Report on the case study of Swedish Biofuels

Retrofitting of an existing bioethanol plant for the production of sustainable aviation fuel (SAF)

Nature, dissemination level	**Report, public**
Dedicated to	**Swedish Biofuels (Sweden)**
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1 Introduction to the case study

BIOFIT Case Study: Benefits, challenges and opportunities of integrating Alcohol to Jet technology on to an existing 1G bioethanol plant

Addressing the increasing demand on sustainable fuels for aviation, this project has investigated a scenario in which an existing maize-based bioethanol plant of Biocarburantes de Castilla y León (BCyL) is retrofitted using Swedish Biofuels alcohol to jet (SB ATJ) technology to produce sustainable aviation fuels (SAF). Currently the bioethanol of BCyL is sold for a gasoline-ethanol fuel blend for road transport. Using the SB ATJ process, the ethanol can be converted into a product for the aviation sector. Swedish Biofuels technology converts alcohols into either synthetic paraffinic kerosene (SPK) or synthetic paraffinic kerosene with aromatics (SKA). ATJ-SPK can be blended up to 50 % with conventional kerosene following the requirements of ASTM D7566. The certification of ATJ-SKA is ongoing. Additional by-products of Swedish Biofuels ATJ process are diesel, meeting diesel standards EN 590 and MK1 (for Sweden), and high-octane gasoline, meeting gasoline standard EN 228.

This case study has identified the benefits of the integration of an alcohol to jet (ATJ) process into an existing 1G ethanol plant from a technical, economic, and environmental perspective. It has targeted the reduction of CO2 emissions, production of new products and of new markets for the existing ethanol plant. This case study has been made with a focus on the aviation sector, where there is a need especially for sustainable liquid fuels.

The following questions have been addressed in the case study:

- Which process streams of ethanol production can be used for the ATJ process?
- Is it possible to use residual products from the fermentation stage (fusel oils?)
- Would the retrofit improve the efficiency of the overall ATJ production process?
- What is the economic and ecological performance of the retrofit?
- Which aspects of the supply chain have to be considered both up and downstream of the conversion plant?

2 Case study team

The case study has been conducted by the following partners:

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3 Confidentiality

The report has been prepared for sharing among the partners of the case study team only. However, during the course of the project, this report has been used as the basis for deliverable D3.3, which, although confidential, has been shared with all the BIOFIT project partners.

Therefore, parts of the chapters 7 (Techno-economic assessment) and 8 (Sustainability), within this report, which are not be distributed to a larger group than the case study team, were removed before creating the deliverable.

4 Case study description

4.1 Current situation

Currently, the aviation sector is entirely supplied with fossil jet fuel, provided to the airport by the refining of fossil crude oil. However, with new ASTM certified technologies, sustainable jet fuels (SAF) can be produced for commercial application. One of these technologies is the alcohol to jet (ATJ) process, which enables the production of a green jet fuel if bio-based alcohol is used as a feedstock (SPK Figure 1). However, with the exception of Swedish Biofuels small scale production delivering SAF for certification programs, there is still no commercial production of ATJ fuel in Europe.

This case study identifies the benefits of the integration of an alcohol to jet (ATJ) process into an existing 1G ethanol plant from a technical, economic, and environmental perspective. The retrofit of a current maize-based bioethanol plant was studied using Swedish Biofuels ATJ (SB ATJ) technology to produce SAF, namely synthetic paraffinic kerosene with aromatics (ATJ-SKA). The suggested retrofit proposes the integration of the SB ATJ process into an existing bioethanol plant in Spain. The alternative scenario to the retrofit would be the operation of two separate plants: an ethanol plant and a standalone ATJ facility close to the airport.

Swedish Biofuels ATJ process

The Swedish Biofuels advanced ATJ process extends the use of alcohols as a raw material by using an individual or a mixture of alcohols with two to five carbon atoms as the starting point for SAF production. The process includes the synthesis of aromatics as well, resulting in advanced SAF called synthetic kerosene with aromatics (SKA) (SKA, Figure 2). The advanced SAF, produced by Swedish Biofuels process, contains the same groups of hydrocarbons as those found in petroleum derived aviation turbine fuels namely, normal paraffins, isoparaffins, monocyclic paraffins, dicyclic paraffins, alkylbenzenes and cycloaromatics. The resulting SAF is identical to jet fuel derived from petroleum with the same or better physical-chemical properties.

In the first step of Swedish Biofuels ATJ process the individual alcohols, namely, ethanol, propanol, butanol, pentanol, or their mixtures are dehydrated to a mixture of the corresponding olefins, which are, in subsequent stages, oligomerised to higher olefins. The higher olefins are then condensed into higher unsaturated compounds, including aromatics. At the final stage, the higher unsaturated compounds are hydrogenated to yield the corresponding paraffins. In the final step, the mixed hydrocarbon product stream is separated into gasoline, kerosene and diesel by rectification.

