unexplored avenues within the field of research, which can assist in directing and delimiting the scope of a problem field. Secondly, existing academic literature contains an abundance of useful information, which should be actively used in research to help construct arguments and new conceptual frameworks (Maxwell, 2006).

Utilisation

In the context of this project, the literature review has been utilised to review existing academic literature on the subject to aggregate a comprehensive understanding of the green transition of the aviation sector, which as a result has uncovered some of the issues related to this issue. These issues have since been utilised to delimit the scope of the project, as described in Section 4.2.2.

Additionally, the literature review has yielded substantial amounts of information concerning technical requirements, regulations, political measures, and more for e-SAF production that have been valuable for the analyses of this project.

Apart from conducting the literature review exclusively for the subject of this project, it has also been utilised for reviewing other sectors that are directly or indirectly connected to the transition of the aviation sector. This covers the remainder of the transport sector as well as other sectors going through a similar transition that would require the same feedstocks as e-SAF production.

The following combinations of keywords have frequently been utilised to search for literature at ScienceDirect:

- ("eSAF" OR "Sustainable Aviation Fuel" OR "Methanol-to-Jet") AND ("Electrolysis") AND ("Cost" OR "Expendetures" OR "Competitiveness" OR "Regulation")
- ("eSAF" OR "Sustainable Aviation Fuel" OR "Methanol-to-Jet" OR "Electrolysis") AND ("CO2 feedstock" OR "Carbon feedstock")
- ("Biogenic" OR "Climate neutral") AND ("CO2 feedstock" OR "Carbon feedstock" OR "Carbon Capture and utilisation" OR "CCU") AND ("Analysis" OR "Mapping")

Reflections

The greatest strength of the literature review is that great amounts of useful information can be obtained due to the sheer volume of academic articles available. However, as the literature review is selective, and not an exhaustive review, it can result in missing out on critical information as relevant articles may have been overlooked (Maxwell, 2006). In a similar vain, selection bias may occur, meaning that academic articles are (un)consciously selected and reviewed to support existing viewpoints.

There has been an emphasis on these potential sources of error during the literature review for this project, hence several factors in the analyses includes an error margin.

4.2.3 Document Analysis

Document Analysis is a method to obtain data and information from written documents. This includes collecting documents from different sources to create a comprehensive data foundation, after which the data and information are reviewed to contextualise and recognise patterns. This allows one to process and synthesise the data and information to utilise it for the specific purpose that is intended for (Bowen, 2009).

Utilisation

In this project, Document Analysis has played a key role in gathering data and information for a wide range of topics for the analyses of this project.

This covers gathering data and information on flights from CPH Airport in order to calculate the current and future fuel demand, which sets the tone for the subsequent steps in the analyses. Furthermore, it has been used to gain information on future trends both within the aviation sector as well as in the remainder of the transport- and energy sector, including but not limited to regulation and political agreements

Document Analysis has also been used to gather information on the requirements for e-SAF production through the Methanol-to-Jet pathway, as this is a key element in determining the feedstock demand to cover the future fuel demand of CPH Airport. Afterwards, this allows for the gathering of geographic data on feedstocks for e-SAF production in Denmark.

Document Analysis has, thus, been essential for creating the backbone of necessary data and information to perform the analyses of this project.

Reflections

When utilising Document Analysis as a data- and information-gathering method, it is important to be critical, as publicly available material can vary in quality. Therefore, there has been an emphasis on factors such as the origin of the material, publication date, bias, and author affiliation to ensure reliability, authenticity, and credibility (Engeldinger, 1988).

Furthermore, it is equally important to have a thorough understanding of the gathered data and information to ensure that it is processed and synthesised correctly relative to the standards specific to the field. Therefore, there has been an emphasis on gaining a thorough understanding of the aviation sector and e-SAF production on a technical level to gather the neccesary data and information, and subsequently process it accordingly (Bowen, 2009).

4.2.4 GIS

In the context of this report, Geographic Information Science and Geographic Information System, in short GIS, is utilised to illustrate areas of interest regarding synthetic production of fuel for aviation at CPH Airport. The double meaning of GIS indicates that GIS is both a way of thinking and a tool to inform others of spatial aspects regarding a field of interest. GIS tools are essentially data manipulation tools, which have a geographical dimension, setting them apart from other data manipulation tools. They enable planners to calculate and illustrate spatial challenges and opportunities within a certain field of interest. It thereby gives decision-makers and the wider public an easy-to-comprehend understanding regarding decisions that affect the spatial landscape (Esri Press team, 2018).

GIS utilises existing data to generate a comprehensive illustration, which gives a deeper understanding of the problem at hand. GPS-data and spatial data can be utilised and generated in GIS, using coordinate systems and orthographic maps, although in a Danish context, data is often available, as the Danish Agency for Data Supply and Infrastructure maintains a comprehensive list of servers where geodata is available for manipulation (Esri Press team, 2018).

Utilisation

For this project, the application, QGIS, is utilised as the Geographic Information System. The application is open source, with a relatively large global community supporting and updating the application regularly. Furthermore, the application has an extensive library of extensions, which are easy to implement into the QGIS application.

Regarding data, both international and Danish domestic data are utilised in the context of this report. The following table lists the utilised data.

Table 4.3. Data utilised in QGIS to generate the maps present in this project

Data	Source	Data type	Utilisation
Airports globally	(OpenFlights, 2024)	Vector (points)	Fuel demand analysis
→ Destination Airports from CPH Airport	(Copenhagen Airport, 2024)	Attribute (no geometry)	Fuel demand analysis
→ Aircraft information	(AviatorJoe, 2024)	Attribute (no geometry)	Fuel demand analysis
→ Flight frequency to each destination airport	(Flightradar24, 2024)	Attribute (no geometry)	Fuel demand analysis
Wind Turbines (off-shore)	(The Danish Data Supply and Infrastructure Agency, 2024)	Vector (polygons)	Feedstock sourcing analysis
→ Capacity of wind farms in tender	(The Danish Energy Agency, 2024a)	Attribute (no geometry)	Feedstock sourcing analysis
Electricity grid infrastructure	(OpenStreetMap, 2024)	Vector (lines)	Feedstock sourcing analysis
Waste Incineration plants	Attained from ENS	Vector (points)	Feedstock sourcing analysis
Biogas plants	(Aalborg University, Sustainable Energy Planning, 2024)	Vector (points)	Feedstock sourcing analysis
Drinking water interests	(The Danish Environmental Agency, 2024)	Vector (polygons)	Feedstock sourcing analysis
Urban waste water facilities	(The Danish Environmental Portal, 2024)	Vector (points)	Feedstock sourcing analysis

As can be seen above, some of the data utilised in QGIS does not have any geography. However, through analysing the data, common denominators can be found between non-geographical and geographical data, enabling geographic analyses of data that does not have geographical information.

Central QGIS tools in relation to this project include the 'Field Calculator', 'Join by Attribute', and 'Kernel Density'.

The 'Join by Attribute' tool enables the user to couple two datasets with one identical value per attribute. This could for example be airport ID, which is always the same across datasets. The tool enables the user to give data without geography a geographic value, enabling a spatial visualisation of the data.

The 'Field Calculator', similar to functions in Microsoft Excel, enables the user to do calculations relating to each attribute. The Field Calculator has a package of functions, where some of them relate to geography, including the length of lines and areas of polygons. Other functions are generally similar to functions that can be performed in Microsoft Excel.

The 'Kernel Density' tool is utilised to make a heatmap, which illustrates the density of a certain thing. In relation to the project, it is utilised to illustrate the concentration of CO_2 in Denmark.

Reflections

Although GIS is a powerful tool, it is often best supported by other statistics, which gives a different overview. It should therefore also be regarded as a data visualisation tool similar to graphs and plots.

GIS can be utilised both on a macro level, illustrating national and global trends and aspects, or it can be used on a local scale in local planning practice. In the context of this report, the tool is not utilised to illustrate local factors. It is, however, very likely that a GIS tool will be utilised to illustrate local factors if the findings in this report are to be realised.

4.2.5 EnergyPLAN

To evaluate the performance of different pathways in this project, the simulation programme EnergyPLAN has been utilised. EnergyPLAN simulates the operation of an energy system annually on an hourly basis, where each technology has a distribution file based on real-life operation patterns or future projections (Lund, 2014; Lund et al., 2021).

The output of the simulations displays the cost structure, production patterns, renewable energy share, critical excess electricity production, and more, which enables a comprehensive comparison between energy systems (Lund, 2014; Lund et al., 2021).

Utilisation

In the context of this project, EnergyPLAN has been utilised to evaluate the economic performance of e-SAF compared to fossil jet fuel when covering the fuel demand at CPH Airport.

To further enhance the economic evaluation, a sensitivity analysis has been performed, where the variables electricity price and CO_2 cost have iteratively been adjusted within a selected range based on projections to identify the break-even cost.

The techno-economic data to perform the cost evaluation originates from the following technical reports and academic articles: The Danish Energy Agency (2024e,b); Bube et al. (2024); Salem (2023); Skov and Abid (2024), where the demand stems from the results of Chapter 5.

Reflections

EnergyPLAN is an efficient tool for comparing the economic performance of different scenarios or pathways, but there are some uncertainties related to the simulations. These uncertainties relate to the techno-economic data due to it being based on projections and forecasts, as the economic performance of projects typically is evaluated over an extended time frame several years ahead. This makes the analysis fragile, as external factors and other variables can result in a different reality than what is projected. This is especially true the farther ahead you look into the future (Stobierski, 2019).

4.3 Analytical Framework

This section describes the framework for the analyses performed in this project. This includes the composition of concepts and methods utilised for each analysis as well as reflections regarding the utilised concepts and methods.

4.3.1 First Analysis - Mapping Analysis for Present and Future Fuel Demand

The first analysis of this project is a *Mapping Analysis*, whose purpose is to determine the present and future annual fuel demand at CPH Airport. This is achieved through the mapping of current flights from the airport as well as calculations utilising projections on aviation demand, the efficiency of aircraft, and the introduction of alternative modes of aviation transport.

As the projected fuel demand is uncovered, an estimation of the feedstock demand to produce the necessary amount of e-SAF to fully replace fossil jet fuel is calculated.

The Mapping Analysis approach is chosen, as this method provides reliable results and enables scientific replicability regarding the fuel demand at other airports (Cooper, 2016).

4.3.2 Second Analysis - Feedstock Sourcing Analysis for e-SAF production

As the feedstock demand is uncovered, the following analysis delves into feedstock availability and locations of each potential source.

In locating each source of feedstock a GIS mapping approach is utilised as it enables a rational and spatial understanding of availability from each source.(Esri Press team, 2018).

4.4 Chapter Summary

To summarise the methodology chapter, the research design, encompassing the composition of concepts and methods relative to the analyses of the project, is presented in Figure 4.1.

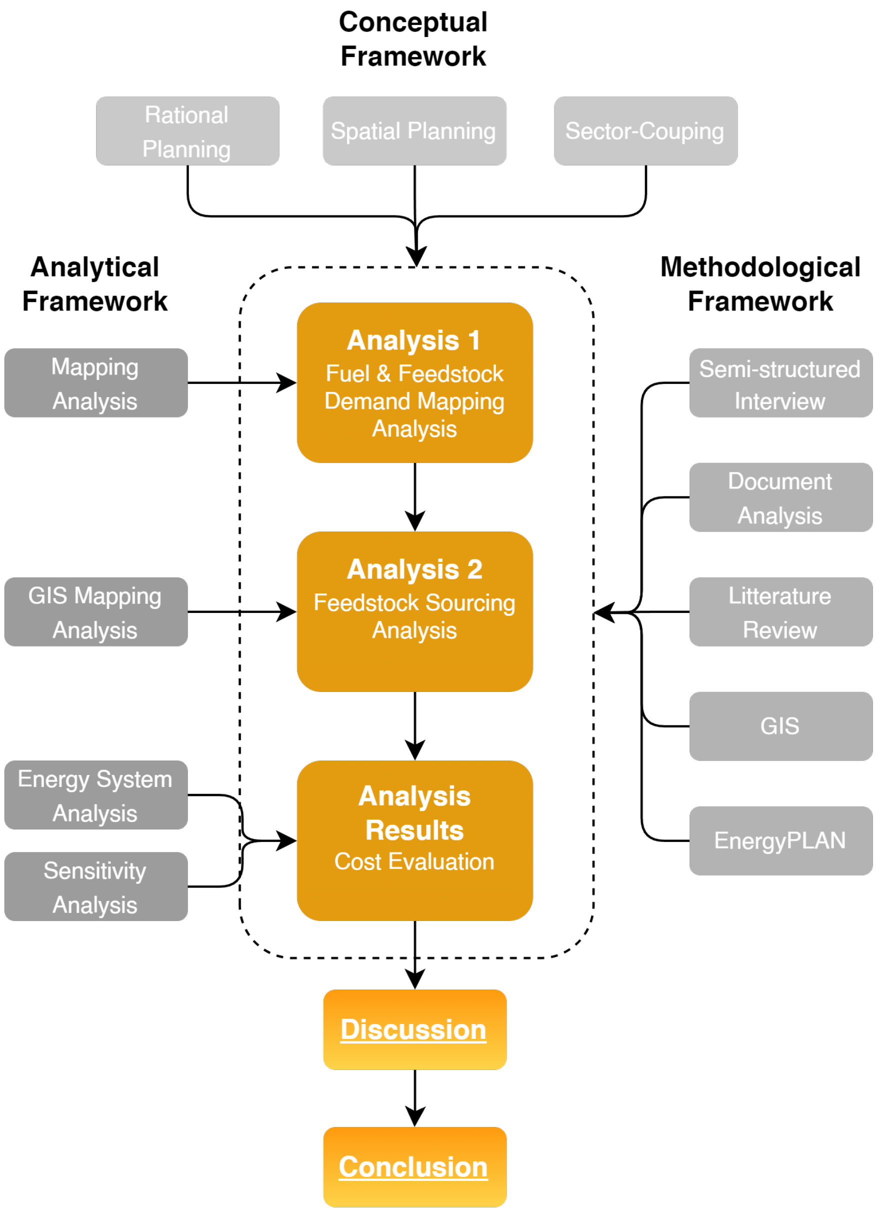

Figure 4.1. Research Design displaying the utilisation of concepts, methods, and analytical approaches.

