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Fossil-free Airborne Search and Rescue Services

A pilot study

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In cooperation with the Swedish Maritime Administration

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Foreword

This document reports the findings from a separate part of the project Fossil free SAR Helicopters 2045 – A Pilot Study, which in full is funded by the Swedish Energy Agency, Grant number: 52430-1. The part which is reported herein has been performed by IVL Swedish Environmental Research Institute as subconsultants to the Swedish Maritime Administration. Reoccurring and regular meetings have been held between the Swedish Maritime Administration and IVL to ensure quality and orientation of the study to make it coherent with the rest of the overall project.

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Abbreviations

ATJ	Alcohol-to-Jet
CJF	Conventional Jet Fuel
FT	Fischer- Tropsh
G-FT	Gasification-based Fischer-Tropsch
GHG	Greenhouse gas/gases
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	Hydrothermal Liquefaction
LCA	Life Cycle Assessment
PtL	Power-to-Liquid
REDII	The recast of the Renewable Energy Directive
SAF	Sustainable Aviation Fuel

Summary

Due to the Swedish climate target of net-zero greenhouse gas (GHG) emissions by 2045, it has become more and more urgent for the aviation sector, which consumes a large amount of fossil fuels, to reduce its climate footprint. However, this represents a challenge for the non-commercial part of the aviation sector such as the air borne search-and-rescue services as their activities cannot be compromised by the climate target. Increased use of sustainable aviation fuels (SAF) is a way to achieve the climate target, while still not compromising the mission for this part of aviation.

However, due to a high demand on SAF, their availability and possibility to supply the aviation sector in Sweden as well as their environmental impact in relation to the climate target is still somewhat uncertain. This report aims to increase the understanding in these issues by first reviewing the domestic feedstock availability and calculating the SAF production potential within Sweden. Thereafter an assessment was done on how the aviation fuel market could vary in Sweden by 2045 due to the strength of the GHG reduction mandate and the dependence or independence of fuel from outside Sweden. This was done through 4 different future scenarios based on a mathematical model. Finally, the environmental impact of selected SAFs was evaluated by life cycle assessment (LCA) following the method described in the recast of the Renewable Energy Directive (REDII). The assessment was done based on the currently available data. Thus, the future change in the technology and other circumstances were not taken into account.

The current and future (2045) Swedish production potential of jet fuel was investigated via 4 different pathways, i.e., Hydroprocessed Esters and Fatty Acids (HEFA) from biogenic waste oils, Gasification-based Fischer-Tropsch (G-FT) from forest residues, Hydrothermal Liquefaction (HTL) from forest residues and Power-to-Liquid (PtL) from biogenic captured CO_2 and H_2 from electrolysis via Fischer-Tropsh (FT). The pathways, of the assessed ones, having the highest current and future potential considering feedstock supply are G-FT and HTL. The results were however considerably affected by the assumptions made on process yield. The production potential of PtL was not as high as the other pathways due to low availability of feedstock. Finally, HEFA was the pathway with the lowest potential due to the low availability of domestic raw material.

Based on the scenario analysis, the future of fossil free jet fuel is highly dependent of the price of fuel as well as the maximum allowed blending ratio of fossil free jet fuel. In this particular scenario analysis, domestic ATJ and HEFA was favored by the model thanks to their low production costs and avoided import costs, since the fuel is produced in Sweden. However, although the production plants used in the model will be constructed within Swedish borders, it is unlikely that domestic HEFA feedstock would be sufficient to supply them and there would likely be an import of waste oils to meet the demand of the plants.

The environmental assessment was done on UCO-based HEFA and PtL. HEFA was assessed as it is the fuel that the Search and Rescue fleet used during the pilot phase of this project. PtL was assessed for the sake of comparison and also because most data for PtL production was already available. Both HEFA and PtL show the potential of reducing the fossil GHG emissions up to 70 and 77%, respectively. However, with the technical and legislative limitations, it is not yet possible to use pure SAF in the aviation sector. This leads to the potential emission reduction of the greenhouse gases being lower than 42%. SAF production and transportation of feedstock are one of the main contributors to the emissions. In general, HEFA production has higher climate impact than the production of PtL. In addition, UCO which is the feedstock for HEFA was assumed to be collected in China. This gives a significantly higher impact compared to the PtL-process where all activities were assumed to take place in Sweden. This implies that the climate impact of HEFA can be reduced if the UCO can be collected domestically. However, as the assessment shows, the

climate target will be difficult to achieve when using HEFA or PtL. The challenge lies on the upstream processes of these two SAF which currently are still fossil-based. For HEFA, it is common that H_2 is produced from natural gas while for PtL, the production of raw materials used in electrolysis and carbon capture process such as chemicals and catalysts contribute to fossil emissions.

1 Introduction

Airborne Swedish rescue services are investigating what pathways to follow to contribute to the transition towards the national target of net-zero green-house gas emissions by 2045 [1]. Though rescue services share similarities with other airborne sectors such as commercial aviation, they also have unique conditions that affect their ability to decrease their greenhouse gas emissions: readiness and reliability in operations are crucial and it could be argued that they should be prioritized over climate goals.

According to SOU 2021:48 [2], a measure to phase out the use of fossil-based fuels by 2040 in Sweden, is to allocate biofuels and electrofuels to the transport sectors that are more difficult to electrify, such as the maritime, aviation and industry (working machines). Road transport is on the other hand easier to electrify. As the road transport is increasingly electrified, the demand of biofuels for road transport decreases, liberating its use for ship and airplane fuels.

In the SOU 2019:11 [3] it is proposed that the Swedish Armed Forces should procure Sustainable Aviation Fuel (SAF) for the government aircrafts and that they, together with The Swedish Defense Material Administration, should analyze the preconditions for domestic production. These proposals raise the question whether the use of SAF should also be a priority in the Swedish rescue fleet since their service is necessary and cannot be hindered by the unavailability of fuel. This leads to an interest among the search and rescue operators to investigate their contribution and feasibility toward the sustainability transition of the aviation sector.

This report aims to increase the understanding of domestic production potential of SAF today and in the future, the availability of SAF to the Swedish airborne rescue services, and what the market demand of both fossil and fossil free jet fuel, from the entire aviation industry in Sweden in 2045 looks like. The report also aims to investigate the environmental impact of two types of SAF-blended jet fuels throughout their life cycle and evaluate the greenhouse gas emission savings that would contribute to the national climate goal. The two SAF-blended jet fuels that are environmentally assessed are HEFA based on UCO and power-to-liquid fuel (PtL) from biogenic CO_2 and H_2. The UCO-based HEFA was assessed as it was already used by the Swedish rescue fleet during their pilot phase and the PtL fuel was assessed for the sake of comparison and because its production data is already available from an earlier project from IVL Swedish Environmental Institute [4].

The report contains four chapters, where the three first chapters report the results of three separate parts of the project, with different aim and system boundaries. The first chapter describe the availability of feedstock and the potential production of SAF in Sweden. The second chapter presents an illustrative scenario analysis of the Swedish market demands in relation to different policies and resource availability. Chapter three includes the life cycle assessment of two SAF value chains, with and without a mixture of fossil jet fuel. Lastly, chapter four discusses the findings and their potential impact to the Swedish rescue fleet, including some take-away points from this report.

2 Methodology

This report includes three main analyses: (1) Production potential of sustainable aviation fuels using domestic feedstock, (2) Future scenario analysis and (3) Environmental assessment of SAF. Each of them has a different goal and methodology. The methodology is presented below.

For the first analysis, the theoretical production of fossil free jet fuel in Sweden was calculated for 2020 and 2045 based on data of raw material existent in Sweden and the yield of jet fuel from four different production pathways, i.e., HTL, G-FT, HEFA and PtL with FT. The raw materials that are included in these calculations are waste oils of renewable origin, forest residues, biogenic CO_2 and H_2 produced via electrolysis using renewable electricity. For the case of 2045, prediction on stock availability were used based on literature. A sensitivity analysis was performed to evaluate the influence that the yield range of the different pathways had in the final production of jet fuel. A second sensitivity analysis was performed on the PtL pathway with more refined values of CO_2 and H_2 based on constructed or announced projects in Sweden on CO_2 capture and electrolysers.

For the second analysis, four different future scenarios of the market demand of both fossil and fossil free jet fuel, from the entire aviation industry in Sweden in 2045 were studied. The scenarios differ on how strict the GHG reduction mandate is and how dependent or independent is Sweden from fuel outside is borders. The scenarios were built using a mathematical model coded in python. They were optimized to minimize cost of the system. The demand of jet fuel was estimated until 2045 taking into account an annual increase rate and an improvement in fuel efficiency in aircrafts. The jet fuel used as input to the models is based on domestic production plants and imported fuel. Furthermore, the results from section 1 on feedstock availability were used to simulate additional domestic jet fuel plants that would supply jet fuel to the market.

Lastly, the environmental assessment was done by doing a life cycle assessment (LCA) according to the recast of the renewable energy directive (EU) 2018/2001 (REDII) framework [5]. Two LCAs were performed on two types of SAFs, one is to HEFA based on used cooking oil (UCO) and the other is to PtL from biogenic CO_2 and H_2. The data used in the assessment was mostly based on generic data and some assumption, especially on the origin of the UCO. The LCA of PtL was based on the study which is previously done by IVL called "Large scale bio electro jet fuel production integration at CHP plant in Östersund, Sweden" [4]. As the assessment follow the REDII framework, the environmental impact that is in focus is climate change. In addition, since the assessment was based on the current production of SAF, the change in technology and other circumstances such as improvement in the SAF production both in terms of energy efficiency and energy source were not taken into account. This may affect how the results is interpreted in relation to net-zero climate target in 2030 and 2045.

The results from the two LCAs were also used to identify the hotspot in the value chain i.e., the activities that are the main contributor to fossil greenhouse gases (GHG) emissions. The fossil GHG reduction potential of HEFA and PtL was also calculated by comparing with emission from fossil biofuels which has a value of 94 gCO2eq/MJ [5].

3 Production potential of sustainable aviation fuels using domestic feedstock

The aim of this chapter of the report is to provide the technical outline of some of the production routes used for SAF production and to present the production potential using domestic feedstock eligible for those selected pathways.

The *potential* as a concept needs to be defined in order to distinguish between options for different assumptions and constraints. In this case, the feedstock potential is the basis that provides the production potential of different fuels. The *theoretical potential* for feedstock is usually defined as the amount that is the result of physical processes [6] such as solar irradiation in solar energy potential, and the amount of vegetation growing in an area as the theoretical potential of biomass-based fuel feedstock. Constraints on this amount due to ecological limitations (such as biodiversity or carbon or nutrient soil content) are applied in order to define an *ecological potential* and when this amount is narrowed further by technical constraints (e.g. due to unretrievable amounts) the *technical potential* can be obtained. More constraints such as economic or market aspects could be applied (see for example in [7]), but the basis of the evaluation in this report has been to use the ecological potential of a certain feedstock as the largest amount that could be used for SAF production. The feedstock potential has then been combined with technical constraints for yield.

The evaluation of production potential is made for four fuel production pathways: hydroprocessed fatty acid esters and fatty acids (HEFA), gasification-based Fischer-Tropsch (G-FT), hydrothermal liquefaction (HTL) and power-to-liquid (PtL), based on dialogue in the project group and data availability.

3.1 Synthesis of fossil free fuels

There are multiple pathways in which material containing carbon and H_2 could be converted into hydrocarbons in a blend that is suitable for drop-in with conventional jet fuels. As of 2022, there are nine pathways in total that are certified by the ASTM (American Society for Testing and Materials)[8]: Fischer Tropsch synthesized isoparaffinic synthesized paraffinic kerosene (FT), Synthesized iso-paraffins (SIP), Hydroprocessed Hydrocarbons- synthesized isoparaffinic kerosene (HH-SPK or HC-HEFA), Hydroprocessed fatty acid esters and fatty acids (HEFA), Alcohol to jet (ATJ), Catalytic Hydrothermolysis Jet fuel (CHJ), synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA), and lastly, pathways for HEFA and FT that are co-processed in conventional refineries.

In this study, four pathways are evaluated for future jet fuel production: Hydroprocessed Esters and Fatty Acids (HEFA) from biogenic waste oils, Gasification-based Fischer-Tropsch (G-FT) from forest residues, Hydrothermal Liquefaction (HTL) of forest residues and Power-to-Liquid (PtL) from biogenic captured CO_2 and H_2 from electrolysis. Three of these pathways are certified by ASTM: HEFA, G-FT and PtL pathways which correspond to named certified processes HEFA, and

FT. PtL pathway includes the Fischer-Tropsch process step and it is therefore also certified for blend-in up to 50%. The remaining process, Hydrothermal Liquefaction (HTL) pathway, is thus far uncertified.

3.1.1 Hydroprocessed Esters and Fatty Acids (HEFA) from waste oils

Hydroprocessed Esters and Fatty Acids (HEFA) is a biofuel produced from raw materials that are mainly composed by triglycerides, which forms the base material for any natural fats and oils. The process of producing HEFA jet fuel is similar to the process of Hydrotreated Vegetable Oil (HVO), with additional process steps to meet the technological requirements in the standard for jet fuel [9]. Any type of fats and oils could be used as feedstock to produce HEFA, with the most common ones being virgin vegetable oils, waste oils and animal fats. In the HEFA process the main product output is renewable diesel (HVO), with about 15% of bio-jet fuel of the total liquid yield under normal processing conditions. The main process steps to produce HEFA are the following: pre-treatment, deoxygenation and hydrogenation, hydrocracking and isomerization and lastly distillation [10], [11]. A schematic of the process is presented in Figure 1.

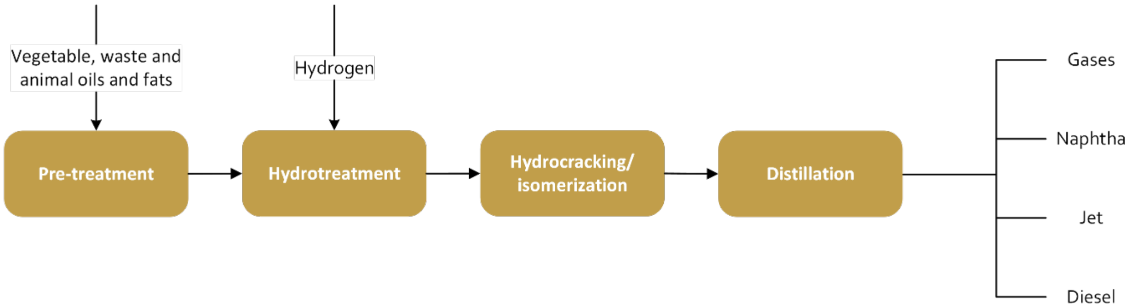

Figure 1. Schematic of the HEFA-process. Modified from source: [11], [12]

In the first step, the feedstock is pre-treated to remove impurities such as phosphorous compounds, trace metals and soaps, to avoid catalyst poisoning. Three processes are generally used in the pre-treatment which includes neutralization, degumming and bleaching. Depending on the type of feedstock used for producing HEFA, the pre-treatment process varies. The pre-treatment is especially necessary when feedstock sourced from residues are used, such as waste oils [12], [13].

Following, deoxygenation and hydrogenation reactions take place in a reactor in the presence of catalysts and hydrogen. Depending on the configuration of the reactor and catalysts used, the reactions take place in a temperature range of 250–450°C and hydrogen pressure of 10–300 bar. Unsaturated carbon chains and oxygen are removed from the triglyceride molecule, which improves the stability of the final fuel as well as lowers reactivity with water and increases the calorific value. In the process, long-chain liquid hydrocarbons are produced along with other by-products such as water, propane, CO and CO_2 in different proportions [13], [14].

In the next step, cracking and isomerization reactions take place to yield smaller hydrocarbons and branched hydrocarbons. The chemical and physical properties are greatly influenced by the length and degree of branching of the hydrocarbons, making this step necessary to meet the requirements in the standard for jet fuel. In the isomerization step, catalysts are used to rearrange the linear hydrocarbons into branched species of the same molecular formula, which helps improve the cold flow properties [11], [14].

Finally, the distillation occurs, during which the product is separated in two steps. First water and gaseous components are removed, followed by the distillation that yields the final products of kerosene, diesel and naphtha in different proportions [10].

3.1.2 Gasification-based Fischer-Tropsch (FT) from forest residues

Fischer-Tropsch (FT) is a conversion technology used to produce synthetic hydrocarbon from any carbon-based material. Bio-jet fuel could be produced through gasification-based FT using biomass feedstock such as forestry residue and municipal waste. The process for gasification-based FT includes the following steps: feedstock preparation and pre-treatment, syngas production, syngas refinement, FT-synthesis, isomerization, and hydrocracking, and lastly distillation [10], [15]. A schematic of the process is presented in Figure 2.

