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What Are the Policy Impacts on Renewable Jet Fuel in Sweden?

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Abstract: The aviation industry contributes to more than 2% of global human-induced CO_2-emissions, and it is expected to increase to 3% by 2050 as demand for aviation grows. As the industry is still dependent on conventional jet fuel, an essential component for a carbon-neutral growth is low-carbon, sustainable aviation fuels, for example alternative drop-in fuels with biobased components. An optimization model was developed for the case of Sweden to examine the impacts of carbon price, blending mandates and penalty fee (for not reaching the blending mandate) on the production of renewable jet fuel (RJF). The model included biomass gasification-based Fischer–Tropsch (FT) jet fuel, Power-to-Liquid (PTL) jet fuel through the FT route and Hydrothermal liquefaction (HTL)-based jet fuel. Thus, this study aims at answering how combining different policies for the aviation sector can support the production of RJF in Sweden while reducing greenhouse gas (GHG) emissions. The results demonstrate the importance of implementing policy instruments to promote the production of RJF in Sweden. The blending mandate is an effective policy to both promote RJF production while reducing emissions. The current level of the penalty fee is not sufficient to support the fuel switch to RJF. A higher blending mandate and carbon price will accelerate the transition towards renewable and sustainable fuels for the aviation industry.

Keywords: policy mix; sustainable aviation fuels; biofuels; electrofuels; supply-chain optimization; spatial and temporal analysis; techno-economic analysis; Sweden

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1. Introduction

1.1. Background

The transport sector is the second largest contributor to global CO_2 emissions after the electricity and heat industry, releasing a total of 8260 million tons (Mton) of CO_2 in 2018 [1]. Fossil fuels represent the dominating energy source in the transport sector, accounting for approximately a quarter of global energy consumption. Measures such as energy efficiency, deployment of renewable fuels, and modal shifts to low-carbon alternatives have been put in place to decarbonize the transport sector [2,3]. However, challenges still remain in fully transitioning into sustainable pathways as the transportation demand increases, and the sector is still highly reliant on fossil fuels, which is particularly true for the aviation industry [4]. The aviation industry currently contributes to more than 2% of global human-induced CO_2 emissions, which is expected to increase to 3% by 2050 as demand for aviation grows [4,5]. The expected increase does not consider the effects of the COVID-19 pandemic. Accelerating the transition to renewable jet fuel becomes crucial for the industry to contribute to climate goals aiming to reduce greenhouse gas (GHG) emissions. Within the European Union (EU), Sweden has relatively ambitious climate goals and aims to reach net-zero GHG emissions by 2045 [6]. The Swedish climate policy framework also sets the targets of reducing GHG-emissions by 63% by 2030 and 75% by 2040, compared to 1990 [6,7].

The aviation industry addresses the call to reduce its environmental impacts through investments in more fuel-efficient technologies and environmentally friendly operating practices [8] as well as in alternative fuel sources [9]. According to the Air Transport Action Group [10], an essential component of the overall strategy for carbon-neutral growth in the aviation sector is low-carbon, sustainable aviation fuels, namely alternative drop-in fuels with biobased components. Other potential solutions for a carbon-neutral growth are alternative aviation propulsion technologies, which include hydrogen, hybrid or electric powered aircrafts, as described in Dahal et al. [11]. Renewable aviation fuels are not expected to be competitive with fossil jet prices at least in the short term [12]. This indicates that policy support is important to accelerate the deployment of renewable and sustainable aviation fuels.

The impacts of policies on the aviation sector's economic and environmental performance are explored in the recent literature. The most studied policy instruments include the EU Emissions Trading System (EU ETS) [13–17], aviation tax [18,19], carbon price [20], and the multiplier mechanism applied on energy content of biofuel to stimulate biofuel uptake [19]. These studies have demonstrated different degrees of policy effectiveness on reducing GHG emissions from the aviation industry. The inclusion of aviation tax may or may not be significant in reducing emissions depending on the carbon price [13,17], but may incentivize airports to maximize their revenue [14]. A study at the global level concluded that policy mixing including enhanced technology efficiency, carbon price, use of alternative fuels and demand shift are required for sustainable air transport [20]. Similar policies introduced in different countries may have different degrees of effectiveness depending on national circumstances, e.g., resource availability, technology availability, interaction with other policies, institutional aspects, etc. Hence, national, regional and local assessments of policy impacts are needed.

There are various quantitative and qualitative analyses used to evaluate policy impacts. Energy system modeling has been widely applied in scientific studies to address policy questions, e.g., evaluate the policy impacts within the aviation industry [20,21]. In general, energy system modeling can be categorized into top-down and bottom-up approaches. While top-down tools usually have a macroeconomic perspective, bottom-up tools have a technological perspective and is called technology-rich models. The bottom-up tools look at the deployment and use of different technologies and represent in detail their characteristics. Both modeling approaches have been applied in literature addressing policy questions within the aviation sector. In Sgouridis et al. [20], a system dynamic model (top-down tool), i.e., Global Aviation Industry Dynamics (GAID), was used to evaluate the impacts of five policies. The policies were technological efficiency improvement, operational efficiency improvement, use of alternative fuels, demand shift and carbon price, on total emissions, air transport mobility, airfares and airline profitability. The open-source global aviation systems model AIM (bottom-up tool) was utilized in Dray et al. [21] to model carbon leakages for aviation emissions policy in a single country. Economic instruments such as a feed-in tariff and capital investment subsidy to promote bio-jet fuel production were studied in Moncada et al. [22] using a spatially explicit agent-based model (bottom-up).

Optimization models, another type of bottom-up tool, are often deployed to optimize energy investment decisions endogenously, meeting a specific target under certain constraints [23]. Optimization tools can help to identify cost-effective and sustainable fuel production pathways [24]. Optimization models have also shown to be valuable as decision-making tools for planning and designing supply chains for RJF fuel provision [25]. A geographically explicit cost optimization model was used in de Jong et al. [26] to explore cost reduction strategies and required policy support for the production of bio-jet fuel in Sweden. In the study, de Jong et al. [26] examined distributed or centralized production and the opportunities to co-locate bio-jet-fuel production with existing industries in Sweden (e.g., oil refinery, pulp and paper mill, sawmill). The study analyzed only one technological conversion pathway, i.e., hydrothermal liquefaction (HTL), to produce bio-jet fuel. In Leong et al. [27] an optimization framework was applied for a bioenergy supply chain while considering a CO_2 reduction target. In the study, a two-step optimization was performed on cost and emissions by combining carbon emission pinch analysis (CEPA) implemented through the automated targeting model (ATM), with superstructural optimization [27].

To the best of our knowledge, no study examines the impact of multiple policy instruments on the production of renewable jet fuel (RJF) while exploring multiple production pathways. This study sheds lights on the impacts of carbon price, blending mandates and penalty fee for not reaching the blending mandate, on the production of RJF through the following production pathways (i) biomass gasification-based Fischer–Tropsch (FT) (ii) Power-to-Liquid (PTL) through the FT route and (iii) the HTL route. In this study, alternative propulsion technologies such as hydrogen and hybrid or electric engines are not included. More specifically, this study aims to answer how combining different policies in the aviation sector can support the production of RJF to meet the emission reduction targets in Sweden by using an optimization model incorporating spatial and temporal aspects, specifically developed for this purpose. Evidence-based policies are essential for the successful and sustainable implementation of the RJF fuel supply chains. The case of Sweden is explored due to the relatively large domestic resource availability of, i.e., forestry residues [28,29], biogenic CO_2 and renewable energy [30], and the ambitious national climate target of net zero GHG emissions by 2045.

Following the introduction, the climate and energy policies of Sweden, that are of relevance to the aviation industry are summarized in Section 1.2. In Section 2, the methodology is presented, including an overview of the chosen conversion pathways, the technoeconomic parameters, the objective of the optimization model and a description of the scenarios to be explored. In Section 3, the results of the optimization model and scenario development are presented and discussed. Section 4 summarizes and concludes the key insights from the research findings.

1.2. Climate and Energy Policies for the Aviation Industry in Sweden

In Sweden, climate and energy policies have been introduced in the transport sector, and for specific transport modes, with the aim to reduce the impact on climate change. The policy support is expected to contribute to meeting fossil-free domestic aviation by 2030 and for all flights departing from Swedish airports to be fossil-free by 2045 [31].

The Swedish climate and energy targets adopted under the Energy Agreement (2016) and the Climate Policy Framework (2017) [6] include:

- By 2045, Sweden is to achieve no net GHG-emissions into the atmosphere.
- By 2040, 100% of the electricity generation should be from renewable sources.
- By 2030, the emissions from domestic transport should be reduced by 70% compared with 2010 (excluding domestic aviation since it is included in EU ETS) [6].

To mitigate the climate impact from the aviation sector, the Swedish government introduced policy instruments, such as an aviation tax and a blending mandate. The aviation tax was launched in 2018 primarily to reduce demand for air travels [7,32–34]. The tax is included in the price of the passenger flight ticket. Different taxes are applied depending on travel destination. An assessment of the aviation tax was conducted by the Swedish Transport Agency in 2018, estimating a reduction of a total of 350,000 passengers [32].

A blending mandate, which sets a mandatory requirement on jet fuel suppliers to blend bio-jet fuel into fossil jet fuel was introduced in Sweden on 1 July 2021. The blending ratio starts at 0.8% in 2021 and will gradually increase to 27% in 2030. A penalty fee of 6 SEK/kg$CO_{2,\ eq}$ is imposed to the supplier if they fail to fulfil the blending ratio requirement during a calendar year or fail to report how the requirements have been met in time [35].

In 1991, Sweden introduced a carbon tax on fossil fuels in proportion to their carbon content. The tax started at a value of 250 SEK/ton-CO_2 emitted and has gradually increased to its current value of 1200 SEK/ton-CO_2, in 2021 [36]. However, the carbon tax does not include aviation fuels used for commercial purposes and only covers fuels used in private flights in Sweden. The Chicago Convention (signed in 1944), together with a resolution adopted by International Civil Aviation Organization (ICAO) in 1993, makes the implementation of a carbon tax on international flights in practice impossible [32,37]. In this study, the carbon tax will be explored for both domestic and international flights to investigate its impact on the use of RJF.

2. Materials and Methods

2.1. Technological Conversion Pathways

Three conversion pathways of drop-in RJF are analyzed in detail in this study, namely: gasification-based Fischer–Tropsch (FT), hydrothermal liquefaction (HTL) and Power-to-Liquid (PTL) with the FT route. In addition to these pathways, Hydrotreated Esters and Fatty Acids (HEFA) and conventional jet fuel (CJF) are also considered in the optimization model, by including their current market prices and import. Thus, without considering the supply chain and technoeconomic performances of HEFA and CJF. A more detailed investigation on HEFA (which is produced from vegetable oils) is not included, since priority is placed on abundant, raw biomass materials in Sweden (mainly forestry residue).

The conversion pathways were selected considering three main reasons. First, the standard ASTM for drop-in fuel specification. An RJF certified under ASTM is suitable for blending with CJF. ASTM has approved a total of seven technology pathways to produce biomass-based RJF (Table 1). Additional technologies are currently under evaluation by ASTM and the latest approvals were made in 2020, however, the time frame of evaluation can vary between different pathways [32,38,39].

Table 1. Approved technology pathways for RJF by ASTM until November 2020.