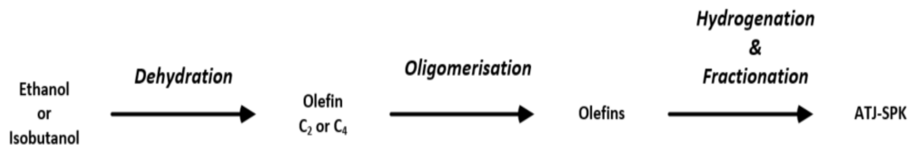

Figure 1: Overall ATJ-SPK process

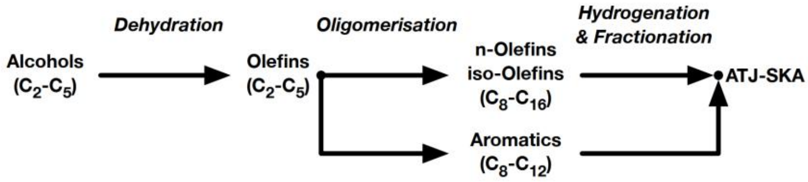

Figure 2: Overall ATJ-SKA process

The Swedish Biofuels ATJ technology is innovative in its utilization of well-known process steps, which are combined to a new production process for SAF. Another innovative aspect of the Swedish Biofuels concept is the selection of reaction steps which makes it possible to utilize intermediate process streams of carbon dioxide (CO_2) and hydrogen (H2), to produce syngas and its further use for production of SAF, diesel and gasoline.

The production of ethanol, propanol, butanol and pentanol can be made using various pathways from renewable and fossil sources. The alcohols used by Swedish Biofuels for SAF production are obtained by: 1) sugar fermentation, 2) oxosynthesis aka. hydroformylation, and 3) as the fusel oil by-product of ethanol production from energy crops and lignocellulosic raw material such as forest residues. The feedstock flexibility of Swedish Biofuels ATJ process, allowing the use of any combination of C2-C5 alcohols or a single alcohol in this range, gives a commercial advantage to reduce the production costs.

To demonstrate that the process is independent of the precise nature of the feedstock, the SAF has been produced by SB ATJ process both from ethanol, currently the most widely available alcohol, and from mixed C2-C5 alcohols. As a result of Swedish Biofuels ten year's experiences of SAF production and the large market availability of bioethanol, this case study is made for the combination of the production processes.

Vertex ethanol process

Bioethanol is a liquid and clean biofuel that can replace gasoline directly for use in modified spark ignition engines or can be used in the form of different gasoline-ethanol blends (E5, E10, E20 etc.). Currently, bioethanol is mainly produced from crops containing sugar and starch, such as sugar beet, grain and wheat (the so-called first-generation ethanol or 1G ethanol), but it can also be produced from agricultural residues (straw, non-food lignocellulosic materials) and wastes. In the latter case bioethanol is considered as advanced ethanol.

Project partner Vertex Bioenergy owns all of the three bioethanol production facilities in Spain, located in Galicia (Bioetanol Galicia S.A), Cartagena (Ecocarburantes Españoles) and Salamanca (Biocarburantes de Castilla y Leon S.A.). Together with another facility in France, Vertex Bioenergy has a total annual production capacity of 780 million litres of ethanol (391.2 ktoe/y or 615.5 kt/y). For classification, the European production of bioethanol as fuel has been almost stable since 2014, and was at a level of approximately 5.4 million tonnes in 2018 (Naumann, et al., 2019). In addition to bioethanol, other valuable products such as animal feed (DDGS), electricity, captured CO_2 and corn oil are produced in some of those plants.

For the case study, bioethanol plant of Biocarburantes de Castilla y León (BCyL) has been studied. The plant uses corn grain as raw material. In the first step, the raw material is cleaned and milled. Then, it is mixed with water and heated with steam prior to enzyme addition. This process allows the conversion of starch polymers into free sugars. Subsequently, the sugars produced are fermented to obtain an ethanol-rich stream. The CO_2 produced in this process leaves the fermenter and 30% of it is being captured for other uses, reducing the overall process emissions. After fermentation, the bioethanol-rich stream is subjected to distillation for obtaining high-purity bioethanol. The remaining stillage is treated and dried to obtain a protein-rich animal feed (DDGS, distillers dried grains with solubles). In order to fulfil the thermal energy demand of the process, this facility has three natural gas boilers producing the steam required for the plant, and a gas turbine, where electricity is generated. The hot gases from the gas turbine are used to dry the DDGS, while the electricity produced is sold to the grid.

Figure 3 illustrates the current situation for the BCyL bioethanol plant and the current fossil jet fuel provision at the airports.