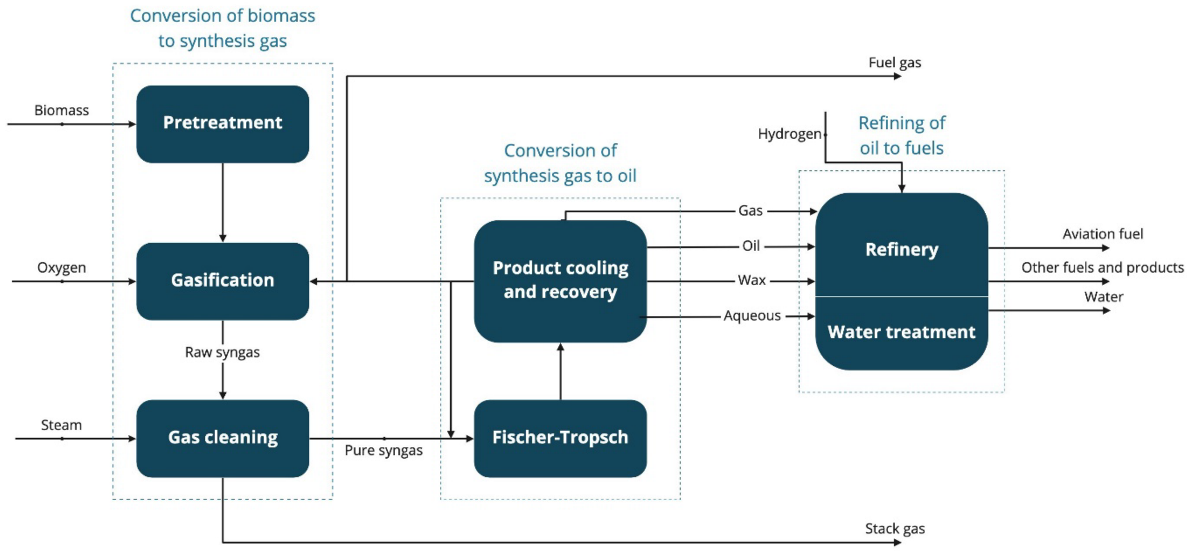

Figure 2. Schematic of the gasification-based Fischer-Tropsch process. Modified from source: [16]

In the first step, the feedstock undergoes size reduction and drying processes to prepare for the following conversion steps. The type and degree of preparation varies depending on the feedstock and type of gasifier used. With forest residue as feedstock, the process starts with the drying of the forest residues to achieve a moisture content between 5–30%.

In the following step, the biomass is converted to synthesis gas (syngas) through gasification. The thermochemical process is operated in a temperature range of 800 to 1800 °C, in which oxygen and steam are used as gasification agents to produce syngas from any carbon-based material. Pure syngas is a mixture of CO and H_2, the ratio of which varies depending on the feedstock used [10], [15]–[17].

In the next step, the syngas is purified to remove contaminants such as tars, acidic gases, and particulates, which is necessary to avoid catalyst poisoning in downstream processes. The syngas is then conditioned prior to the FT-synthesis to optimize the ratio of CO and H_2 in the gas. The conditioning is mostly performed through the water-gas-shift (WGS) reaction during which CO is released by reacting with steam to yield CO_2 and H_2 [10], [16].

Following, the clean syngas goes through the FT-synthesis. Through a stepwise polymerization process the syngas is converted into hydrocarbon liquids and waxy solids in the presence of a catalyst. Depending on the type of catalyst used and the operating conditions, the product and product yield varies. Iron and cobalt are the most common catalysts used. The FT-synthesis is usually performed in a low temperature range (200–240 °C) with iron or cobalt catalysts, or in a high temperature range (300–350 °C) with iron catalysts [15], [17].

In the last steps, the resulting hydrocarbons from the FT-synthesis are purified and refined to produce jet fuel. In the process, isomerization and hydrocracking reactions take place to improve the cold properties of the final product and to obtain a higher yield of jet fuel. Through distillation the fuel mix is then separated based on chain length, yielding naphtha, kerosene, diesel and wax components in different proportions. From gasification-based FT, the jet fuel yield from the total conversion output is around 50–70%, where it is impossible to solely obtain bio-jet fuels from the process [10], [12], [17].

3.1.3 Hydrothermal Liquefaction (HTL) from forest residues

Hydrothermal liquefaction (HTL) is a thermochemical conversion process of biomass into liquid fuels. The process is suitable for conversion of a wide range of biobased and waste feedstock, such as woody biomass, waste from the forestry industry, food waste, industrial waste, manure, algae etc. In the process of producing jet fuel through HTL, there are five main steps: pre-treatment, the HTL-process, hydrotreating, hydrogen production and wastewater treatment [18], [19]. A schematic of the process is presented in Figure 3.

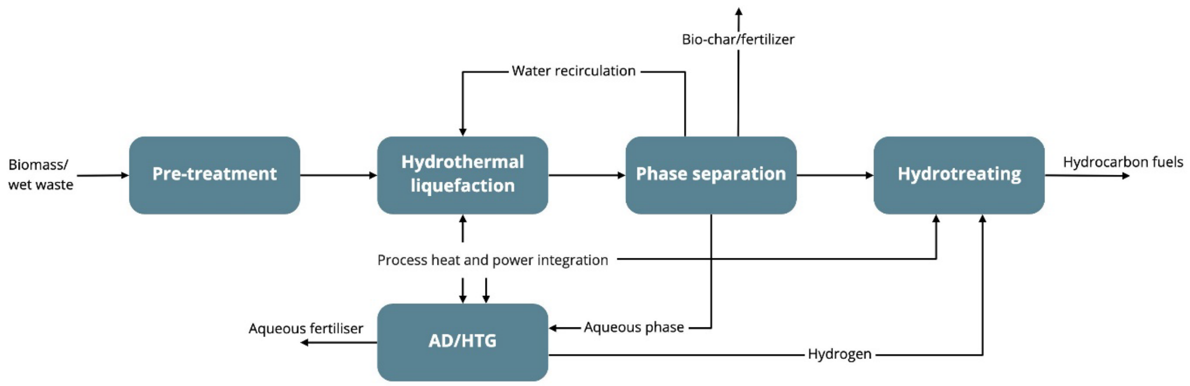

Figure 3. Schematic of the HTL-process. Modified from source: [20]

As with most biomass conversion technologies, the pre-treatment process varies depending on the feedstock used. With forestry residue, the feedstock undergoes a size reduction by being ground into fine particles. Following, water is added by direct injection of hot water, to create a pumpable slurry [19], [20].

The feedstock is then processed through HTL, which is performed at a temperature range between 250–375 °C and a pressure level between 5 and 28 MPa. In the HTL process, three main steps take place (i) hydrolysis to yield smaller fragments of the macromolecules, (ii) dehydration and decarboxylation to convert into smaller compounds, (iii) condensation, cyclization, and polymerization to rearrange into larger, hydrophobic macromolecules. During the process water acts both as a solvent and reaction medium. After the reaction a spontaneous phase separation occurs with water remaining in a liquid state, a gaseous phase with rich levels of CO_2, solid residue, and the desired bio-crude fraction [20], [21].

In the last steps, separation of the different phases occurs, and the bio-crude phase undergoes a hydrotreatment to be upgraded into the final fuel product. The upgrading process is primarily performed to remove oxygen, which is necessary to retrieve a hydrocarbon fuel with characteristics suitable as a drop-in jet fuel. Additionally, the liquid water from the HTL-process can also be recycled after being separated from the other phases and undergoing pre-treatment for the water-soluble organics it contains. The pre-treatment could either be performed through anaerobic digestion yielding methane-rich biogas or through catalytic/non-catalytic hydrothermal gasification yielding a methane and hydrogen-rich gas. The gaseous phase from the HTL-process also has further potential, as it could be used to produce hydrogen in a hydrogen plant [19], [20], [22].

3.1.4 Power-to-Liquid (PtL) through the FT route, CO_2 + H_2 feedstock

Power-to-Liquid (PtL) is a process to produce synthetic fuels with the main constituents of renewable electricity, water, and CO_2. The basic principle of producing PtL involves H_2-production through water electrolysis, capturing and provision of CO_2, synthesis of liquid hydrocarbons from H_2 and CO_2, and lastly further conditioning to achieve the desired fuels. The final jet fuel product could be produced either by utilizing the Fischer-Tropsch pathway or by producing an E-alcohol and then form the longer chains of hydrocarbons that are required. In this project, the FT pathway will be further explored. A schematic of the process is presented in Figure 4.

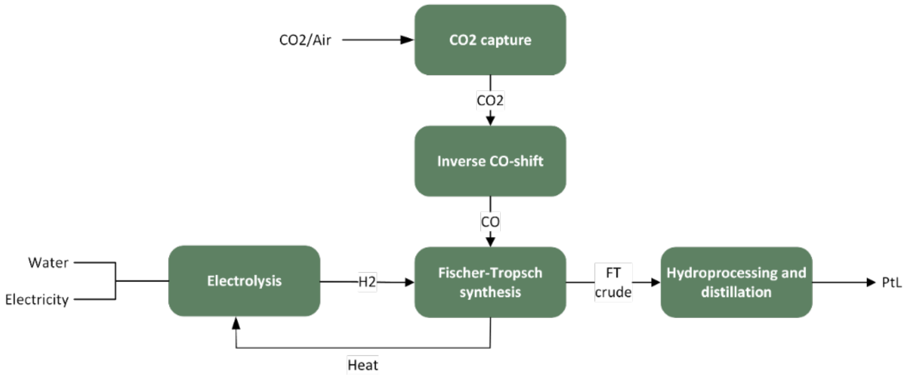

Figure 4. Schematic of the PTL-process through the Fischer-Tropsch route. Modified from source: [23]

Hydrogen can be produced through water electrolysis with electricity as energy source and water as raw material. In the process, water is split into H_2 and O_2 gas with a direct current in an electrochemical cell. The electrochemical cell consists of a positive (anode) and negative (cathode) electrode which are submerged into an ion conductive electrolyte. In the electrolysis process, water is reduced at the cathode and oxidized at the anode, splitting the water into H_2 and O_2 gas [24].

Electrolysis can be performed using either liquid water in low temperature or high-temperature steam. Low-temperature technologies are the most mature, which include Alkaline electrolysis (AEL) and Proton Exchange Membrane electrolysis (PEM). High-temperature technologies are still in the research and development stage, which include Solid Oxide Electrolyzer Cell (SOEC) and Molten Carbonate Electrolyzer Cell (MCEC) [4], [24] Carbon dioxide (CO_2) can be captured from three major sources: fossil, mineral and renewable origin. The different capturing technologies available are generally divided into pre-combustion, post-combustion, and oxy-fuel combustion technologies [4], [25].

In pre-combustion capture, the CO_2 is removed before the combustion. The process involves three steps: (i) conversion of the hydrocarbon fuel into synthesis gas (H_2 and CO), (ii) conversion of CO into CO_2 through the water gas shift reaction, (iii) separation of CO_2 from H_2. Post-combustion technologies can be used to capture CO_2 from exhaust gases and is suitable for industrial and power plant application as these could be retrofitted. In oxy-fuel combustion, the fuel is combusted in nearly pure oxygen, which provides a relatively pure CO_2 for capturing. Following the capturing, CO_2 can be separated through absorption, adsorption, membranes and cryogenics. CO_2 can also be extracted directly from the atmosphere through Direct Air Capture (DAC), which applies the same absorption and adsorption technologies for separation [4], [26].Following the CO_2 capturing, the CO_2 undergoes an inverse CO-shift reaction, using the reverse water-gas-shift process, to be converted into CO. The H_2 from the electrolysis process and the CO are mixed to obtain a syngas which can be used in the FT-synthesis process to produce hydrocarbons. The resulting FT-crude from the synthesis is then upgraded through several steps involving hydrocracking, isomerization and distillation, yielding jet fuel and other hydrocarbon products. From the FT pathway, the share of jet fuel from the total products are approximately 50–60% [23].

3.2 Available feedstock in Sweden

In order to calculate the amount of fuel that could potentially be produced in Sweden, the availability of raw material needed for each production route has been assessed based on the theoretical feedstock potential, combined with ecological constraints. Competition with other sectors and applications has not been considered. Instead, the largest possible quantity of SAF that could be produced from the estimated feedstock potential has been determined, regardless of whether the feedstock is used in other processes today. Due to the complexity of the value chains using the same type of feedstock, some assumptions have been applied in the assessment. The assumptions and data found for each type of feedstock are described below. An assumption that concerns all production pathways was the simplification of hydrogen as a feedstock: whereas hydrogen is used in small (negligible) amounts in the fuel processing of several of the pathways, it is only accounted for as feedstock in the PtL pathway. The results of the compilation of available feedstock are presented in Figure 7 in section 3.3.2.

3.2.1 Waste oils of renewable origin

As mentioned in 3.1.1, HEFA could be produced from a range of oil-based products. However, to ensure a fraction of feedstock that is sustainable, all use of primary bio-oils were excluded from the eligible amount for SAF production in Sweden. Instead, only oil products that could be considered as residual or as by-products were used.

The available feedstock for HEFA production today is based on numbers presented in [27], an assessment of feedstock in Sweden available for HVO production, which is equivalent to feedstock available for HEFA production because of their similar production routes. The potential of each feedstock type has been converted from HVO to oil product via the conversion factor of 0.97 MJ of HVO per MJ of fats.

Included in the potential feedstock today are waste animal fats, used cooking oil (UCO) and tall oil. Used cooking oils (UCO) are oils that have been used for cooking in households, industry or restaurants, while animal fats are comprised of slaughterhouse waste and other waste animal oils. These are two common types of feedstocks used in commercial production of biofuels [27] and are included for this reason. Together, they amount to 0.67 TWh/year. Tall oil is another renewable and residual product from the pulp and paper industry [27]. Although it requires refinement before conversion into jet fuel, it is feasible to use as feedstock and is thus also included in the 2020 potential. Aggregating the numbers on tall oil, UCO and waste animal fats result in the current potential of **2.7 TWh/year**.

Other types of waste material, such as forest residue (lignocellulosic material), could be converted into oil via a process using oleaginous yeast, this is however not a technologically mature process as of today and is therefore not included in the current potential [27].

In 2045, processes and practices that are not established as of 2020 may have developed and become commercially available. Apart from the oleaginous yeast process that may enable forest residues to be used in the HEFA process, oil and energy crops grown on marginal land could be used for HEFA production if they are harvested and collected. However, the biomass potential grown on this type of land is hard to quantify and can merely be suggested based on scenarios. A small potential also exists in using algae for jet fuel production, based on the same process principle that the method might be established by 2045 [27]. In [27], numbers are compiled for the potential in 2050. In this report, the same numbers are used for 2045, since the difference in forecasted potential between 2045 and 2050 was considered negligible for the considered types of feedstocks.

When only including the potential resulting from more established technologies and feedstock types are considered, UCO, animal fats and tall oil, the potential has the same range of order, or increases marginally, to 2–3 TWh/year in 2045 [27]. However, if other types of feedstocks (to be used in less established technologies) would also be considered, such as forest residues (using oleaginous yeast), energy crops grown on marginal land (using oleaginous yeast, not competing with food production) and algae, the future potential would instead be 25–27 TWh [27]. In this project, the potential is quantified based only on the more established processes and thus only UCO, animal fats and tall oil remain as a viable option for HEFA production in 2050 and limit the future potential to **the 2–3 TWh/year**.

3.2.2 Forest residues

The ecological potential of forest residues was determined based on estimates presented in [28], building on [29] The forest residue category includes tops, branches and stumps, fuel wood and wood chips from thinned trees [28].

For the potential in 2020, the number based on the estimated potential in 2030 [28] is used and interpolated to 2020, due to lack of estimate for 2020 in the source material. This number amounts to 83–95 TWh. For 2045, the potential has grown to 91–106 TWh [28].

3.2.3 CO_2

The amount of CO_2 released in Sweden in 2020 according to the European Energy Agency [30], is approximately 45.4 million tons of CO_2. Of this total, 31.4 million tons is biogenic CO_2 (69%) and 14.1 million tons is non-biogenic CO_2 (31%). The largest sector that contributes to these emissions is paper and wood, with 23.1 million tones (51%), although 98% of this emission is biogenic CO_2 (from the combustion of biobased fuels). The energy sector is the second largest emitter, releasing about 10.2 million tons (22.4%) from which 53% is biogenic. The trend of CO_2 release in Sweden has been nearly constant throughout the years as is visualized in Figure 5.

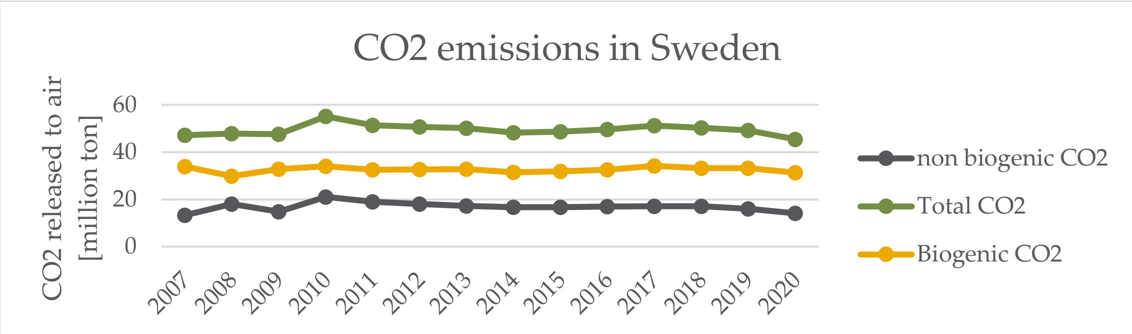

Figure 5. CO_2 emitted to the air in Sweden from 2007 until 2020. Source: [30]

The biogenic CO_2 is the amount selected to be used in the production of SAF. Apart from the CO_2 emissions produced by the combustion of biobased fuels (included in Figure 5) there is CO_2 produced as a waste stream in the production of biofuels such as biogas and bioethanol (not included in Figure 5**).** This amount of CO_2 is also taken into account for the production of SAF.