As illustrated in Figure 4.1, the project is rooted in the concept of Rational Planning, as the analyses within the report take departure in the technical requirements for e-SAF production. As a result, the analyses heavily rely on quantitative information to estimate the fuel demand at CPH Airport and appertaining feedstock demand in 2050. This is coupled with qualitative knowledge gathered from scientific articles and interviews, as the assessment of sustainability for each feedstock option requires a nuanced and contextual understanding.

The utilisation of multiple concepts, methods, and analytical approaches enables a *Mixed*

Methods Design, which ensures a robust and nuanced assessment of the complex problem at hand (Hesse-Biber and Johnson, 2015).

Mapping Analysis for Present and Future Fuel Demand 5

The purpose of this analysis is to determine the fuel demand from flights departing from CPH Airport in 2050. In doing so, current flight data on departures from CPH Airport, location-specific data on destination airports, and additional data are utilised.

The projection on fuel demand in 2050 is then utilised to determine the demand for e-SAF along with the demand for sustainable feedstock for e-SAF production.

The fuel demand is estimated, and a stoichiometric demand analysis is carried out to estimate the feedstock demand for producing e-SAF to cover the fuel demand.

5.1 Present and future fuel demands for CPH Airport

CPH Airport is the largest airport in Scandinavia with more than 29 million visitors annually post Covid-19. In 2023, the airport had approximately 286 departures daily, with direct transit to 129 destinations.

It is ultimately the airlines departing from CPH Airport, that are responsible for the CO_2-emissions from the combustion aviation fuel and fuel supply is also handled externally, however, the airport is a facilitator for air transport, and as departures are accounted for at the airport, fuel demand to support the necessary fuel demand can be estimated. In the context of this report, GIS is utilised to do so.

An array of general trends and assumptions characterise the final estimation for their current fuel demand. The following section presents the most central assumptions.

5.1.1 Sources of uncertainties

It has not been possible to gather data on fuel demand from CPH Airport. Therefore, it has been estimated, through efficiency calculations of aircraft and data on departures from CPH

Airport. The fuel demand is calculated from departures, as it is assumed that the RefuelEU objective to avoid fuel tankering is adhered to, as mentioned in Section 2.2.2.

Data on departures from CPH Airport in 2023 is generated through a collection of flight data for one week during the year. This has been utilised to calculate an estimate for the yearly departures to each destination airport in 2023. The number of departures calculated is, therefore, not the exact number of departures in 2023, as seasonal fluctuations are not taken into consideration (Appendix C, 2024). Airlines book 82% of the seats on average, as it is implausible to fully occupy all departures (IATA, 2023b).

The fuel demand per kilometre varies depending on the distance to the destination airport. This can be pertained to the energy intensity required for take-off and landing, as well as heavy fuel loads on long haul flights, both indicating a higher fuel demand per kilomtre. In relation to the present report, (International Council on Clean Transportation, 2018, p. 8) provides an estimate of CO_2-emission per passenger kilometre (RPK).

To estimate the fuel demand, (ICAO, 2017, p. 6) estimates that 3.16 kg CO_2 is produced per kg jet fuel.

As the method utilised is supported by legitimate sources, it is therefore concluded that the estimate for fuel demand and CPH Airport in 2023 is in close proximity to the actual fuel demand.

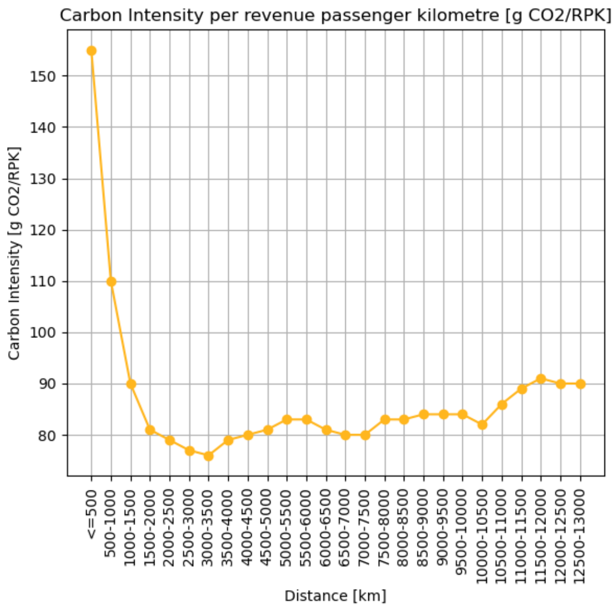

Figure 5.1. Carbon intensity per RPK relative to flight distance (International Council on Clean Transportation, 2018).

5.1.2 Current fuel demand at CPH Airport

To calculate the current fuel demand and CPH Airport, data from 2023 has been gathered and utilised in GIS. The method and utilised GIS tools to do so are illustrated in Figure 5.2.

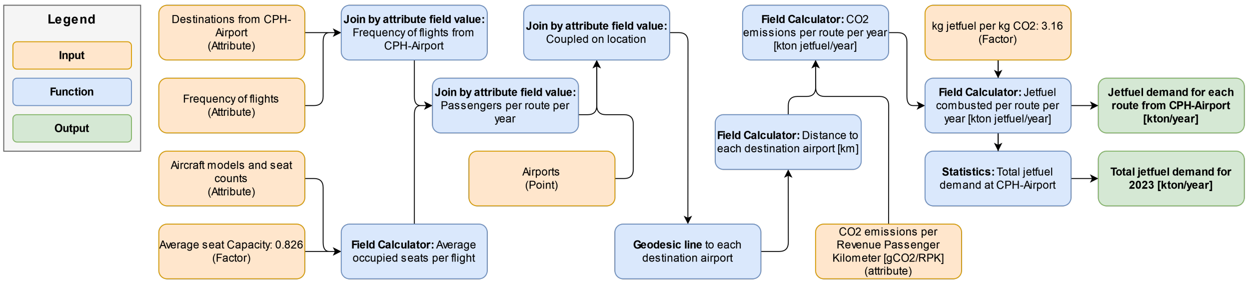

Figure 5.2. Model for course of action to uncover the yearly fuel demand and CPH Airport in QGIS.

Firstly, from the right, the frequency of flights and number of occupied seats per departure to each destination is calculated. Secondly, the distance to each airport, using GIS. Thirdly, the jet fuel per RPK, is calculated from CO_2 emissions for each location. The result of the calculations is illustrated in the following.

The following figure illustrates the current destinations from CPH Airport and the yearly fuel demand of each route. This is summarised to reveal the total yearly fuel demand, as of 2023, at CPH Airport.

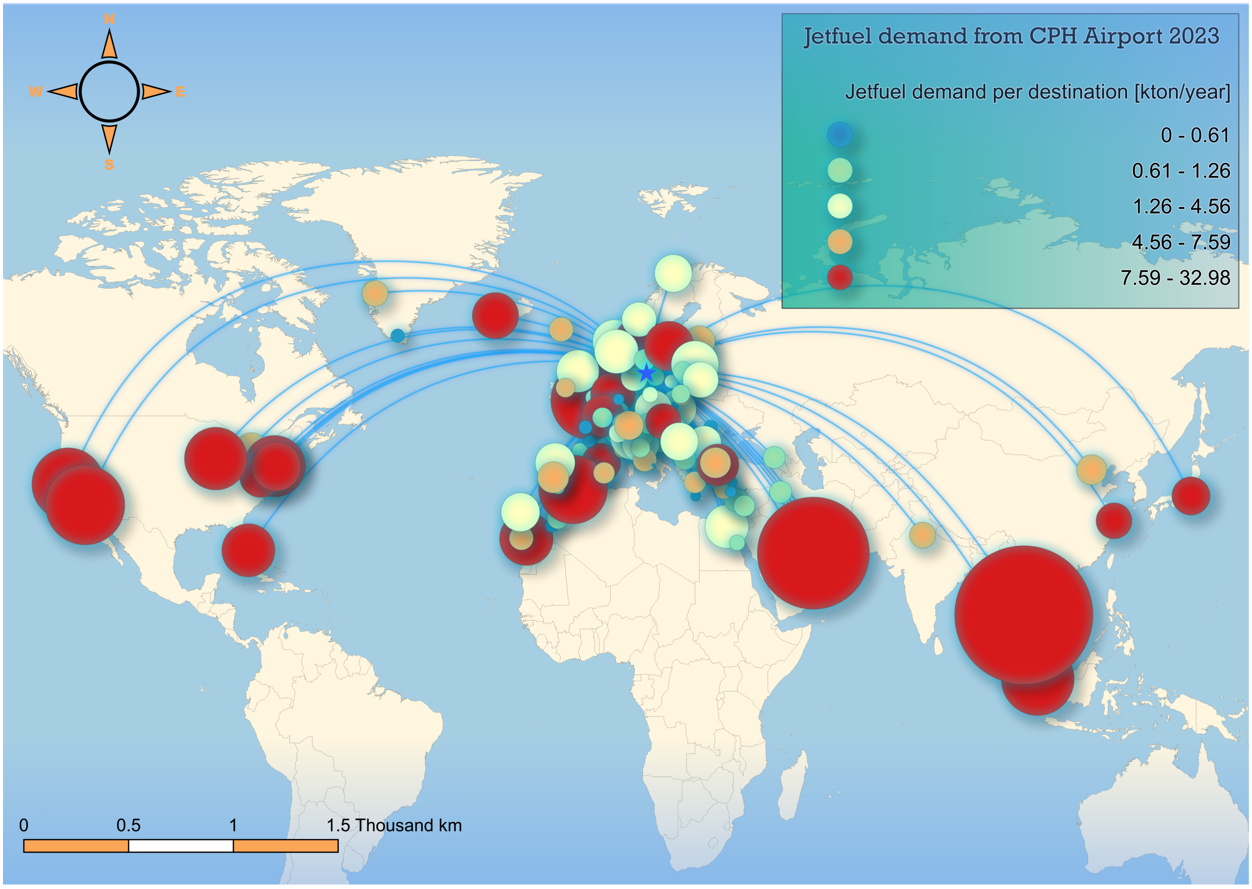

Figure 5.3. Fuel demand for each destination from CPH Airport in 2023.

The colour and size of each dot on Figure 5.3 illustrates the intensity of the yearly fuel demand for flights from CPH Airport to the specific airport destination.

As can be seen, a large share of the fuel is utilised on relatively short routes within Europe. Routes shorter than 5000 km account for approximately 67.5 % of the total fuel demand.

The total fuel demand in 2023, estimated through calculations in GIS, was 603.3 ktonne. This varies only slightly from CPH Airports own estimate at below 700 ktonne (Appendix C, 2024).

Although estimations for future demands at a specific airport are associated with significant uncertainty, general assumptions can be made, through forecasts and trajectories on future demands and efficiencies within the sector. In the context of this report, a modest approach is utilised to present the most realistic scenario for the sector in 2050.

The following section delves into the data utilised to estimate CPH Airports' demands. The same approach can be utilised for other airports.

5.1.3 Future fuel demand at CPH Airport

It is assumed that aviation at CPH Airport follows the same demand curve and gradual implementation of alternative technologies as the remainder of the sector. According to Eurocontrol (2024), the sector is expected to increase anywhere from 19 to 79 % towards 2050, compared to 2019 levels. In the context of this report, the base scenario of an increase of 44% is assumed, as this is a modest projection by Eurocontrol (2024). Assuming that the amount of passengers departing from CPH Airport is at the same level of demand in 2024 as in 2019, the demand in 2050 can be assumed to be 1.44 times higher by 2050. According to Fleming et al. (2022), aircraft efficiency is expected to increase, on average 1.53 % annually. This would indicate an increase in efficiency of 30.9% in 2050 compared to 2024.

As hydrogen and electric aircraft become feasible from 2040 onward, it is assumed that they are implemented gradually towards 2050 and beyond (Eurocontrol, 2022). in the context of this report, about 20 % of the routes shorter than 500 km are expected to be replaced by electric and hydrogen-driven aircraft, whereas 5% is replaced by hydrogen-driven aircraft on routes up to 1850 km (Airbus, 2024; Mukhopadhaya and Graver, 2022; Eurocontrol, 2022). This is also reflected by Peter Wiboe Holm from CPH Airport, who states that pure hydrogen and especially electric aircraft will play a larger role regarding shorter flights in the future (Appendix C, 2024). The destination airports from CPH Airport influenced by this are illustrated in the following figure.

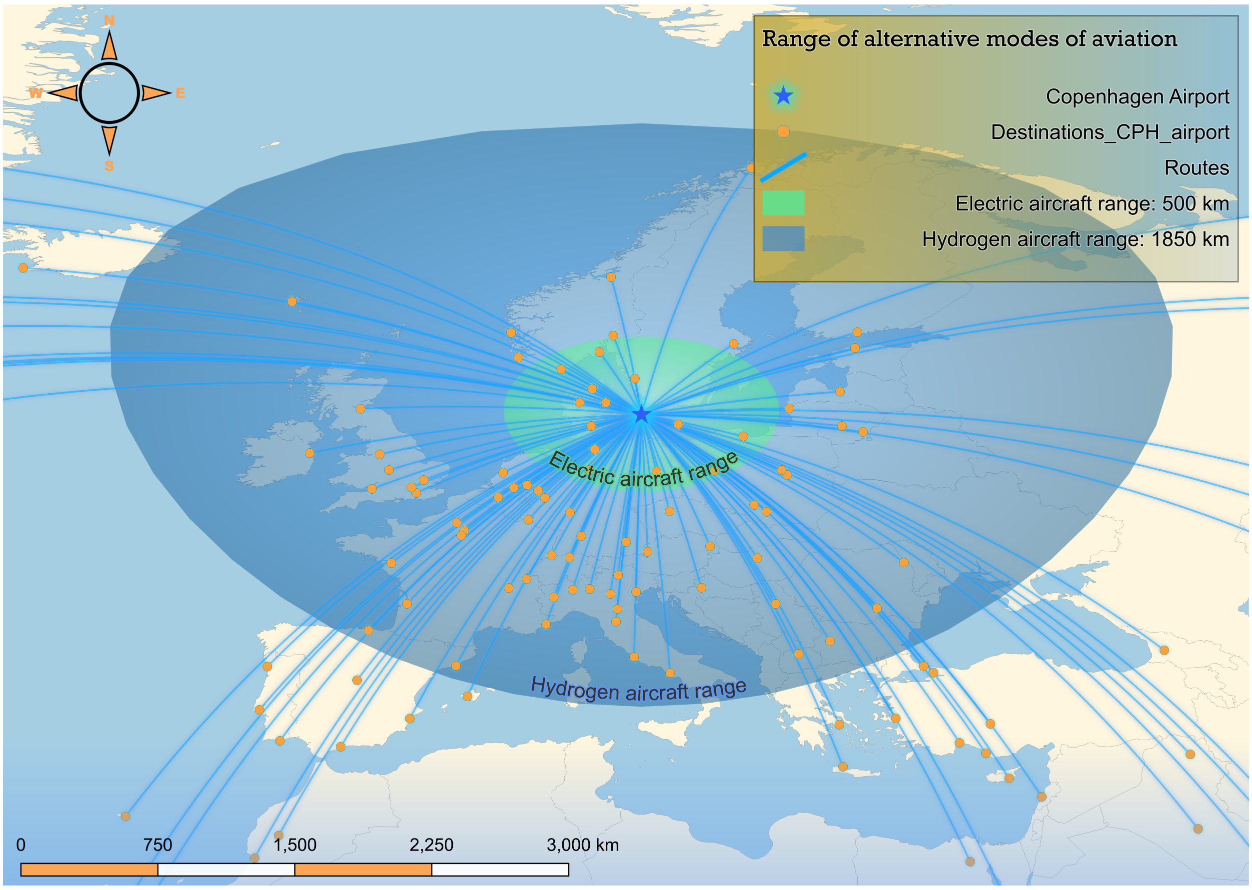

Figure 5.4. Range of electric and hydrogen driven aircraft towards 2050.