Technology	Feedstocks	Maximum Blend	Year
Fisher–Tropsch (FT-SPK)	Wastes (MSW, etc.) coal, gas, sawdust	50%	2009
Hydroprocessed Esters and Fatty Acids (HEFA)	Vegetable oils: palm, camelina, jatropha, used cooking oil	50%	2011
Synthesized Isoparaffin (SIP)	Sugarcane and sugar beet	10%	2014
Fisher–Tropsch containing aromatics (FT-SPK/A)	Wastes (MSW, etc.) coal, gas, sawdust	50%	2015
Alcohol-to-Jet (AtJ) (Isobutanol and Ethanol)	Sugar, sugar beet, saw dust, lignocellulosic residues (straw)	50%	2016/2018
Hydroprocessed Hydrocarbons (HH-SPK or HC-HEFA)	Oils produced from algae	10%	2020
Hydrothermal liquefaction (HTL)	Waste oils or energy oils	50%	2020

Source: International Airport Transport Association [38].

Secondly, the maturity level of a technology is based on the Technology Readiness Level (TRL). The TRL ranges from 1–9, in which TRL 1 is defined as the stage where basic principles have been observed and TRL 9 the stage where the technology has been proven in an operational environment [40,41]. An assessment of the TRL for HEFA, FT, Direct Sugars to Hydrocarbons (DSHC), Alcohol-to-Jet (ATJ), Pyrolysis, HTL was provided from [42] and for PTL from [43], which is depicted in Figure 1.

Thirdly, the selection of the conversion pathways considered the abundant and locally sourced feedstocks. In Sweden and the other Nordic countries, the interest of producing RJF have mainly been directed towards using forestry residue as feedstock [32]. The forestry industry is well-established in Sweden and utilizing the by-products for RJF production provides a great potential for conversion pathways such as FT and HTL. This makes it interesting to analyze the HTL pathway, although it has not been ASTM approved using forestry residues yet, the TRL level is promising with growing interest indicated by demonstration-scale activities [44]. Additionally, industries such as paper and pulp, chemical industries, etc., located in Sweden, have the potential to provide CO_2 through carbon capturing, which could promote the production of PTL jet fuels by utilizing the CO_2 released from industries. Since FT jet fuel has been approved by ASTM for a 50% blend, PTL jet fuel through the FT route is a conversion pathway with promising characteristics suitable as a drop-in jet fuel [45].

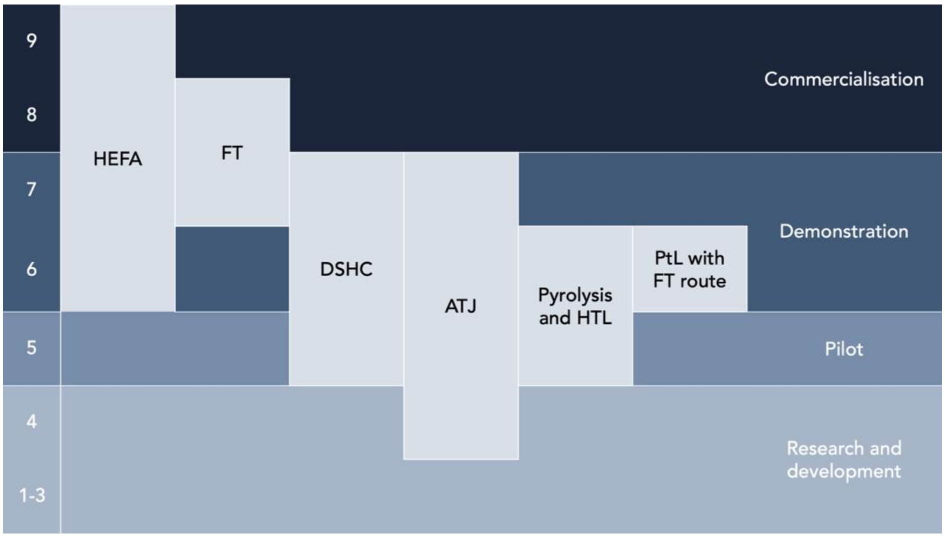


Figure 1. Technological readiness level of different conversion pathways from concept to commercialization. Modified from source: de Jong [42] with Power-to-liquid (PTL) added from O'Connell et al. [43].

There are other potential alternative aviation fuels including hydrogen and hybrid or electric propulsion technologies. These have not been considered in this assessment. The prerequisites for hydrogen for aviation is discussed by for example Dahal et al. (2021) [11], Balli et al. (2018) [46] and Bicer & Dincer (2018) [47] and electric propulsion for example by Brelje and Martins (2019) [48].

This study evaluates the impact of policies including the carbon tax, which is internalized in the model; the blending mandate, which regulates the RJF demand in Sweden; and the penalty fee, which aims to promote the use of RJF by imposing the fee to the jet fuel suppliers that fail to fulfill the requirements of the blending mandate. In this study, the blending mandate is only considered for the RJF conversion pathways FT, HTL and PTL, to prioritize domestic production of RJF from abundant raw materials. Currently, there is no HEFA production in Sweden and the feedstocks used for HEFA are limited in supply, hence HEFA is not considered for the blending ratio in the analysis.

2.1.1. Hydroprocessed Esters and Fatty Acids

Hydroprocessed Esters and Fatty Acids (HEFA) is a biofuel produced from raw materials with the main component being triglycerides, which form the base material for any natural fats and oils. HEFA is also known as HVO (Hydrotreated Vegetable Oils) and HRJ (Hydroprocessed Renewable Jet). Feedstocks that could be used to produce HEFA includes any types of fats and oils. The market of RJF-production is currently dominated by the HEFA pathway, mainly using vegetable oils or waste oils and fats as feedstocks to convert into jet fuel. The process is widely commercialized and provides the lowest cost amongst the certified pathways. In short term, HEFA has the largest potential to grow its production capacity, according to World Economic Forum (WEF) [49]. However, feedstocks used in the HEFA pathway are either first generation biomass considered controversial to use for fuel production or waste oils that face a natural upper limit since there is a finite supply of waste oils and fats. In both cases, there are also competing industries with demand for these feedstocks [49].

The process of producing HEFA mainly involves the following steps: pretreatment, deoxygenation and hydrogenation, cracking and isomerization, and lastly distillation. In the first step, the feedstock is pretreated to remove impurities such as phosphorous compounds, trace metals and soaps, which could result in catalyst poisoning. Following this, deoxygenation and hydrogenation reactions occur in the presence of catalysts and the oil reacts with hydrogen. The reactions take place in a reactor with a temperature range from 250–450 °C and a hydrogen pressure from 10–300 bars. In the process, unsaturated carbon chains and oxygen are removed from the oil molecules, producing long-chain hydrocarbons together with other by-products such as water, propane, CO and CO_2. In the following step, cracking and isomerization reactions occur to yield smaller and more branched hydrocarbon chains. In the final step, the product is separated in two steps; removal of water and gaseous components, and then distillation to yield the final products of kerosene, diesel, and naphtha in different proportions [50–53].

2.1.2. Fischer–Tropsch

Fischer–Tropsch (FT) is a conversion technology used to produce synthetic hydrocarbons (fuels) from any carbon-based material, such as coal, natural gas and biomass. For alternative aviation fuel purposes, feedstocks such as lignocellulosic materials and municipal waste are promising due to their low carbon footprint. The FT-process involves the following steps: feedstock preparation and pretreatment, syngas production, syngas refinement, FT-synthesis, isomerization and branching, and lastly distillation [53–55].

Firstly, the biomass undergoes a size reduction and drying process which is dependent on the type of gasifier used in the subsequent conversion steps. Secondly, the biomass is converted into synthesis gas (syngas) through gasification. The thermochemical process operates in a temperature range of 800–1800 °C with oxygen, steam or both used as gasification agents. Pure syngas is a mixture of CO and H_2, the ratio of which depends on the raw material used. Following this, the syngas is cleaned from contaminants to avoid catalyst poisoning and is conditioned through the water-gas-shift reaction to optimize the ratio of CO and H_2. The clean syngas then undergoes FT-synthesis and is converted into hydrocarbon liquids and waxy solids in the presence of a catalyst. The FT-synthesis is usually carried out in a low temperature range (200–240 °C) using iron or cobalt catalysts or a high temperature range (300–350°C) using iron catalysts. Once the syngas has been converted to hydrocarbons, the crude FT-fuel undergoes a purification and refining process to produce the aviation fuel [53–57].

2.1.3. Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) is a thermochemical process that can convert biomass with high water content into liquid fuel. In the process, a wide variety of biobased and waste feedstocks can be utilized, including woody biomass, wastes from the forestry industry, food wastes, industrial wastes, manure, algae, etc. [58,59]. The main steps involved in the HTL process include pretreatment, the HTL process, hydrotreating, hydrogen production and wastewater treatment [60].

Depending on the type of biomass used as feedstock, the pretreatment step varies. Since biomass slurries are used in the conversion process, it could be necessary to either add or remove water to the feedstock. Following is the HTL process which involves three main steps, in which hydrolysis, dehydration and decarboxylation and condensation, cyclization and polymerization are performed. In the process steps, macromolecules are made into smaller compounds, converted, and then rearranged to yield the desired product. During the process, water acts both as a solvent and reaction medium. A spontaneous phase separation occurs resulting in water remaining in an aqueous phase, a gaseous phase containing rich levels of CO_2, a solid phase, and a bio-crude phase. The different phases from the HTL process are separated, and a hydrotreatment is required to upgrade the bio-crude phase to produce the final fuel product. The upgrading process is primarily performed to remove oxygen and produce a hydrocarbon fuel with characteristics suitable to be used as a drop-in fuel. The liquid water from the HTL-process can also be recycled, which is performed after being separated from the other phases. Before being returned to the environment or reused for the pretreatment step, the water undergoes a treatment since it contains water-soluble organics [59–62].

2.1.4. Power-to-Liquid with Fischer–Tropsch Route

Power-to-X (PTX), also called electrofuels, are carbon-based synthetic fuels which are produced through the PTX processes, which includes power-to-liquids (PTL) and power-to-gas (PTG). In the processes, the main constituents are electricity, water, and CO_2. To achieve climate benefits, conditions such as using renewable energy sources and CO_2 originated from the atmosphere or sustainable point sources, must be fulfilled. In general, the main process steps to produce electrofuels include the following: CO_2 provision, H_2 production, synthesis and fuel conditioning [59,63–65].

Concentrated CO_2 can be provided from three major sources which are of fossil origin, i.e., from fossil industrial flue gases, mineral origin, i.e., from geothermal activities, or renewable origin, i.e., from biofuel production, biomass-based industrial flue gases and extraction from the atmosphere. However, utilizing fossil CO_2 for the production of PTL jet fuel cannot be considered as carbon-free. Different technologies are available for capturing and extracting CO_2 from industrial production processes which in general could be divided into three categories: precombustion, postcombustion or oxyfuel combustion carbon-capturing (CC) technologies. Following the capturing process, the separation of CO_2 can be performed through absorption, adsorption, membranes, and cryogenics. In Direct Air Capture (DAC), CO_2 is removed directly from the air, using absorption or adsorption processes. However, since the concentrations of CO_2 are much lower in the atmosphere than in industrial flue gases, the energy demand and costs are higher for DAC [64–68].

Hydrogen can be produced through different processes utilizing fossil fuels, biomass, or water as a raw material. Approximately 95% of global hydrogen production is currently using natural gas and coal as primary resource [69]. The most common way to produce hydrogen without using fossil fuels is currently through water electrolysis. In the electrolysis process, an electrochemical cell is used with a direct current to split water into H_2 and O_2 gas. Different types of electrolyzers are available, operating in conditions using either liquid water in low-temperature or high-temperature steam [63,65,70].