The effectivity of CO_2 capture depends on the point of source. CO_2 from flue gases appears in lower concentrations (<15%) and the capture technologies have a recovery efficiency of 90%. This will translate in a total CO_2 recover from the flue gases, of **28.2 million tons**. On the other hand, CO_2 from biofuel production is purer (concentrations >90%) and the efficiency of its recovery is assumed to be 100% [31]. Nevertheless, not all the biofuel produced is upgraded to remove impurities such as CO_2 from the biofuel. While almost all ethanol is upgraded (approx. 1 473 GWh produced in Sweden in 2020) yielding an amount of **202 thousand tons** of CO_2, from the biogas produced in 2020, only 1 404 GWh (65%) was upgraded [32] yielding an amount of **204 thousand tons of CO_2**. In this sense, it can be concluded that total amount of CO_2 that could be potentially used from the processing of biofuels by 2020 is **406 thousand tons**. All in all, the total available biogenic CO_2 from combustion flue gases and biofuels production in 2020 is approximately **28.6 million tons**.

For a scenario of 2045, the amount of available biogenic CO_2 is calculated as follows. Since the tendency of biogenic CO_2 emissions from combustion of biobased fuels in several industries is relative stable, having only a reduction of 8% from 2010 until 2020, and the use of biofuels in the energy and manufacturing industry still slowly increasing [33], the same value as 2020 will be considered for biogenic CO_2 available in 2045. When it comes to the biogenic CO_2 from the production of biofuels the number is expected to increase since both biogas production and upgrading have been in average increasing 28% and 55% respectively since 2013. If we assume a linear increase in biogas production maintaining the upgrading fraction of 2020, i.e., 65%, and maintaining the actual capacity of ethanol production, the total available biogenic CO_2 from biofuel production would be **560 thousand tons**. Finally, the total available biogenic CO_2 by 2045 would be **28.8 million tons.**

3.2.3.1 Ongoing projects for CO_2 capture in Sweden

In order to have a better idea on the potential of using CO_2 as a raw material for the production of SAF, some ongoing and planned projects in Sweden are mentioned below. Some of these projects capture non-biogenic CO_2 while other capture biogenic CO_2. This data was used for the sensitivity analysis in Section 3.3.3.2

In Lysekil, Sweden, refinery Preem inaugurated in 2020 a pilot scale carbon capture and storage facility in collaboration with energy engineering Aker Solutions, Chalmers University of Technology and Norwegian research institute SINTEF. The CO_2 comes from Preem's hydrogen gas plant also situated in Lysekil. Hydrogen is produced here by steam methane reforming (SMR), and the methane is nowadays fossil-based [34], meaning that CO_2 captured is non-biogenic. Preem's goal is to scale up the CO_2 capture plant by 2025 to capture 500 thousand ton of CO_2, which corresponds to a quarter of the total refinery emissions [35]. The CO_2 will be stored under the seabed in Norway. This storage is planned to be open in 2024 with an expected capacity of 1.5 Mtons/ year with the ambition to increase it to 5 Mtons/year. [36].

In Stockholm, the cogeneration plant from Stockholm Exergi AB, which combusts biomass to produce district heating and electricity, commissioned in 2019 a pilot plant to capture the biogenic CO_2 emissions of the plant. According to the results of the pilot plant, Stockholm Exergi has the potential to capture 800 thousand tons of biogenic CO_2.

In Gotland, the cement company Cementa (branch from Heidelberg Cement AG), has plans for building a carbon capture plant in 2030 at their site in Slite. This plant will have the capacity to capture all the CO_2 generated on site, which is equivalent to 1.8 million tons/year. Heidelberg Cement AG has experience from CCUS technologies in Norway, Canada and UK.[37].

Vattenfall has plans for constructing carbon capture facilities in their district heating plants in Uppsala, Haninge and Nyköping. So far, the plant in Uppsala has come the furthest in the implementation. The plan is to begin construction within the next 4 years, for a plant that would have the capacity of capturing 200 thousand tons/year. The use of this CO_2 is meant for electro fuels production by the alcohol to jet route [38].

Finally, Liquid Wind will capture 70 thousand tons of biogenic CO_2 from the CHP facility of Övik Energi AB in Örnsköldsvik. The purpose of this CO_2 is to be used for the production of 50 thousand tons of electro methanol, to be used as fuel for shipping, by 2024.

All in all, as seen summarized in Table 1, the amount of CO_2 that can potentially be capture from the industry in Sweden by 2030 is about 3.6 million tons but only **1.9 million tons** is from biogenic CO_2. Except Liquid Wind and Vattenfall who has the purpose to use the CO_2 to produce E-methanol and ATJ respectively, the other companies plan to store the CO_2 in the subsea of the Norwegian coast, a storage is being constructed with a capacity of 1.5 million tons of CO_2 a year [39].

Table 1. Planned carbon capture plants in Sweden until 2030

Company	Location	Amount of CO_2	unit	Year	ref
Preem	Göteborg	500 000 (non-biogenic)	ton	2025	[40]
Stockholm Exergi	Stockholm	800 000	ton	2026	[41]
Cementa	Gotland	1 800 000 (non-biogenic)	ton	2030	[42]
Vattenfall	Uppsala	200 000	ton	2026	[43]
Liquid Wind	Örnsköldsvik	70 000	ton	2024	[44]
	Sundsvall	240 000	ton	2026	[45]
Total CO_2 captured		*3 610 000*	*ton*		

3.2.4 H_2

The current production of H_2 in Sweden comes from 3 main sources: from fossil raw material (4 TWh), as waste stream of industrial processes (2 TWh) and from electrolysis (0.18 TWh) [46]. The largest H_2 production is nowadays concentrated in Gothenburg and surroundings, as well as in Sundsvall, close to Stockholm and close to Malmö [46]. The 3% of H_2 produced by electrolysis is directly used where it is produced, and it is mainly for the steel industry (HYBRIT project, H2 Green Steel project, Ovako's hydrogen plant). Nevertheless, this number is expected to increase with the construction of new plants according *to Fossil Free Sweden's* hydrogen roadmap, which sets the goal of creating 3 GW and 8 GW installed electrolysis power for the production of H_2 by 2030 and 2045 respectively [46].This translates into producing approximately 16 TWh of H_2 by 2030 and 44 TWh by 2045. The Swedish Energy Agency sets a more ambitious goal of 5 GW and 15 GW of installed electrolysis power by 2030 and 2045 respectively which translates into approximately 27 TWh and 82 TWh of H_2 by 2030 and 2045 respectively [47][1].

Nowadays, Sweden produces electricity by both renewable and non-renewable sources, being almost 98% carbon free. As seen in Figure 6, in 2021, 166 TWh of electricity was produced, of which 42.6% was hydropower, 16.5% wind power, 0.9% solar power, 30.8% nuclear power, 8.4% from cogeneration plants and 0.8% gas turbines [48]. In the last 15 years, the number of wind power facilities has exponentially increased and solar cells have slowly increased [49]. These are tendencies that contribute to the increase in electricity production to meet the demands for H_2 production.

[1] Hydrogen amounts in TWh are calculated from the target of electricity needed (GW), using an Electrolyzer efficiency of 65%, 8400 working hours and the LHV of the H_2.

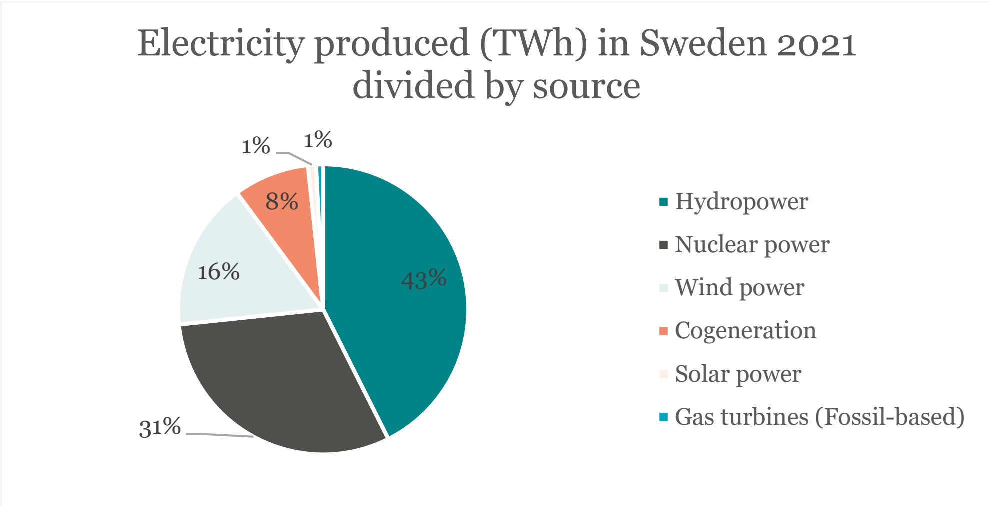

Figure 6: The share of electricity produced in Sweden in 2021 by each generation source.

3.2.4.1 Ongoing projects for H_2 production by electrolysis in Sweden

In order to have a better idea on the potential of using H_2 as a raw material for the production of SAF, some ongoing and planned projects in Sweden are mentioned below. This data was used for the sensitivity analysis in Section 3.3.3.2

Some of the projects that plan to construct electrolyzers in Sweden are summarized in Table 2. The amount of H_2 has been calculated assuming an electrolyzer efficiency of 65% and capacity of 8400 h. The total amount of H_2 that will be produced by 2045 is **21.7 TWh** which corresponds to approximately **657 thousand tons of H_2**. Some of the H_2 that will be produce has a fixed end use, e.g., in the steel or the chemical industry. Some others are planned to be used in fuel production, such as biofuels from Preem or eMethanol from Liquid Wind. A smaller part is open to other industrial uses (1.1 TWh).

Table 2. Projects on constructing electrolysers for H_2 production, in Sweden

Company	Location	Amount of H_2	unit	Year	ref
H2 Green Steel*	Boden	4.4	TWh	2025	[50]
Vattenfall, SSAB, LKAB (Hybrit)	Luleå	7.1	TWh	2045	[51]
Preem & Vattenfall	Göteborg	1.7-4.2	TWh	2030	[52]
Strandmöllen	Ljungby	0.016	TWh	2023	[53]
Uniper*	Oskarshamn	0.004	TWh	1992	[54]
Perstop, Uniper, Fortum, Nature Energy	Stenungsund	0.137	TWh	2025	[55]
Uniper, ABB, Port of Luleå, Luleå Energy and ESL Shipping*	Luleå	0.4	TWh	2027	[56]
Uniper (coowner of Liquid Wind)	Örnsköldsvik	0.355/ 4.26	TWh	2024/2030	[57]

Fertiberia	Luleå-Boden	3.3	TWh	2026	[58]
Rabbalshede Kraft*	Southern Sweden	0.273	TWh	2025	[59]
Ovako, Volvo Technology AB Hitachi, ABB, HS Green Steel, Nel Hydrogen	Hofors	0.093	TWh	2022	[60]
Siemens Energy	Finspång	0.001	TWh	2022	[61]
Total H_2 produced		21.7	TWh		

Projects with a partly open market for hydrogen

3.2.5 Summary of feedstock availability

The results of the evaluation of available feedstock today and 2045 is presented in Table 3 below. The basis for the evaluation was that only the sustainable amount of the feedstock could be eligible for production of SAF. The ecologically viable amount within each category of feedstock will be defined and discussed in the coming subsections.

Table 3. Available feedstock for the different process routes.

Fuel type	Feedstock	Availability of feedstock TWh/year (except for CO2)	
		Now	2045
HEFA	Waste oils	2020: 2.6	2050: 2-3
Gasification-based Fischer-Tropsch	Forest residues	2020: 72	2050: 118-132
HTL	Forest residues	2020: 72	2050: 118-132
Power-to-liquid through FT-route	CO_2	2020: 28.6 (Mt CO_2/year)	2045: 28.8 (Mt CO_2/year)
	H_2	2022: 0.18	2045: 44 (min) 82 (max)

3.3 Theoretical production potential

This section describes applied assumptions, calculations and the subsequent results of the potential amount of SAF production in Sweden.

3.3.1 Assumptions and selection of yield

To compile the production potential of SAF produced via different pathways, the feedstock amount of the different pathways must be combined with their yields. These values are presented in Table 4 below.

Table 4. Process yields of the studied SAF production pathways.

Fuel type	Yield
HEFA	0.75–0.83 t jet fuel/t waste oils and fats[62]
Gasification-based Fischer-Tropsch	0.13–0.22 t jet fuel/t dry forest residues [62]
HTL	0.18–0.36 t jet fuel/t dry forest residues [62]
Power-to-liquid via FT-route	0.21t jet fuel/t of CO_2+H_2 [63]

Yield is defined in this table as ton of fuel product per ton of dry matter feedstock input. As seen in the table above, yields are presented as values in a range due to varying process configurations and assumptions [62]. Thus, the range of yields is considered in the theoretic production potential by selecting the average yield value. The selected values for the compilation of production potential are presented in the table below. Nevertheless, the yield range will be considered in the sensitivity analysis on section 243.3.3.1.

Table 5. Selected yields for the studied production pathways.

Fuel type	Yield
HEFA	0.79 t/t [62]
Gasification-based Fischer-Tropsch	0.18 t/t [62]
HTL	0.27 t/t [62]
Power-to-liquid via Fischer Tropsch route	0.21 t/t [63]

In order to present aggregated numbers for the production potential, a crude assumption was made on the share of feedstock used for each process pathway, in those cases where the feedstock could be used in several of the pathways. This is the case for forest residues, that are feasible for conversion into jet fuel either via the gasification-based Fischer-Tropsch process or through the HTL (hydrothermal liquefaction) process and it was thus assumed that 50% of the forest residues was used for each pathway.

Several assumptions were applied to determine the production potential of jet fuel from biogenic CO_2 and renewable H_2. Firstly, it was assumed that all H_2 produced today via electrolysis and all future capacity would be used to produce fuel. The generous assumption that all biogenic CO_2 from the industry sector would be eligible for capture was also applied. Provided that there is plenty of CO2 and much less of H_2, H_2 was the limiting component. The mass of H_2 content of Jet A1 (13.4%) [64]was then used to determine the maximum theoretic amount that could be produced from domestic, renewable H_2 and biogenic CO_2. Lastly, this number was combined with the yield displayed in Table 5 and expressed as TWh by conversion via LHV.

3.3.2 Results

The resulting compilation of production potential from domestic feedstock is presented in Figure 7. The available feedstock is presented with a span for both the current and future potential. This because of the presented span for the feedstock potential of forest residues. The PtL and HEFA potential have the same size in 2020 (low) and 2045 (high).

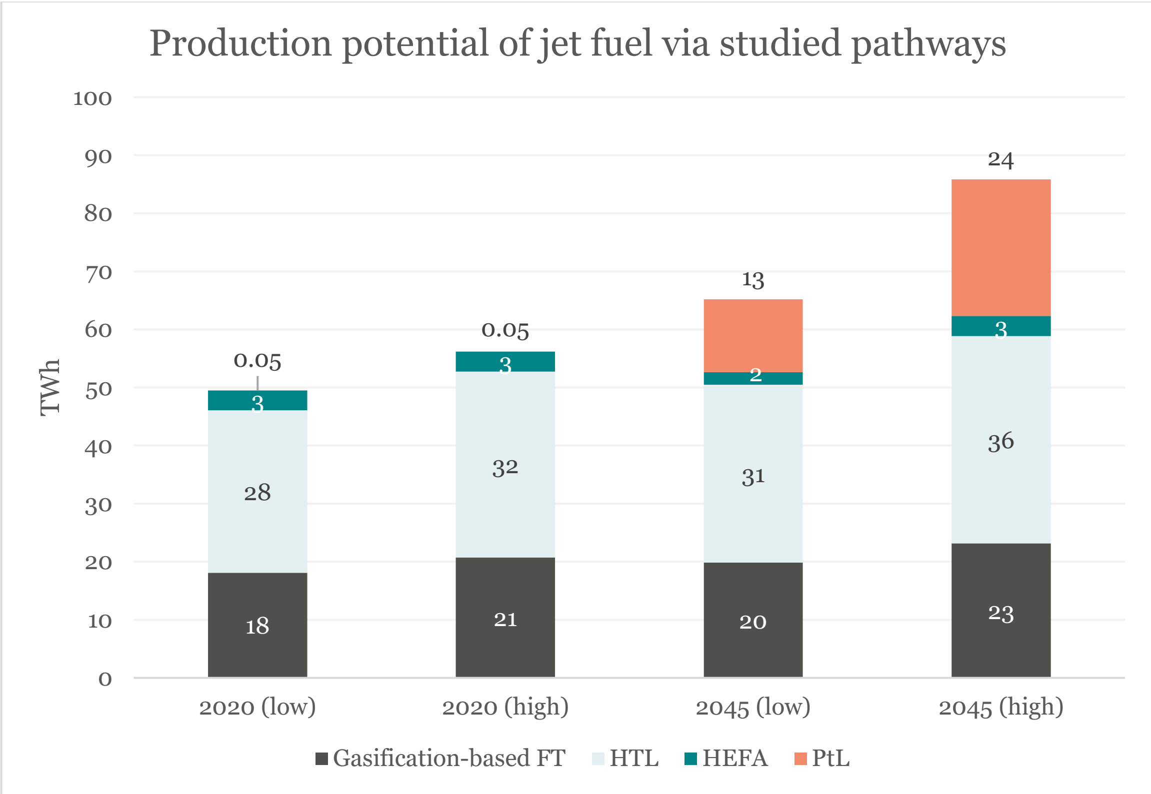

Figure 7. The available feedstock and selected yield combined into the production potential of domestic SAF. The production potential of HTL and FT are presented using 50% of the feedstock each, since both are produced from the same feedstock (forest residues).