To calculate the estimated fuel demand in 2050, based on the above-mentioned parameters, GIS is utilised.

As the fuel efficiency of aircraft increases annually, while transport demand also increases, the total fuel demand remains almost stagnant. However, due to the implementation of alternative modes of aviation propulsion by 2050, the fuel demand on short-haul flights is significantly reduced.

The final fuel demand at CPH Airport, based on the above-mentioned assumptions is estimated to be 585.9 ktonne in 2050. This estimate is associated with relatively high margins of error, as such long projections are associated with significant uncertainties regarding future development in the sector. It is, however, a necessary practice to estimate future demands, as climate neutrality is pivotal for the development of the sector (Eurocontrol, 2022).

The following section delves into feedstock sourcing to cover the fuel demand in 2050.

5.2 e-SAF Production

As mentioned in Section 2.3.2, the most promising technology for the production of e-SAF is likely through electrolysis and Methanol-to-Jet (MtJ). This pathway has the highest potential output of e-SAF as the fractions of by-products are less than for the established Fischer-Tropsch pathway (Bube et al., 2024). MtJ is currently at a lower technology readiness level than other e-SAF pathways, however, as R&D continues, the technology is expected to come closer to realising its theoretical potential.

Figure 5.5 displays a simplified flow diagram of the Methanol-to-Jet pathway, displaying how Hydrogen, and subsequently Methanol, produced through electrolysis functions as intermediary fuels before going through a comprehensive set of electro-chemical processes resulting in e-Kerosene. As the diagram is simplified, only the Kerosene column within the MtJ pathway is displayed, excluding the Naphtha and e-Diesel columns from the figure (Bube et al., 2024).

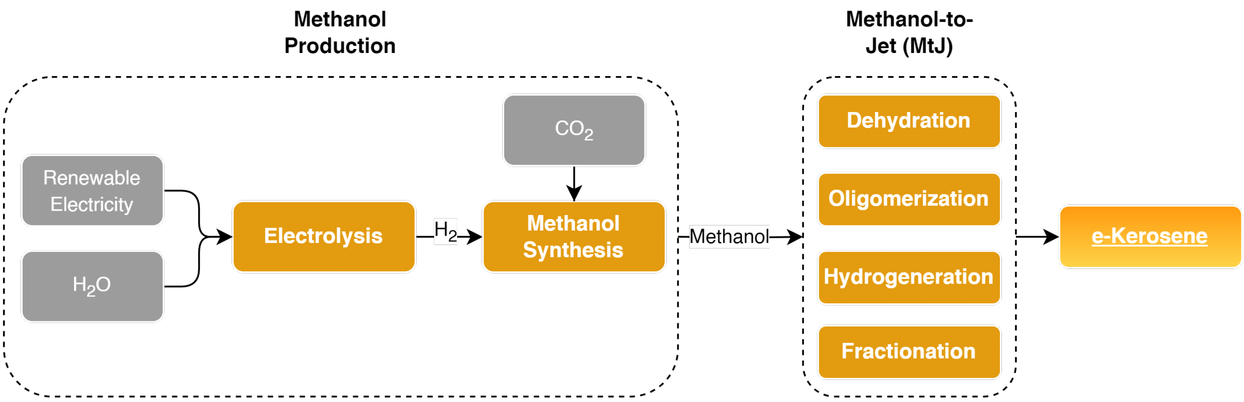

Figure 5.5. Simplified flow diagram of Methanol-to-Jet production (Adapted from (Bube et al., 2024, p. 2)).

5.2.1 Stoichiometric Feedstock Demand

Based on the fuel demand, it is possible to approximate the feedstock demand through the Methanol-to-Jet pathway. These approximations derive from stoichiometric equations, meaning that the values represent the theoretical maximum efficiency, hence these values might grow larger in reality due to external factors hindering the realisation of those (Bube et al., 2024; Salem, 2023).

Table 5.1 illustrates key figures for feedstock inputs in e-SAF production.

Table 5.1. Key figures for Feedstock for e-SAF production (Bube et al., 2024; Salem, 2023; The Danish Energy Agency, 2024e).

Feedstock	Input	Unit
H_2	1.70	$MJ_{H_2}/MJ_{e\text{-}SAF}$
Electricity (MtJ-synthesis)	0.12	$MJ_e/MJ_{e\text{-}SAF}$
Electricity (H_2-synthesis)	2.16	$MJ_e/MJ_{e\text{-}SAF}$
Electricity in total	2.28	$MJ_e/MJ_{e\text{-}SAF}$
CO_2 (MtJ-synthesis)	0.07	$kg_{CO_2}/MJ_{e\text{-}SAF}$
H_2O (H_2-synthesis)	0.14	$kg_{H_2O}/MJ_{e\text{-}SAF}$

As seen in Table 5.1, the total electricity demand is more than double the output in terms of energy. This can by in large be appertained to the electricity required in electrolysis. In addition, by-products of Methanol to jet include 0.066 TJ diesel, 0.044 TJ Naphta, and 0.651 TJ per TJ e-SAF.

Based on the estimated demand at CPH Airport in 2050, the necessary feedstock for e-SAF production are as follows:

Table 5.2. Annual feedstock demand for e-SAF production to cover the total fuel demand at CPH Airport in 2050 (Adapted from Table 5.1).

Feedstock	Input	Unit
Electricity demand for H_2-production	54 508.36	TJ_e/year
Electricity for MtJ-synthesis	3 003.46	TJ_e/year
Combined Electricity Demand	57 511.83	TJ_e/year
CO_2 Demand	1 819.29	$ktonne_{CO_2}$/year
H_2O Demand	3 512.76	$ktonne_{H_2O}$/year

5.3 Chapter Summary

As mentioned in Section 5.1, the fuel demand at CPH Airport as of 2023 is estimated to be **603.3 ktonne**. To estimate the fuel demand in 2050, several tendencies must be taken into consideration. Firstly, it is expected that the passenger transportation demand will increase by 44 % compared to 2019 levels, hence it is assumed that the demand will be 1.44 times larger in 2050. Secondly, it is expected that energy efficiency advancements lead to an improvement of 1.53 % per year, resulting in an energy efficiency improvement of 30.9 % in 2050. Lastly, it is expected that hydrogen- and electric-driven aircraft will be able to replace a portion of conventional aircraft on shorter routes, leading to a decreased fuel demand. When these tendencies are considered, the jet fuel demand at CPH Airport in 2050 is expected to be **586 ktonne**.

As mentioned in Section 5.2, large amounts of feedstock to produce e-SAF are necessary, if this fuel demand is to be covered. The vast majority of the necessary feedstocks are allocated to the production of Green Hydrogen, which amounts to an electricity demand of **54508 TJ_e/year** and a water demand of **3513 $ktonne_{H_2O}$/year**. To process Hydrogen into e-SAF, there is need for an additional demand of electricity amounting to **3003 TJ_e/year**, to which **1819 $ktonne_{CO_2}$/year** is also necessary.

The feedstock and sourcing of those are assessed in the following analysis.

Feedstock Sourcing Analysis for e-SAF production 6

As the fuel demand for aviation from CPH Airport has been estimated in Chapter 5, it enables a feedstock analysis to cover the fuel demand through e-SAF.

The purpose of this analysis is, thus, to explore various feedstock sourcing options. In addition, general areas ideal for feedstock sourcing are illustrated through the utilisation of GIS-mapping.

6.1 Sourcing & Transportation Options for e-SAF Production

This section delves into the different feedstock sourcing options for producing e-SAF; namely electricity for hydrogen- and e-SAF production, water for hydrogen production, and carbon dioxide for methanol synthesis.

6.1.1 Electricity for Hydrogen Production

As mentioned in Section 2.4.1, the production of e-SAF requires substantial amounts of electricity from a stable production profile to achieve optimal energy efficiency. In addition, electricity for the entire production chain of e-SAF has to be sourced sustainably, as the product otherwise is associated with non-sustainable practices (The Danish Energy Agency, 2024e).

In the context of Denmark, there are multiple sources of renewable electricity, including imports of renewable electricity from Norway and Sweden as well as production within the Danish power sectors. As of 2023, Danish electricity production consisted of 63 % renewables.(EnergiNet, 2023b). The Danish renewable power production derives from three sources, namely: Biomass-fired plants, Wind turbines, and Solar PV-panels (The Danish Energy Agency, 2023).

In the context of e-SAF production, combustion of biomass for power production should be avoided due to the risk of lock-in effects and indirect land use change, as mentioned in Section 2.4.1. This leaves Wind and Solar as the only viable electricity sources for e-SAF production in Denmark. An e-SAF facility can be connected to the electricity source in three ways: through a grid connection, through direct lines to the electricity source, or a combination of the two, although each solution has its advantages and disadvantages:

A grid connection offers a stable supply of electricity, as it is supplied by multiple sources, but 100 % renewable electricity cannot be guaranteed as long as fossil energy sources are part of the energy mix, which is a problem for the classification of e-SAF. This is, however, subject to change in the coming years, as fossil energy sources are gradually getting phased out by renewable energy sources (Appendix A, 2024), resulting in a renewable energy share of approximately 90 %. Another factor is, however, that a grid connection limits the placement of e-SAF facilities, as straining of the electricity grid needs to be taken into consideration (Appendix A, 2024; The Danish Energy Agency, 2024c).

Direct lines have the potential to enable a fully renewable production, as the facility can be directly connected to a renewable energy source. Additionally, tariff payments are avoided, as the facility is not connected to the electricity grid (The Danish Energy Agency, 2021a). Direct lines can, however, be problematic in terms of achieving a stable production profile, as the Danish renewable electricity sources all have fluctuating characteristics, which entails periods with less power production. This can be observed on a monthly basis, as seen in Figure 6.1, which displays the monthly production profiles of wind turbines and solar PV-panels in Denmark.

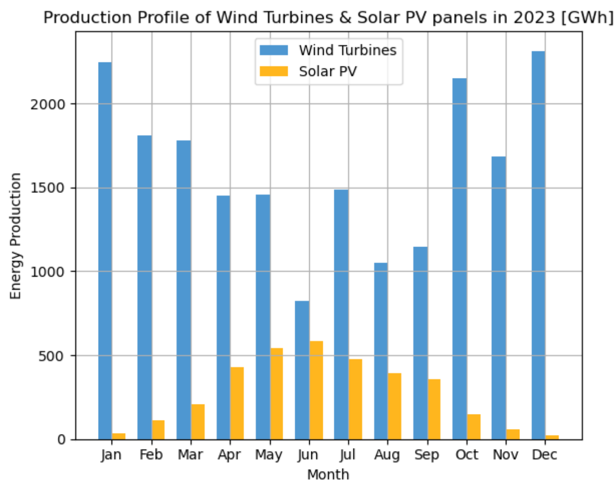

Figure 6.1. Comparison of Wind Turbine & Solar PV Production in Denmark, 2023 [GWh] (Data from (The Danish Energy Agency, 2023).

Highlighted in yellow, it is evident that PV-panels reach their peak production during months with more direct sunlight, whereas the energy output during months characterised by less direct sun is significantly lower (The Danish Energy Agency, 2023). Highlighted in blue, The production profile from wind turbines indicates a higher production during the colder half of the year, with less electricity output during the summer months. Due to the difference in production profiles, wind turbines operate closer to their peak capacity annually compared to solar. This entails in a substantially higher annual production per installed capacity for wind turbines, compared to solar PV-panels (The Danish Energy Agency, 2024d, 2023).

Although wind turbines are more efficient in producing electricity, the periods of power generation from wind are associated with higher uncertainty than PV-panels, as the production pattern of PV-panels depends on daylight and wind turbines depend on weather patterns associated with uncertainty (The Danish Energy Agency, 2024d).

To achieve a stable production without straining the electricity grid too the same extent, a combination of a grid connection and direct lines offers a constant and efficient production as well as inexpensive renewable power production when available from the direct line (Appendix A, 2024; Appendix B, 2024; The Danish Energy Agency, 2024c). As wind turbines have a better production profile yearly, they should be prioritised for direct line connections. If the energy mix in the electricity grid is not fully renewable, Power Purchase Agreements have to be made to ensure sustainable production of e-SAF (Ørsted, nd).

As the expansion of the electricity grid is associated with a relatively high cost, it is preferable to locate hydrogen electrolysis facilities near the point of production or near high voltage power lines (The Danish Energy Agency, 2021a). In addition, the transportation of hydrogen is associated with much lower cost than the electricity grid, which further incentives hydrogen production near power production or high voltage power lines (The Danish Energy Agency, 2024e).

6.1.2 Water for Hydrogen production

As mentioned in Section 2.4.1, hydrogen production requires substantial amounts of water with a low conductivity, dubbed technical water.