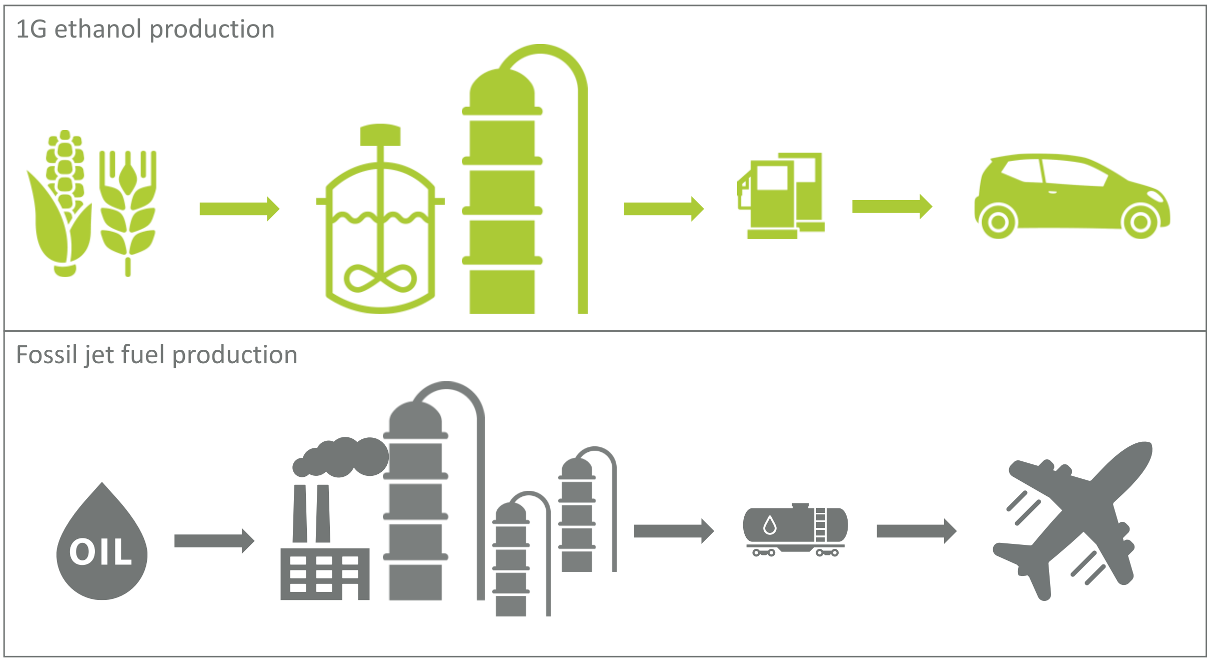

Figure 3: Current situation with 1G bioethanol production for road transport fuels and jet fuel production from fossil resources.

4.2 Suggested retrofit

The suggested retrofit proposes the integration of an ATJ-SKA process into the existing bioethanol plant from Biocarburantes de Castilla y León in Babilafuente, Salamanca. Provided that the reduction of CO2 emissions is greater than 60 %, this retrofit opens up the possible creation of new sales markets for the plant concerned so as to overcome possible periods of low ethanol demand. Furthermore, the current production and utilisation of synthetic jet fuel in Europe is practically zero, even though the interest of airlines and logistic companies is high. This issue might be addressed by a combined facility for the production of ethanol and ATJ. The aim of the case study is to address the following questions:

- Which process streams of ethanol production can be used for the ATJ process?
- Is it possible to use residual products from the fermentation stage (fusel oils?)
- Would the retrofit improve the efficiency of the overall ATJ production process?
- What is the economic and ecological performance of the retrofit?
- Which aspects of the supply chain have to be considered both upstream and downstream of the conversion plant?

The suggested retrofit concept is illustrated in Figure 4. For the retrofit scenario the ATJ process uses alcohols as feedstock, and energy, both provided by the Biocarburantes de Castilla y León facility. In this case study, part of the product stream (ethanol) is used as the alcohol source for the ATJ plant and the utilities supply the energy demand. The alcohol to be used in the ATJ process is drawn from the ethanol plant prior to purification, since any parts of water remaining do not adversely affect the dehydration step of the ATJ process. Without the need to purify the alcohol, energy can be saved in the ethanol plant. Furthermore, the flexibility of the Swedish Biofuels catalyst makes it possible to convert the fusel oils, a waste stream from the production of ethanol, that are higher chain alcohols. The water from the dehydration step can be recycled to the utilities of the ethanol plant.

The analysis of the existing steam boilers at the ethanol plant showed that the boilers do not have spare capacity to provide steam to the ATJ process. Therefore, the steam needed for ATJ process was assumed to be provided by a waste wood boiler for the retrofit scenario. It should be noted, that the main objective of the ethanol plant retrofit is to produce sustainable synthetic jet fuel contributing to a minimum 60% CO2 reduction, as required by airlines, by integrating the ATJ process into the production of ethanol. Therefore, also the achievable GHG-emission reductions when changing both the electricity and the entire process energy demand of the process to renewable energy were calculated in a sensitivity analysis.