As seen in Figure 7, the HEFA pathway provides the lowest production potential out of the four studied pathways and remains nearly at the same level in the future, compared to the current potential. The 2045 (low) is lower than the 2020 potential due to uncertainty in the extent to which tall oil will be available in the future, as discussed in [65].

The potential of Gasification-based Fischer-Tropsch (FT) from forest residues is higher than using forest residues in the HTL pathway and this is due to the higher yield of the gasification-based Fischer-Tropsch.

The current potential of the PtL pathway is indistinguishable, because of the limited availability of H_2 produced via electrolysis. In contrast, the future targets are set high enough to make PtL a significant candidate for future SAF production.

All combined, the four pathways provide a future potential of **66-86 TWh**, depending on the available amount of feedstock.

3.3.3 Sensitivity analysis

3.3.3.1 Variations in yield

The product yields of the different fuel production pathways were in three out of four cases (G-FT, HTL and HEFA) presented as a span. Therefore, a sensitivity analysis was performed, where the yield of each process was set to the lowest possible and highest possible value. The results of the sensitivity analysis are presented in Figure 8. Large variations in theoretical production potential can be observed when using higher or lower yields for the four different pathways, although the results remain in the same range of order.

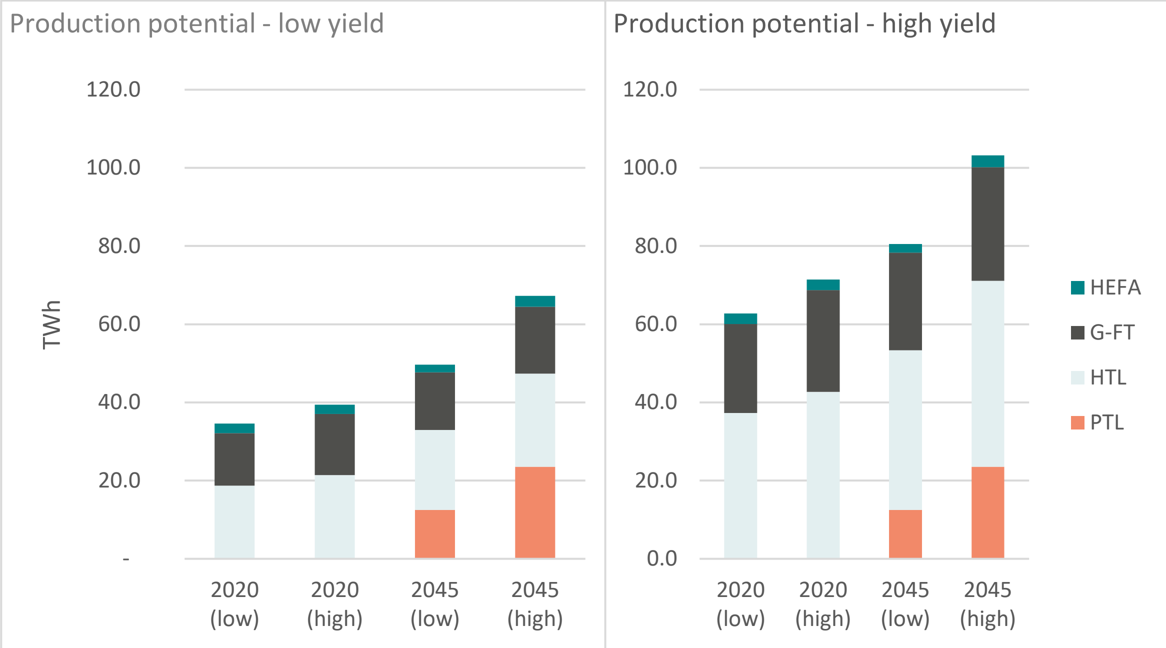

Figure 8: Sensitivity analysis. In the left figure the lower end of the span is selected for the process yields, while in the right figure the higher end of the span for each process yield is selected.

3.3.3.2 H_2 and CO_2 availability for PtL - low scenario

As seen in section 3.2.3.1 and section 3.2.4.1, there are some planned projects to *capture* CO_2 from industrial sites by 2030 and some planned projects for H_2 production with open market by 2030. There were no announced projects beyond 2030. This sensitivity analysis shows how the theoretical production of PtL would change, if these values were taken instead of the ones in Figure 7, which correspond to the total *emissions* of biogenic CO_2 and the goal of installed electrolysis power. Using these new values of H_2 and CO_2, it was seen that the limiting feedstock was again H_2, since there is more than enough captured CO_2 to produce fuel via PtL. As seen in Figure 9, the results show a low potential production of PtL for jet fuel by 2030 (which are the same for 2045 since there are no announced projects beyond 2030) compared to the results in Figure 7. Nevertheless, 0.18 TWh of jet fuel via PtL is a more realistic value since the potential of 2045 in Figure 7 assumes that all the H_2 produced by the new installed electrolyzer power are to be used for jet fuel, which will not be the case in reality. Other markets will also make use of that potential H_2.

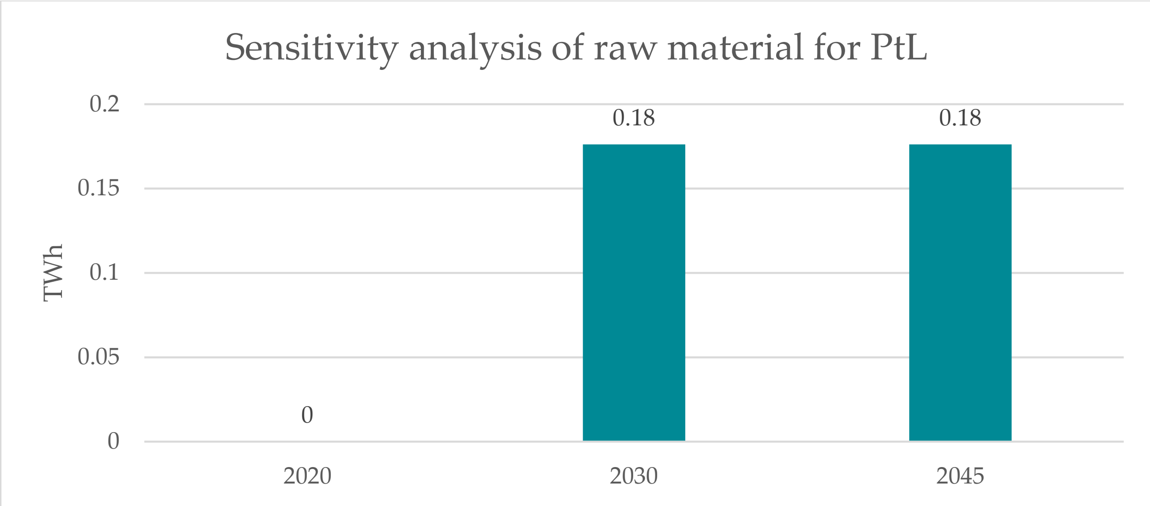

Figure 9: Sensitivity analysis of raw material for PtL

3.4 Discussion and conclusions – production potential

From all the feedstocks assessed, UCO and tall oil is the smallest in quantity, followed by H_2, with the assumed time perspective and assumptions made. Forest residues are by far the biggest resource available in Sweden. All of these resources are used in other sectors other than jet fuel production and there is therefore competition for the use of resources. Competing use of UCO is HVO production [65], production of soap, make-up, and other chemicals [66]. Forest residues are used for energy production or in biorefineries to produce intermediate chemicals. Most of the plans for CO_2 capture include end storage of the carbon, while planned production of H_2 will meet demand from the steel and chemical industry. Thus, the practical potential production of jet fuel based on the feedstock available in Sweden will be lower than the one found in this study. Nevertheless, the resulting theoretic production potential of SAF in 2045 (66-86 TWh) exceeds by far the current demand of jet fuel in Sweden (3.26 TWh in 2021).

The result of the feedstock availability analysis showed that the jet fuel types with the largest production potential in Sweden are the Gasification-based FT and the HTL (which sum in total 51-59 TWh for the min and max case respectively).   HTL has a larger theoretic production potential (31-36 TWh) than the Gasification-based FT pathway (20-23 TWh), despite them utilizing the same feedstock. This is only due to the slightly lower yield of the the Gasification-based FT pathway. There are however, as mentioned before, competing sectors and uses and the true availability of forest residues (and all other feedstock types) thus depends on what sector is willing to pay the most. It is not unlikely, however, that use of biomass for advanced purposes (e.g. for fuel production rather than simple combustion) is the most value-creating option in line with the EU Bioeconomy strategy [67].

The assumptions on yield and jet-fuel output fraction impact the results for all studied pathways. Whereas the yield could be improved through technological development, the jet-fuel output fraction is not only a technological matter but an economic one. In a report from the International Renewable Energy Agency (IRENA) [68], the issue of the additional cost of hydrocracking HEFA output to produce jet fuel is highlighted. To optimize for jet fuel instead of other low-carbon biofuels, economic incentives may be required, according to the authors of [68].

As shown in the sensitivity analysis, the PtL production potential is highly dependent on what assumptions on H_2 availability were applied. When only the planned H_2 production without decided purpose was considered, the production potential was reduced from **13-24 TWh** to merely **0.18 TWh** by 2030. This is still larger than the current demand of the Swedish rescue fleet. By 2045, there are no new announced plans on carbon capture plants nor of H_2 electrolyzers. Nevertheless, the fact that there are increasingly more projects starting in this decade could be seen as the introduction and establishment of the technology to the market. The efficiency of the electrolyzers could increase in the next years thanks to the advance in research. The efficiency assumed for now is 65% but if it increases, it will increase the amount of H_2 per electrolyzer. Many of the carbon capture projects have the goal to store the carbon in subterranean storages. Nevertheless, there is a potential to use this CO_2 for other purposes if there is a demand. Liquid Wind is an example of a project where the plan is to use CO_2 for the production of e-methanol. Even with generous assumptions for future H_2 availability and conservative assumptions for CO_2 availability, H_2 remains the limiting ingredient in the PtL pathway.

4 Future scenario analysis

4.1 Introduction

This part of the project investigates the market demand of both fossil and fossil free jet fuel, from the entire aviation industry in Sweden in 2045. The study incorporates an overview of planned SAF capacity and a scenario analysis to investigate the impact of policies and available resources on the future potential of fossil free jet fuel to meet future demand. The aim is to illustrate what quantities could be available from different fuel pathways by 2045 and the distribution between the different fuels, based on examples of the costs of the production. While only domestic feedstock was studied in the previous chapter, the scope is now extended to include both international production of SAF and imports of feedstock for domestic fuel production.

4.2 Scenario description

In this chapter, the four scenarios developed for the future analysis are presented, these include:

- Scenario 1 – Base case (SC1)
- Scenario 2 – Worst Case for Climate (SC2)
- Scenario 3 – Self-sufficient Case (SC3)
- Scenario 4 – 100% fossil free by 2030 (SC4)

4.2.1 Scenario 1 – Base case

Scenario 1 (SC1) represents a base case, reflecting the current situation in Sweden. In this scenario, the GHG reduction mandate is taken into consideration without adding any changes. The goal is to investigate how, given the current situation, the availability and prices of the fossil free fuels will be affected. According to Law (2017:1201)[2] the GHG reduction level for aviation fuel begins at 0.8% in 2021 and reaches 27% in 2030, and by following this trend through extrapolation the reduction level approaches 100% in 2038. In this scenario, both fossil and fossil free aviation fuel is imported, and domestic production of fossil free aviation fuel is expected from the planned plants and additional plants when necessary. For the domestic production in the additional plants, both imported and domestic raw materials are considered.

4.2.2 Scenario 2 – Worst Case for Climate

In scenario 2 (SC2), the goal is to investigate the outcome for the future SAF fuel demand when the demand is not forced by the reduction mandate. Therefore, the reduction level of the Law (2017:1201) is assumed to be constant at 27% beyond 2030. Therefore, the previous efforts to reduce GHG emissions are assumed to be less ambitious, thus the scenario is named "Worst Case for Climate". In this scenario, both fossil and fossil free aviation fuel is imported, and domestic production of fossil free aviation fuel is expected from the planned plants and additional plants

[2] As of late 2022, the reduction mandate system is undergoing re-evaluation. It is thus far uncertain whether the aviation sector would be included in any changes of the reduction mandate. Therefore, such a development, where the reduction mandate is minimized, has not been considered in this analysis.

when necessary. For the domestic production in the additional plants, both imported and domestic raw materials are considered.

4.2.3 Scenario 3 – Self-sufficient Case

In scenario 3 (SC3), the goal is to investigate the potential for self-sufficiency in Sweden. The reduction levels in the GHG reduction mandate follows the same trend as the base case but can only be met through fossil free fuel produced in Sweden. Therefore, in this scenario only fossil aviation fuel is imported while the fossil free fuel is represented by the domestic production from planned and additional plants. The raw materials for fossil free fuel production in the additional plants, namely waste oils, forest residues and CO_2 and H_2 are sourced from Sweden.

4.2.4 Scenario 4 – 100% fossil free by 2030

In scenario 4 (SC4) a more ambitious effort towards reducing GHG emissions is made, with a GHG reduction level of 100% in 2030 and beyond. The reduction level is set in line with the goal of *Fossilfritt Sverige 2045* [51] which aims for fossil free domestic flights by 2030. In this scenario, both fossil and fossil free aviation fuel is imported, and domestic production of fossil free aviation fuel is expected from the planned plants and additional plants when necessary. For the domestic production in the additional plants, both imported and domestic raw materials are considered.

4.3 Main assumptions for all scenarios

In the scenario modeling, a period spanning from 2021 to 2045 was considered with a five-year time step. In all scenarios, the total demand for jet fuel was assumed to start at the value of the total jet fuel delivered in Sweden 2021 at 3.3 TWh [69] with a 2.3% annual increase [70]. The jet fuel demand from the Swedish Maritime Administration represents approximately 1% of the total amount [71]. To account for improved fuel efficiency in aircrafts, linear approximation was made based on assumptions from [72] of 3% improvement in 2040 and 20% in 2060. The estimated annual jet fuel demand with and without fuel efficiency improvement considered, is presented in Figure 10.

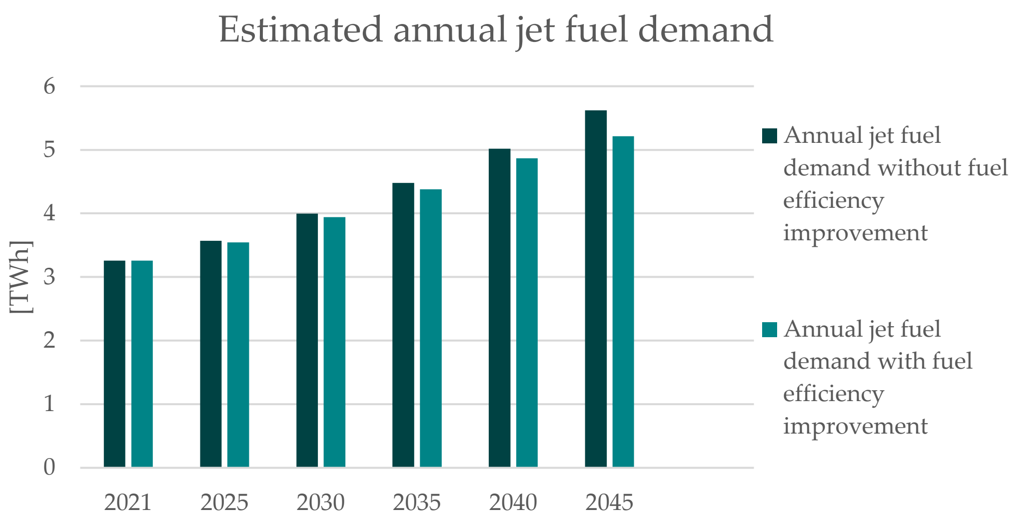

Figure 10. Estimated annual jet fuel demand.

The Swedish GHG reduction mandate was implemented in 2021. In the policy, a mandatory requirement to blend fossil jet fuel with sustainable aviation fuel (SAF) is set on jet fuel suppliers, with yearly GHG reduction levels presented in Table 6 [73], [74]. Jet fuel suppliers who fail to fulfil the reduction levels are subject to a penalty fee at a maximum level of 7 SEK/kgCO_2-eq. In the scenario modelling, the GHG reduction mandate was considered with a constant penalty fee of 7 SEK/kgCO_2-eq in all four scenarios.

Table 6. Annual GHG emission reduction requirement 2021-2030.

Year	Percentage
2021	0.80
2022	1.70
2023	2.60
2024	3.50
2025	4.50
2026	7.20
2027	10.80
2028	15.30
2029	20.70
2030	27.00

Additionally, a constraint on the maximum blend in of SAF has been set based on the ASTM D7566 *Drop-In Fuel Specification.* ASTM D7566 regulates the technical certification of fossil free jet fuel and is a specification that consists of fuel blends of conventional and synthetic components. The ASTM D1655 regulates the technical specification for fossil jet fuel, and a SAF certified under ASTM D7566 would also meet the requirements of ASTM D1655. As of October 2021, ASTM have approved a total of 9 conversion processes to produce SAF, listed in Table 7. Since the evaluated time frame spans until 2045, an assumption was made that the certification for all fuels will reach 100% blending ratio beyond 2038 for SC1 and SC3, and 2030 for SC4, while the blending ratio remains at 50% throughout the period for SC2.