Following the CO_2 capturing and the H_2 production is a synthesis that can be performed through biological, mechanical, chemical, and thermal processes. To produce jet fuel, processes such as the FT-synthesis and the production of methanol as an intermediate product could be utilized [59,65].

2.2. Supply Chain Model

In this study, a centralized supply chain model was considered for RJF production in Sweden. The supply chain encompasses the raw material production, conversion and upgrading of jet fuel and downstream transportation to the jet fuel demand sites. A co-location strategy was implemented considering the raw material production sites as potential locations for the jet fuel conversion and upgrading facilities to be built. These sites are represented by 121 sawmills [71] and 136 industrial facilities (pulp and paper, combined heat and power, chemical industries, waste treatment and incineration, biofuel and biogas upgrading facilities) [72,73]. From the production sites, the jet fuel will be transported directly to the demand sites, represented by 39 airports in Sweden [74,75]. In Figure 2, a visualization of the supply chain model considered is provided.

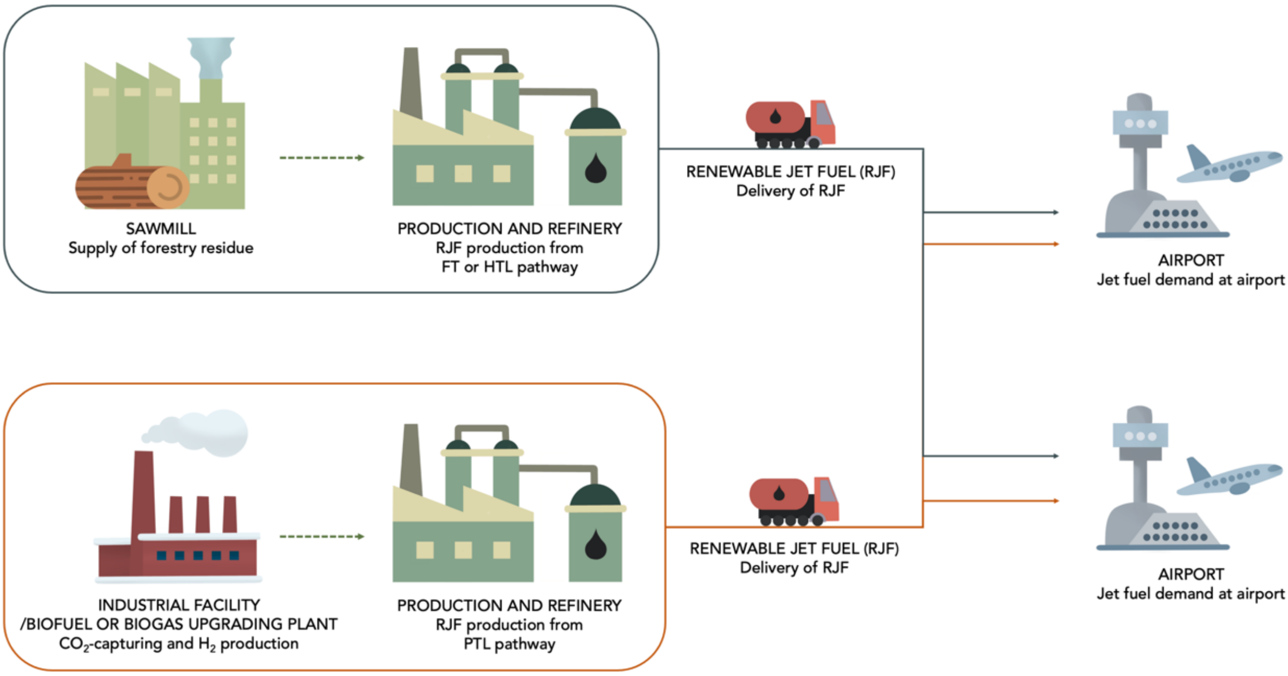


Figure 2. Visualization of developed supply chain model. FT (Fischer–Tropsch); HTL (Hydrothermal liquefaction); PTL (Power to liquid). Graphic content illustrated with inspiration from [76–80].

2.3. Feedstock Supply to Produce RJF

The sawmills were considered as potential locations to produce RJF through biomass gasification-based FT (which will be referred to as FT in text) and HTL due to the access to forestry residue as feedstock. Only sawmills with an output capacity of wood products equal to or greater than 30,000 m^3/year were considered, to ensure that the availability of feedstock is high enough for the site to be considered feasible for RJF production. To account for biomass competition from other sectors, a starting value of 30% availability of forestry residue was set in the base case. The output capacity of wood products from the sawmills, thus the feedstock supply, was assumed to be constant throughout the modeling period.

To produce PTL jet fuel through the FT route (which will be referred to as PTL in text), 136 industrial facilities were considered as potential locations due to the availability of CO_2 as feedstock for PTL. A list of 74 industrial facilities were extracted from the European Pollutant Release and Transfer Register (E-PRTR) [73] which includes industries such as paper and pulp (PP), combined heat and power (CHP), chemical industries (CI) and waste treatment and incineration plants (WT/WI). From these industrial facilities, only the biogenic fraction of their CO_2 release was considered for the production of PTL, with a recoverable share assumed to be 70% [65]. Biogenic carbon emissions are released from biomass sources and are part of the natural carbon cycle [81]. The industrial facilities also include 62 biofuel (BF) and biogas (BG) upgrading plants, with a 100% recoverable share, as these plants can provide relatively pure streams of CO_2 [30]. Data used to estimate the CO_2 release from the biofuel and biogas upgrading are provided in the Supplementary Materials in Table S3 from [30,82–84]. In the model, the electricity generated [85–102] at the CHP plants will be utilized in the production of the PTL jet fuel. The additional electricity demand for PTL will be supplied from the grid. The annual CO_2 release and electricity generation at the CHPs are assumed to be constant throughout the modeling period.

In Figure 3, maps of the sawmills and industrial facilities are presented. In the model, the four electricity pricing areas of Sweden (SE1, SE2, SE3 and SE4) were included to consider the differences in electricity pricing, which could help reflect limitations in transmission capacity between the areas [103]. In Figure 4, a map of the four pricing areas in

Sweden is provided and the electricity prices can be found in the Supplementary Materials in Table S4 from [104,105].

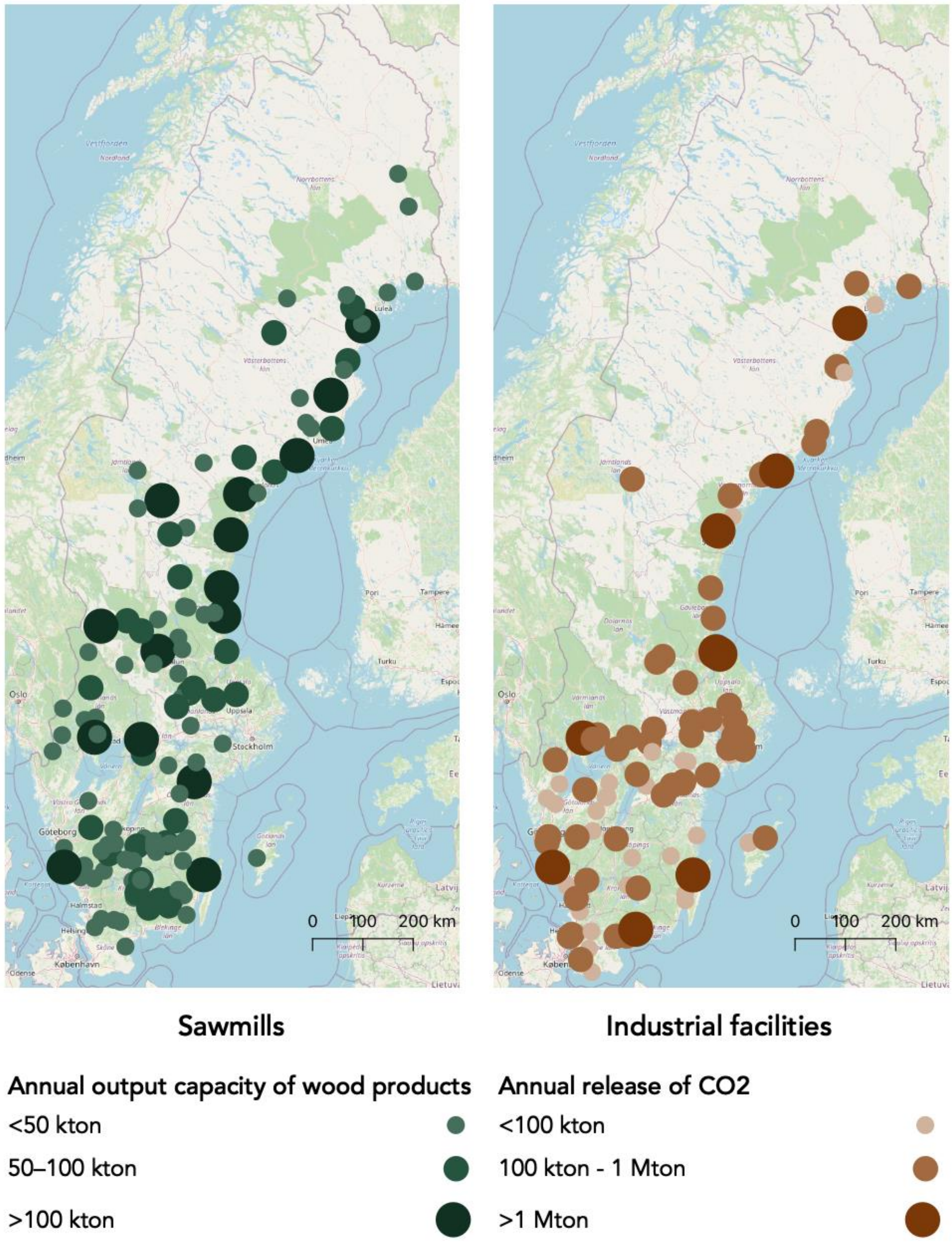


Figure 3. Locations and annual capacity of sawmills (sources of biomass) and industrial facilities (sources of CO_2). Base map data © OpenStreetMap contributors, available under the Open Database License, terms further described in [106].

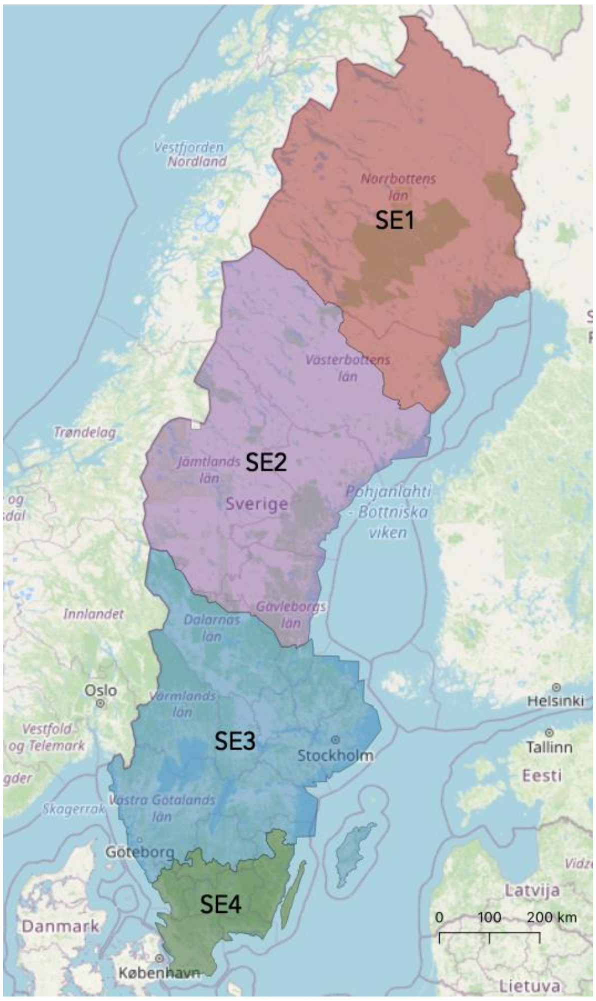


Figure 4. Map of the electricity pricing areas in Sweden. SE1 and SE2 generally have lower electricity prices than SE3 and SE4 [95,96]. Based on the maps of electricity price areas in Vindbrukskollen [107]. Base map data © OpenStreetMap contributors, available under the Open Database License, terms further described in [106].