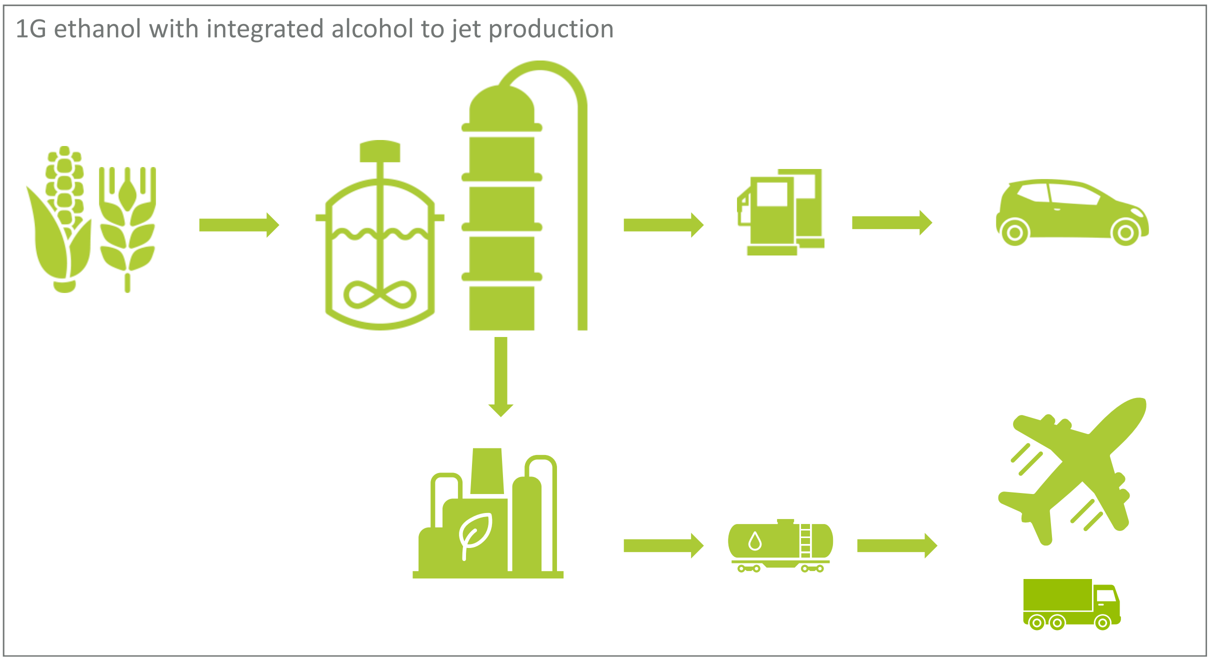

Figure 4: Suggested retrofit with the integration of an alcohol to jet process into the existing 1G ethanol plant.

4.3 Alternative to retrofit

The alternative scenario to the retrofit would be the operation of two separate plants: an ethanol plant and a standalone ATJ facility close to the airport. For this case study, the airport of Madrid is considered as the hypothetical location for a standalone ATJ plant. A similar concept is currently being planned by Swedish Biofuels for the airport in Arlanda, Sweden, using green electricity from the national grid. For the case study, the concept is transferred, making reasonable modifications to fit the Spanish framework. The ethanol production remains unchanged, as currently produced by BCyL.

For the ATJ plant, the general process flow is run as described for the retrofit case. A major difference can be seen in the logistics for the supply of feedstock, as a mixture of C2 – C5 alcohols could be used for the alternative process. For example, the process could use alcohols partially from bioethanol and from butanol producers, if available. Similarly, Vertex could supply fusel oil from different ethanol plants to the ATJ production. The feedstock would be transported to the ATJ plant and all of the necessary infrastructure and utilities for the ATJ process would be built for the ATJ plant only. Figure 5 exemplifies the alternative scenario of transporting the ethanol feedstock from the 1G production plant to a stand-alone ATJ refinery near the airport.

Figure 5: Alternative scenario to produce sustainable aviation fuel in a standalone ATJ plant, not integrated with the production of ethanol.

5 Supply Chain

The supply chain assessment of the case study was conducted for a retrofit in Sweden, which was initially the foreseen location. Subsequently, the case study location was changed to Spain.

The supply chain assessment includes potential feedstocks for advanced bioethanol production and corresponding costs and availability. Logistics and by-products are not part of this case study. Figure 6 shows first-generation ethanol production, illustrated in blue, and two possible retrofit options. Aviation fuel production is illustrated in orange.