Table 7. Currently allowed blending ratio for the approved conversion processed for fossil free jet fuel by ASTM until October 2021 [75], [76]**.**

Conversion process	Possible feedstocks	Blending ratio by volume
Fischer Tropsch synthesized isoparaffinic kerosene (FT-SPK)	Wastes, coal, gas, sawdust	50%
Hydroprocessed esters and fatty acids (HEFA)	Vegetable oils, animal fats, used cooking oil	50%
Hydroprocessed hydrocarbons synthesized isoparaffinic kerosene (HH-SPK or HC-SPK)	Algae	10%
Synthesized iso-paraffins (SIP)	Sugar cane, sugar beet	10%
Alcohol-to-Jet (ATJ)	Sugar cane, sugar beet, saw dust, lignocellulosic residues (straw)	50%

Catalytic hydrothermolysis jet fuel (CHJ)	Waste oils or energy oils	
Co-processed HEFA in a conventional petroleum refinery	Fats, oils, and greases (FOG) co-processed with petroleum	5%
Co-processed FT in a conventional petroleum refinery	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

4.3.1 Aviation fuel pathways

In this section, the modelling assumptions and reference data are presented for the aviation fuel pathways included in the scenario analysis. Additional information is also provided in Annex II – Modelling parameters for scenario analysis.

4.3.1.1 Imported and domestic planned capacity

In the scenario analysis, both domestic and imported aviation fuels meet the annual demand from the aviation sector in Sweden. In all scenarios, fossil or conventional jet fuel (CJF) is imported and the price is set to start at 76.5 USD$_{2022}$/bbl [77] in 2021 (4.9 SEK$_{2021}$/liter with an average conversion rate of 8.58 SEK/USD for 2021 [78]). During 2022, the price of CJF has increased significantly compared to 2021 reaching an average of 143 USD/bbl in July 2022 [79]. To consider the significant increase, the price of CJF is assumed to increase throughout the period according to the jet fuel prices from the scenario “High oil price case” as presented by EIA for 2025–2045 [80]. In addition, all imported fuels are assumed to have an additional import cost at approximately 4 SEK$_{2021}$/liter, which is represented by the import cost of crude oil in Sweden [81]. In Table 8, the prices of domestic and imported fossil free fuels are presented. As can be seen in the table, the domestic fuels have the lowest costs thanks to the avoided import cost. The ATJ production price is notably on the lower side, but this is based on a LanzaTech production plant in operation today in the United States [82]. There is evidently uncertainty involved with selecting accurate prices that could

Table 8. Assumed prices of domestic and imported fossil free jet fuel in SEK/liter.

Price of domestic fuels [SEK/liter]		Price of imported fuels [SEK/liter]				
HEFA[a]	ATJ	HEFA*	FT PTL	ATJ	FT FR	FT W
10.7 [83]	6.8 [82]	14.1 [84]	16.2 [85]	10.8 [82]	15.5 [86]	17.4 [83]

Different prices are assumed for domestic and imported HEFA, to consider a price adjusted to European conditions compared to the global price of HEFA.

In all scenarios, domestic production of fossil free jet fuel is sourced from fuel pathways that are currently being planned for production in Sweden (see below). In addition, domestic production is also considered from additional plants further described in section 4.3.1.1.

In Sweden, various actors are currently planning for production of fossil free jet fuel through different pathways. In 2021, SCA and St1 entered a joint venture to produce and deliver 200 000 tons of Hydrotreated Vegetable Oil (HVO) for road transport and Hydroprocessed Esters and Fatty Acids (HEFA) for aviation fuel, from used cooking oil and tall oil, by 2023 [87]. A production of 300 000 m^3 HEFA is also expected to start in 2022, by Preem [9]. In 2021, a partnership between Vattenfall, SAS, Shell and LanzaTech was announced to produce 50 000 tons of synthetic aviation fuel through the pathway Alcohol-to-Jet (ATJ) by 2026-2027 using ethanol produced from CO_2 and H_2 [88]. In 2022, COWI and Swedish Biofuels announced a partnership to supply 400 000 tons of SAF through the ATJ pathway to the Swedish market by 2025 [89], [90]. Therefore, the planned capacity of HEFA and ATJ has been considered in the scenario analysis for domestic production of fossil free jet fuel.

In addition, Vattenfall and St1 announced a partnership in June 2022, to investigate the potential to produce electrofuel for aviation by 2029, with a volume corresponding to the yearly aviation fuel consumption by Arlanda Airport [91]. However, since the partnership has not announced what pathway the electrofuel is produced through, the production has not been considered for the scenario analysis. A study done by RISE in the potential of SAF production from forest residues in Småland states that 16 200 tons of SAF could be produced in two plants in Växjö and Mörrum [92]. This is a theoretical potential and therefore has not been included in the scenario analysis either.

In all scenarios, except SC3, fossil free aviation fuel is also imported based on the current situation and planned capacities of different fuel pathways, these include:

- Hydroprocessed Esters and Fatty Acids (HEFA) from waste oils
- Gasification-based Fischer-Tropsch from forest residues (FT FR) and municipal solid waste (FT W)
- Alcohol-to-Jet (ATJ) to produce electrofuel for aviation from ethanol produced from CO_2 and H_2 and from unspecified renewable ethanol
- Power-to-liquid (PTL) through the FT route from CO_2 and H_2 (FT PTL)

For the scenario analysis, the prices of domestic planned and imported fossil free jet fuel were assumed based on prices found in the literature, presented previously in Table 8. The prices were also assumed to be constant throughout the time frame, with import costs added to the price of imported fuels. The price assumptions were made due to difficulty in finding specific cost information regarding the planned plants of fossil free jet fuel. Therefore, it is important to note that the prices of these fossil free jet fuel pathways may be subject to change, for example due to different construction costs, changes in feedstock prices, demand etc. Additionally, a constraint on feedstock availability was excluded for the domestic planned and imported fossil free jet fuel, due to difficulty in finding information regarding the specific processes of the planned plants. In addition, an assumption was made that an analysis of the feedstock requirement would already be performed by the partners of the planned plants. However, although a constraint was not added to the model, an analysis will be performed on the amount of feedstock required based on the model results for SC1, the assumptions and input data of which are provided in Annex II – Modelling parameters for scenario analysis..

Figure 11 presents the assumed capacities of the fossil free jet fuels based on the literature. For more details of mapped projects, see Annex III – Planned production of SAF. As the figure shows, the capacity increases for some pathways throughout the period, which is based on when additional planned plants are expected to be operational.

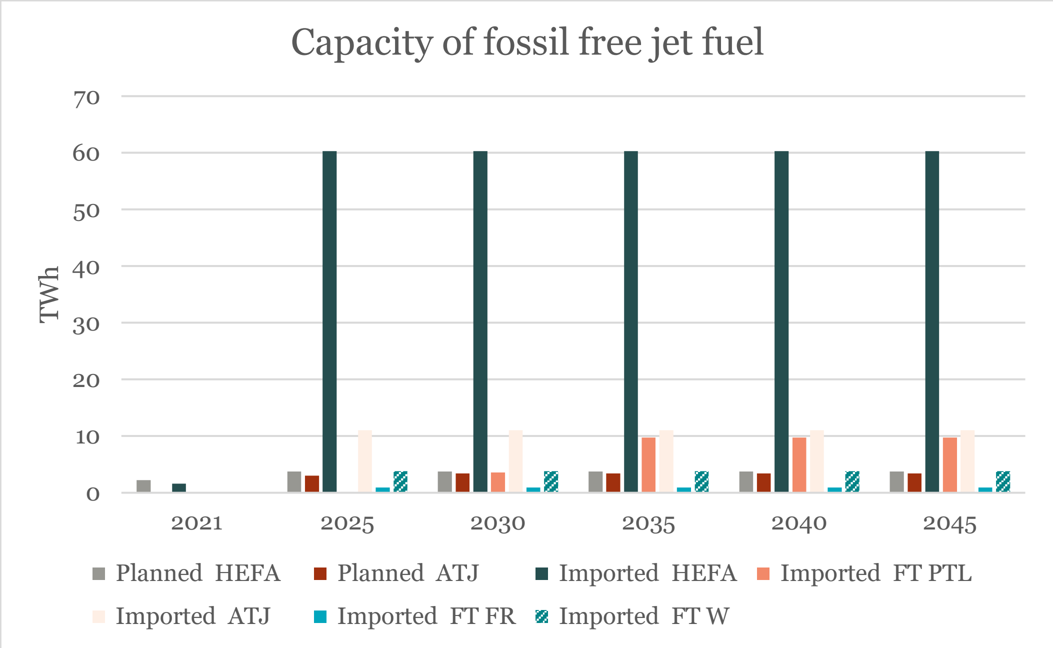

Figure 11. Assumed capacity of imported and domestic planned fossil free jet fuel based on announced plans for SAF production.

4.3.1.2 Additional domestic production

To investigate the potential of additional domestic plants to produce fossil free aviation fuel, the fuel pathways listed below are also taken into consideration:

- Hydroprocessed Esters and Fatty Acids (HEFA) from waste oils
- Gasification-based Fischer-Tropsch (FT) from forest residues
- Hydrothermal liquefaction (HTL) from forest residues
- Power-to-liquid (PTL) through the FT route from CO_2 and H_2 (FT PTL)

For these fuel pathways, detailed techno-economic parameters were included in the scenario analysis considering capital, fixed and variable costs as well as potential revenues from by-products. The production of these fuel pathways was constrained by the available amounts of domestic raw materials of waste oils, forest residues and CO_2 and H_2. Imported waste oil were also considered in all scenarios except SC3.

In Table 9, the reference values used to determine the economic parameters of the pathways, for the additional plants, are presented. A discount rate of 10% and a lifetime of 30 years were assumed to calculate the annualized capital expenditure (CAPEX), based on the total capital investment (TCI). The fixed costs were assumed to be 4% of CAPEX [93] and the variable costs were calculated based on the utilities required during production of each fuel pathway (i.e., water, electricity, hydrogen as well as catalysts and chemicals). In Table 10, the production yield of jet fuel and by-products from each conversion pathway are presented.

Table 9. Economic parameters used and description of the jet fuel pathways added in the scenario analysis.

Conversion pathway	Feedstock	Product output	Input capacity of the ref. study [t_{in}/year]	TCI	TCI [$MSEK_{2021}$][b]	Ref.
HEFA	Used cooking oil	Jet fuel, Diesel, Naphtha	912 500	133 MEUR2013	1 257	[94]
FT	Forest residue	Jet fuel, Diesel, Naphtha	615 000	532.7 MUSD2016	5 471	[95]
HTL	Forest residue	Jet fuel, Diesel, Gasoline	164 670[a]	132.2 MEUR2015	1 355	[96]
FT PTL	CO_2 (+H_2)	Jet fuel, Diesel, Gasoline	58 160	65 MEUR2021	659	[4]

a. Calculated based on a biomass density of 16.7 MJ/kg.

b. Total capital investment (TCI) has been adjusted to SEK2021 through consumer price index.

Table 10. Production yields for each pathway,

Conversion pathway	Jet fuel	Naphtha	Gasoline	Diesel	Unit	Ref
HEFA	0.06	0.02	-	0.68	[t_{out}/t_{in}]	[97]
FT	0.10	-	-	0.01	[t_{out}/t_{in}]	[97]
HTL	0.06	-	0.09	0.25	[t_{out}/t_{in}]	[96], [97]
FT PTL	0.10	-	0.09	0.03	[$t_{out}/tCO_{2,\ in}$][a]	[4]

a. The yield for FT PTL has been adjusted to CO2 as input feedstock.

4.4 Model results

The scenario analysis was performed by developing an optimization model in Python. The objective function of the model was to minimize the total costs of the system, considering a period spanning from 2021 to 2045. In the model, constraints were set based on the capacity of planned production of fossil free jet fuel, available raw material of waste oils, forest residues and CO_2 and H_2 (based on assumptions in section 3.2) for the additional plants, as well as by the GHG reduction mandate. For the planned and imported fossil free jet fuel, no constraint on raw material availability was set. In this section, the results from the scenario analysis which compares all scenario results is presented. In the scenario analysis, the resulting jet fuel from the blend in of fossil free jet fuel in CJF is called the jet fuel mix. Following, fossil free jet fuel is referred to as SAF.

4.4.1 Results from the scenario analysis

In Figure 12, the annual jet fuel supply of Imported CJF and SAF is presented for all scenarios in the period 2021-2045 (matching their respective yearly demands), in which SC1 represents the base case for the other scenarios to be compared with. As the figure shows, SC2 has the lowest blend in of SAF in which the blending ratio remains at 50% throughout most of the period. Since the certification remained unchanged at 50%, the possibility to blend in more SAF was not possible. In SC3, the reduction levels of the GHG mandate remained the same as in SC1, therefore the distribution between CJF and SAF remains the same. As a more ambitious effort towards reducing GHG emissions was assumed in SC4, with 100% reduction level a blend in of 100% SAF is achieved by 2030.

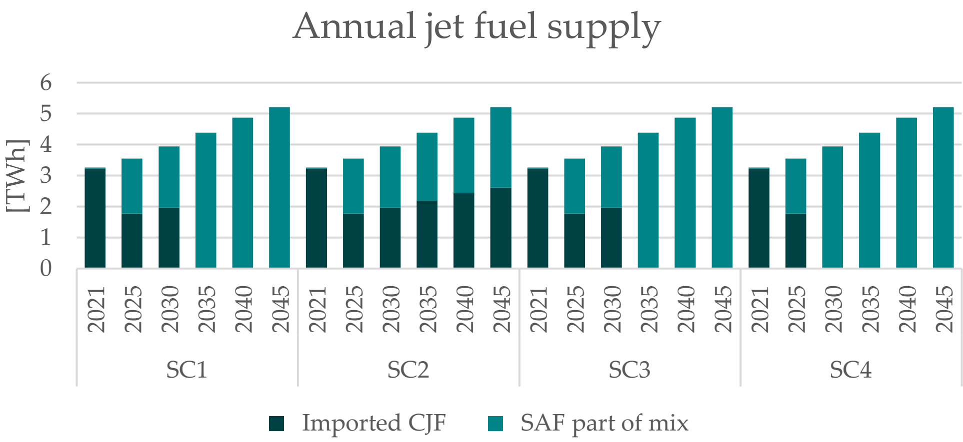

Figure 12. Annual jet fuel supply in SC1, SC2, SC3 and SC4 for 2021–2045.

In Figure 13, the types of SAF are presented for all scenarios in the period 2021-2045. Since the reduction level remains the same beyond 2030 in SC2 the blend in of SAF is the lowest compared to the other scenarios, while SC4 has the highest blend in of SAF to meet the requirement of 100% GHG reduction from 2030. In all scenarios, only the domestic planned production of ATJ and HEFA are utilized to meet the demand of SAF, and the requirement set by the GHG reduction mandate. Since ATJ provides the lowest price option it is the prioritized choice in all scenarios, with an increasing contribution of HEFA as the maximum capacity of planned production of ATJ is reached.

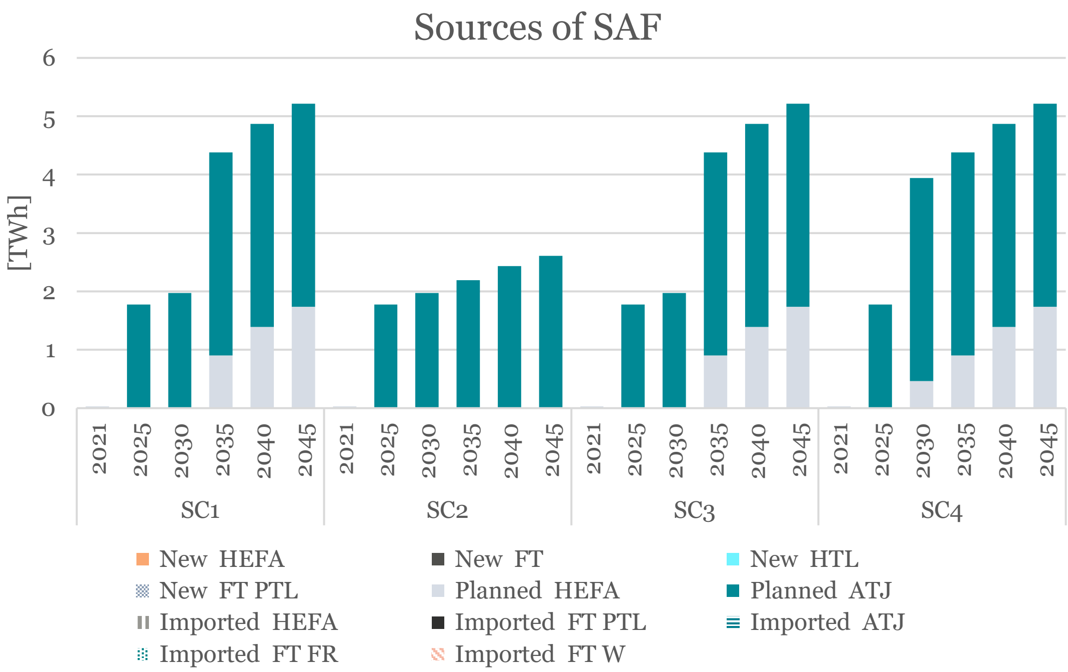

Figure 13. Types of SAF in SC1, SC2, SC3 and SC4 for 2021-2045.