Several sources of water are suited for hydrogen production, provided that the water is processed to the necessary quality. These sources cover groundwater, treated wastewater, seawater, surface water, as well as different types of borings such as remediation wells, etc. The suitability of each type does, however, depend on the size of the Power-to-X plant, meaning that some sources do not have the capacity for large-scale plants (The Danish Environment Agency, 2023; Appendix D, 2024). Simultaneously, the most suitable source of water depends on the location of the plant, since different locations possess larger concentrations of some sources of water than others (Appendix D, 2024).

Despite this, factors such as conflict of interest and future management should, therefore, be considered when determining the placement of a Power-to-X facility and the water source (The Danish Environment Agency, 2023; Appendix D, 2024). In addition, there might be some uncertainties relative to permits, as the current regulation of water is not adapted to this practice.

To summarise, although there are several suitable sources of water and they seem readily available, the sourcing of water is still associated with challenges and uncertainties. These challenges concern the placement of the Power-to-X facility, as this is the determining factor for these challenges. Apart from this, there are some uncertainties related to regulation that need to be clarified.

6.1.3 Carbondioxide for methanol synthesis

As mentioned in Section 2.4.1, it is required that the CO_2 for producing e-SAF is either biogenic or non-fossil, as the fuel otherwise cannot be classified as sustainable.

In a Danish context, this entails that the amount of green CO_2 for e-SAF production is limited to the incineration of biogenic waste, and biogas upgrading facilities. The process of extracting CO_2 from biogas is developed technology, as it already serves to increase the quality of the biogas by removing CO_2. It is therefore likely that biogas upgrading facilities can deliver CO_2 at a very low cost (Salem, 2023).

Biomass incineration at power plants is excluded, as it is associated with a lock-in effect and risks creating Indirect Land Use Change (ILUC) and while CO_2-sourcing pathways like pyrolysis of lignocellulosic biomass present large potentials for CO_2-extraction they are also associated with ILUC.

Another technology, Direct Air Capture (DAC) is able to extract seemingly endless amounts of CO_2 (The Danish Energy Agency, 2024b). The technology is currently associated with a relatively high cost, however, this cost is expected to decrease significantly towards 2050, as expansion of renewable electricity and R&D within the field continues (The Danish Energy Agency, 2024b).

Compared to the other CO_2-extraction technologies, DAC is expected that the cost gap will be significantly smaller and decreasing from 2030 onward (The Danish Energy Agency, 2024b). Although costs are expected to decrease, it is, as illustrated in Figure 6.2 still expected to be more expensive than point source extraction.

Additionally, the projections regarding a decrease in cost are generally associated with higher uncertainties than point source extraction, due to their current low technology readiness level (The Danish Energy Agency, 2024b). Therefore, to limit the cost of non-fossil CO_2, DAC is considered the least attractive of the viable options for CO_2-extraction.

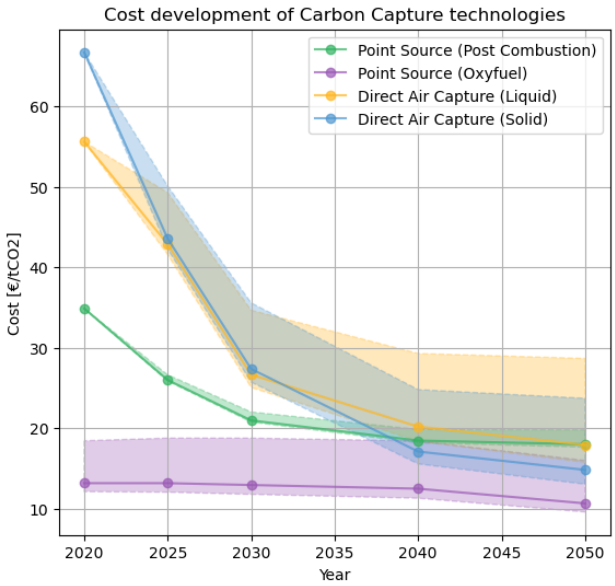

Figure 6.2. Development in costs of different Carbon Capture technologies towards 2050 (The Danish Energy Agency, 2024b,e).

Other potential sources of CO_2 are imports from neighbouring countries (Appendix A, 2024). This could be a prospect for Denmark, as the northern parts of Jutland have very suitable geological structures for long-term CO_2-storage. This indicates that Denmark could become a CO_2 hub, wherein the non-fossil imports of CO_2 could be utilised for green fuel production (Appendix A, 2024). A central constraint with imported CO_2 is that it hinders other geographical areas in utilising green CO_2, thereby hindering global adaption of renewable fuel production. Therefore, in the context of this report, it is not taken into consideration as a source for fuel production.

To summarise, the least cost-intensive sources are exhausted first. This entails that CO_2 from biogas upgrading is the highest priority, followed by point source extraction from waste incineration, and lastly DAC.

To transport CO_2 from point sources to fuel production sites and long term CO_2-storage facilities, a pipeline infrastructure can be constructed. The infrastructure can serve to transport both fossil and green CO_2 and a certification system similar to power purchase agreements could ensure that no additional CO_2 is emitted as the share of fossil CO_2 is stored in geological structures. By introducing a certification system, the infrastructure costs are lowered significantly, as one pipeline would be sufficient to ensure that no additional CO_2 is emitted (Appendix A, 2024).

A grid is preferable compared to lorries and trains, as it is associated with lower OPEX and the risks of accidents are near zero. Furthermore, a pipeline infrastructure would enable relatively inexpensive transport of CO_2 to geological structures for CO_2 storage, compared to ships (Appendix A, 2024; The Danish Energy Agency, 2024b).

6.2 Localising Sourcing Options

As the different sourcing options have been described in the section above, this section delves further into each feedstock sourcing option to determine the availability relative to the demand. This is carried out through a spatial GIS analysis.

6.2.1 Sourcing biogenic carbondioxide

There are, as mentioned in Section 6.1.3, three sources that are taken into consideration for sourcing CO_2 for e-SAF production in the context of this report. Of these, waste incineration and biogas upgrading are the least expensive. The potential amount CO_2 that can be extracted from these sources is therefore uncovered in this section.

Biogas upgrading

In Denmark, subsidies for biogas upgrading are given to enable the injection of bio-methane into the existing natural gas grid. This entails a high share of extracted CO_2 from biogas upgrading as the share of CO_2 in biogas ranges from 25% to 55% in volume (International Energy Agency (IEA), 2020). As CO_2 has a density of 1.836 kg/Nm$_3$, the gravimetric amount of CO_2 from biogas can be approximated.

Biogas derivatives in the Danish context include agriculture, municipal wastewater treatment, heavy industry, and landfills, although CO_2 deriving from heavy industry and landfills are excluded from this analysis, as they entail a dependence on sectors, that otherwise are likely to phase out (Mayeres et al., 2023). Furthermore, it is expected that biogas production from agriculture and waste incineration will remain at the same intensity as the 2020-level.

In the context of this report, it is assumed that every biogas facility will upgrade its biogas to bio-methane towards 2050.

With data from Nielsen et al. (2020), it is evident that Denmark has a yearly biogas production at approximately 16 PJ deriving from urban wastewater treatment and agriculture, resulting in approximately 625 ktonne CO_2 available for extraction.

Waste incineration

Denmark has an extensive history of utilising waste as a resource for both heat and electricity production through waste incineration plants. Denmark currently has 23 dedicated waste incineration plants with a collective capacity for 4 Gtonne waste. Each waste incineration plant is obligated to publish its share of biogenic waste, enabling a precise analysis of the available biogenic CO_2 from waste incineration. Biogenic waste produces 107.64 tonne CO_2 per TJ (The Danish Ministry of Climate, Energy, and Utilities, 2024). As the Danish waste incineration facilities collectively incinerated approximately 20 000 TJ annually, the corresponding CO_2 emission equates to 2 153 ktonne CO_2 annually (The Danish Energy Agency (Energistyrelsen), 2024).

In the context of this report, the Danish production of CO_2 from biogenic waste incineration is expected to remain constant towards 2050.

To extract the CO_2 from the flue gas, two technologies are relevant, namely post combustion and oxyfuel. As evident in Figure 6.2, oxyfuel is associated with a much lower cost per extracted CO_2, as less filtration of the flue gas is necessary, compared to post combustion (The Danish Energy Agency, 2024b). Therefore this technology is preferred.

As waste incineration plants are active constantly, the oxyfuel technology is the most favourable option and would run approximately 96% of the time. According to The Danish Energy Agency (2024b), oxyfuel is able to extract 97.5 % of the CO_2 from the flue gas, leading to a potential CO_2 extraction from waste incineration at approximately 2 099 ktonne annually.

Summary

The following figure illustrates the concentration of CO_2 from biogas and waste incineration in Denmark.

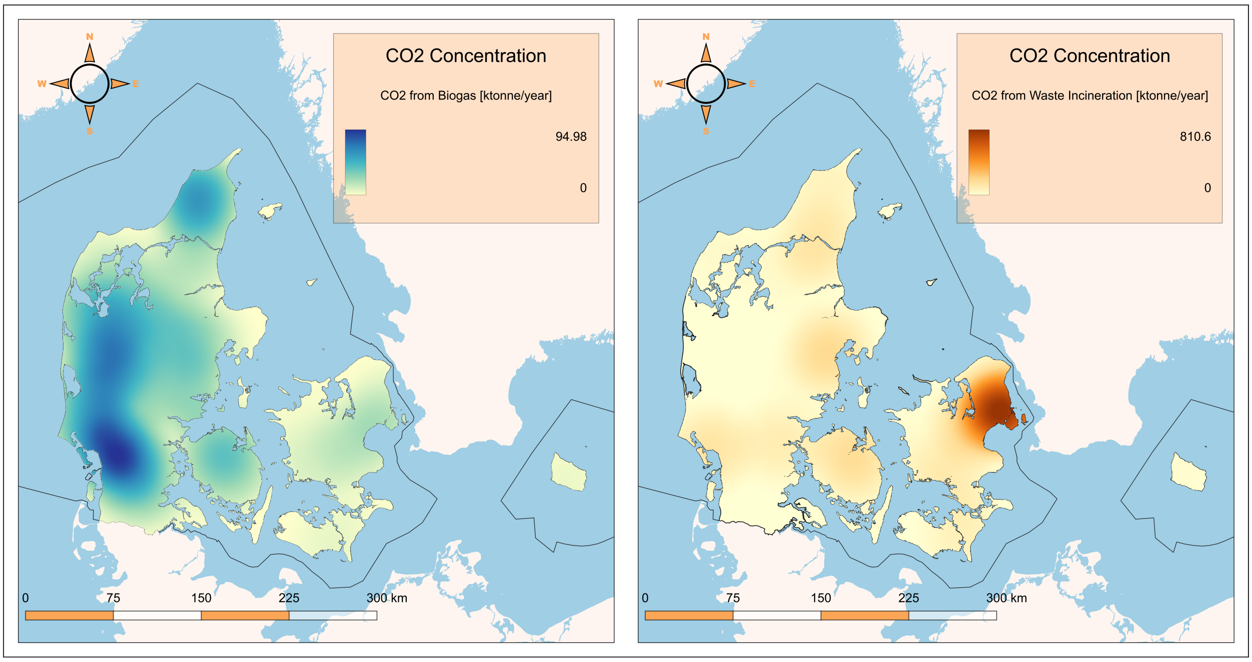

Figure 6.3. CO_2 from waste incineration and biogas upgrading (Aalborg University, Sustainable Energy Planning, 2024).

As illustrated in Figure 6.3, the majority of CO_2 from biogas can be extracted in the western parts of Denmark, whereas CO_2 from waste incineration is most prominent near CPH Airport.

The available amount of CO_2 that can be extracted from biogas facilities is approximately 623 ktonne annually and biogas production is distributed across many locations. Additionally, most biogas plants are located on the western parts of Jutland, away from CPH Airport. These factors make utilisation of CO_2 from biogas upgrading less favourable than biogenic CO_2 extracted from waste incineration, as the social and economic consequences of transporting CO_2 from each biogas upgrading facility exceeds the consequenses of extracting biogenic CO_2 from waste incineration.

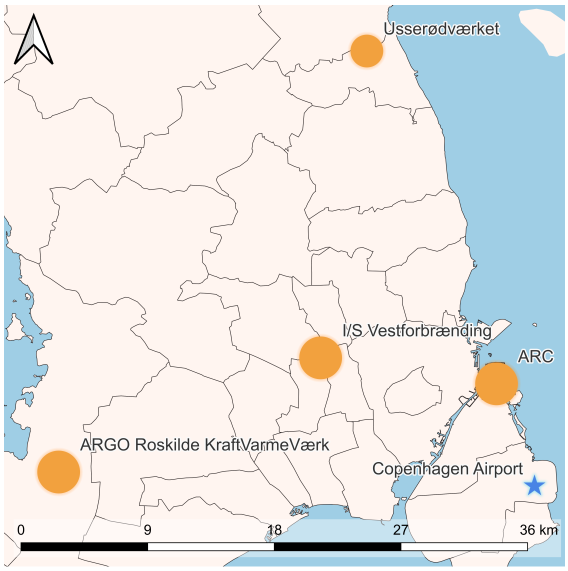

Figure 6.4. Sources of Biogenic CO_2 from Waste Incineration near CPH Airport.

As shown in Figure 6.4, there are four large waste incineration facilities within 40 kilometers of CPH Airport. These have a collective annual biogenic CO_2-emission at approximately 983 ktonne. This entails that approximately half of the CO_2-demand potentially could be covered by waste incineration within 40 km of the airport. The general demand of CO_2 in the future is, as mentioned above, associated with high uncertainties, although it is generally assumed that there will be a cross-sectoral demand. As other sectors are interested in CO_2 as a resource in the future, it is likely that a cohesive market for non-fossil CO_2 will be established, with the cost per tonne CO_2 depending on the cost of CO_2 extraction for the mix of CO_2-extraction technologies in the market, transmission costs, and other factors. As it is assumed that the cross-sectoral CO_2-demand is going to exceed the supply of biogenic CO_2, Direct Air Capture would be able to cover the remaining demand of CO_2.

To ensure that enough CO_2 is available to cover the e-SAF demand at CPH Airport, Direct Air Capture is shortly analysed in the following section.

6.2.2 Sourcing electricity for green hydrogen production & non-fossil carbon dioxide extraction

The production of e-SAF is highly dependent on renewable electricity production, for a sustainable end product. This is evident, as the production of e-SAF requires a substantial amount of electricity for hydrogen production through electrolysis and potentially CO_2-extraction, through Direct Air Capture.