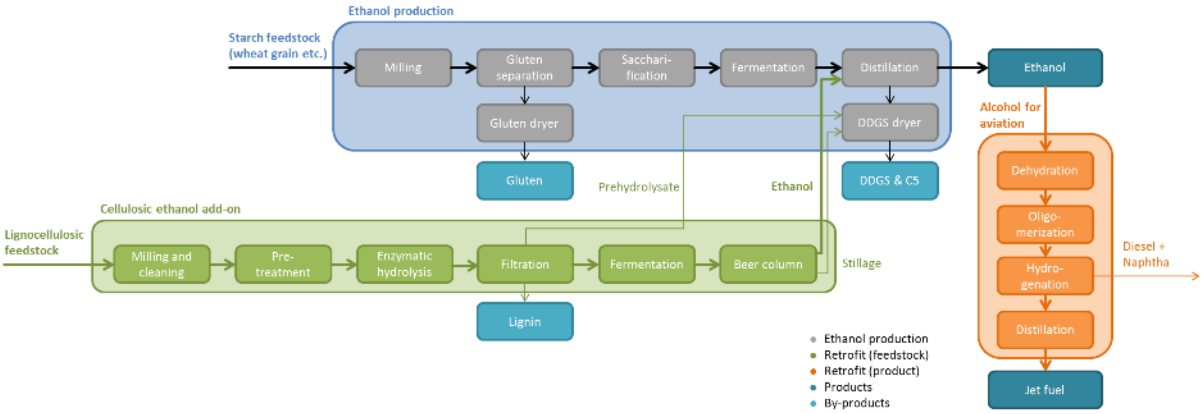

Figure 6: Ethanol and aviation fuel production scheme

5.1 Feedstock type and costs

Feedstocks for production of SAF are regulated by Annex IX Part A of the RED II. Suitable feedstocks for ethanol production according to the RED II, are the following: biomass fraction of mixed municipal or industrial waste, straw, wine lees, corn cobs, forestry and agricultural residues and other non-food lignocellulosic materials.

Important and available feedstocks for the production of advanced biofuels in Sweden are: agricultural and forestry residues, lignocellulosic by-products from industry and biodegradable fractions of municipal solid waste (MSW). Feedstocks for SAF production should have large yields and a wide distribution area. Further they should not compete with food production or cause deforestation. (Wei, et al., 2019)

<u>Agricultural residues and SRC</u>: Residues from agriculture, include straw from various crops (wheat straw, rice husks, etc), corn stover and black/brown liquor. These residues often remain on the fields, are used as feed, or used for energy production. Energy crops, such as miscanthus or short rotation coppice (SRC) are grown specifically for energy production and

therefore are not residues. However, short rotation coppice is considered as advanced according to RED II.

Forestry residues: Forest or logging residues include tree sections above ground, such as branches, needles, tree top pieces, trunk sections etc., mainly from harvest operations. Since these residues are not suitable for material use, they are chipped and used energetically.

Lignocellulosic by-products: Lignocellulosic by-products from wood processing industries, such as saw mills or pulp and paper plants, include sawdust, bark, fibres.

Biogenic fractions of MSW: Municipal solid waste consists of fossil organic (plastics) and biogenic fractions, such as food, paper and wood.

Figure 7 shows the development of different feedstock prices on the Swedish market since 1993. Prices are valid for district heating providers, but they are expected to be similar for other industries. The prices are shown in SEK/MWh, without taxes (2020 exchange rate: 1 SEK = 0.095 €). The prices of all fuels have increased over the last years. Refined fuels (pre-treated fuels, such as pellets or briquettes) were, and still are, more expensive compared to wood chips, by-products and recycled fuels. Wood chips and other woody by-products are similar in price, between 160 and 200 SEK/MWh (15-19 €/MWh). The cheapest fuel for about 100 SEK/MWh (9.5€/MWh) is recycled fuel, which can be fossil, renewable or a blend of both.

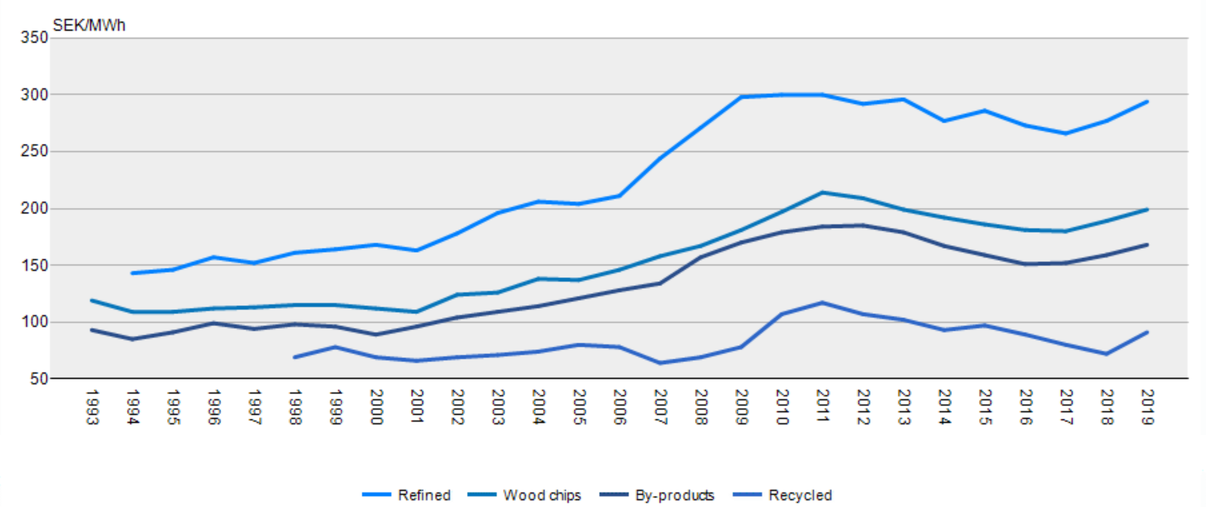

Figure 7: Fuel prices excl. taxes in SEK/MWh[1]