In Figure 14 the price of the individual jet fuels is shown and in Figure 15, the total price of the jet fuel mix is presented for all scenarios in 2021–2045. As the reduction levels are at the same level for each year in SC1 and SC3, the price of the jet fuel mix is the same in both scenarios. The highest price of the jet fuel mix is found in SC2 beyond 2025, reaching 10.37 SEK/liter in 2045. Since the relative amount of CJF and SAF remains the same in SC2, increasing at equal amounts as the jet fuel demand increases, the higher blend in of CJF compared to the other scenarios results in a higher price. In SC4, allowing a blend in of 100% SAF results in reaching the lowest price of the jet fuel mix in 2030 at 7.26 SEK/liter. As the CJF has been set at a higher price than both HEFA and ATJ throughout the time span, a higher blend in of SAF results in a lower price. However, the real development for prices of both CJF and SAF is uncertain and the volatility of fossil fuels could also impact the price of SAF.

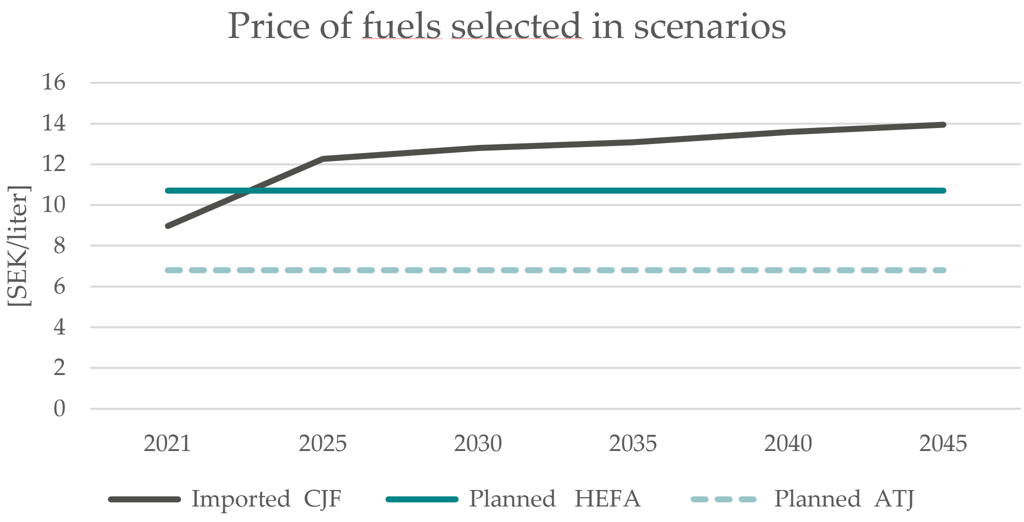

Figure 14. The price of the fuels selected for the mix in the scenarios.

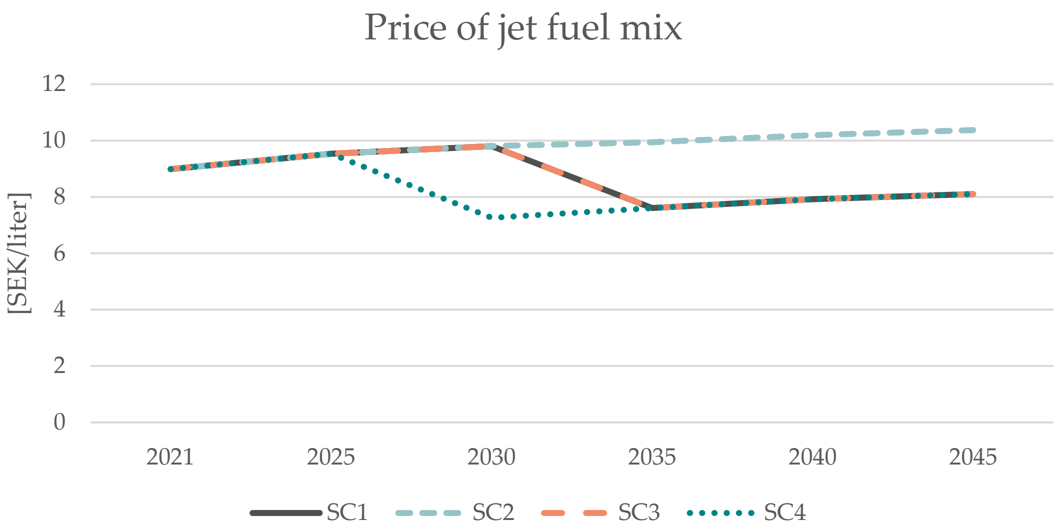

Figure 15. Price of jet fuel mix in SC1, SC2, SC3 and SC4 for 2021-2045.

Since the scenario modelling optimizes based on costs, the domestic planned plants provide the lowest prices compared to opening new plants and importing other sources of SAF. In the beginning of the period of all scenarios, the SAF is entirely supplied from domestic production of HEFA from planned plants, although this number is so small it is indistinguishable from the horizontal axis in Figure 13. As the ATJ plants open from 2025 and forward, the HEFA is replaced by ATJ since ATJ is assumed to have a lower price and the capacity is sufficient to meet the demand. However, in 2035 and forward HEFA increases again as the maximum output capacity of the ATJ plants are reached.

4.5 Discussion and conclusions – scenario analysis

The results of the scenario analysis are highly dependent of its input assumptions on the cost of fuels and the import cost. As previously mentioned, the model favors domestic fuel production due to the high cost of importing fuels, set to 4 SEK/liter in line with the cost of crude oil imports (see section 4.3.1.1). Moreover, the volatile energy prices have been considered for CJF but has not been considered when selecting estimates of the price of SAF. These aspects combined lead to the price of CJF surpassing that of SAF in all cases in the scenarios. The low cost of the domestic planned ATJ production plants has a large impact on the end result of the model, where the need to import fuel is reduced entirely, although the model does not consider whether feedstock has been imported or not. The low price is based on an ATJ plant in the United States operating today [82] and if the production cost of ATJ becomes higher in Sweden because of different conditions it might be subject to more competition from the other production plants. These selected prices together set one example of how the SAF demand could develop. However, it is likely not the exact pathway that SAF fuel prices will follow. Instead, these results should serve as an illustration of how the future could develop if the cost of carbon emissions continues to increase, while SAF production could be obtained at a more favorable price.

Based on the scenario analysis, it is clear that the future of fossil free jet fuel depends on the fuel price development, as well as the maximum allowed blending ratio of fossil free jet fuel. Despite its initially high cost, the demand for fossil free jet fuel could still increase if the reduction mandate prevails at a minimum of 30% blend-in rate and if the price of SAF could be produced to the assumed costs. In the base case SC1, the price of the jet fuel mix had the highest price at 9.80 SEK/liter in 2030 and the lowest at 7.61 SEK/liter in 2035. However, as long as there is a safety limitation on the blend-in rate of SAF it is not possible to reach the full potential in carbon reductions.

The combined literature review and scenario analysis revealed that HEFA is likely to remain a fossil free jet fuel of high demand, due to the high amount of available capacity combined with a continued high demand for fossil free jet fuel to be blended with CJF. However, based on the literature review other conversion pathways that are especially gaining more attention are ATJ and PTL through the FT-route, as there are current plans to start production of these in Sweden and other countries as well. Moreover, the feedstock is subject to competition for HVO production, where most of the exploited potential is used today.

As the scenario analysis is based on the total jet fuel demand in Sweden, the results indicate that the domestic production currently planned is sufficient to meet the current and future demand of the aviation sector in Sweden. Furthermore, the total capacity of HEFA of approximately 495 000 tons is not required to meet the jet fuel demand, even towards the end of the period, thus indicating that a maximum quantity of 270 000 tons could be utilized for helicopters and other stakeholders in the project.

5 Environmental assessment of SAF

In this chapter, the environmental impact of SAF and their potential reduction of fossil greenhouse gas (GHG) emission were assessed. The assessment was done according to the calculation method described in the recast of the Renewable Energy Directive (EU) 2018/2001, known as REDII [5]. The REDII framework applies a life cycle thinking where the emissions of biofuels, defined as liquid fuels for transport produced from biomass, are accounted from the extraction process of the raw material to when the fuel is used. Following the REDII framework, the environmental impact is limited to climate change, where three GHG are relevant: carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O). When the climate impact, expressed in gram carbon dioxide equivalent per megajoule of fuel (gCO_2eq/MJ) is calculated, the GHG emissions reduction (saving) from biofuels can be calculated by comparing to the emission from a fossil fuel, referred as fossil comparator. The fossil comparator for biofuels according to the REDII is 94 gCO_2eq/MJ.

In this study, SAF based on HEFA and PtL from biogenic CO2 and H2 were assessed. HEFA based on UCO was chosen since this is the fuel that the helicopter of the search and rescue fleet used during the pilot phase of this project. PtL fuel was included in the assessment for comparison purpose and also because the life cycle data for PtL production was already available from a previously done project by IVL [4]. According to the American Society for Testing and Materials (ASTM) standard, ASTM D7566, SAF can be blended with a fossil jet fuel up to 50% [98]. However, with current practice, the blend rate of SAF is normally lower than 50%. The batched specific SAF delivered by Air BP has a blend rate of 34.63%. On the other hand, The Boeing Company has announced their target to deliver a 100% biofuel-driven commercial airplane by 2030 [99]. Thus, three different blend rates: 34.63%, 50% and 100% were modelled in order to give a full understanding on how the use of SAF can have an impact to the airborne rescue services and aviation sector in general.

The functional unit was defined as 1 MJ SAF used in a helicopter engine. In the case of HEFA, imported Used Cooking Oil (UCO) was chosen as feedstock. Fisher-Tropsch (F-T) fuel was the outcome product from the PtL production pathway.

High-altitude effect, which occurs when an airplane combusts more fuel at a higher altitude than 8000 km [100] is not considered in this study. The high-altitude effect causes emissions of nitrogen oxides and formation of vapors and particles which induce global warming effect [100]. However, as the warming mechanism is complex and experts have different views on the matter, there is no consensus within LCA methodology of how to correctly account for the high-altitude effect [101]. Another reason that the high altitude is not considered in this study is because the search-and rescue services are operated domestically and at a low altitude.

5.1 HEFA-based SAF

The value chain of the HEFA-based SAF considered in the LCA consists of the following processes:

- Collection of UCO
- Pretreatment of UCO
- Transportation of treated UCO to HEFA production site
- HEFA production

- Jet A1 production
- Blending between HEFA and Jet A1
- Distribution of SAF to Sweden
- Transport of SAF to helicopter base in Kristianstad, Sweden
- Combustion of fuel

HEFA can be produced from different types of oils. In this study, the feedstock of HEFA was assumed to come from 100% UCO. UCO is considered as waste according to the REDII, and therefore does not carry any upstream environmental burden i.e., burden from production and use from its previous life cycle. The applied system boundary is shown in Figure 16.

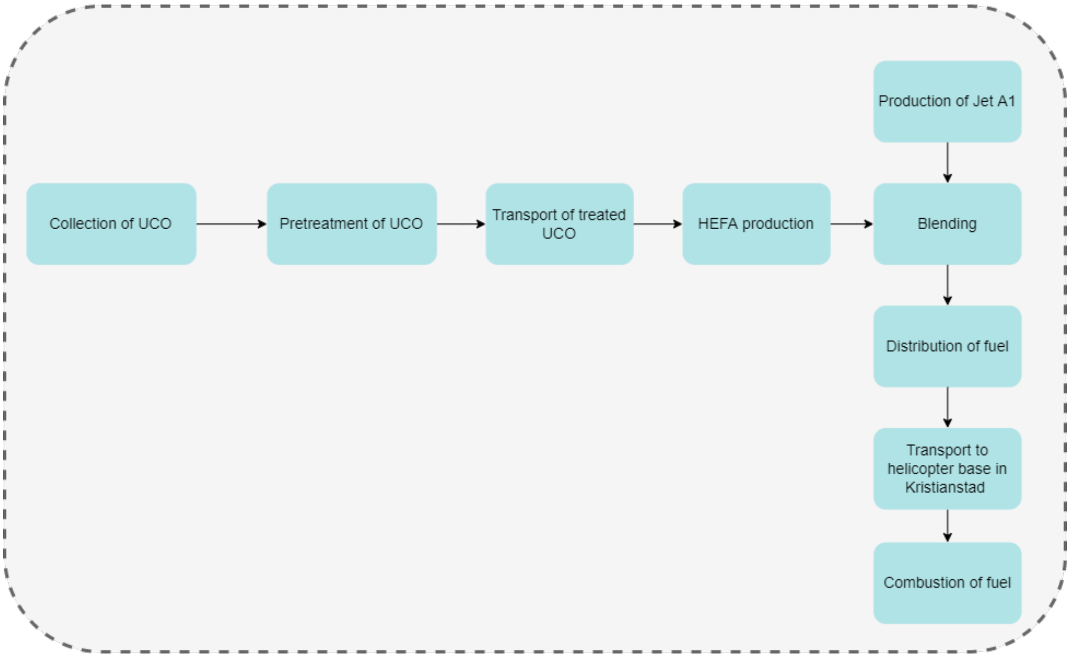

Figure 16. The system boundary of HEFA-based SAF.

The collection of UCO was assumed to occur in China as the country is one of the biggest UCO exporters to Europe and the USA [102]. The collection distance was assumed to be within 50 km. It was also assumed that the UCO is collected in 4 different provinces in China where there are the biggest and most ISCC-certified UCO collectors, namely Jiangsu, Hebei, Guangdong and Sichuan [103]. After the UCO is collected, it undergoes a pretreatment process, which was also assumed to take place in China. The data of the pretreatment process was obtained from Hamelinck et al. [104]. The electricity consumption in the pre-treatment of UCO was modelled using Chinese average consumption mix dataset from Gabi database [105].

The treated UCO was then transported to Shanghai port with an average distance of 1690 km by truck and then shipped to Belgium, which according to Air BP is the country where HEFA is produced. In this case it was assumed that the treated UCO is shipped to the port in Antwerp in an oil tanker and the sea distance is 19963 km.

The production of HEFA require H_2, which was assumed to be produced from natural gas via steam reformation. Steam used in the process was also assumed to come from natural gas. The data that was used for the calculation of the HEFA production is generic and it was obtained from Hamelinck et al. [104]. The process produces four co-products: UCO-based HEFA, UCO-based HVO, propane and naphtha. Propane can be used internally as an energy source. However, in this study, the propane was assumed to be one of the co-products and it can be sold to the market. The allocation of the environmental impact between the four co-products was done based their energy contents. The allocation factor of the UCO-based HEFA is 0.66. The electricity consumption in the production of HEFA was modelled using the Belgium average consumption mix dataset from Gabi database [105].

It is noteworthy that the choice of data used for the pretreatment of UCO and the production of HEFA were obtained from a study commissioned by EWAB (European Waste Advanced Biofuels Association and MVaK (Mittelstandsverband abfallbasierter Kraftstoffe e.V., waste-based biofuels association) [104]. The data was considered reliable representative for the calculation in this study. The production of Jet A1 was modelled by using the existing dataset in Gabi software. The data is an average of European production and the allocation between the co-products is based on energy content. It was assumed that the production site of the jet fuel is in Rotterdam and that the blending between the jet A1 and HEFA occur at the same place. The HEFA is shipped in an oil tanker from Antwerp to Rotterdam with the distance of 163 km. The blending of the fossil and biobased fuels can be mixed by using pumps which require electricity. However, due to a lack of data, the electricity demand for the blending is excluded from the model.

After blending, the fuel is then distributed to Gävle, Sweden by ship with a distance of 1724 km. The SAF is then transported by truck (32-34 t payload) to the rescue fleet's base which is located in Kristianstad. The transport distance is 730 km. The SAF is assumed to be used in a helicopter. The combustion of fuel emits CO_2 and N_2O. Since the emissions comes from both biogenic and fossil components, it was assumed that the fossil CO_2 is emitted in proportion to its carbon content. Biogenic CO_2 is zero according to the REDII framework. According to the International Civil Aviation Organization (ICAO), 3.16 tons CO_2 is emitted per ton aviation fuel burned [106]. The average N_2O emission from an aircraft is 0.15 g per kilogram fuel [107]. The amount of N_2O emission is assumed to be the same disregarding the blend rate of the biogenic component in the fuel. The effect of high-altitude effect is not included in the calculation.

The data used in the LCA calculation for different life cycle stages can be found in the Appendix I.

5.2 PtL-based SAF

The value chain of the PtL-based SAF includes the following processes.

- Combined heat and power plant (CHP)
- Capture of CO_2
- Electrolysis of water
- Synthesis of FT-based jet fuel
- Production of Jet A1
- Blending
- Distribution to the helicopter base in Kristianstad
- Combustion of fuel

The system boundary of the PtL-based SAF is shown in Figure 17.