2.4. Technoeconomic Parameters

In this study, the time frame was set from 2020–2050 with a five-year time step, to consider the long-term GHG emission targets of Sweden. The baseline year was 2020. The lifetime of the jet-fuel plants was therefore set to 30 years and the discount rate at 10% in accordance with [108,109], see Table 2. The technoeconomic data is based on scientific literatures that provide a detailed breakdown of the production processes. In Table 3, an overview of the capacities used, and total capital investment (TCI) is provided and in Table 4 the production yields of each conversion pathway are listed.

Table 2. Economic parameters to estimate annual investment cost.

Parameter	Value	Unit
Plant lifetime	30	Year
Discount rate	10	%
Start of time frame	2020	
End of time frame	2050	

Table 3. Reference studies used to determine total capital investment (TCI) and the capacity for each conversion pathway in this study.

Conversion Pathway	Feedstock	Product Output	Input Capacity of the Ref. Study [t_{in}/Year] [1]	Output Capacity of the Ref. Study [t_{out}/Year]	TCI [MEUR]	TCI [MSEK] [2]	Ref.
Gasification-based Fischer–Tropsch (FT)	Forestry residue	Jet fuel, Diesel, Naphtha	614,010	79,820	482 [3]	4842	[109]
Hydrothermal liquefaction (HTL)	Forestry residue	Jet fuel, Diesel, Gasoline	164,670 [4]	57,320 [5]	132.3 [6]	1240	[26]
Power-to-Liquid (PTL) through the FT route	CO_2 [7]	Jet fuel, Diesel, Gasoline	58,162	14,080	65	682	[65]

[1] The output capacity is based on total product output (jet fuel, diesel, naphtha and gasoline). [2] Total capital investment (TCI) has been adjusted to SEK_{2020} using consumer price index [110]. [3] TCI in EUR_{2016}, currency data presented in Supplementary Materials in Table S2 from [111,112]. [4] Calculated based on a biomass density of 16.7 MJ/kg from [26]. [5] Calculated based on a biofuel density of 40.3 MJ/kg from [26]. [6] TCI in EUR_{2015}, currency data presented in Supplementary Materials in Table S2 from [111,112]. [7] Based on CO_2 input, the H_2 input is considered in the costs related to the PTL production.

Table 4. Assumed production yields for the included production pathways.

Conversion Pathway	Total Product Yield	Jet Fuel	Naphtha	Gasoline	Diesel	Unit	Ref.
Gasification-based Fischer–Tropsch (FT) [1]	0.13	0.10	-	-	0.01	t_{out}/t_{in}	[109]
Hydrothermal liquefaction (HTL)	0.35	0.06	-	0.09	0.25	t_{out}/t_{in}	[26]
Power-to-Liquid (PTL) through the FT route [2]	0.24	0.10	-	0.09	0.03	$t_{out}/tCO_{2,\ in}$	[65]

[1] The yields of jet fuel, naphtha, gasoline and diesel were based of [108]. [2] The yield for PTL has been adjusted to CO_2 as input feedstock.

From the technoeconomic data presented in Tables 3 and 4, the annual capital expenditure (CAPEX), fixed costs and variable costs were determined. The TCI cost was annualized with the capital recovery factor, as shown in Equations (1) and (2). The capacity of the jet-fuel plants is determined by the model. The annualized plant capital cost was divided by the total output capacity of the jet fuel to obtain the CAPEX per ton of jet-fuel output. The fixed costs were set as 4% of CAPEX [113]. The variable costs were determined based on the utilities required, considering the electricity, water, and hydrogen as well as catalysts and chemicals. In the model, economies of scale and labor costs were not taken into consideration. In Table 5, the CAPEX, fixed costs, and parameters required to determine the variable costs are listed. The CAPEX and fixed costs are constant throughout the assessment period (2020–2050), while the variable costs changes based on the values in Table 6.

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

$$\text{Annualised capital cos t} = \text{CRF}\cdot\text{TCI} \quad (2)$$

r Discount rate
N Number or years

The production of RJF through PTL involves a syngas process, in which the input is CO_2 captured from the industrial facilities and hydrogen produced onsite. In this study, only CO_2 is considered as the main raw material input in the PTL process. Therefore, the cost of the onsite hydrogen production and the fixed costs of CO_2 capturing has been internalized in the economic parameters of the PTL plant, while the variable costs (electricity and water demand) in the capturing process of CO_2 represents the cost of raw material.

In Table 6, the utility prices used to determine the variable costs are listed (2020–2050) as well as the market prices of HEFA and CJF. The annual increase in the fossil products was based on the increase of price of fossil diesel as modelled by the Swedish Energy Agency [104]. The values for 2025, 2035, 2045 were interpolated based on the values in Table 6.

Table 5. Economic parameters of the studied RJF conversion pathways.

Parameter	FT [108]	HTL [26]	PTL [65]		Unit
			RJF Production	CO_2 Capture	
Annualized capital cost (CAPEX)	7924	13,420	12,900	-	$SEK/t_{RJF,out}$
Fixed cost	317	537	516	-	$SEK/t_{RJF,out}$
Utilities for variable cost					
Electricity demand	0.06	0.09	10.30	0.54 [2]	MWh/t_{in}
Water demand	-	0.86	14.50	19.70	m^3/t_{in}
Catalysts and chemicals	808.6	71.76	-	-	SEK/t_{in}
Hydrogen	-	411	See footnote. [1]	-	SEK/t_{in}

[1] The cost of hydrogen is internalized in the CAPEX, fixed costs, and operational costs of PTL. [2] The unit is defined as MWh/tCO_2 out from the capturing process and into the PTL production.

Table 6. Annual utility prices and market prices of HEFA and CJF.

Parameter	2020	2030	2040	2050	Unit	Ref.
Water [1]	12.4	18.35	27.17	40.22	SEK/m^3	[114–118]
Forestry residue [2]	952.78	996.4	1 043.74	1093.33	SEK/t	[119]
Naphtha [3]	4239.96	5596.74	6439.89	7554.39	SEK/t	[120]
Gasoline [3]	5595.96	7386.67	8499.47	9970.41	SEK/t	[120]
Diesel	875	1155	1329	1559	SEK/t	[104]
HEFA	13,450.68 (10.81)	13,450.68 (10.81)	13,450.68 (10.81)	13,450.68 (10.81)	SEK/t (SEK/liter)	[121]
CJF [3]	2918 (2.35)	3851 (3.10)	4431.38 (3.56)	5198.28 (4.18)	SEK/t (SEK/liter)	[122]

[1] Average water price for 2020 based on Stockholm, Gothenburg, Malmö, Uppsala and Linköping. The annual increase is assumed to be 4% based on [123]. [2] The annual increase has been calculated based on the increase of biomass prices for 2020–2050 in [124]. [3] The annual increase was calculated based on the annual increase for diesel.

2.5. Jet Fuel Demand

The jet fuel demand for small airports was partly calculated by using the values (for average distance, fuel consumption per passenger and number of passengers travelling in 2019 [74,75]) presented in Table 7 and Equation (3) and partly by contacting the airports [125–131] to retrieve information on annual jet fuel demand. For medium–large scale airports, the fuel consumption was calculated by applying methodology from ICAO [132], considering domestic and international flights. The domestic and international flight frequencies were based on [133], using the annual average between 2015–2019. The airport fuel demand only considers flights departing from the Swedish airports.

$$\text{Fuel demand}_{\text{small airport}} = \tilde{f}_{\text{passenger}} \cdot \left(\tilde{p}_{a,\text{Europe}} \cdot \delta_{\text{Europe}} + \tilde{p}_{a,\text{domestic}} \cdot \delta_{\text{domestic}} \right) \quad (3)$$

Table 7. Parameters used to calculate fuel demand for small Swedish airports.

Parameter	Variable	Value	Unit	Ref.
Average domestic trip length	$\delta_{domestic}$	486.9	km	[134]
Average European trip length	δ_{Europe}	3000	km	See footnote. [1]
Average fuel burn/passenger	$\tilde{f}_{passenger}$	0.03	liter/km	[32]
Departing passengers domestic	$\tilde{p}_{a,domestic}$	-	-	[74,75]
Departing passengers to Europe	$\tilde{p}_{a,Europe}$	-	-	[74,75]

[1] The average trip length to a destination in Europe was determined with a straight-line approximation to the most common destinations from the airports and by taking the average of that.

In Figure 5, a map of the location of the airports with their estimated annual jet fuel demand in 2020, is provided. In 2020, the Swedish Transport Administration investigated the future trends in commercial aviation in Sweden [134] and forecasted an average growth of 2.3% in passenger frequency for both domestic and international flights until 2040 [134], which was used in this study for the estimation of future jet fuel demand. In Figure 6, the projection of jet fuel demand per year is presented.

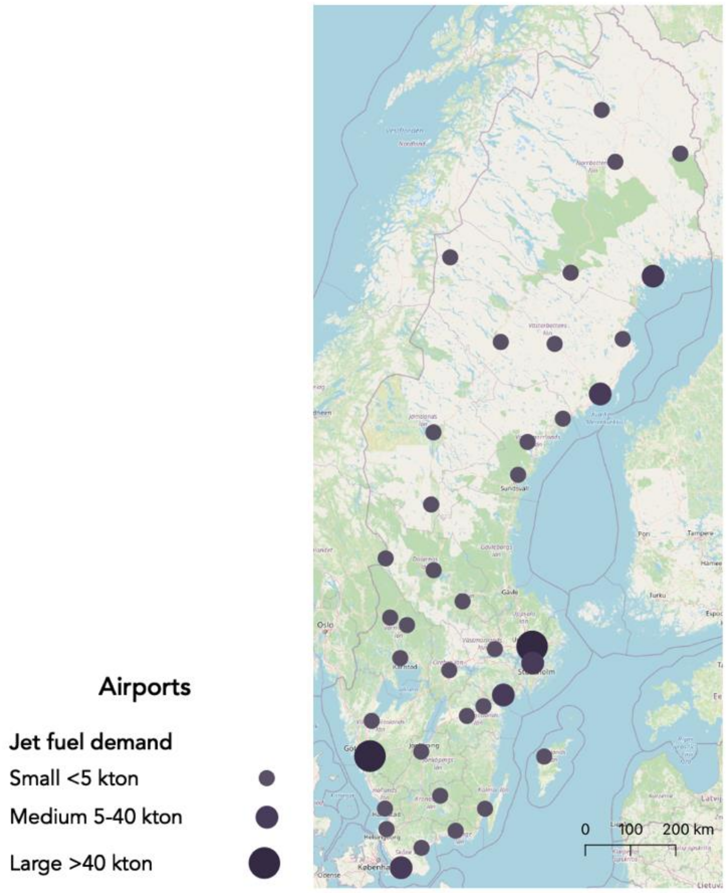


Figure 5. Airport locations in Sweden and annual jet fuel demand. Base map data © OpenStreetMap contributors, available under the Open Database License, terms further described in [106].