In a Danish context, there are, as mentioned above, generally two options for renewable power production, namely wind turbines and Photo Voltaic panels. Within renewable power production, off-shore wind turbines represent the highest production per installed capacity (The Danish Energy Agency, 2024d). In addition, renewable power production on land is associated with a certain level of disturbance for the local population. It, therefore, seems that future renewable power production will be characterised by a substantial expansion of off-shore wind turbine capacity, compared to renewable power production on land. Figure

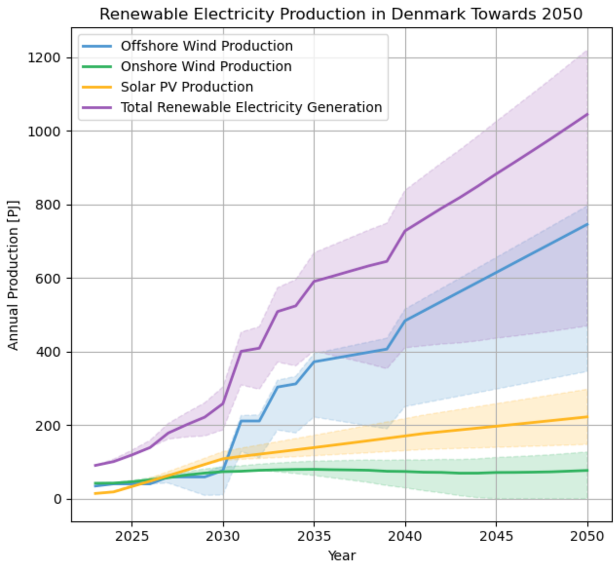

Figure 6.5. Renewable electricity production towards 2050 (EnergiNet, 2023a).

6.5 illustrates the projected production from renewable sources in Denmark towards 2050, with differing levels of uncertainty depending on the technology. The uncertainties can pertain to the potential political change of direction regarding electricity generation and renewable agendas.

As off-shore wind capacity is expected to expand much more than the remainder of the renewable electricity production, this technology seems to be paramount for the sustainable production of e-SAF towards 2050.

The following figure illustrates off-shore wind capacity, both currently, in pipeline, and areas of interest.

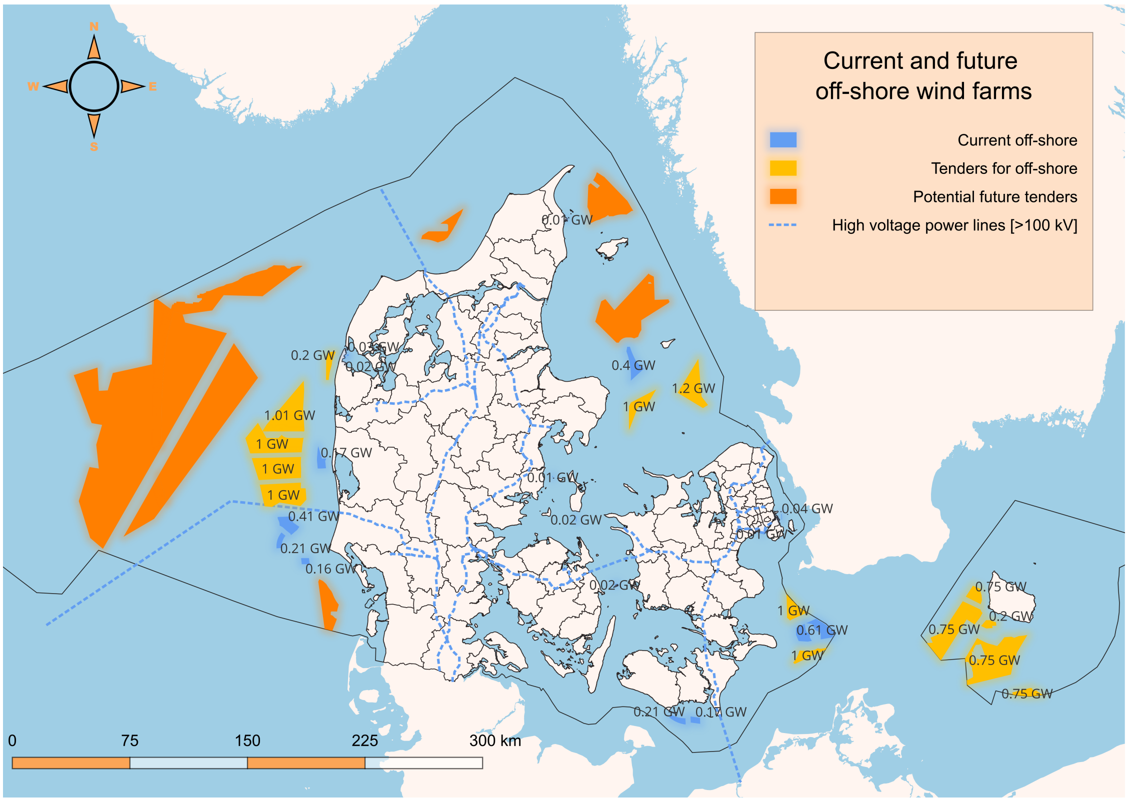

Figure 6.6. Off-shore wind capacity currently, in pipeline and areas of interest (The Danish Data Supply and Infrastructure Agency, 2024).

As illustrated in Figure 6.6, the off-shore wind production is expected to increase dramatically in the coming years. In the context of this report, the current off-shore wind capacity is expected to remain, as they are replaced when they reach their expected lifespan.

If all off-shore wind farms in pipeline are realised and installed on time, the collective off-shore capacity would thereby reach 11.85 GW by 2033, corresponding to a production of 196.3 PJ annually (EnergiNet, 2023a).

In addition to off-shore wind farms that are currently in pipeline, future wind farms beyond 2030 are expected to further increase the Danish off-shore wind capacity by 31.9 GW towards 2050, corresponding to an addition of 549.1 PJ and a total off-shore production at 745.4 PJ (EnergiNet, 2023a). It should be noted that the capacity of future wind farms are associated with relatively high uncertainty, as the political landscape might change towards 2030 and beyond.

The electricity required for hydrogen production and Methanol-to-Jet synthesis to produce e-SAF to cover the demand at CPH Airport is, as concluded in Chapter 5 57511.83 TJ. This would correspond to 5.5 % of the projected renewable production and 7.7 % of the total off-shore production in 2050.

As electrolysis is very energy intensive, it requires a high-voltage power line to supply the facility with sufficient electricity. It would be possible to establish sufficient electricity infrastructure near the airport, however, as it is unlikely, that any large wind farm will be connected to the electricity grid near Copenhagen, the plant is more likely to be located close to the off-shore wind farm connection point. This would ensure less tension on the grid, as well as the possibility of connecting directly to the off-shore electricity production. Figure 6.7 illustrates four potential locations based on the location of connection points for high-voltage power lines.

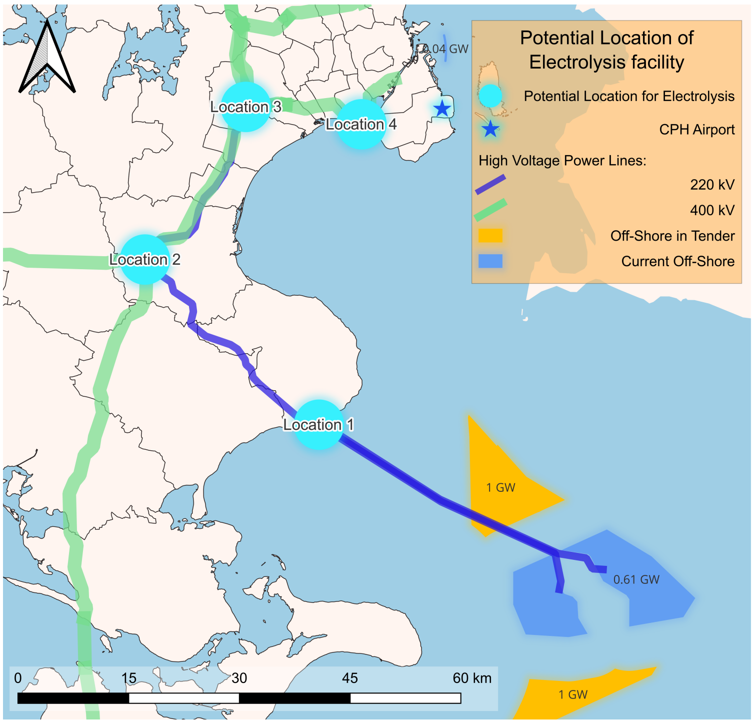

Figure 6.7. Potential location for Hydrogen Electrolysis (The Danish Data Supply and Infrastructure Agency, 2024; OpenStreetMap, 2024).

The annual production from offshore wind in 2050 is associated with a high level of uncertainty, as the level of expansion and location of offshore wind farms beyond 2030 are to be determined. If the current tenders for offshore wind farms that are going to be connected to Zealand are realised, the collective offshore wind production, directly supplied to the grid would be approximately 73 380 TJ annually, exceeding the electricity demand for e-SAF production by more than 20 % (The Danish Data Supply and Infrastructure Agency, 2024). With additional electricity production from on-shore wind turbines, PV-panels, and the import of renewable electricity, it does not seem to be implausible that the required sustainable electricity can be sourced for e-SAF production in the vicinity of CPH Airport.

CO_2 from Direct Air Capture (DAC) might become relevant, depending on the future cross-sectoral demand for non-fossil and sustainable CO_2 from waste incineration and biogas upgrading. If these sources are fully exhausted, DAC is likely to fill the remainder of the demand. The cost of CO_2 from DAC is highly dependant on the cost of electricity, as the technology requires substantial amounts of electricity (Skov and Abid, 2024). As mentioned above, the future production from off-shore wind farms are planned to reach 745.4 PJ, it is likely that a share of this can be utilised for DAC. The amount of DAC derived CO_2 required for e-SAF is associated with much uncertainty, as there is little to no knowledge on the cros-sectoral demand of CO_2 in the future, however surplus CO_2-production could be utilised for Carbon Capture and Storage, thereby sequestering CO_2 from the atmosphere. The location of DAC, similar to hydrogen electrolysis, depends on the location of high voltage power lines because of the amount of electricity required. They could therefore potentially be located in the same general areas as the electrolysis plants.

It is therefore important that the cost of renewable electricity decreases in order to produce as cost-effective DAC-derived CO_2 as possible. In the context of this report, it is assumed that about half of the CO_2 for production of e-SAF will derive from DAC, which entails an annual supply at about 918.5 ktonne CO_2.

6.2.3 Sourcing water for hydrogen production

The availability of water is highly dependent on the political landscape as well as geographical and geological factors, which determine the availability of sources. It is therefore important to delve into the potential sources of water in a Danish context

Water Supply Networks and Groundwater

As mentioned in Section 6.1.2, there is an array of viable sources for water to produce hydrogen through electrolysis, and subsequently, e-SAF. Water quality is an important factor to consider when choosing a source, as hydrogen electrolysis requires ultra-pure water. In terms of purity, water supply networks, and direct groundwater are the most suitable sources of water, as these sources are associated with little to no contamination

(The Danish Energy Agency, 2024e; Simoes et al., 2021). As other factors, apart from purity, are taken into account, groundwater and water from water supply networks seems less likely to be utilised for hydrogen production due to social aspects and availability. Groundwater availability is very sensitive to the specific location, as sediment structures and other local interests determine if groundwater is available for utilisation (The Danish Environment Agency, 2023). According to The Danish Environment Agency (2023), the groundwater resource is sufficiently available in Jutland and Fyn, but Zealand is by in large characterised by overexploitation of groundwater. This is in particular true in the capital region. Areas characterised by overexploitation of groundwater are generally reserved from further exploitation, as it would affect the current utilisation (The Danish Environment Agency, 2023).

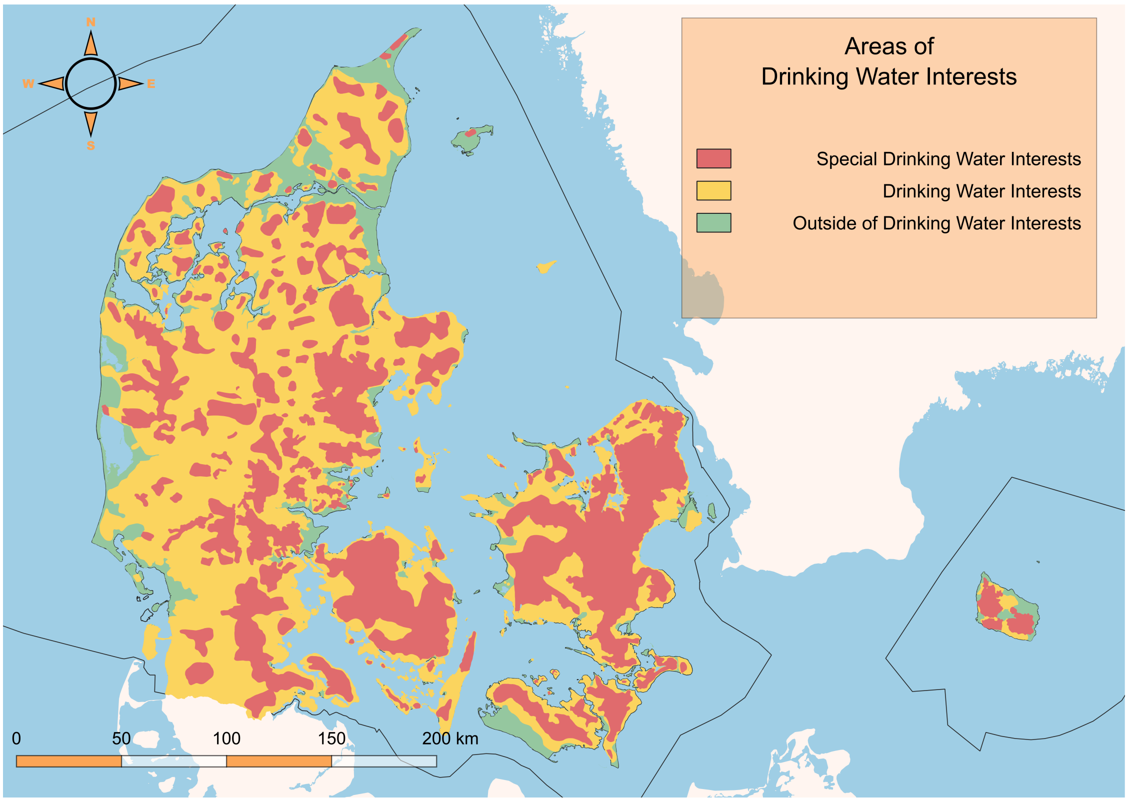

Figure 6.8. Areas of groundwater interests in Denmark (The Danish Environmental Agency, 2024).