The price of straw is estimated at between 5-6 €/GJ (18.0-21.6 €/MWh). Prices of logging residues or by-products from industries in Sweden, range from 5.1-5.8 €/GJ (18.4-

[1] http://pxexternal.energimyndigheten.se/pxweb/en/?rxid=ee03e1ee-e561-4ef6-8f06-aae44b13c8b3

20.9 €/MWh). (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) Harvesting and extraction operation of forestry residues cost between 23-25 €/m³. (Lundmark, Athanassiadis, & Wetterlund, Supply assessment of forest biomass - A bottom-up approach for Sweden, 2015) From an economic point of view, the most interesting residual feedstocks for biofuels production are forest residues, bark and sawdust. (Lundmark, et al., 2017)

For the production of 241,670m³/y first-generation bioethanol, 562,800 t/y of corn (with a water content of 14 wt.%) would be needed. Estimating a price of 200 €/t corn, feedstock costs per year amount to 112,560,000 €/y. Assuming a calorific value of corn of 18.6 MJ/kg dm, the energy input of the feedstock amounts to 2,556,000 MWh. This indicates the following annual feedstock costs:

- Straw (18.0-21.6 €/MWh): 46,000,000 € - 55,200,000 €
- Wood chips (19 €/MWh): 48,560,000 €
- Logging residues and by-products (15 – 20.9 €/MWh): 38,340,000 € - 53,420,000 €

These costs are just a first estimate. Real feedstock costs rely on contracts with suppliers. Using residues reduces feedstocks costs by more than the half. However, pre-treatment, such as drying, increases feedstock costs again. Additionally, prices are highly dependent on area, transport distance and competing utilization.

Feedstock costs are a main part of ethanol production and represent on average 33-39% of total production costs. (Witcover & B. Williams, 2020) Increasing biofuel production, generally results in increasing feedstock prices. However, according to the integrated modelling approach of (Ouraich, Wetterlund, Forsell, & Lundmark, 2018), price increases of forestry residues will not exceed 3%, with a biofuels production target of 30 TWh by 2030. This indicates that production of large amounts of biofuels does not significantly increase feedstock competition. Competition is expected to be local only and affected by local availability of forestry residues.

5.2 Feedstock availability and logistics

Table 1 shows the theoretical potential of feedstock production in some parts of Sweden in 2020. Production figures are calculated by the recognized S2Biom tool, which was co-funded by the EU. This tool considers technical and sustainable limits, but not the current utilization rate of the various feedstocks. The theoretical potential of feedstock production is allocated to Swedish regions. The different regions are illustrated in Figure 8. Arlanda, the location of the bioethanol production plant, is located in Östra Sverige. This means that, due to the shorter distance, feedstock from this region is favoured, followed by Södra Sverige and Norra Mellansverige.

Figure 8: Map of Sweden

Table 1: Feedstock production Sweden [kt dm/y][2]

Feedstock	Södra Sverige	Östra Sverige	Norra Mellansverige	Total
Logging residues	1,293	834	769	2,896
Road side vegetation	64	38	27	129
Energy grasses	506	331	66	903
Straw	1,015	1,053	151	2,219
Grassland	431	150	36	617
Saw mill residues	3,849	916	1,389	6,154
Wood processing residues	248	201	55	504
Bark	761	346	415	1,522
MSW (biodegradable)	849	758	170	1,777

In Östra Sverige, straw, saw mill by-products and logging residues are the most available fuels. The energy input of the feedstock has to be 2,556 GWh, which is equal to 9,201 TJ. Using logging residues or saw mill residues (18.85 MJ/kg dm), would require an amount of about 488,150 t per year. Using straw (17.28 MJ/kg dm) would require about 532,500 t. Comparing the theoretical production with the demand of the bioethanol production plant shows that theoretically there would be sufficient feedstock available. However, the share of feedstock which would be needed by the bioethanol production plant, is quite high. Additionally, the EU emission trading system (EU-ETS), introduced in 2013, gives incentives to industries for

[2] https://s2biom.wenr.wur.nl/

producing their own renewable electricity. This reduced the availability and increased the price of wood residues for biofuel production. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) An increase of biofuels production could lead to increased profitability of material-producing industries, due to increasing demand for their by-products. (Lundmark, et al., 2017)

In the following, the use of previously mentioned feedstocks is briefly described.