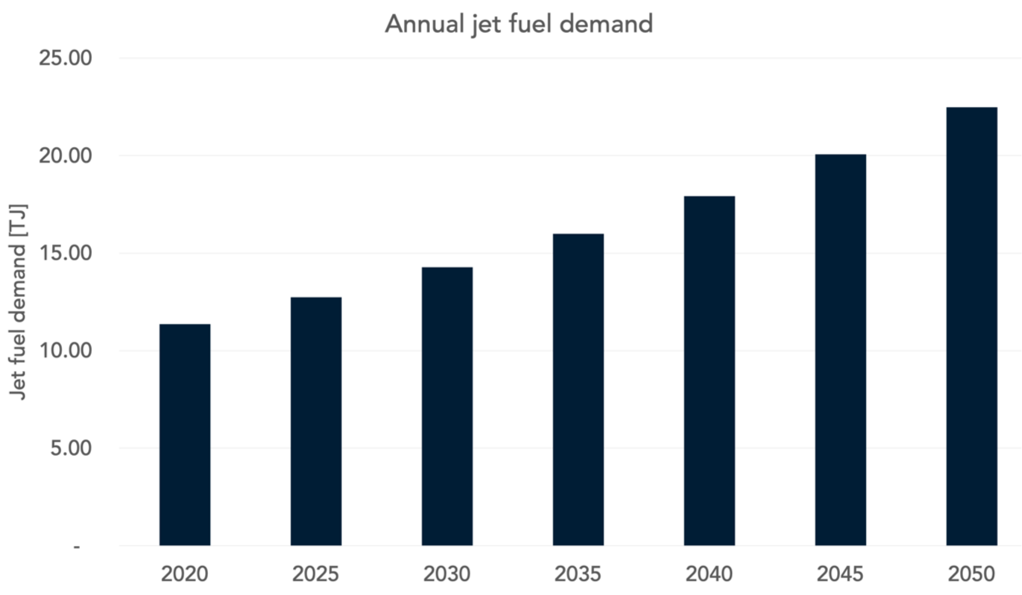


Figure 6. Estimation of annual jet fuel demand in Sweden (2020–2050).

For the transportation of RJF, only transport by trucks from the production sites to the airport demand sites were considered. The distance from the sites were modeled in QGIS 3.16 [135] using a straight-line approximation. Further details on the truck transportation and the technoeconomic data used is provided in the Supplementary Materials in Table S5, based on data from [136–138].

2.6. Life Cycle Emissions

In this study, the life cycle GHG emissions during the production of jet fuel were considered for the feedstock cultivation and processing for FT and HTL, for the feedstock to fuel conversion for FT, and for the chemicals and catalysts used during the PTL production. For HTL, the GHG emissions during feedstock to fuel conversion is assumed to be zero [139]. The emissions from the electricity consumption during production and the transport from production to demand site were considered for all three pathways. For PTL, the biogenic CO_2 captured was assumed to have zero emissions and therefore assumed to be accounted for by the industrial facilities instead, as applied by [140]. The grid emission factor is assumed to decrease as more renewable energy is introduced to the electricity grid system of Sweden. As mentioned in Section 2.3, the electricity generated from the CHP plants is utilized in the process for the PTL jet fuel production. The electricity from the CHP plants is assumed to have zero emissions and have the same electricity prices as presented in the Supplementary Materials in Table S4. However, if additional electricity from the grid is required during the production of PTL jet fuel at the CHP plants, the grid emission factor will be considered. The emission factors used in the modeling are presented in Table 8.

Table 8. Emission factors used in the modeling.

Emission Factor	Value	Unit	Ref.
Forestry residue feedstock cultivation and collection	2.4	$gCO_{2,\,eq}$/MJ jet fuel	[141]
Feedstock to fuel conversion for FT production	0.03	$gCO_{2,\,eq}$/MJ jet fuel	[141]
Chemicals and catalysts used in PTL production	0.1	$gCO_{2,\,eq}$/MJ jet fuel	[140]
HEFA	16	$gCO_{2,\,eq}$/MJ jet fuel	[32]
CJF	94	$gCO_{2,\,eq}$/MJ jet fuel	[32]

2.7. Optimization Model

A Mixed Integer Linear Programming (MILP) optimization model was developed using Python 3.9 and the PuLP 2.4 library to solve the Facility Location Problem [142–144]. The spatial (supply chain components as presented in Figure 2) and temporal (multi-years assessment from 2020 to 2050) aspects are incorporated in the model. The objective of the MILP optimization model was to minimize the system cost of the supply chain, while determining an optimal location and production capacity of the jet-fuel plants. The model only considers the aviation sector in Sweden, considering the production of RJF from FT, HTL and PTL conversion pathways at the sawmills and industrial facilities, and the demand of jet fuel from and transportation of RJF to airports.

In the model, the production of FT, HTL and PTL are required to meet the jet fuel demand set by the blending mandate, while HEFA has been excluded since the feedstocks used for HEFA are either 1st generation feedstocks or are limited in supply. However, in the model, HEFA and CJF can be used to meet the remaining jet fuel demand that is not covered by the blending ratio, in which the choice is optimized based on their market prices and the internalized cost of emissions. For the RJF production, the GHG emissions during production and transport is included, which are based on the emission factors in Table 8.

As Equation (4) shows, the objective function comprises the cost of production, transport, raw materials, emissions, revenues from by-products and the cost of purchasing

HEFA and CJF. A detailed mathematical formulation is provided in the supplementary materials in Section S3.

$$\text{Minimise } C_S = C_P - C_N + C_T + C_R + C_E + C_{HEFA,CJF} \quad (4)$$

C_S Total system cost of supply chain
C_P Total cost of production
C_N Total revenues from by-products
C_T Total cost of transport
C_R Total cost of raw materials
C_E Total cost of emissions
$C_{HEFA,\ CJF}$ Total cost of HEFA and/or CJF

2.8. Scenario Description

To investigate the potential of producing RJF in Sweden, six scenarios were developed:

- Reference scenario (REF)
- Scenario 1–Higher carbon tax (SC1-HCT)
- Scenario 2–Higher blending mandate (SC2-HBM)
- Scenario 3–Higher carbon tax without blending mandate (SC3-HCT-B)
- Scenario 4–Higher or lower raw material availability (SC4-RMA)
- Scenario 5–Inclusion of penalty fee (SC5-PF)

The scenarios are presented in Table 9. As the scenario names indicate, the parameters considered for the scenarios were the carbon tax for emissions, the blending ratio of the blending mandate policy, the availability of raw materials used in the processes of the conversion pathways and the penalty fee from the blending mandate policy.

A base case was modeled in REF to be compared with the other scenarios. In REF the variables have been set partly based on information found in the literature review and partly from other references that reflect the current situation in Sweden. The carbon tax was set to a constant 1.2 SEK/kgCO_2 [36] throughout the years. As mentioned in Section 1.2, a blending mandate for RJF in Sweden is effective from 2021, starting with a blending ratio of 0.8%, rising to 27% in 2030. In REF, the blending mandate was included without considering a penalty fee, starting with a blending ratio of 0% in 2020 and was gradually increased to 4.5%, 27%, 39%, 51%, 63% and 75% in 2025–2050, respectively. As mentioned in Section 2.1, in the modeling, HEFA was not included in the blending mandate since the feedstocks used for HEFA are either 1st generation feedstocks or are limited in supply. Therefore, priority was instead set on domestic production of RJF from forestry residues and captured biogenic CO_2 for the blending mandate. As mentioned in Section 2.3, the availability of forestry residue was set at 30% of the output capacity from the sawmills and for the CO_2 the recoverable share from the capturing process was set to 70% and 100% for the E-PRTR industries and biofuels and biogas plants, respectively.

In SC1-HCT, the carbon tax was increased to investigate how the life cycle emissions could affect the results of the optimization model. From the base value of 1.2 SEK/kgCO_2 in 2020, the carbon tax was increased based on the annual percentage increase on the price of EU ETS emission allowances as modelled by [104] from 2018–2050. The carbon tax was set to 1.44, 2.54 and 4.4 SEK/kgCO_2 in 2030, 2040 and 2050, respectively. For 2025, 2035 and 2045 the carbon tax was interpolated from the values of the year before and after.

In SC2-HBM, the impact of implementing a higher blend ratio for the blending mandate was investigated, aiming to reach 100% in 2050. The blending ratio for 2025–2050 was set to 6.7%, 40%, 55%, 70%, 85% and 100%, respectively.

Table 9. Summary of scenarios development and key parameters altered in each scenario.

Scenario	Blending Ratio	Carbon Tax	Raw Material Availability			Penalty Fee	Description
		SEK/kg CO_2	Forestry Residue	CO_2 from PP, CHP, CI and WT/WI Plants [1]	CO_2 from BG and BF Plants [1]	SEK/kgCO_2	
Reference (REF)	0–75%	1.2	30%	70%	100%	0	The REF scenario is a base case to which the other scenarios are compared. The variables have been set to reflect the current situation in Sweden.
Scenario 1–Higher carbon tax (SC1-HCT)	0–75%	1.2–4.4	30%	70%	100%	0	In SC1-HCT, the carbon tax is increased to investigate how the life cycle GHG emissions affect the outcome of the model.
Scenario 2–Higher blending mandate (SC2-HBM)	0–100%	1.2	30%	70%	100%	0	In SC2-HBM, the blending mandate is increased to investigate how the policy will affect the outcome of the model.
Scenario 3–Higher carbon tax without a blending mandate (SC3-HCT-B)	0%	1.2–8.7	30%	70%	100%	0	In SC3-HCT-B, the carbon tax is further increased while the blending mandate has been removed.
Scenario 4–Raw material availability (SC4-RMA)	0–75%	1.2	10–30%	70–100%	100%	0	In SC4-RMA, the raw material availability is changed. Due to rising demand in other sectors the availability of forestry residue is reduced, and the availability of CO_2 is increased due to technological improvements.
Scenario 5–Penalty fee (SC5-PF)	0–75%	1.2	30%	70	100%	6	In SC5-PF, the penalty fee from the blending mandate has been added. In the optimization model, a constraint has also been changed which is described in the Supplementary Materials in Section S3, Equations (S23)–(S27).

[1] PP (pulp and paper industries); CHP (combined heat and power plants); CI (chemical industries); WT/WI (waste treatment and incineration plants); BF (biofuel plants); BG (biogas upgrading plants).

In SC3-HCT-B, the blending mandate has been removed while the carbon tax is further increased and builds upon the SC1-HCT scenario. From the base value of 1.2 SEK/kgCO_2 in 2020, the carbon tax was set to 2.4, 2.9, 4.0, 5.1, 6.9 and 8.7 SEK/kgCO_2 in 2025–2050.

In SC4-RMA, the availability of forestry residue was gradually reduced from 30% in 2020 to 10% in 2050 as the demand from other sectors would increase. For the recoverable share of CO_2 from the industries, the share was assumed to increase due to technological improvements. The starting value of the carbon capturing efficiency was set to 70% in 2020 [65], and gradually increased to 100% for the E-PRTR facilities. The sources of CO_2 derived from the biogas and biofuel plants were set at a constant 100% throughout the time frame as they emit relatively pure streams of CO_2.