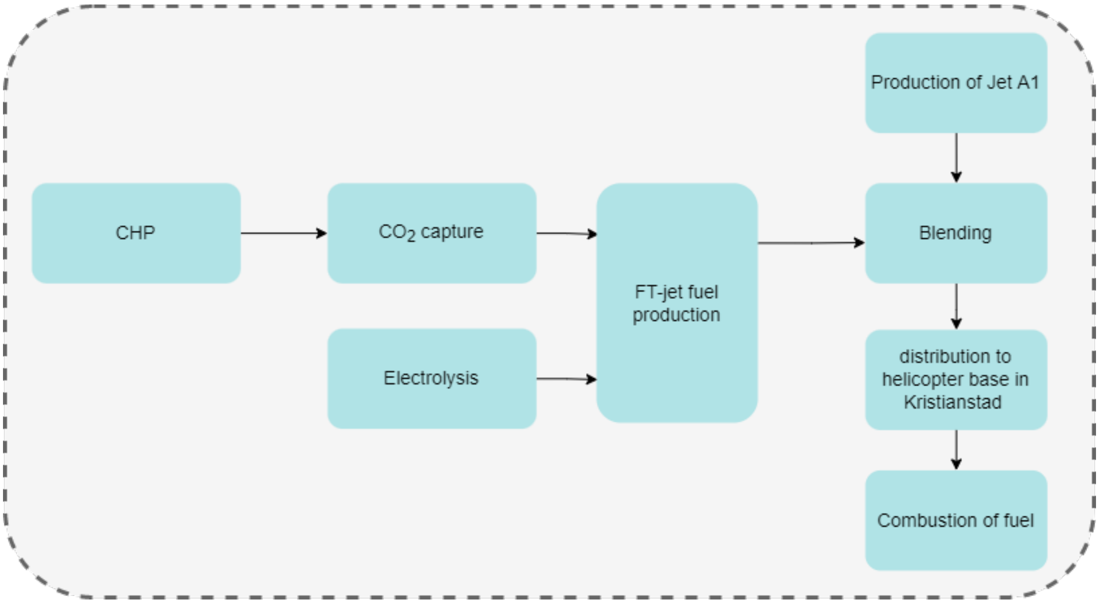

Figure 17. The system boundary of PtL-based SAF

In this study, PtL via FT-pathway was chosen and the fuel production data was obtained from a previously done project from IVL, by Fagerström et al. [4]. Based on the existing LCA model, the production site is in Östersund. The source of CO_2 captured is from a biomass CHP plant, which means that the CO_2 feedstock is biogenic. The electricity mix used in the process including the electrolysis process comes from 86% wind power and 14% hydropower. More details of the production process can be found in [4]. The dataset is considered to be applicable to this study since the geographical scope is Sweden and the 100% renewable electricity is appropriate for an electro-fuel plant.

The production of Jet A1 and the blending stage were assumed to take place in Östersund. The fuel mixture was then distributed to Kristianstad where the helicopter base is located. The transport distance in the distribution stage is estimated to be 730 km. The same assumption about the combustion of the HEFA-based jet fuel is applied in this case.

5.3 LCA results and interpretation

The climate impacts obtained from the LCA of the HEFA-and PtL-based SAF in different blend rates are presented quantitatively in Table 11 and illustratively in Figure 18. For each fuel type and blend rate, the climate impact shown in Figure 18 is divided into different life cycle stages in their respective value chains. Including in Figure 18 is the impact from conventional fossil fuel given in the REDII framework, which can facilitate the comparison between different fuels.

Table 11. Climate impact result of different type of SAF and blend rate, including a fossil comparator

Types of fuels	34.6%	50%	100%	Unit
HEFA	66.3	57.4	28.7	gCO_2eq/MJ
PtL	64.6	54.5	21.9	gCO_2eq/MJ
Fossil comparator		94		gCO_2eq/MJ

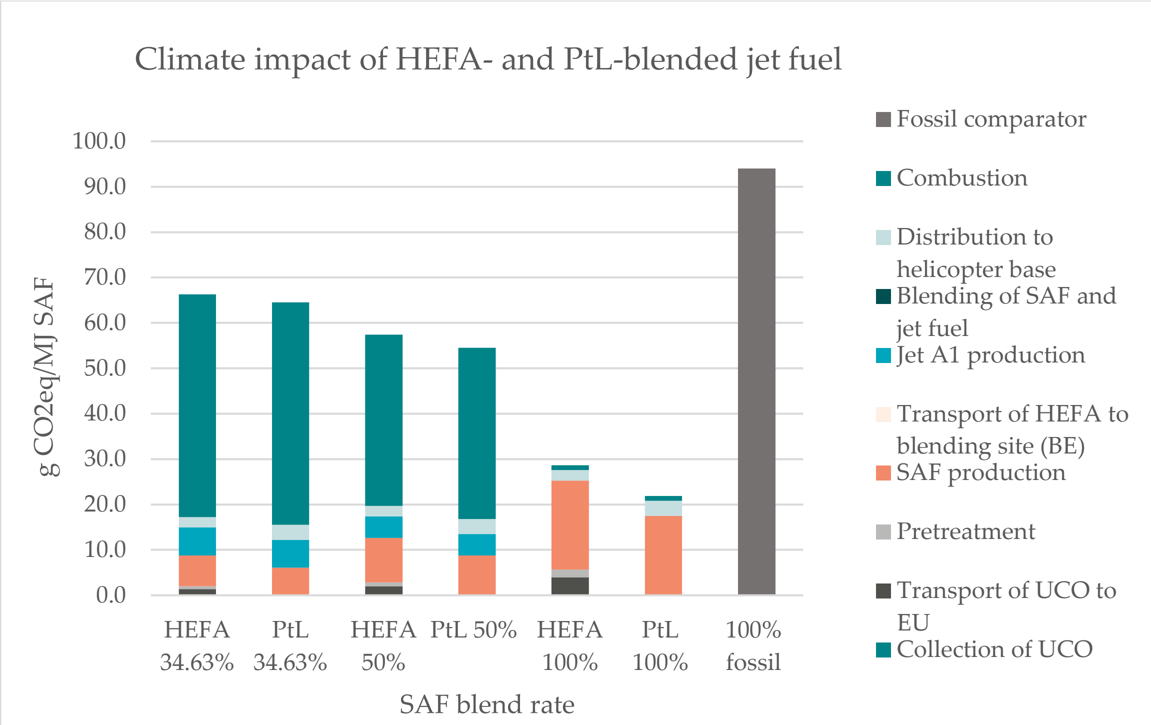

Figure 18. Climate impact of HEFA-and PtL-blended jet fuel in different blend rate

Figure 18 shows that the increased use of SAF lead to a decrease in climate impact for both fuel types. HEFA-based SAF gives a slightly higher climate impact than the PtL-based SAF in all three blend rates. With the actual blend rate of 34.63%, the GHG emission of the HEFA- and PtL-based SAF is reduced by 29% and 31% respectively. With 50% blend rate, the GHG emission reduction is between 39% and 42% respectively. With 100% blend rate, the GHG emission can be reduced by 70% for the HEFA-based SAF and 77% for the PtL-based.

Looking at the contribution of different life cycle stages, the result in Figure 17 shows that the combustion process is the biggest contributing activity for the blend rate of 34.63% and 50%. For 100% SAF, the biggest contributor is the SAF production process itself. The third contributing factor is the production of fossil Jet A1. Comparing climate impact of the value chain of 100% HEFA and PtL, it can be seen that the differences between the two are the impact from transportation. For HEFA, the UCO which is used as feedstock needs be transported from China to Europe while in the case of PtL, the fuel is assumed to be produced in Sweden and the only transport considered is the distribution stage from Östersund to Kristianstad.

The impact from transportation implies that the origin of feedstock is crucial. If the UCO were to be collected within Europe, the difference between the HEFA and PtL may be insignificant. As both value chains are not modelled based on specific data, the results may not be used to state with uncertainty which fuel perform better from an environmental perspective. However, it can give a better understanding of the importance of the choice of production pathway, feedstock and transportation.

5.3.1 Sensitivity Analysis

In the assessment, the heat demand in HEFA production was assumed to be supplied by natural gas, which is a conservative assumption. However, the energy source may as well come from bio-based source. Since HEFA production is a significant contributing process, the choice of energy source may affect the result. Hence, a sensitivity analysis is done to the production of HEFA by changing the energy sources in the model. In this case, the natural gas which modelled in the reference case is compared with biogas. The result is shown in Figure 19.

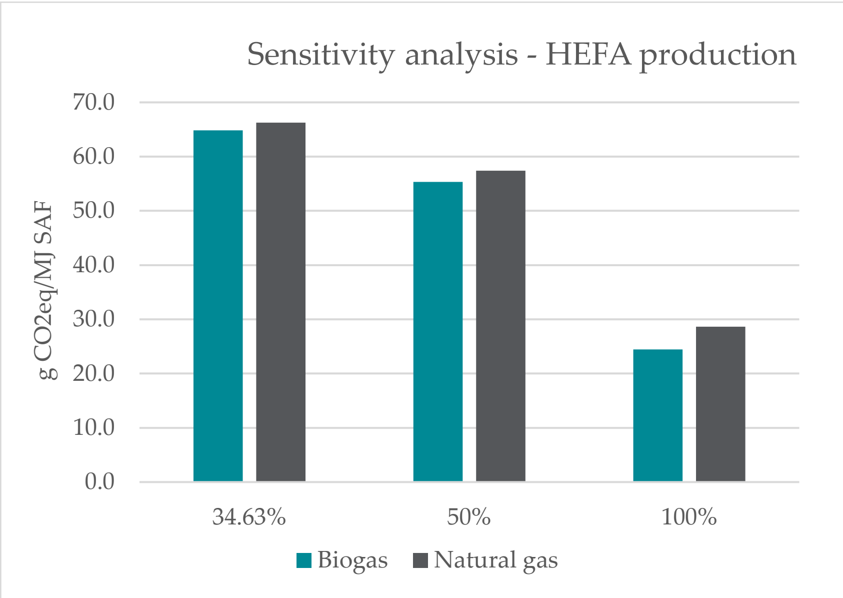

Figure 19. Sensitivity analysis of energy source of heat demand in HEFA production where biogas is compared with natural gas.

The result from the sensitivity analysis shown in Figure 19 shows that the climate impact of HEFA value chain is reduced 2.2% and 3.7% for the blend rate of 34.63% and 50% respectively. For 100% HEFA, the climate impact is 14.7% lower when biogas is used. This change is more significant. However, these changes correspond to a GHG emission saving between 31-74% which is not much change compared to the cases where natural gas is used.

For the PtL-case, a 100% renewable electricity is modelled. However, since substantial amount of electricity is required in the PtL process, it can be interesting to see if how the result can change if Swedish electricity (consumption mix) is used instead. The result of this sensitivity analysis is shown in Figure 20.

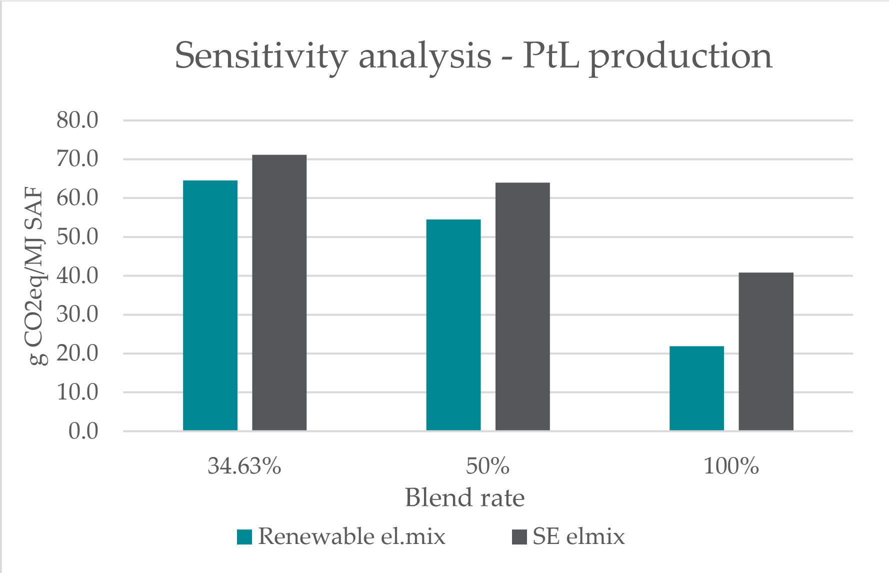

Figure 20. Sensitivity analysis of electricity model in PtL-based SAF where Swedish electricity mix is used instead of renewable energy

Figure 20 shows that the climate impact increases significantly when Swedish electricity mix is used. With more share of PtL in the aviation fuel, the higher the increase in impact (87%). This implies that electricity is the main contributing factor in the PtL-based fuel production.

5.3.2 Uncertainty analysis

It should be emphasized that the LCA model and calculations are not based on specific data. Several assumptions were made in the assessment of HEFA regarding geographical choices such as source of UCO, collection site, production of Jet A1 etc. which leads further assumption on transportation distance. The data used for HEFA production was a European average production which is considered to be an appropriate data. Hence, apart from the assumption on transportation model, the result for the HEFA value chain in this study should be quite representative.
On the other hand, the modelling of PtL production which came from another project was highly specific and may have some parameters that may not fit with this study. However, as the production of PtL has not been commercialized yet, this data is considered to be adequate and representative for the LCA calculation in terms of geographical and technical scope.

5.4 Environmental benefits

The environmental benefits of replacing fossil jet fuel with SAF, partly or completely, can be estimated in term of how much fossil GHG emissions can be reduced. In 2021, the total emission from using fossil jet fuel by the Swedish Maritime Administration (Sjöfartsverket), Polisflyget, Kustbevakningen (KBV) and Svensk Luftambulans is 18 218 t. The Swedish Maritime Administration stands for 27% of the total emissions of the jet fuel consumption in 2021. If Sjöfartsverket were to use HEFA or PtL with current blend rate, it can reduce 1451 t CO_2eq or 1541 tCO_2eq respectively.With 100% HEFA, the CO_2eq emissions can be reduced up to 3420 t. If 100% PtL is used, 3775 t CO_2eq can be reduced.

5.5 Discussion and conclusions – Life-cycle Analysis

From the LCA results, HEFA and PtL have a potential to reduce fossil greenhouse gases up to 70% respective 77% when compared to a conventional fossil fuel which emit 94 gCO_2eq/MJ. None of the two fuels met the 100% fossil free target. This implies that it will be a challenge for the aviation sector to reach the Swedish climate target by 2030 even though a 100% SAF are implemented. One of the obstacles is the production of H_2 used in HEFA production which today is still produced conventionally from fossil origin. For the PtL, the fossil emissions may result from the upstream production of raw materials used in processes such as electrolysis and CO_2 capture. Fossil fuel was also used in the CHP plant which gives the production of the PtL not 100% fossil free. These obstacles should be addressed in order to further reduce the climate impact of SAF. It is possible that by 2045, the SAF production will be improved e.g being less fossil dependent, which would lead to the climate impact of SAF being reduced further. By then, the GHG emission reduction potential of SAF may be closer to 100%.

In general, the UCO-based HEFA shows a higher climate impact than PtL. This is due to a significantly longer transportation of UCO from China compared to the value chain of the PtL where all activities occur within Sweden. This implies that the climate impact of HEFA can be reduced if the UCO are collected domestically.

Sensitivity analysis shows that the climate impact of HEFA is not very sensitive to the choice of energy source in the production of HEFA (natural gas vs biogas) when its mixture is below 50%. This is since the total climate change impact only increased by 2-3%. However, the climate impact increases by 15% when pure HEFA is calculated. For the PtL-case, the choice of electricity is based on the assumption that PtL can only be produced on a commercial scale when 100% renewable electricity is used. Otherwise, the environmental benefit would not be high enough to invest. This is also proven in the sensitivity analysis when the electricity model is change to the Swedish consumption mix instead and the climate impact increases drastically up to 87%.
For the Swedish Maritime Administration, the emissions reduction potential of HEFA and PtL would correspond to a decrease in CO_2eq by up to 3420 t and 3775 t respectively.

6 Discussion

This section presents a broader discussion resulting from combining each separate part of IVL's contributions in the project. For discussion that addresses each part in more detail, see section 3.4 for the evaluation of the production potential, section 4.5 for the scenario analysis and 5.5 for discussion on results of the life-cycle analysis.

Forest residues is the most abundant feedstock type, while domestic HEFA feedstock is limited

There seems to a discrepancy between the planned production capacity and the amount of available feedstock. The planned domestic jet fuel capacity via the HEFA (hydrotreated esters and fatty acids) pathway will already in 2025 require more feedstock (3.8 TWh) than the maximum amount of UCO (used cooking oil), animal fats and tall oil that is estimated to be available in Sweden by that time (2.6 TWh), assuming that the feedstock potential by that time is roughly the same as today. To fulfill the planned HEFA capacity, imported feedstock would be required. There is however already planned capacity outside of Sweden that will compete for the same resources. As can be seen in Figure 11, the amount of HEFA that could be imported from planned plants abroad is 60 TWh. In [108], the estimated future amount of UCO in the European Union and the United Kingdom is 1.7 Mtons per year, which translates to about 17 TWh of feedstock. To produce all the planned domestic HEFA from UCO, feedstock or fuel would need to be imported from outside of the EU and it would then be significantly more difficult to trace the origin of the HEFA and ensure sustainable sourcing of feedstock. UCO as well as other feedstock such as tall oil are subject to competition from other bioenergy and chemical applications. As the scenarios illustrated other alternative jet fuels like ATJ (alcohol-to-jet), given that it can be produced in Sweden with lower costs than other jet fuels which is uncertain, can reduce the demand for HEFA, but if not there might be a continued pressure of finding more feedstock for HEFA.