Agricultural residues and SRC: The land use for agriculture in Sweden is about 8%, which is relatively low within the EU. However, straw is produced in large amounts in Sweden. It is mostly used for feed and bedding material for animals, but significant amounts remain on the field for soil amendment. It is estimated that the potential of straw is about 3% of biomass supply in Sweden. The potential is estimated to be about 1 million tonnes, equivalent to 15 PJ, which makes straw promising as a feedstock. The availability of straw depends on location, and there is competition with other uses. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016)

In 2016, about 14 ha were used to produce biomass from short rotation coppice. (Calderón, Gauthier, & Jossart, 2018) The short-term potential of short rotation coppice is small, about 1.5 PJ. However, in order to avoid that, roundwood is used for energy generation. In the long-term, short rotation coppice could be fostered. (Lundmark, et al., 2017)

Forestry residues: Sweden practises sustainable forest management, which means that less wood is felled than grows back annually, resulting in a net growth of Swedish forests. In Sweden, forests cover more than 60% of the landscape and forest biomass counts for about 85% of bioenergy, mostly for heat and power. About half of the forests are privately owned, 25% are owned by the state and the other 25% are public owners. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) In 2016, Sweden produced 74 million m³ of roundwood, which was the highest amount within the EU. (Calderón, Gauthier, & Jossart, 2018) About 60% of global roundwood is produced in four countries, one of them is Sweden. Therefore, the amount of logging residues is also high and Sweden can mobilize large volumes at reasonable prices. (Fulvio, Forsell, Lindroos , Korosuo, & Gusti, 2016) Due to changed harvesting methods (whole tree harvesting), logging residues are becoming more important. However, not all forest residues can be removed from the forest because of economic and ecological reasons, since these residues provide habitat, improve soils and provide nutrients.

Production, import, export, consumption and stock of wood fuels in the EU28 Member States is nearly balanced. Domestically produced wood fuel is often consumed in the same country. (Calderón, Gauthier, & Jossart, 2018) In particular for residues, transport is not expected to be economically feasible.

Logging residues are mainly used for heat and energy production. In Sweden there are about 40 power plants with more than 0.2MW. (Fulvio, Forsell, Lindroos , Korosuo, & Gusti, 2016) Availability of logging residues depends on location and transportation distance. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) In general, wood residues have the most promising potential in Sweden. The technical potential is estimated at 54-130PJ. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016)

Lignocellulosic by-products:

Since the forest industry is important in Sweden, there is also a highly developed wood processing industry. Wood fibre consumption in Sweden amounted to 81 million m³ (solid volume), without bark. Most of the wood fibres were used in the pulp and paper industry (46.4 million m³), followed by sawmills (33.6%) and the wood-panel industry (0.8 million m³). By-products from the sawmills are used in the pulp and paper and wood-panel industries. Nearly all of the residues from the pulp and paper industry are used for plant energy and heating. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) In Sweden there are about 57 pulp mills. (Fulvio, Forsell, Lindroos , Korosuo, & Gusti, 2016) About 86.4 PJ of lignocellulosic by-products were used for energy production and could be partly also used for biofuels production (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) The potential of lignocellulosic by-products in Sweden is estimated as high.

Biogenic fraction of MSW: Waste from households is mainly used for decentralized heat and power plants and district heating. The demand for incineration is higher than domestic production, which leads to import, mainly from Norway. The most common method for treatment of biodegradable fractions of municipal solid waste is anaerobic digestion, for the production of biogas, heat and electricity. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) In 2015, Sweden had 33 operational Waste-to-Energy plants and treated 5.62 million tonnes of waste thermally. (Calderón, Gauthier, & Jossart, 2018) The potential is seen as low, due to large import and long transport distances. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016)

Future feedstock demand is expected to increase, due to increasing demand for SAF. The study "Sustainable jet fuel for aviation" by (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) estimate future feedstock demand via three scenarios regarding fuel conversion efficiency (low 5%, medium 15% and high 25%) An average energy content of 15 GJ/t (dried wood residues 20 GJ/t, waste 10 GJ/t) is assumed. According to that study, in 2020, the amount of feedstock needed for SAF production in Sweden lies between 140 and 700 kt, in 2030 between 1,500 and 7,500 kt and in 2050 between 4,000 and 21,000 kt.

5.3 Conclusion on supply chain

In this case study, the following feedstocks were considered: agricultural and forestry residues, lignocellulosic by-products and biogenic fractions of municipal solid waste. The latter show only low potential in Sweden. From an economic point of view, the most interesting residual feedstocks for biofuels production are wood residues and lignocellulosic by-products, in particular bark and sawdust. In Östra Sverige, straw, saw mill residues and logging residues are the most available fuels. However, the size of the plant would require a high share of the potential feedstocks (see Table 2).

Table 2: Feedstock availability Sweden (dm = dry matter)

Feedstock	Availability [kt dm/y]	Demand [kt dm/y]	Demand [%]
Straw	1,053	606	57.5
Saw mill residues	916	555	60.6
Logging residues	834	555	66.5

Since the current utilization of the various feedstocks is hard to estimate, it is expected that either some different feedstocks have to be used, or transport distance has to be increased. Additionally, sustainability criteria, e.g. from RED II, have to be considered.

6 Market assessment

The market assessment of the case study was conducted for a retrofit in Sweden, which was initially the foreseen location. Subsequently the case study location was changed to Spain.

The market assessment of this case study gives an overview of the European conventional aviation fuel (CAF) market, sustainable aviation fuel (SAF) market and advanced bioethanol market. Additionally, bioethanol production costs and the legal and political framework regarding carbon free aviation in the EU and Sweden are addressed.