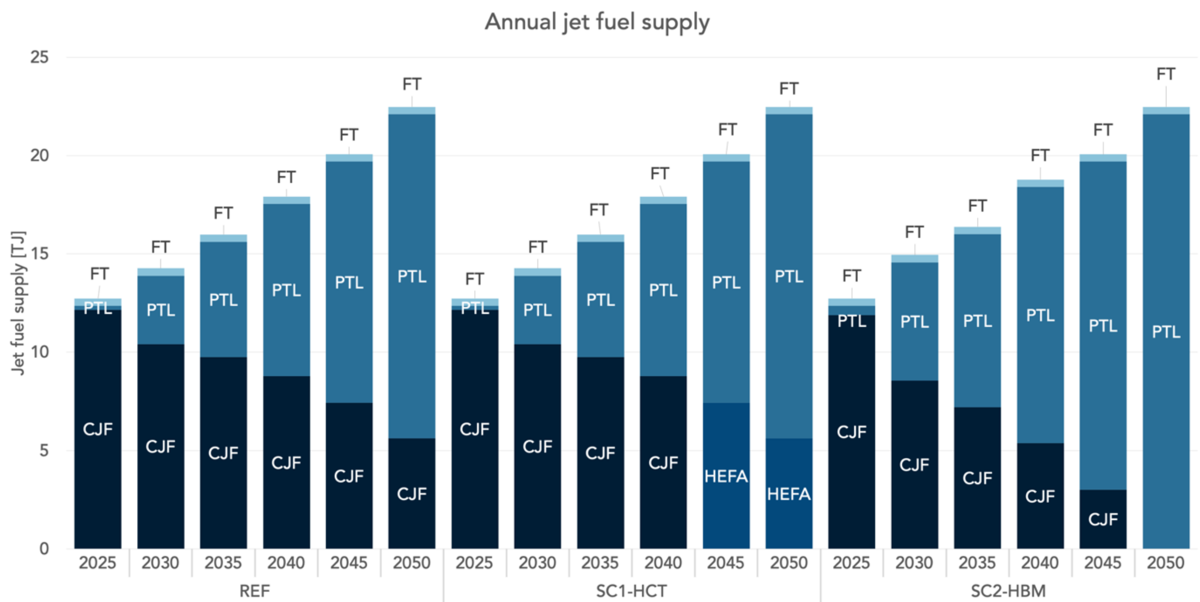
In SC5-PF, the penalty fee of 6 SEK/kg$CO_{2,\ eq}$ from the blending mandate is implemented and imposed on jet fuel suppliers that fail to fulfill the requirements of the blending ratio. While HEFA is not included in the blending ratio, the penalty fee is only imposed on CJF when the blending mandate is not fulfilled. When the penalty fee was not taken into account (in REF, SC1-HCT, SC2-HBM, SC3-HCT-B, SC4-RMA), a constraint was set in the optimization model in which the blending mandate had to be met by an RJF production, setting the RJF production strictly equal to the blending ratio requirement. In SC5-PF, the constraint was changed to count for the penalty fee, in which the RJF production could be less than or equal to the blending ratio requirement. As for the entire jet fuel demand, any type of jet fuel (FT, HTL, PTL, HEFA or CJF) can be used. Further details of the modeling are described in the Supplementary Materials in Section S3, Equations (S23)–(S27).

3. Results and Discussion

3.1. Optimal Conversion Pathway and Production Site

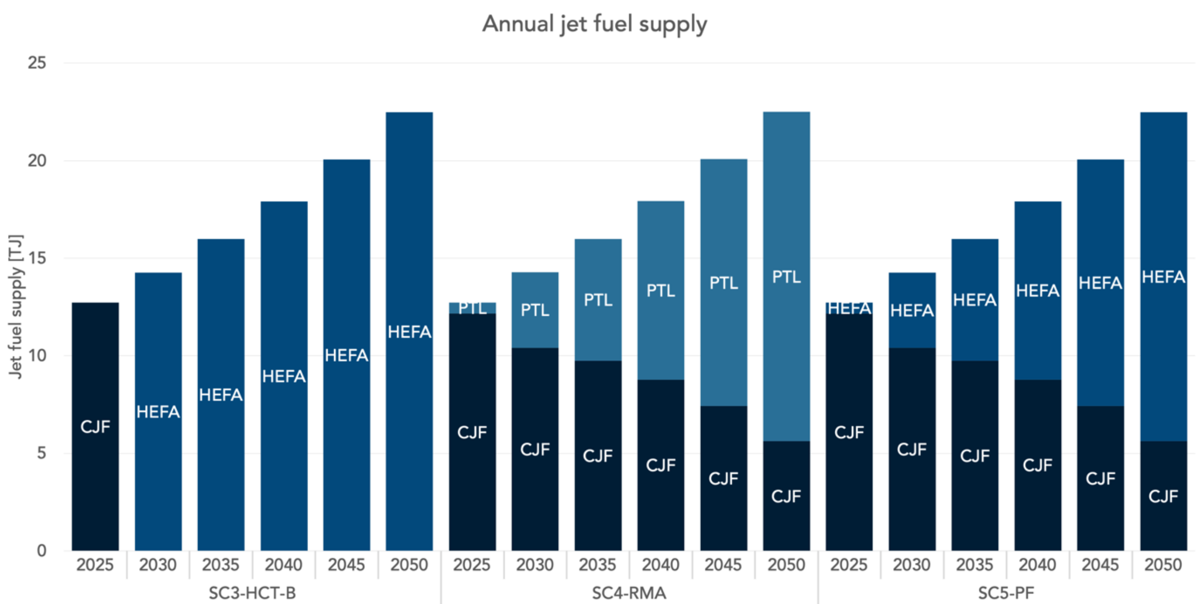
The objective of this study is to evaluate the impacts of aviation policies in Sweden on RJF production in 2020–2050. Several RJF technological conversion pathways were investigated to identify the optimal solutions for minimizing the total system cost considering feedstock supply and demand constraints. The results show different pathways chosen to supply the jet fuel demand during 2025–2050 in all six scenarios (Figures 7 and 8). In the REF, the increased demand of aviation fuels is met by CJF and RJF (through the FT and PTL production pathways). At the beginning of the studied time period, CJF represents most of the supply but is gradually replaced by RJF mainly from the PTL pathway as the blending ratio increases throughout the years, but to a minor extent also from the FT pathway. The small amount of FT is likely due to the constraints set on forestry availability. As mentioned in Section 2.1, in this study, HEFA was not included in the blending mandate because the priority was given to domestic RJF production from forestry residues and biogenic CO_2. This explains why HEFA is not selected to meet the blending mandate of the jet fuel demand in the REF. Furthermore, HEFA has a higher market price (10.81 SEK/liter) compared to CJF (2.31–4.18 SEK/liter) in 2020–2050 (Table 6).

In SC1-HCT, with an increased carbon tax (Figure 7), the results are similar to REF at the beginning of the studied time period. In SC1-HCT the jet fuel demand was met by CJF, PTL and FT pathways. However, from 2045, the demand previously met by CJF was entirely replaced by HEFA, indicating that the carbon tax at 3.5 SEK/kgCO2 is effective to substitute the entire supply of CJF. The amount of PTL and FT jet fuel produced is sufficient to meet the blending ratio demand, while the rest of the jet fuel demand is met by HEFA from year 2045. The reason for the latter is that since the market price of HEFA is lower than the production cost of PTL and FT jet fuel (as later presented in Section 3.2), HEFA will substitute the supply of CJF. In this study no upper constraint was set for the availability of HEFA, however, for HEFA to entirely replace CJF and meet a demand of 7.43 TJ in 2045 in Sweden, the current production of HEFA jet fuels would have to increase to also meet the jet fuel demand from markets outside of Sweden. In the EU28, HVO/HEFA had an estimated installed capacity 56.82 TJ in 2019, out of which 8.07 TJ were expected for aviation biofuels [145].



	REF 2025	REF 2030	REF 2035	REF 2040	REF 2045	REF 2050	SC1-HCT 2025	SC1-HCT 2030	SC1-HCT 2035	SC1-HCT 2040	SC1-HCT 2045	SC1-HCT 2050	SC2-HBM 2025	SC2-HBM 2030	SC2-HBM 2035	SC2-HBM 2040	SC2-HBM 2045	SC2-HBM 2050
FT	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
HTL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PTL	0.20	3.47	5.86	8.76	12.27	16.49	0.20	3.47	5.86	8.76	12.27	16.49	0.47	6.01	8.80	13.03	16.68	22.11
HEFA	-	-	-	-	-	-	-	-	-	-	7.43	5.62	-	-	-	-	-	-
CJF	12.16	10.42	9.75	8.78	7.43	5.62	12.16	10.42	9.75	8.78	-	-	11.88	8.56	7.19	5.37	3.01	-

Figure 7. Annual jet fuel supply in scenarios REF, SC1-HCT and SC2-HBM with different policy configurations for 2025–2050. REF (Reference scenario); SC1-HCT (Higher carbon tax); SC2-HBM (Higher blending mandate. FT (Fischer–Tropsch); HTL (Hydrothermal liquefaction); PTL (Power-to-liquid); CJF (Conventional jet fuel); HEFA (Hydroprocessed esters and fatty acids).



	SC3-HCT-B 2025	SC3-HCT-B 2030	SC3-HCT-B 2035	SC3-HCT-B 2040	SC3-HCT-B 2045	SC3-HCT-B 2050	SC4-RMA 2025	SC4-RMA 2030	SC4-RMA 2035	SC4-RMA 2040	SC4-RMA 2045	SC4-RMA 2050	SC5-PF 2025	SC5-PF 2030	SC5-PF 2035	SC5-PF 2040	SC5-PF 2045	SC5-PF 2050
FT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HTL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PTL	-	-	-	-	-	-	0.57	3.86	6.24	9.15	12.66	16.88	-	-	-	-	-	-
HEFA	-	14.27	15.99	17.91	20.07	22.49	-	-	-	-	-	-	0.57	3.85	6.24	9.14	12.64	16.86
CJF	12.74	-	-	-	-	-	12.16	10.42	9.75	8.78	7.43	5.62	12.16	10.42	9.75	8.78	7.43	5.62

Figure 8. Annual jet fuel supply in scenarios SC3-HCT-B, SC4-RMA and SC5-PF with different policy configurations for 2025–2050. SC3-HCT-B (Higher carbon tax without blending mandate); SC4-RMA (High/Low raw material availability); SC5-PF (With penalty fee); CJF (Conventional jet fuel). FT (Fischer–Tropsch); HTL (Hydrothermal liquefaction); PTL (Power-to-liquid); CJF (Conventional jet fuel); HEFA (Hydroprocessed esters and fatty acids).

In SC2-HBM, with the increased blending mandate, the production of PTL increased while the amount of FT remains the same, compared to REF (Figure 7). The blending mandate demonstrates an effective policy to promote RJF production. An 85% blending mandate in 2045 allows a reduction of 75% of CJF supply compared to 2025. Increasing the blending ratio does not have an impact on the production of FT, likely due to the constraints set on the availability of forestry residue. This implies that, given the limited supply potential of forestry residue, locating PTL plants at the industrial sites is more feasible than locating FT or HTL plants at the sawmills since the supply of forestry residues would not be sufficient to produce RJF to meet the blending ratio demand throughout the years.

In SC3-HCT-B, the blending mandate was eliminated, and the carbon tax further increased compared to SC1-HCT. As a result, the entire jet fuel demand is met by CJF in 2020–2025 with a carbon tax of 1.2–2.4 SEK/kg$CO_{2.}$ From 2030, with a carbon tax of 2.9 SEK/kgCO_2, the entire demand is met by HEFA when it becomes cost competitive compared to CJF (Figure 8). The results indicate that without the blending mandate, none of the RJF pathways are cost-effective in comparison to CJF or HEFA.