Domestic HEFA feedstock significantly improves LCA performance of HEFA-based SAF

The environmental assessment of HEFA illuminates the importance of the geographical origin of the feedstock. The climate impact of the UCO would be reduced significantly if the UCO were to be collected within Sweden or at least within the EU. Reducing the climate impact of the HEFA production will also make the climate impact more comparable to that of PtL (power-to-liquid). However, as the feedstock potential analysis shows that feedstock viable for HEFA production is limited in Sweden and that all HEFA feedstock is subject to strong competition from HVO (hydrogenated vegetable oil) production (among other products and chemicals), it would not be feasible to reach the climate target of the entire aviation sector only relying on HEFA.

The sustainability classification of forest residues

Forest residues such as tops, branches and stumps are the most abundant feedstock for the production of fossil free biofuels in Sweden. Their future potential corresponds to 91–106 TWh/year. However, on the 14th of September 2022, the EU parliament voted to limit the use of primary woody biomass for energy purposes based on historic level (2017–2022) [109] in the upcoming revision of the Renewable Energy Directive (REDII) [110]. This proposal means that primary woody biomass, including treetops and branches, will only be categorized as a renewable energy resource up to a certain level, in which this cap will gradually be phased down by 2030 [111].

It is yet to be decided whether this proposal from the EU parliament would be accepted in the upcoming recast of the renewable energy directive (REDIII). If this proposal is accepted, it would have a large impact on the forest industry as well as the planned investments for forest-based biofuels including aviation fuels.

The (maximum) production potential of SAF is larger than the future domestic demand

As seen in section 3.3.2, the estimated domestic production potential ranges between 66 TWh in 2045, when the most restrictive assumptions on H_2 availability and process yields are applied, and 86 TWh in 2045 when less restrictive assumptions are applied. In contrast, the foreseen future total demand from the domestic aviation sector is around 5 TWh. This means that the overall maximum production potential from sustainable feedstock is theoretically enough to supply both air-borne rescue services and domestic commercial flights with fossil free jet fuel, provided that there is willingness to pay and compete with other sectors for feedstock and that production plants for alternative jet fuels are built in Sweden. This could be ensured through e.g., policy tools such as the reduction mandate, or by supporting the producers so that jet fuel could be produced at a favorable price. Without intervention however, the actual produced amounts of SAF would likely be far less also in the future, due to factors like the design of the bio-refineries, competition, and other market aspects.

Could direct electrification of aircraft have a role in the decarbonization of air-borne rescue services?

Direct electrification of aircraft has received considerable attention, with numerous demonstration and research projects aimed at bringing electric aircraft into operation in both the short- and mid-term (2020s and early 2030s) [112]. Many of the near-term initiatives are focused on electrification of passenger flights and airplanes, e.g., the Swedish company Heart Aircraft [113], but there are also examples of electrification of VTOL (vertical take-off and landing), e.g., Lilium [114] and Beta Technologies' Alia [115]. A project of particular interest to airborne search and rescue services is the research financed by Vinnova on VTOL, where a VTOL prototype aimed at use within air ambulance or rescue services is developed [116]. Many of the VTOL concepts will only cover shorter distances (flights shorter than one hour and distances below 100 km), while there is undergoing research and development of airplanes for longer, regional, distances [112].

Moreover, there are some examples of hydrogen aircraft being the focal point, to provide somewhat longer ranges in unmanned aerial vehicles [117], in passenger flight [118] and in VTOL aircraft that could potentially be used in emergency response [119], although the latter two cited examples are not yet concretized enough to have a determined year for launch.

It is clear the aircraft sector could see one or many technological break-throughs in the oncoming years. However, the future ideal use of these technologies is uncertain. Electric VTOL aircraft might be considered eligible for use within the military or within air search and rescue, as intended in the Alia case [115], but the technology could also be deemed insufficient to meet operational requirements from its users. The adoption of such technologies within airborne search and rescue services would most likely require changes in how search and rescue actions are operated compared to today. It is therefore recommended to follow the development of electrified aircraft technology and explore alternative operation strategies in parallel to decarbonizing current operations.

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Annex I - Inventory data for the environmental assessment

The inventory data used for the environmental assessment are presented below.

1. HEFA-based SAF value chain

Table 12 and 13 shows the data used for the pretreatment of UCO and the production process of HEFA respectively. The data are obtained from Hamelinck et al. (2021) [104]. Table 14 shows transportation data for the HEFA value chain.

Table 12. Inventory data for the pretreatment process of UCO

Flows	Quantity	Unit
Inputs		
UCO untreated	1000	kg
H3PO4	7.8	kg
Bleaching clay	1	kg
Electricity	9.8	kWh
Steam	464	MJ
Outputs		
Treated waste oil	980	kg

Table 13. Inventory data for the production of HEFA

Flows	Quantity	Unit
Inputs		
Treated UCO	1000	kg
H2	44	kg
Electricity	46.5	kWh
Steam	4445	MJ
Outputs		
UCO-HEFA	610	kg
UCO-HVO	135.7	kg
Propane	84	kg
Naphtha	93.9	kg

Table 14. Transportation data for HEFA value chain.

Activity	Distance [km]	Transportation mode	Route
Collection	50	Truck	Within China
Transport to production site	21 123	Truck + Ship	Within China - Shanghai- Belgium
Transport to blending site	163	Ship	Belgium – the Netherlands
Transport to Sweden	1 724	Ship	The Netherlands – Gävle, Sweden

Distribution to helicopter base	730	Truck	Gävle - Kristianstad

1. PtL value chain

For PtL value chain, only the data for transportation is presented in Table 15. Information on the production of PtL can be found in the report *Large scale bio electro jet fuel production integration at CHP-plant in Östersund, Sweden* by Fagerström et al. (2021) [4].

Table 15. Transportation data for the value chain of PtL.

Activity	Distance [km]	transportation mode	Route
Distribution to helicopter base	1190	Truck	Östersund – Kristianstad

Annex II – Modelling parameters for scenario analysis

In Table 16, the assumed values for the energy content and emission factors of domestic planned and imported fuel pathways are presented. The values in Table 16 are also representative for the additional plants of HEFA. The energy content of CJF was assumed for all the fuel pathways in which no specific details could be found. The emission factors for the additional plants of HTL and FT were gathered from [120] and for FT PTL from [121]. For all jet fuel types a density of 0.804 ton/m^3 has been assumed [122].

Table 16. Assumed energy content and emission factor values for domestic planned and imported fuel pathways.

	Energy content [MJ/l]	Emission factor [gCO_2eq/MJ]
CJF	34.6 [123]	94 [9]
FT forest residue/waste	33 [123]	8.3/14.8
HEFA	34 [123]	16 [9]
ATJ	Assumed to be the same as CJF	16 [9]
FT PtL	Assumed to be the same as FT	15 [4]

The annualized capital expenditure was calculated by using the following equations, with a discount rate of 10% and lifetime of 30 years.

$$Capital\ recovery\ factor\ (CRF) = \frac{r \cdot (1+r)^N}{(1+r)^N - 1}$$

$$Annualised\ capital\ cost = CRF \cdot TCI$$

r – Discount rate

N – Number of years

The electricity demand for the FT PTL production has been re-calculated and divided into two parts based on the information in [4] The electricity required to produce hydrogen (electrolysis process), syngas and converting hydrocarbons to jet fuel has been summarized and represents the "RJF prod." in Table 17, and has the unit MWh/ton CO_2 input. The cost of consuming electricity for "RJF prod." is then considered to be a variable cost in the process of producing jet fuel. The electricity required to capture CO_2 is separate and has been included in the price of raw materials for FT PTL.

Table 17. Economic parameters for the fuel pathways for the additional plants.

Parameter	HEFA	FT	HTL	PTL		Unit
				Jet fuel	CO_2	
Annualised capital expenditure (CAPEX)	1 142	9 499	13 710	12 470		SEK/t jet $fuel_{out}$
Fixed cost	46	380	548	499		SEK/t jet $fuel_{out}$
Demand for utilities (variable cost)						
Electricity	0.088	0.06	0.09	10.30[a]	0.54[b]	MWh/t_{in}
Water	-	-	-	14.50	19.70	m^3/t_{in}

[a] Incorporates the electricity demand from hydrogen production.
[b] The unit is defined as MWh/tCO_2 as CO_2 output from the capturing process and input to the production of FT PTL.

The revenues of the by-products were based on current prices of diesel, naphtha, and gasoline [77]. The prices were increased throughout the period based on the price of diesel in [124] for the base case during 2030-2050. The price of water was based on an average of the fee in Stockholm, Gothenburg, Malmö, Uppsala and Linköping [125]–[129] and was gradually increased with 4% annually [128]. The electricity prices were based on values in [130] from the increased electrification from renewable sources scenario (Elektrifiering förnybart).

The price of domestic and imported waste oils was assumed to be the average price of used cooking oil from Northwest Europe during 2021 [131]. The price of forestry residue was gathered from [132] and was assumed to increase at the same rate as the average biomass price from [133]. The price of CO_2 was assumed to be the variable cost from the water and electricity consumption during the capturing process.

For the analysis of the amount of feedstock required to produce the supplied jet fuel from planned HEFA and ATJ, information regarding the specific processes were difficult to find. Therefore, an assumption was made that the HEFA expected to be produced in Sweden has a feedstock requirement corresponding to a yield presented in Table 4. For ATJ the yield was based on [134]. However, it is important to note that these assumptions might not be representative of reality and the expected yields from these planned plants.

Annex III – Planned production of SAF

Table 18: Planned production of SAF

Company	Location	Stage	Fuel type	URL	Unit [ton]
OMV	Austria	TRL 9 2022	HEFA for diesel and SAF	https://www.omv.com/en/news/220412-omv-supplies-austrian-airlines-with-sustainable-aviation-fuel-under-the-partnership-agreement	200 000
Cresta	Canada	Planned TRL 9	HEFA	https://www.prnewswire.com/news-releases/come-by-chance-refinery-now-braya-renewable-fuels-introduces-new-executive-team-301478245.html	643 200
Copenhagen airport, A.P. Moller - Maersk, DSV Panalpina, DFDS, SAS and Ørsted	Denmark	Planned	FT Electrofuel	Fact_sheet.pdf (presscloud.com)	250 000
Neste	Finland	Commercial	HEFA Certified by ASTM D7566	https://www.neste.com/products/all-products/neste-my-sustainable-aviation-fuel#ee276454	100 000
Bionext	France	TRL 4-5 2022	FT from gasification of lignocellulosic	https://www.ifpenergiesnouvelles.com/article/biotfuelr-project-entry-industrialization-and-commercialization-phase	30 000-100 000
Total	France	TRL 9 2024	HEFA	https://www.ieabioenergy.com/installations/	170 000
Total	France	TRL 9 2019	HEFA	https://www.argusmedia.com/en/news/2203248-total-starts-biojet-production-at-la-mede-biorefinery	100 000

HCS Group and Gevo	Germany	TRL 6-7 demonstartion 2024	AtJ	https://demoplants21.best-research.eu/projects/info/4007/8JBaZy	60 000
Atmosfair	Germany	Commercial 2020	Synthetic kerosene (FT electrofuel)	World's first commercial plant making clean jet fuel has opened in Germany, says NGO | Euronews	19 000
Eni	Italy	TRL 9 construction 2021	HEFA for diesel and SAF	https://www.eni.com/en-IT/operations/italy-gela-innovative-biorefinery.html	10000 (2021) - 150 000 (2024)
SkyNRG	Netherlands	Planned	HEFA (from wsate and residue streams such as cooking oil)	https://www.greenairnews.com/?p=594#:~:text=SkyNRG%20is%20already%20leading%20a,reviewed%20and%20updated%2C%20says%20SkyNRG.	100 000
Synkero with Port of Amsterdam , Royal Schiphol Group, SkyNRG and KLM,	Netherlands	Planned	FT Electrofuel (green H2 and CO2)	https://skynrg.com/producing-saf/	50 000
FLITE	Netherlands	TRL 8 first of a kind commercial Planned 2024	AtJ from ethanol	https://www.ieabioenergy.com/installations/	30 000
Shell	Netherlands	TRL 9 2024	HEFA	https://www.ieabioenergy.com/installations/	410 000
Joint venture Air liquide, Enerkem, Port of rotterdam and Shell	Netherlands	TRL 8 first of a kind commercial 2026	FT (Gasification of organic residues and waste streams (plastic))	https://www.ieabioenergy.com/installations/	60 000
norsk e-fuel	Norway	Construction planned on 2023	FT Electrofuel (CO2 from DAC and waste gas processes H2 from electrolysis with	https://www.norsk-e-fuel.com/technology	10050 (2023) - 20 100 (2026)

			renewable electricity)		
Nordic Electrofuel (former Nordic Blue crude)	Norway	Production planned by 2024	FT Electrofuel (start with fossil CO2 from industry, planned to get DAC when cost is feasable)	https://nordicelectrofuel.no/#whatwedo	8040 (2024) - 804 000 (2032)
ExxonMobil	Norway	Planned planned by 2025	FT (gasification of forest residues)	ExxonMobil expands interest in biofuels, acquires stake in Biojet AS	480 000
Neste	Singapore + Rotterdam	Planned	HEFA	https://www.neste.com/products/all-products/neste-my-sustainable-aviation-fuel#ee276454	1500000
BP	Spain	TRL 9 2021	HEFA	https://www.bp.com/en/global/air-bp/news-and-views/press-releases/Airbp-announces-netjets-europe-first-to-purchase-iscc-plus-saf.html	52 000
Repsol	Spain	TRL 9 2023	HEFA for diesel, SAF and naphta	https://www.repsol.com/en/press-room/press-releases/2022/repsol-starts-construction-of-spains-first-advanced-biofuels-plant-at-its-cartagena-refinery/index.cshtml	250 000
st1	Sweden	Planned to start operation	HEFA and HVO (from used cooking oil and talloil)	SAF producers | NISA	200 000
Swedish Biofuels and COWI	Sweden	Planned	Alcohol to jet	COWI och Swedish Biofuels samarbetar om att producera flygbränsle vid Arlanda | Bioenergitidningen	400 000
SAS, Vattenfall, Shell	Sweden	Planned	Alcohol to jet	SAS, Vattenfall, Shell och LanzaTech ska undersöka möjligheten att producera hållbart flygbränsle - Vattenfall (cision.com)	50 000

Liquid Wind/ Orsted	Sweden	Planned	Electrofuels --> e-methanol (captured biogenic CO2 and green H2 from wind power)	https://www.ieabioenergy.com/installations/	50 000
Preem	Sweden	TRL 9 2021	HEFA for diesel and SAF	https://www.ieabioenergy.com/installations/	295 068
Vattenfall and ST1	Sweden	Planned 2029	Electrofuel (not sure what process)	Vattenfall och St1 ingår nytt partnerskap för att producera en stor mängd fossilfritt e-flygbränsle på den svenska västkusten - Vattenfall	804 000
FlexJET consortium	UK	TRL 6-7 demonstartion 2022	HEFA	https://www.ieabioenergy.com/installations/	1 200
Fulcurm bioenergy and Essar oil	UK	TRL 8 first of a kind commercial 2025	FT (gasification organic residues and waste streams)	https://demoplants21.best-research.eu/projects/info/3910/8JBaZy	80 400
LanzaTach UK	UK	TRL 8 first of a kind commercial	AtJ from ethanol	https://demoplants21.best-research.eu/projects/info/3976/8JBaZy	80 400
Velocys	UK	TRL 8 first of a kind commercial 2025	FT (gasification of municpal solid waste)	https://www.velocys.com/2019/08/20/plans-submitted-for-the-first-waste-to-jet-fuel-plant-in-the-uk-and-europe/	58 000
BayouFuels	USA		FT from forestry residues	https://www.bayoufuels.com/	76 000
Aemetis	USA	Planned start 2024	HEFA	https://www.aemetis.com/products/renewable-jet-and-diesel/	274 164
Fulcrum Bioenergy	USA	TRL 9 2023	FT (gasification of waste)	https://fulcrum-bioenergy.com/wp-content/uploads/2021/07/2021-07-06-Sierra-Construction-Completion-Press-Release-FINAL.pdf	100 500

Gevo	USA	TRL 8 first of a kind commercial 2023	AtJ from isobutanol	https://demoplants21.best-research.eu/projects/info/3913/8JBaZy	160 800
Gevo	USA	TRL 9 2024	FT (e-fuels biomass hybrids from sugar and start crops)	https://gevo.com/why-biofuels/food-and-fuel/gevo-breaks-ground-on-net-zero-a-construction/	136 680
Indaba renewable fuels	USA	TRL 9 2024	HEFA for diesel and SAF	https://www.ieabioenergy.com/installations/	297 480
LanzaJt	USA	TRL 8 first of a kind commercial 2022	AtJ from ethanol	https://demoplants21.best-research.eu/projects/info/3920/8JBaZy	1 286 400
Phillips 66	USA	TRL 9 2024	HEFA for diesel and SAF	https://investor.phillips66.com/financial-information/news-releases/news-release-details/2022/Phillips-66-Makes-Final-Investment-Decision-to-Convert-San-Francisco-Refinery-to-a-Renewable-Fuels-Facility/default.aspx	1 608 000
Red Rock Biofuels	USA	TRL 8 first of a kind commercial 2022	FT (gasification of forest residues)	https://demoplants21.best-research.eu/projects/info/3731/8JBaZy	17 600
World Energy	USA	TRL 8 first of a kind commercial 2022	HEFA for diesel and SAF	https://www.airproducts.com/news-center/2022/04/0422-air-products-and-world-energy-sustainable-aviation-fuel-facility-in-california	804 000

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