As illustrated in Figure 6.8, the majority of Zealand is characterised by areas. This can by in large be pertained to the limited availability of high quality groundwater. Furthermore, additional areas in Zealand will likely be characterised as areas of special drinking water interests (The Danish Environment Agency, 2023).

Because of the general scarcity of high-quality groundwater it is unlikely that groundwater and water supply networks will be considered as eligible sources for hydrogen production through electrolysis in a Danish context. The more extreme scarcity of groundwater around the Copenhagen further affirms that groundwater is out of question if an electrolysis plant for e-SAF production is to be located near the demand (The Danish Environment Agency, 2023; Appendix D, 2024).

Urban Wastewater & Seawater

Following groundwater and water supply networks, treated urban wastewater followed by seawater are the most suitable sources of water for hydrogen electrolysis production in terms of purity (The Danish Environment Agency, 2023). These sources are readily available and associated with little to no conflict of interest from other sectors. As they are less pure than groundwater and water from water supply networks, they include additional expenses of treating the water to reach the desired purity. This is especially true when utilising seawater, as this source requires additional cost-intensive desalination to be eligible for hydrogen production through electrolysis (Appendix D, 2024). An alternative hydrogen production pathway, photocatalytic electrolysis, which can use seawater directly is, however, gaining traction, which might cement seawater as the most suitable source in the future (Li et al., 2024). Another option is industrial wastewater. Utilisation of this should, however, be refrained from in favour of urban wastewater and seawater, as it could create lock-in effects with industries associated with fossil CO_2-emissions (Simoes et al., 2021).

Figure 6.9 illustrates the national concentration of annual discharges from urban wastewater facilities, whereas Figure 6.10 displays urban wastewater treatment facilities near CPH Airport.

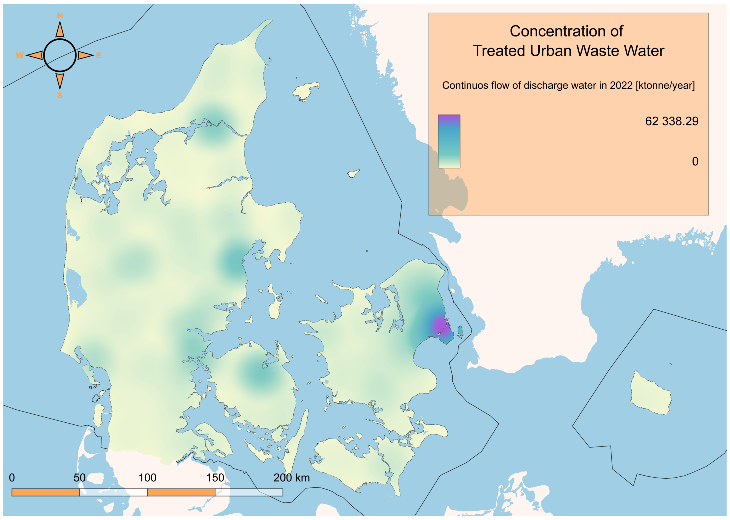

Figure 6.9. Water from discharges of urban wastewater facilities (The Danish Environmental Portal, 2024).

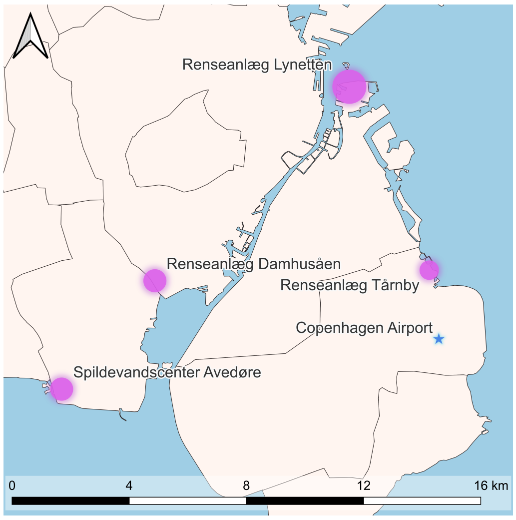

Figure 6.10. Sources of Water from Urban Wastewater Treatment facilities near CPH Airport.

In Figure 6.9, it is evident that the largest concentration of discharges from such facilities is located in the Capital Region. In Figure 6.10.

The largest urban wastewater treatment facility in Denmark, Renseanlæg Lynetten, as seen in Figure 6.10, is located within 10 kilometres of CPH Airport. The facility has a continuous flow of treated wastewater at approximately 15 000 ktonne annually, which exceeds the water demand for water for e-SAF production, uncovered in Chapter 5, many times over (The Danish Environmental Portal, 2024). The other three facilities are also able to cover the water demand individually.

The economic perspective regarding urban wastewater and other sources of water for Power-to-X, dubbed *Technical Water*, is associated with high uncertainty, as current regulation serves societal and environmental purposes and not Power-to-X. Currently, there is an ongoing discourse on whether wastewater treatment companies or PtX companies should bear the financial burdens of managing wastewater discharge. For wastewater treatment companies the cost of rinsing water must remain relatively constant as it is the suppliers of wastewater that pays for the water treatment. They are, by law, not allowed to significantly increase the expenses of treatment as it would affect the suppliers of wastewater negatively. It is furthermore not allowed to discharge contaminated water that exceeds EU and nationally regulated limits. This includes the discharging of warm water and water with too high chemical or biological concentrations (Appendix D, 2024). This indicates additional costs of treating the outlet water from electrolysis.

Although the expenses of water and subsequent treatment for hydrogen electrolysis are associated with many uncertainties, it is not expected to exceed more than 10 % of the total expenses of running an electrolysis facility, as electricity cost has a much larger impact (The Danish Energy Agency, 2024e; Appendix D, 2024). The source of water is, therefore, not considered of high importance, as long as lock-in effects and conflicts of interest are avoided.

Summary

As mentioned in Section 5.2, approximately 3 512 ktonne of water per year is required to cover the e-SAF demand at CPH Airport in 2050. The sources eligible for utilisation are highly dependent on their availability and other current interests, making urban wastewater the most suitable source. This source is, unlike groundwater not a converted source of water, as it is less clean for human consumption. It is, however, close to the same quality as water for hydrogen electrolysis. Therefore, this source is of special interest regarding this project. Lastly, seawater might be of interest depending on the R&D of desalination and potentially alternative hydrogen production pathways.

Changes in regulation for utilisation of treated urban wastewater for Power-to-X purposes as well as rearrangement of cost structures must be pursued, as current regulation and cost structures are insufficient to support Power-to-X purposes from the economic perspective of wastewater treatment companies.

6.3 Chapter Summary

As mentioned above, there are generally a wide range of options available for sourcing the necessary feedstock for the e-SAF production to meet the fuel demand at CPH Airport.

As uncovered in this chapter, electricity, which is mostly used for hydrogen electrolysis can be sourced, utilising an array of technologies. It does, however, seem that off-shore wind turbines will play a crucial role in expanding Danish renewable electricity production to support the production of green hydrogen for fuel production and other purposes. The cost of electricity for hydrogen electrolysis will therefore be strongly associated with the cost of electricity production from off-shore wind turbines.

For CO_2, it is important that sustainable and the least cost-intensive sources are utilised first, as this ensures a lower cost of the end product. In the Danish context, there are three sources, which are considered environmentally sustainable, as they avoid Indirect Land Use Change and Lock-in effects. These are CO_2-extraction from biogenic waste incineration, biogas upgrading from agriculture and urban wastewater treatment facilities, and lastly, Direct Air Capture. As Direct Air Capture is considered an expensive option compared to the other sustainable CO_2-sources, the technology is considered the least desirable, although as the CO_2 from waste incineration and biogas upgrading is unlikely to support the cross-sectoral demand of CO_2 towards 2050, DAC seems to be the only remaining option.

As for water for the hydrogen electrolysis, there are multiple sources of interest. The most desirable sources, such as direct groundwater and water from the water supply network are, in a Danish context, strongly associated with conflicts of interest with other parts of the society. The sources associated with less conflict of interest, such as water from urban wastewater treatment facilities and to some extent seawater seem to be the most favourable and realistic options for sourcing water for hydrogen production.

In terms of uncovering the ideal location for e-SAF production, it is highly dependant on the locations of future offshore wind farms, as these enable direct line connections associated with lower production costs. Additionally, renewable production within the specific electricity sector plays a key role in assuring a sustainable and stable e-SAF production. Although most current tenders for offshore windfarms are located on the west coast of Denmark, it is likely that a substantial offshore wind capacity will be connected to Zealand. This would entail that production of e-SAF near CPH Airport to cover the fuel demand at the airport is realistic, as water and substantial amounts of biogenic CO_2 is available.

The sources that have been chosen in this report reflect the results of certain projections and conversations with people within the industry. They are, however, associated with a level of uncertainty, as the political landscape and future technical breakthroughs might change the opportunities and challenges completely.

The following chapter delves into the cost of production, utilising the chosen sources of feedstock, uncovered in this chapter. Furthermore, the chapter delves into economic tools that can be utilised to lower the potentially much more expensive ticket price associated with e-SAF, compared with fossil jet fuel.

Analysis Results - Cost Evaluation 7

This chapter delves into the potential cost of future e-SAF production, as well as the appertained ticket prices for passengers on e-SAF-fuelled aircraft. In the chapter, a cost comparison of fossil jet fuel and Methanol-to-Jet derived e-SAF is performed to determine the feasibility of e-SAF.

To perform the cost evaluation of e-SAF, projections on efficiencies and economic performances of each relevant technology from the Danish technology catalogues have been utilised. To enable a substantial e-SAF production by 2050, it is assumed that the relevant technologies will be established between 2030 and 2049. Therefore, the technology projections take departure in 2040.

7.1 Cost Evaluation

The technologies and appertained costs associated with e-SAF production are presented in key figures in the following table:

Table 7.1. Key figures of financial data for each utilised technology for e-SAF production (The Danish Energy Agency, 2024b,e).

Technology	Unit	Efficiencies [%]	Investment [MEUR/unit]	Lifetime [years]	O&M cost [% of investment]
Point Source Carbon Capture (Oxyfuel)	[Mt_{CO_2}/y]	96	154.5	25	3.1
Direct Carbon Capture (Liquid)	[Mt_{CO_2}/y]	86	250.5	30	2.51
Electrolyser (SOEC)	[MW]	68	0.5	25	10
Hydrogen-to-Methanol and Methanol-to-Jet synthesis	[MW]	76	1.17	25	4.7

In addition to the financial data, the price for technical water from rinsing treated urban wastewater has been determined to be 0.94 EUR/tonne, according to NIRAS (2024). The electricity demand of DAC is determined to be 1.517 TWh/Mt_{CO_2}. The electricity demand for the point source extraction is not accounted for, as it is assumed that this is accounted for by the waste incineration facilities.

To assess the cost of e-SAF, the EnergyPLAN software, described in Section 4.2.5, has been utilised.

To determine the annual cost of the system, the electricity price is central, as the price of electricity can make or break the feasibility of the system. It is therefore important to analyse how the economy and competitiveness of e-SAF is affected by the price of electricity. The economic sensitivity of the system, based on the electricity price is analysed in the following section, where it is compared to a scenario based on fossil jet fuel.

7.2 Sensitivity Analysis

As substantial amounts of electricity are necessary in the production chain of e-SAF, the cost of production strongly correlates to the price of electricity. Additionally, the profitability of e-SAF depends on the CO_2-trading price in the EU ETS and the price of fossil jet fuel. The price of fossil fuel is assumed to be 90 EUR/MWh in 2050 (DCC & Shell Aviation Denmark, 2024).

For this reason, a sensitivity analysis has been performed, where the variables being adjusted are the electricity price and CO_2-trading price, as those are the key variables impacting the price for each pathway, as mentioned above. As illustrated in Figure 7.1 projections suggest that the EU-ETS CO_2 trading price could increase to 500 EUR/tCO_2 by 2050. Figure 7.2 illustrates the total annual cost of e-SAF production depending on the electricity price, with the grey horizontal lines representing the potential annual cost of flying with fossil fuel depending on the future CO_2-trading price.

Figure 7.3 illustrates the annual cost of utilising fossil fuel, dependent on the CO_2-trading price. In this figure, the grey area represents the annual cost of e-SAF depending on an electricity price at 92 EUR/MWh and 30 EUR/MWh.

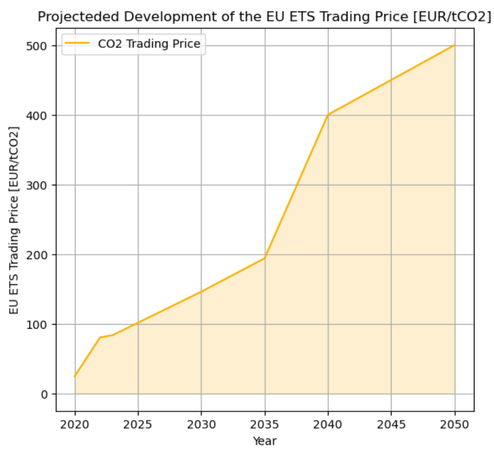

Figure 7.1. Projection for the price development of the EU ETS CO2 trading price [EUR/tCO2] (BNEF, 2024; GMK Center, 2023; Enerdata, 2023).

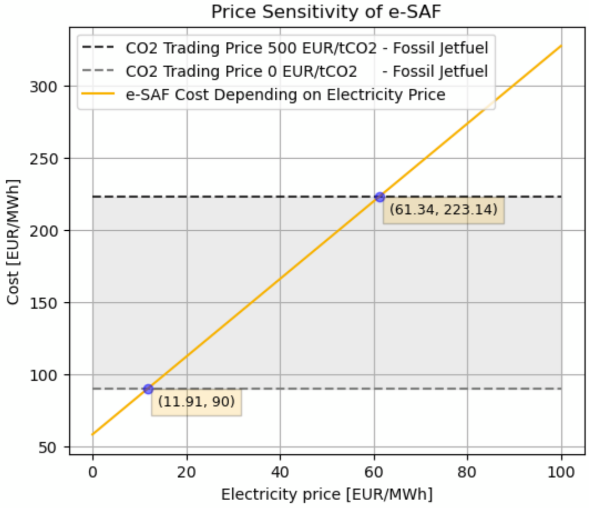

Figure 7.2. Price sensitivity for e-SAF depending on electricity price.