In SC4-RMA, where the lignocellulosic biomass availability is reduced and the CO_2 availability increased, PTL is the only cost-effective alternative fuel option (Figure 8). This means that the demand previously met by the small share of FT has been entirely replaced by PTL, thus resulting in no FT-plants opening during the entire time frame. In SC4-RMA, PTL jet fuel meets the entire blending ratio demand while CJF meets the remaining jet fuel demand. Since the availability of forestry residues have been significantly decreased, producing jet fuel through the FT pathway is not considered economically feasible compared to producing jet fuel through the PTL pathway.

In SC5-PF, where a penalty fee is imposed when the blending mandate is not fulfilled, the jet fuel demand is mostly met by CJF coupled with an increasing amount of HEFA between 2025–2045 (Figure 8). The penalty fee was not included in the other five scenarios (i.e., REF, SC1-HCT, SC2-HBM, SC3-HCT-B, SC4-RMA). The results show that the additional cost imposed by the penalty fee is not set high enough to have an impact on the blending mandate, if it has to be met with forestry residue or CO_2 and electricity-based jet fuels, since there is no production of PTL, FT or HTL jet fuel. In this case, HEFA becomes more cost competitive than CJF with the additional cost of 6 SEK/$CO_{2,\ eq}$ and as the price of CJF increases. Ultimately, the jet fuel volume to meet the blending mandate would be fulfilled by HEFA in 2030.

In all scenarios except scenarios SC3-HCT-B and SC5-PF, the amount of RJF corresponding to the blending mandate needs to be fulfilled (see Section 2.8). The type of fuel to meet the demand for jet fuel considers the economic parameters through comparison of RJF production cost (FT, HTL, PTL) or market prices (HEFA, CJF) as well as the internalized cost of emissions by the carbon tax. As a result of this modeling, the amount of RJF produced was sufficient to meet the demand of the blending mandate, while the rest of the jet fuel demand was met by CJF or HEFA. Since the objective of the optimization model was to minimize the total system cost, none of the RJF pathways were considered economically feasible compared to CJF without policies supporting its introduction.

The technology selections in all scenarios through the application of the optimization model are highly dependent on the technological efficiency (yield), availability of resources, the economic parameters, and the spatial location of the plants. Considering the economic parameters for RJF production, FT has the lowest CAPEX and fixed costs compared to HTL and PTL. However, since the availability of forestry residues is limited, the production of RJF from PTL is more favorable than FT and HTL. Additionally, HTL and FT are competing for the same raw material (forestry residues) from the sawmills, but the higher yield of FT makes it a more favorable technology than HTL.

In Figure 9, a map of the optimal production and demand sites in all scenarios, is provided. In REF, a total of 41 plants were optimal to supply RJF, consisting of 3 FT plants and 38 PTL plants in 2050, while no RJF plants appeared in SC3-HCT-B and SC5-PF. In

REF, at the beginning of the modeling period, smaller plants were preferred mostly in the southern regions, and as the demand for RJF increases with the blending mandate, larger plants were preferred mostly along the coast in northeast Sweden. Most of the smaller PTL plants are located at CHP plants with proximity to most airports and which also provides electricity without a grid emission factor, while the larger plants are concentrated in areas with lower electricity prices (see Figure 4 for price areas). As presented in Table 5, the production of PTL jet fuel has an electricity demand of 10.84 MWh/t_{in}, which includes the electricity demand for hydrogen production, CO_2 capturing and production of jet fuel. In REF, the total electricity consumption for all PTL plants in 2025–2050 was 0.98, 17.19, 28.98, 43.34, 60.7 and 81.58 TWh, respectively. In 2020, the total electricity generation in Sweden amounted to a total of 158.8 TWh, out of which 62% came from hydropower and wind power, 30% from nuclear power and 8% from conventional thermal power [146]. The electricity consumption of the PTL plants corresponds to 0.6%, 10.8%, 18.3%, 27.3%, 38.2% and 51.4% of the total 158.8 TWh. Based on the high electricity consumption of the RJF production from PTL, the results indicate that the location of the plants are more dependent on the availability of resources along with the internalized cost of emission at the beginning of the modeling period, while towards the end, it is more dependent on the electricity pricing as the RJF output capacity increases.

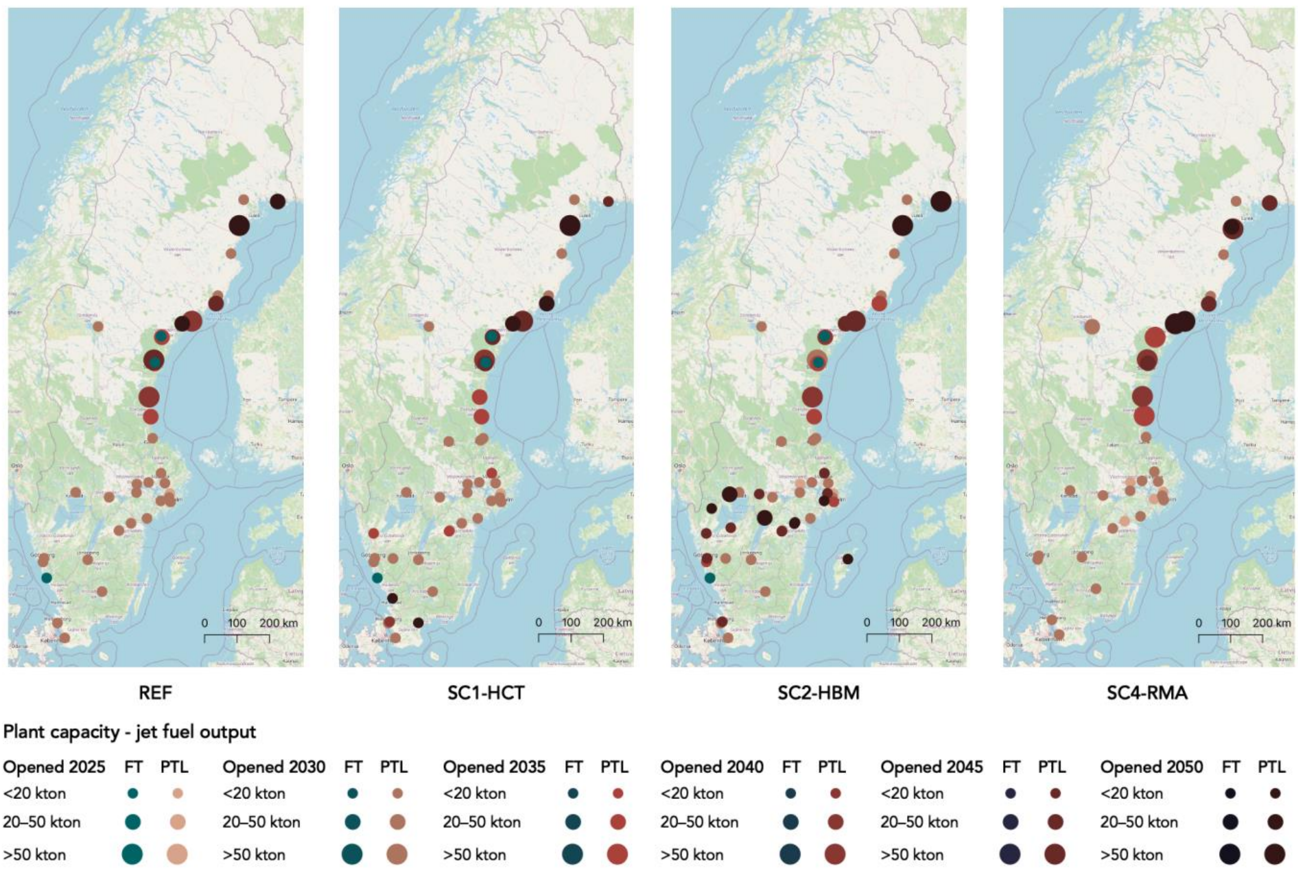


Figure 9. Optimal RJF production sites from all scenarios. REF (Reference scenario); SC1-HCT (Higher carbon tax); SC2-HBM (Higher blending mandate); SC4-RMA (High/Low raw material availability). FT (Fischer–Tropsch); HTL (Hydrothermal liquefaction); PTL (Power-to-liquid); CJF (Conventional jet fuel); HEFA (Hydroprocessed esters and fatty acids). Base map data © OpenStreetMap contributors, available under the Open Database License, terms further described in [106].

Furthermore, the renewable electricity generation in Sweden would need to increase throughout the time frame to meet the demand for renewable electricity for the PTL pathway and from other sectors as well. Thus, the electricity supply has not been limited in the model.

3.2. Production Cost of Renewable Jet Fuel

In this study, the total system cost encompasses the RJF production cost, the price of CJF and HEFA, the external cost (cost of emissions) from transport, production of RJF, CJF and HEFA as well as the revenues from the by-products diesel, gasoline, and naphtha. The cost parameters included in the total production cost of the RJF pathways were the annualized capital costs (CAPEX), fixed costs, variable costs, raw material (forestry residue and CO_2) costs and transport costs.

In Table 10, the production cost per unit of fuel produced for each conversion pathway is presented for 2025–2050. When excluding the revenues from by-products, PTL has the highest unit production cost. By including all cost components while also considering the revenues from by-products, FT provides the lowest production cost at 21.5–22.4 SEK/liter, followed by PTL at 22.9–29.2 SEK/liter. In the model, the price of utilities and by-products were gradually increased and thereby reached the highest cost level towards the end of the time frame. The FT and PTL pathways have quite similar unit production costs and including the revenues from the by-products is an important factor for reducing the production costs of PTL. The results also indicate that the amount of FT jet fuel produced is likely to have been limited by the availability of forestry residue in all scenarios.

Table 10. Production costs per unit jet fuel output in 2025–2050.

	FT		PTL	
	SEK/liter	**SEK/GJ**	**SEK/liter**	**SEK/GJ**
Total production cost excl. transport costs	15.3–16.3	432.9–460.3	16.8–23.1	474.9–652.8
Total production cost incl. transport costs	21.5–22.4	606.9–634.0	22.9–29.2	646.6–826.1
Revenues from by-products	0.1–0.2	3.0–4.6	5.0–7.7	142.1–218.3
Total production cost excl. transport costs minus revenues of by-products	15.2–16.1	429.9–455.7	11.8–15.4	332.8–434.6

The production cost, excluding transport cost, from this analysis is compared with other studies [26,65,108,147] which explore different RJF conversion technologies as a decarbonization pathway through technoeconomic analysis, and in some cases, through a spatial analysis as well. The RJF production cost through the PTL process [65,147] was between 16.8–21.1 SEK/liter and through the FT process [108] between 12.4–18.0 SEK/liter. Another study yielded production costs for PTL at 24.0–69.2 SEK/liter and for FT at 10.2–24.6 SEK/liter [11] (using an exchange rate for USD_{2021} provided from [111]). This indicates that the results for FT and PTL pathways in this study are within the range of other existing research. The RJF unit production cost is highly dependent on the assumptions made for the economic parameters and the boundaries that were set for the supply chain. In this study, the feedstock cost for FT was likely the major influencing cost component for the higher unit production cost compared to the existing literature. For PTL, the CAPEX and the electricity pricing were likely the main influencing parameters.