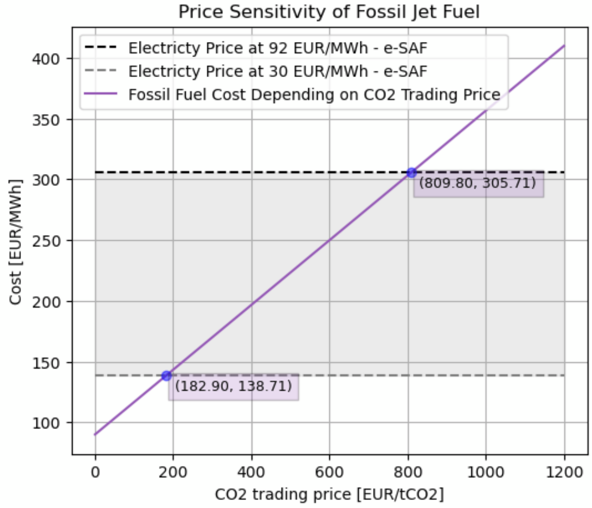

Figure 7.3. Price sensitivity of fossil jet fuel depending on CO_2 trading price.

As seen in Figure 7.2, the profitability of e-SAF is challenged as the price of electricity exceeds 61 EUR/MWh. If the aviation sector continues to be exempt from the EU ETS and the price of fossil fuels remains constant, the cost of electricity for e-SAF production would need to be below 12 EUR/MWh to be competitive.

To utilise the oxyfuel technology on waste incineration facilities, a constant supply of pure oxygen is required. The costs associated with oxygen supply are excluded from this analysis, as these expenses are managed by the waste incineration facilities.

For the EU ETS to enable a competitive market for e-SAF, the CO_2-trading price has to exceed at least 183 EUR/tonne if the electricity price is 30 EUR/MWh and 810 EUR/tonne if the electricity price reaches 92 EUR/MWh.

As carbon allowances are surrendered each year, projections for the EU-ETS CO_2-trading price suggest an increase to approximately 500 EUR/tonne CO_2 by 2050, according to Enerdata (2023). At this trading price, the electricity price would need to be at or below 61 EUR/MWh for e-SAF to be competitive with fossil jet fuel. With an average electricity price at 86.9 EUR/MWh on Zealand in 2023 and a further expansion of renewable electricity generation, it is very likely that the electricity price will fall below 66 EUR/MWh before 2050 (EnergiNet, nd; The Danish Government, 2022b). This indicates that a feasible production of e-SAF is a possibility, although it is highly dependent on the price of CO_2-allowances and expansion of inexpensive renewable power generation to drive down the price of electricity. Additionally, to reach this scenario by 2050, significant investments in R&D of the relevant technologies for e-SAF production are necessary to improve the efficiencies and lower the costs of each technology.

It is important to note that the cost per MWh would increase if the fuel demand increases. This is due to the necessary inclusion of technologies associated with higher costs, as the least expensive options are prioritised. At the same time, if the fuel demand is decreased, the cost per MWh would decrease, as more cost-intensive technologies are limited.

7.3 Chapter summary

The competitiveness of e-SAF in 2050 is highly dependent on the electricity price, as e-SAF utilises substantial amounts of electricity in the production chain, especially for hydrogen production through electrolysis and CO_2-extraction from Direct Air Capture. The substantial amounts of electricity needed in e-SAF production entails that the cost of the fuel is highly dependant on the cost of electricity. The impact of e-SAF cost relative to the electricity price can be observed in Figure 7.2. As the cost of fossil jet fuel is approximately 90 EUR/MWh, it is apparent that regulatory measures have to be implemented to ensure a competitive market for e-SAF. In Figure 7.3, cost of fuel, depending on the EU ETS trading price is illustrated. It can be observed that the EU ETS trading price has to be somewhere between 183 and 810 EUR/t_{CO_2}, depending on the electricity price, for e-SAF to be competitive with fossil jet fuel.

Discussion 8

As the demand, sourcing of feedstock, and the cost structure of e-SAF have been uncovered in the previous chapters, the purpose of this chapter is to discuss the analysis results.

This chapter delves into factors that could hinder the realisation of an e-SAF production to cover the fuel demand at CPH Airport These include feedstock uncertainties and social dynamics & tendencies. Afterwards, mitigating mechanisms & strategies, and alternative pathways to e-SAF are discussed.

8.1 Feedstock Uncertainties

This section delves into uncertainties and drawbacks related to the feedstock which have been found to be the most suitable for e-SAF production.

8.1.1 Offshore Windfarms & Hydrogen Availability

The availability of renewable electricity is one of the most crucial factors for realising the Power-to-X adventure in Denmark, as the expansion of renewable electricity has the potential to drive down the cost of electricity and enable a higher percentage of renewable energy in the electricity mix. The most promising renewable technology is off-shore wind, as this technology has a relatively high production per installed capacity, while being associated with less conflict of interest, compared to on-shore wind turbines and PV-panels (Appendix A, 2024; Appendix B, 2024; The Danish Energy Agency, 2024d). Additionally, national agreements on further expansion of offshore wind farms indicate that the future Danish electricity mix will be characterised by a large share of off-shore wind (The Danish Government, 2022b). The current plans in pipeline for the expansion of offshore capacity is, however, associated with a level of uncertainty, as the Open Door Policy has been suspended for not complying with international legislation (Ministry of Climate, Energy and Utilities, 2023). This entails that multiple offshore wind farm projects have either been cancelled or postponed indefinitely, which risks jeopardising the Danish PtX adventure, including e-SAF production (Appendix A, 2024; Appendix B, 2024).

In addition to the reliance of realising the wind farm projects in pipeline, another factor is whether a hydrogen infrastructure is established or not and whether the state or project developers should cover the associated costs hereof. The establishment of a hydrogen backbone in Jutland could enable substantial exports of hydrogen to Germany, potentially making large-scale hydrogen production more feasible, as hydrogen transport costs are lowered significantly, however, uncertainties on the future hydrogen demand, as well as the unwillingness of the state to cover the expenses of establishing the infrastructure risks jeopardising the plans for a hydrogen backbone (Appendix A, 2024; Appendix B, 2024).

8.1.2 Treated Wastewater Regulation & Availability

As the availability of electricity is often a major subject in Power-to-X planning, the importance of water availability and regulation is often overlooked. This entails that PtX projects are often projected to be located near areas of high electricity production. There is, however, no guarantee that sufficient amounts of water are available in the same location or that it is possible to transport sufficient amounts of water to the location. Although water is considered to be inexpensive, compared to the other feedstock, it is important that water is sourced responsibly and sustainably, to avoid social and environmental conflicts of interest (Appendix D, 2024). Additionally, regulation regarding utilisation of water is still not conditioned for PtX purposes. This could entail that it might become difficult to obtain water connection permits and permits for the required water treatment plant to reach the desired purity of water necessary in hydrogen electrolysis and the subsequent handling of processed wastewater. If these permits cannot be obtained, the PtX projects cannot be realised, which emphasises the importance of a change in regulation in water utilisation and management regarding hydrogen electrolysis (Appendix D, 2024; NIRAS, 2024).

8.1.3 Carbon Sourcing & Regulation

As for CO_2, the preferred sources are from biogas upgrading- and waste incineration plants, as these has the potential to create additional revenue streams from existing activities, and are associated with lower costs of extraction than Direct Air Capture (DAC). It is, however, unlikely that the aviation sector is the only sector that would require non-fossil CO_2 from these sources. This could entail a shortage in CO_2-supply.

As mentioned in Sections 2.4.1 and 6.1.3, the lock-in effect could result in the production of CO_2 becoming the primary revenue stream instead of the original purpose of each point source. This would make DAC a more suitable option to source CO_2, but this technology is associated with some problems. Firstly, it would require substantial amounts of renewable electricity, which, as covered in Section 8.1.1 is associated with uncertainty. Secondly, the technologies are still in development, and although projections estimate a progressive decrease in cost per amount of captured CO_2 it is uncertain if the technology will develop as projected (The Danish Energy Agency, 2024b).

These concerns could be mitigated by utilising an alternative source of CO_2, namely imported CO_2 from neighbouring countries, as the conditions for either storing or utilising CO_2 in Denmark are ideal (Appendix A, 2024). It can, however, be argued that importing CO_2 from neighbouring countries comes with several downsides, as production of e-SAF no longer can be considered an independent activity, and it challenges other countries to follow suit and develop fully non-fossil aviation sectors. In addition, if a multinational CO_2-grid is established, it would require a robust certification system similar to Power Purchase Agreements, to ensure that only the non-fossil share of CO_2 is utilised for e-SAF production. An advantage of a multinational CO_2-grid might be a lower cost of non-fossil CO_2.

8.1.4 Summary

The realisation of Danish PtX projects, including potential e-SAF production are all associated with high uncertainty, as they depend on the establishment of substantial amounts of renewable power generation, which in itself is associated with uncertainties. Additionally, the realisation of infrastructure projects which has the potential to further lower the cost of PtX products is associated with uncertainties. Until these uncertainties are resolved, it is unlikely that large PtX-projects, including e-SAF production, will be established on a large scale in Denmark (Appendix A, 2024; Appendix B, 2024; Appendix D, 2024).

8.2 Social Dynamics & Tendencies

As uncovered in the previous section, codependency between sectors or groups of actors can be the deciding factor in realising a project. This section, therefore, delves further into the implementation of e-SAF and its impact on social dynamics from an economic perspective.

8.2.1 CPH Airport, Airlines, and Fuel Suppliers

As CPH Airport will be the facilitator for utilisation of e-SAF, the dynamics between CPH Airport, airlines, and fuel suppliers at CPH Airport are meaningful to discuss.

At CPH Airport, External fuel suppliers are responsible for supplying jet fuel, which means that CPH Airport is not directly involved in this operation. For this reason, fuel suppliers are the main actors in deciding the selection of fuels available at CPH Airport. This structure is unlikely to change towards 2050 (DCC & Shell Aviation Denmark, nda,n; Appendix C, 2024).

As a result, both fossil Jet A-1 and MtJ-derived e-SAF may be available at CPH Airport in 2050, indicating that airlines could be inclined to continue using fossil jet fuel since it is likely to remain cheaper than e-SAF as uncovered in Section 7.2.

Although the airport is not directly responsible for emissions associated with the combustion of fossil jet fuel, they might have social concerns regarding emissions in the aviation sector. Evidently, the airport already has a measure in place, which could be applicable in the context of e-SAF implementation. Currently, the airport encourages the use of fuel-efficient aircraft by imposing an additional tax on less efficient aircraft and distributing this revenue hereof to airlines operating fuel-efficient aircraft. Therefore, it is not unthinkable that CPH Airport could introduce a similar economic measure, where the use of e-SAF is rewarded by penalising the use of fossil jet fuel (Appendix C, 2024).

8.2.2 Social Impact of Implementing e-SAF

As mentioned in Section 7.2, e-SAF is likely to be more expensive than fossil jet fuel, which negatively impacts the profitability of airlines, as 25-30 % of airlines' operating costs derive from the procurement of jet fuels (IATA, 2023a). To recover these costs, ticket prices are expected to increase.

Despite this, it is difficult to determine the exact price increase on plane tickets when e-SAF is introduced, as the relation between fuel prices and ticket prices is asymmetrical according to Scotti and Volta (2018) and Pal and Mitra (2022). This means that the price increase or decrease in ticket prices does not respond proportionally to the price fluctuations in fuel prices. Ticket prices are also impacted by market competition, which results in increasing asymmetry between ticket prices and fuel prices, as airlines are willing to reduce their profit margins (Scotti and Volta, 2018; Pal and Mitra, 2022).

According to Seymour et al. (2024), it is, however, estimated that ticket prices will increase by 7 % in 2050 with a 35 % share of e-SAF in fuel blends if RefuelEU mandates are followed. By extrapolating the equation through linear regression, the price increase of tickets can, however, be estimated to be 20 % with a 100 % share of e-SAF in fuel blends.

The price of tickets is, however, already expected to increase when utilising fossil fuel, as environmental passenger taxes recently have been added to the price of tickets (Capion and Have, 2023). This could incentivise airlines to invest in R&D of e-SAF and alternative propulsion to bridge the gap between ticket prices from an economic profit perspective. (Mayeres et al., 2023).

It is, therefore, expected that social impacts symbolised by the demand for aviation will remain unchanged despite the estimated increase in ticket prices when introducing e-SAF, as an environmental tax for fossil fuel is added to plane tickets, indicating that ticket prices will differ significantly.

8.2.3 Summary

The social dynamics concerning the implementation of e-SAF primarily revolve around passengers' willingness to pay for e-SAF, as this is likely to be more expensive than fossil jet fuel. It is, therefore, important that R&D in e-SAF is supported, and measures are taken to make e-SAF competitive with fossil jet fuel.

8.3 Mitigating Mechanisms and Strategies

As mentioned in Section 8.2, additional measures to promote the use of e-SAF could be necessary for e-SAF to be able to compete with fossil jet fuel. For this reason, this section delves further into mitigating mechanisms and strategies to streamline the implementation of e-SAF from a political perspective.

8.3.1 Economic Mechanisms

One of the mitigating mechanisms that can be applied when introducing a new product to an established market, is economic policy instruments in the form of subsidies, penalties, etc., as these can make the market conditions more favourable for the new product (Mayeres et al., 2023). This subsection, therefore, discusses the different policy instruments that can be applied.

The significance of such mechanisms is visible in Chapter 7, where a CO_2 trading price has been applied to the fossil jet fuel pathway. Without introducing this additional expenditure to the fossil pathway, it would require an extremely low electricity price for e-SAF to be competitive. When the electricity price is within a more plausible interval, it becomes clear that the CO_2 expenditure bridges the gap between the pathways. Important to note is that this expenditure is not exclusive for fossil jet fuel, but for all emitting activities from different sectors. This means that fossil jet fuel is not directly penalised for the sake of creating favourable market conditions for e-SAF, but is part of the broader EU ETS system (European Commission, nd). As policymakers can adjust the amount of EU ETS carbon allowances surrendered each year, as mentioned in 2.2.2, it is evident that this system is a powerful tool to control and increase the price for emitting CO_2, which in turn creates more favourable market conditions for climate neutral alternatives.