Based on the results of this study, the RJF production through FT and PTL pathways are not economically feasible in comparison to CJF or HEFA, which in this study have been modeled with the current market prices of 2.35 and 10.81 SEK/liter in 2020, respectively. Based on these market prices, the resulting unit production cost (without transport costs or revenues) of FT is 693% and 151% higher than the market price of CJF and HEFA, while for PTL it is 1195% and 203%. Since the blending mandate only incorporated FT, HTL and PTL, and the modeling required the blending mandate to be met in all scenarios except SC3-HCT-B and SC5-PF, HEFA was not chosen to meet the jet fuel demand in REF, SC2-HBM and SC4-RMA. However, restricting the HEFA supply could provide incentives for RJF production based on biomass residues and at the same time move towards a more sustainable production pathway as it would avoid potential feedstock competition with food.

3.3. Environmental Performance

The total annual $CO_{2,\ eq}$ emissions from the supply chain for all scenarios are presented in Figure 10. The figure shows that for REF and SC4-RMA, the emissions increase throughout the years and both scenarios provide a similar outcome for the emissions of $CO_{2,\ eq}$. In the other scenarios the emissions decrease in various amounts. The main difference between REF and SC4-RMA is the replacement of RJF from FT with RJF from PTL, however since only a small amount of FT is produced in REF, there is only a small difference in emissions between the two scenarios. As shown in Figure 10, increasing the carbon tax in SC1-HCT does not affect the amount of emissions during 2025–2040, resulting in the same amount of emissions as REF. Not until 2045, when the carbon tax has been increased to 3.5 SEK/kg $CO_{2,\ eq}$ does the carbon tax take effect, resulting in the emissions plummeting as the CJF is entirely replaced by HEFA. However, as the blending mandate is increased in 2050, a higher PTL amount is introduced, resulting in higher emissions. The results indicate that PTL has a higher overall emission factor than HEFA, which is likely due to the choice of grid emission factor.

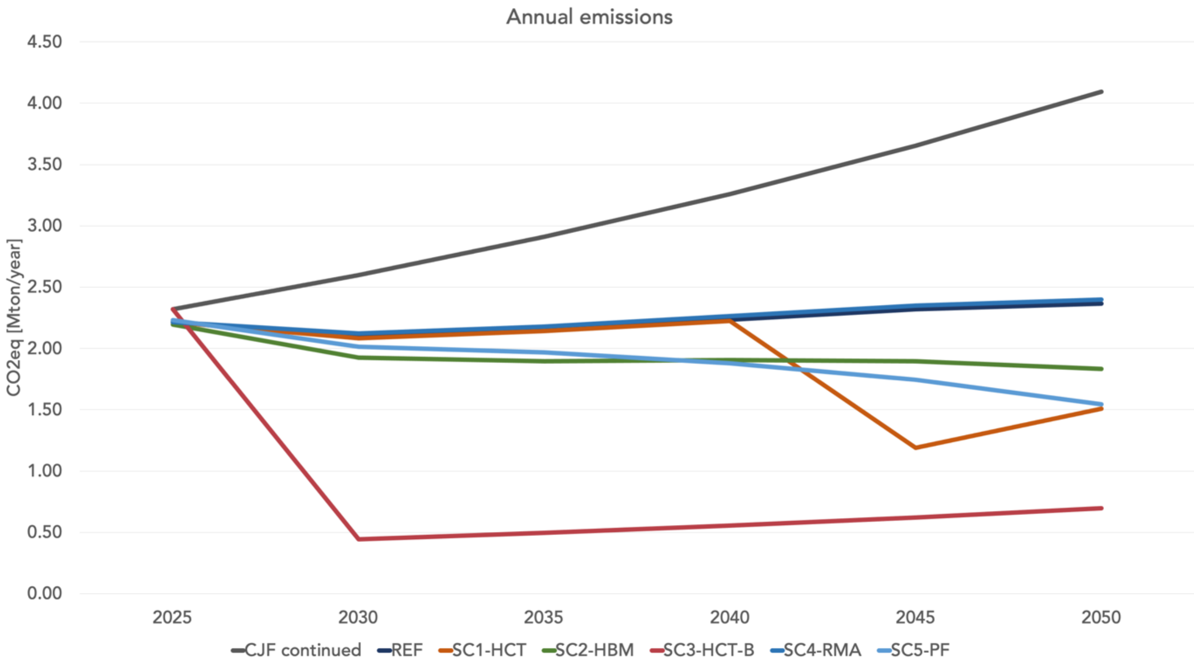


Figure 10. Annual emissions from the total system. REF (Reference scenario); SC1-HCT (Higher carbon tax); SC2-HBM (Higher blending mandate); SC4-RMA (High/Low raw material availability); SC5-PF (with penalty fee); CJF (Conventional jet fuel).

Implementing a higher blending mandate in SC2-HBM has also shown to be effective to reduce the emissions, as CJF is gradually replaced by RJF. In SC3-HCT-B, a significant reduction in emissions is achieved as the blending mandate is removed and the carbon tax set to a level in which CJF is completely replaced by HEFA to meet the jet fuel demand. In SC5-PF, the emissions are gradually decreased compared to REF and follows a similar trend as in SC2-HBM until HEFA is gradually increased from 2030.

In Table 11, the potential emissions reductions relative to REF and from continuing to only use CJF, is presented. SC3-HCT-B provides the highest reduction potential of the assessed scenarios.

Table 11. Annual emissions reduction potential from all scenarios relative REF.

Scenario	Emissions Reduction Relative REF						Emissions Reduction Relative CJF					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
REF	-	-	-	-	-	-	4.43%	19.60%	26.18%	31.51%	36.54%	42.17%
SC1-HCT	0.00%	0.22%	0.35%	0.40%	95.19%	57.08%	4.43%	19.78%	26.43%	31.78%	67.49%	63.18%
SC2-HBM	0.99%	8.56%	13.24%	17.09%	22.24%	29.11%	5.34%	25.94%	34.81%	44.22%	48.08%	55.21%
SC3-HCT-B	−4.41%	372.35%	333.71%	302.37%	272.85%	239.75%	0.00%	82.98%	82.98%	82.98%	82.98%	82.98%
SC4-RMA	0.00%	−1.59%	−1.38%	−1.36%	−1.35%	−1.33%	4.41%	18.37%	25.15%	30.62%	35.71%	41.43%
SC5-PF	2025	2030	2035	2040	2045	2050	3.73%	22.40%	32.36%	42.32%	52.28%	62.23%

Notes: REF (Reference scenario); SC1-HCT (Higher carbon tax); SC2-HBM (Higher blending mandate); SC3-HCT-B (Higher carbon tax without blending mandate); SC4-RMA (High/Low raw material availability); SC5-PF (With penalty fee); CJF (Conventional jet fuel).

The CO_2 emissions per unit fuel produced were 2.68 $gCO_{2,\,eq}$/MJ jet fuel for FT, and 46.11 $gCO_{2,\,eq}$/MJ jet fuel for PTL. Including the transport emissions only yields an insignificant difference. As presented in Table 8, the emission factor of HEFA was set to 16 $gCO_{2,\,eq}$/MJ, which confirms that the higher emissions in 2050 relative to 2045 for SC1-HCT is due to the higher emission factor of PTL. The emissions from the grid are also included in the emission factors of FT and PTL, based on the electricity consumption during production of these fuels. The grid emission factor considers an electricity mix including all electricity generation in Sweden. Therefore, the choice of grid emission factor has an important impact on the emissions related to the electricity consumption, especially during the PTL production process. By only considering renewable energy for the PTL production, the resulting emission factor would be significantly reduced.

Previous studies [65,139] have yielded an emission factor of 6 $gCO_{2,\,eq}$/MJ jet fuel for FT from forestry residue and 19 $gCO_{2,\,eq}$/MJ jet fuel for PTL. Based on this, the resulting emission factors from this study are rather different, with a significantly lower emission factor for FT and higher for PTL, which are most likely due to the low level of detail for the life-cycle emissions and somewhat different assumptions. Since a detailed life-cycle assessment was not within the scope of this paper, the emissions from the RJF production were considered by using emission factors for the forestry residue cultivation and collection, feedstock to fuel conversion for FT, chemicals and catalysts used during PTL jet fuel production, electricity consumption from the grid and the transport of jet fuel to airports. The choice of only including these emission factors was mainly due to limited data availability.

4. Conclusions and Policy Implications

This study sheds lights on the impact on aviation fuel production of aviation policies in Sweden, namely carbon price, blending mandates and penalty fee. An optimization model incorporating spatial, temporal, environmental and technoeconomic aspects was developed which is valuable as a decision-making tool for planning and designing supply chains for RJF fuel provision. The results demonstrate the importance of implementing policy instruments to promote the production of RJF in Sweden. Furthermore, the model and the results from the model can also be used to plan, design, and optimize the relative influence of different policy instruments.

Sweden has abundant domestic resources (forestry residues, biogenic CO_2 and renewable energy) to produce sustainable RJF, provided the provision of effective policy supports are in place. The blending mandate is indicated to be an effective policy to both promote the RJF production while reducing emissions, given that possible associated penalty fees are high enough to stimulate the use of RJF. The inclusion of a penalty fee at the present level (6 SEK/$kgCO_{2,\,eq}$), which is imposed to the supplier if they fail to meet the blending mandate, is not significant to justify the production of RJF from FT, HTL or PTL. It does however justify the utilization of HEFA with a market price of 10.81 SEK/liter. The PTL process can generate additional revenues from selling the by-products of diesel and gasoline, making it economically feasible to meet the jet fuel demand set by the blending mandate when a strict requirement is set without the penalty fee. In the PTL process, revenues could also be generated from additional by-products such as heat and oxygen, however this was not included in this study.

The optimal location of the RJF production plants for PTL were found to be at CHP plant sites with electricity generation and proximity to most airports or in the northern part of Sweden providing the lowest electricity prices (pricing areas SE1 and SE2). The RJF through PTL demands high electricity consumption. Areas with higher electricity prices indicates a limited capacity of the transmission grid, which could affect the production cost and output capacity of RJF from PTL. In terms of RJF from the FT process, the most cost-effective production facilities are found in the southern part of Sweden, indicating that this type of RJF production is not as dependent on electricity prices.

The analysis also reveals that increasing the carbon tax, without implementing a blending mandate, from today's level of 1.2 SEK/kgCO_2 to 2.9 SEK/kgCO_2 could be effective in replacing CJF with an alternative fuel that has a lower emission factor, i.e., HEFA. However, implementing a higher blending mandate while the carbon tax remains at the current level, will only result in a gradual phasing out of CJF. A higher blending mandate and carbon price will accelerate the transition towards renewable and sustainable fuels for the aviation industry in Sweden.

For future research, the analysis performed within this study could be expanded by incorporating more details to the technoeconomic, environmental and spatial parameters. To further investigate the potential of producing RJF in Sweden, other conversion pathways (i.e., ATJ, pyrolysis, etc.) could also be included in the analysis. By including other or more pathways, other feedstocks could also be considered and allow for a broader spatial range for the production sites. Further investigation could also include assessing the potential effect on modal shift (i.e., shift from air transport to other transport modes) and other emissions as well as evaluating and monitoring potential social effects from different policy measures such as taxes and fees. In general, detailed impact assessments before implementation and control stations where the impacts of the implemented policies are assessed by the national authorities from a broader perspective, i.e., considering several environmental and social targets, represent one way of initiating this.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14217194/s1, Table S1: Properties of biomass and fuel products., Table S2: Currency data and index values., Table S3: Properties used to calculate CO2 release from biofuel and biogas upgrading plants., Table S4: Annual electricity prices per pricing area., Table S5: Transport parameters and costs., Table S6: Sets and decision variables used in the proposed optimization model.

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