Further promotion of e-SAF could be achieved through subsidies or additional taxation exclusively for this purpose, but each instrument has its strengths and weaknesses. Both instruments can accelerate the implementation of e-SAF, but subsidies are an expensive solution for artificially sustaining a low market price, as it is publicly financed. Further taxation alternatively brings revenue to the government but will result in increased user prices due to increased market prices (OECD, 2022; Mayeres et al., 2023).

The drawback with each instrument is, however, that they are not sustainable in the long-term, as the industry could tend to rely on such initiatives rather than make e-SAF production more effective and cheaper through R&D (OECD, 2022; Mayeres et al., 2023). For this reason, it can be argued that it would be more beneficial to primarily rely on EU ETS and R&D in e-SAF production, as this would encourage the aviation industry to lower the cost of e-SAF, through market conditions.

8.3.2 System Integration & Additional Business Perspectives

Apart from policy instruments, it is also possible to make e-SAF production more profitable through system integration.

This pertains to process heat generated through the multiple production phases, as this has the potential to be an additional revenue stream for the business case rather than a by-product. For this reason, it would be beneficial to include this business perspective in the planning process (Appendix D, 2024; The Danish Energy Agency, 2024e).

This requires the e-SAF facility to be close to a district heating system in order to connect to the grid. This can, however, be difficult, as the largest concentrations of district heating usually are located near densely populated areas, whereas electricity production from offshore wind farms and their respective substations are typically located in less densely populated areas. In some areas in Denmark, it is possible to achieve this level of system integration, but as the location of PtX projects often has a strong correlation to electricity production, this might be difficult to achieve (Appendix D, 2024).

Apart from district heating, minor fractions of Naphtha and e-Diesel are also produced in the Methanol-to-Jet synthesis, which adds an additional revenue stream (Bube et al., 2024).

8.3.3 Summary

As e-SAF is expected to be more expensive than fossil jet fuel, mitigating mechanisms and strategies could be necessary to deploy, as these are able to make the e-SAF business case more profitable.

8.4 Alternative Pathways to e-SAF

The primary purpose of replacing fossil jet fuel with e-SAF is to achieve climate neutrality in the aviation sector. This section, therefore, delves into alternative, feasible pathways that could be able to achieve climate neutrality.

8.4.1 Fossil Pathway & Carbon Offsetting

One option is to continue using fossil jet fuel, whilst combining it with carbon offsetting. This is in principle what is done through both EU ETS and the CORSIA scheme, where the generated income ostensibly is allocated for climate initiatives such as carbon capture or reforestation, which can absorb and balance emissions (UNFCCC, 2018; European Commission, nd).

From an accounting perspective, carbon neutrality is achieved, but there are some long-term impacts associated with this pathway. Firstly, it does not promote the development of e-SAF and other types of propulsion, which can make the propulsion types cheaper and more effective in the future (Mayeres et al., 2023). Secondly, it retains Denmark in a position, where oil import is required, making Denmark dependent on other countries. This is a challenge in the long term, as oil is not an infinite resource, meaning that the aviation sector will be required to transition to alternative modes of propulsion at some point in time (Nygren et al., 2009).

For this reason, it is more beneficial to commit to e-SAF as early as possible, when considering the long-term impacts of continuing with a fossil pathway (Mayeres et al., 2023).

8.5 Chapter Summary

As uncovered in this chapter, some factors could hinder the implementation and utilisation of e-SAF. These cover feedstock uncertainties as well as the cost difference when compared to fossil jet fuel.

As mentioned in Section 8.1.1, one of the primary factors that could hinder the implementation of e-SAF is uncertainties related to feedstock, where the challenges entail both availability, regulation, and codependency between the feedstock types. The major challenge is the availability of renewable electricity from offshore wind, as the planned expansions have been halted due to the suspension of the Open Door Policy. Power-to-X projects have since stagnated, as they have been developed with these expansions in mind, meaning that there are uncertainties related to the availability of green hydrogen. Additionally, offshore wind farm projects have also been developed with the Power-to-X projects in mind, which explains the co-dependency between the two. The challenge for treated wastewater is on the contrary not availability, but a need for a change in the regulation of water, as it can be difficult to obtain the necessary permits. As for CO_2, multiple sourcing options are available, but there are uncertainties related to availability, technology readiness level, and regulation.

As mentioned in Sections 8.2 and 8.3, e-SAF is likely to be more expensive than fossil jet fuel, hence it can be necessary to introduce a range of mechanisms and strategies to enable a competitive market for e-SAF. These include measures from CPH Airport, policy instruments including taxation and emissions trading schemes, as well as system integration to promote the utilisation and R&D of e-SAF.

Since there is a necessity to eliminate fossil fuel emissions, due to their contribution to global climate change, measures have to be taken to eliminate emissions in the aviation sector. While e-SAF is considered relatively more expensive than bio-SAF pathways, the e-SAF pathway, analysed in the present report avoids risks of Indirect land use change and lock-in effects, while maintaining a relatively low cost. Compared to fossil fuel coupled with Carbon Capture and Storage, e-SAF might be less expensive in itself as the expenses of storing the required amount of CO_2 might entail in an overall more expensive fuel product than e-SAF. Additionally, e-SAF-production within the national borders enables fuel independence from other states.

With these factors in mind, e-SAF is a viable option compared to fossil jet fuel, as e-SAF has the potential to become more competitive. In addition, it has the potential to create independence from other states as it relies on domestic products rather than imported fuel.

9 Conclusion

The present project has sought to answer the following research question:

How can e-SAF production through Methanol-to-Jet cover the fuel demand at CPH Airport towards 2050, and how should feedstocks for production be sourced responsibly to meet the demands?

CPH Airport has been chosen as a case, as it stands as the most important airport in Denmark, currently covering more than 80 % of Danish air travel.

To answer the research question, three analyses have been performed.

Firstly, the required production of e-SAF to cover the demand for fuel at CPH Airport is determined through a spatial analysis of the fuel demand at CPH Airport and projected towards 2050, using projections that apply to the aviation sector as a whole. This results in a slightly lower fuel demand in 2050, compared to 2030, despite a projected increase in passengers departing from the airport. This is partly due to the projected implementation of alternative modes of propulsion, but also due to projected efficiency improvements of aircraft, airport traffic management, and airlines. This entails in a future fuel demand of 586 ktonne at CPH Airport in 2050.

Following the fuel demand analysis, it is sought to uncover the required amounts of each feedstock and the potential sources for each feedstock. For this reason, a comprehensive spatial analysis of Denmark has been performed to determine the availabilities and general locations for each source. The required feedstock for the production of e-SAF is water and electricity for hydrogen electrolysis and CO_2 for the subsequent e-SAF production through the Methanol-to-Jet synthesis.

It is possible to source about half of the necessary CO_2 from waste incineration near CPH Airport, although the remaining must either be sourced from biogas upgrading or waste incineration further away from CPH Airport. As the demand of CO_2 in 2050 is expected to exceed the available CO_2 from biogas upgrading and waste incineration, a substantial capacity of Direct Air Capture is required to cover the total CO_2-demand.

The water demand for electrolysis can easily be covered by one of the urban wastewater management facilities near the airport. The supply of electricity in 2050 is, however, associated with a much higher uncertainty.

Although Denmark has concrete plans for the expansion of renewable electricity production to cover the future electricity demand, including electricity for substantial PtX-production, the political and legislative landscape has been characterised by uncertainty, as of late. This pattern risks jeopardising the expansion of renewable electricity production and the subsequent PtX- and e-SAF production.

If plans for expansion of off-shore wind farms are realised, the business case for domestic e-SAF production becomes much stronger, as the cost of electricity is driven down and environmental sustainability is assured. In terms of location for hydrogen electrolysis production, it is ideally located near the west coast of Denmark, far away from CPH Airport, as most tenders for off-shore wind farms are located in that area in general. Although, as covered in Section 6.2.2, a hydrogen electrolysis facility could also be located relatively close to CPH Airport, with electricity supply from the electricity grid and 2.61 GW off-shore capacity. The following three figures illustrate the sourcing options for feedstock near CPH Airport.

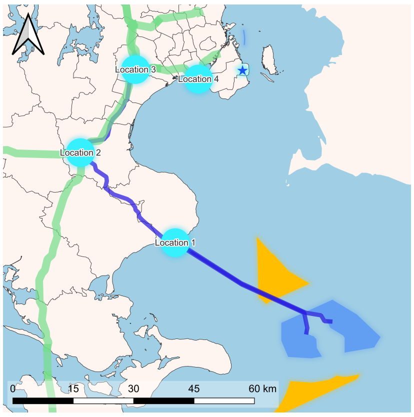

Figure 9.1. Potential location for hydrogen electrolysis.

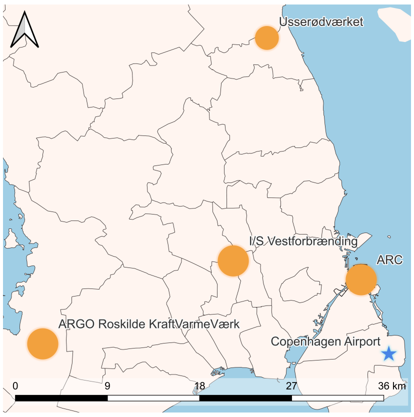

Figure 9.2. CO_2-sourcing from waste incineration.

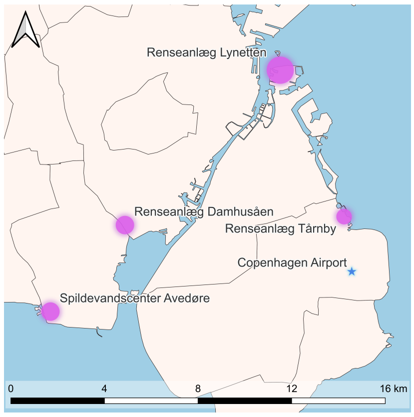

Figure 9.3. Water from urban wastewater treatment facilities.

Figure 9.1 illustrates four potential locations for hydrogen electrolysis and Direct Air Capture that have been selected, based on the existing electricity infrastructure and the potential future electricity generation from off-shore wind farms. Figure 9.2 Illustrates four large waste incineration facilities, which collectively are able to cover more than half of the CO_2 demand for e-SAF production. Figure 9.3 illustrates four large wastewater treatment facilities, each of which are able to cover the demand of water required for hydrogen electrolysis to cover the hydrogen demand. From the three figures, it is apparent that it is plausible that e-SAF production and the pertained electrolysis can be produced in the vicinity of CPH Airport. The question is then if the political landscape allows for a production near Copenhagen. If not, parts of or the whole production of e-SAF could take place in Jutland, where power generation from renewables are expected to increase more than on Zealand. If this path is chosen, water and CO_2 would likely be sourced elsewhere than on wastewater treatment facilities and waste incineration, as the capacities of these sources are lower in Jutland. Additionally, a production in Jutland entails that the e-SAF has to be transported to Zealand. Likely through a pipeline or by ship.

Following the spatial analyses to determine the availabilities of feedstock, a cost evaluation is performed to assess the competitiveness of the e-SAF product, compared to fossil jet fuel. In this, a sensitivity analysis of the cost of e-SAF relative to the electricity price is performed to illustrate the importance of driving down the electricity cost. Simultaneously, a sensitivity analysis on the cost of fossil jet fuel relative to the price of CO_2 emissions trading price is performed to visualise how the EU ETS can enable a competitive market for e-SAF in 2050. The findings suggest that the electricity price should be below 61 EUR/MWh, for e-SAF to be economically competitive with fossil jet fuel. This requires that the EU ETS trading price increases to the projected 500 EUR/tonne_{CO_2}.

In conclusion, this project has uncovered the feedstock demand for e-SAF production to cover the fuel demand at CPH Airport, as well as the appertained cost of e-SAF, depending on the electricity price and available sources of feedstock. The methods utilised in the project can be utilised on any other airport globally to determine the future fuel demand, as well as feedstock availability and the appertained cost of e-SAF. To determine the feedstock availability in other regions, it requires that comprehensive data is available or that it can be generated to assess the availability of the required feedstock. The methodological framework to determine the required feedstock and sources of feedstock is illustrated on the following page.

METHODOLOGICAL FRAMEWORK

Method for assessing feedstock & sourcing options to introduce e-SAF at an arbitrary airport

1

FUEL DEMAND ANALYSIS

ASSESSMENT OF THE FUTURE FUEL DEMAND

COURSE OF ACTION

1) Location of the case and destination airport **2)** Number of flights to destination and aircraft type in use **3)** Projections on the future demand for aviation at the case airport

2 PART ONE

FEEDSTOCK ANALYSIS

DETERMINING THE REQUIRED FEEDSTOCK

COURSE OF ACTION

1) Technology specific data on efficiencies and by-products from scientific articles or technology catalogues

2 PART TWO

FEEDSTOCK SOURCING ANALYSIS

DETERMINING THE AVAILABILITY AND LOCATION FOR EXTRACTING FEEDSTOCK

COURSE OF ACTION

1) Assessment of available sources for extracting the required feedstock **2)** Point specific data on each available source **3)** Considerations regarding cross-sectoral demands

3

COST EVALUATION

DETERMINING THE COMPETETIVENESS OF e-SAF

COURSE OF ACTION

1) Techno-economic projections regarding each relevant technology
2) Price sensitivity of key variables
3) Market instruments to enable the competitiveness of e-SAF

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Appendix A. Interview with Morten Poulsen - GrønAgenda.

Appendix B. Interview with Martin Hartvig - EnergiNet (The Danish TSO).

Appendix C. Interview with Peter Wiboe Holm - CPH Airport.

Appendix D. Interview with Thomas Bo Sørensen - DANVA.

Appendix E. Excel sheet - Calculations performed in the present report.

Appendix F. EnergyPLAN output - e-SAF scenario (electricity price at 92 EUR/MWh).

Appendix G. EnergyPLAN output - Fossil scenario (CO_2-trading price at 500 EUR/t_{CO2}).