6.1 Market overview

6.1.1 EU conventional aviation fuels (CAF) market

According to Fuels Europe the demand for CAF in the EU amounted to 62.8 million tonnes in 2018.[3] More than 3.8 billion passengers were transported by air in 2016 and this amount will double over the next 20 years. The largest and fastest growing air passenger markets are the USA, China and India. (Wei, et al., 2019) In 2016, the final energy consumption of international aviation amounted to 47,482 ktoe (equal to 46,3 million t) and of domestic aviation in EU28 it amounted to 5,849 ktoe (equal to 5.7 million t). All of this CAF had fossil origin, according to Bioenergy Europe. (Calderón, Gauthier, & Jossart, 2018) The development of CAF consumption, production and import is shown in Figure 9. Since 2012, consumption rose

[3] https://www.fuelseurope.eu/dataroom/static-graphs/

steadily up to nearly 60,000 kt in 2018. CAF consumption is expected to increase further at a 1.5% annual growth rate. (Wei, et al., 2019)

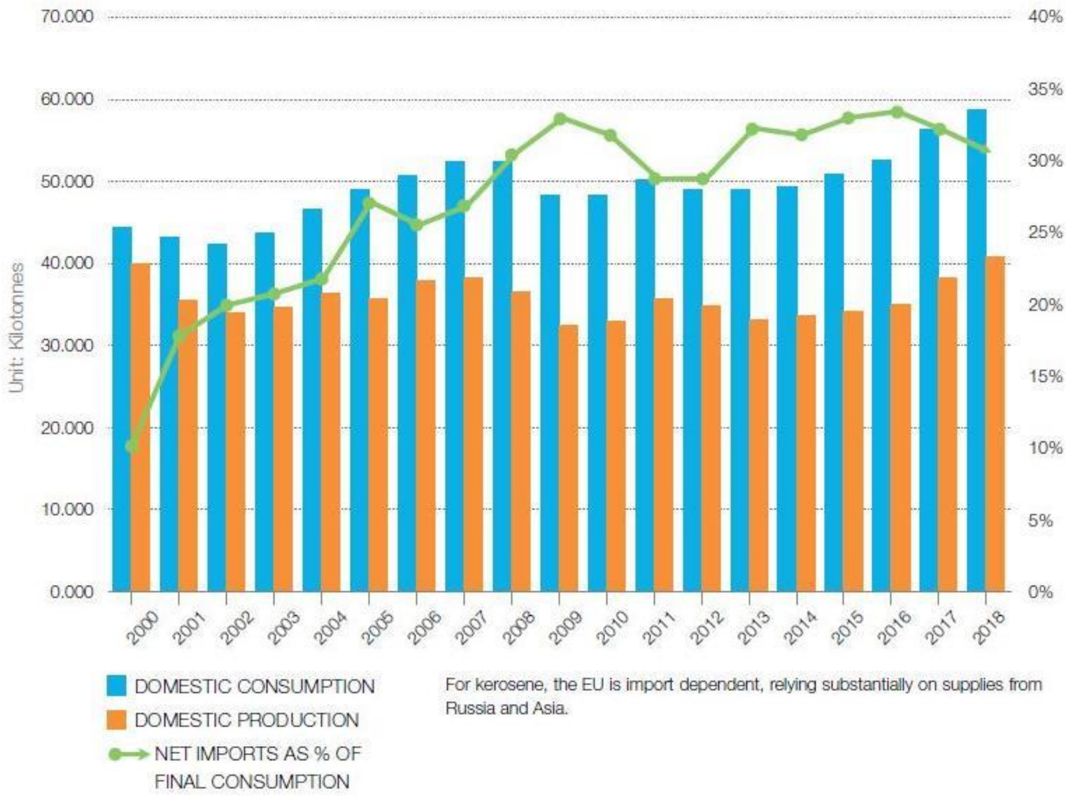

Figure 9: Net trade flows for CAF in EU28 (in kt)[4]

In Europe, almost 100 refineries were operating, but due to uneconomic conditions caused by, gasoline overproduction, among others, 16 of them have already shut down. Production capacity and utilization rate are both decreasing. However, this situation was a driving force for biorefineries in some cases. (Chiaramonti & Goumas, 2019) Before 2000, the EU28 was exporting CAF, since then it is imported. The amount of imported CAF was growing continuously and reached 18,300 ktoe (equal to 17.8 million t) in 2017. (EUROSTAT, 2019) The main suppliers for CAF in the EU are countries from Middle East (60%) and Asia (30%). There is a lack of domestic CAF supply, the import dependency lies above 30%. (Chiaramonti & Goumas, 2019)

According to the EU Reference Scenario, the current share of CAF in final energy demand in the transport sector is about 16%. A slight increase to 17% by 2030 and up to 18% by 2050 is estimated. (Capros, 2016) Aviation needs about 12% of the refined products. (Chiaramonti & Goumas, 2019)

[4] https://www.fuelseurope.eu/dataroom/static-graphs/

In 2015, fuel costs accounted for about 27% of airlines operation costs. (Wei, et al., 2019) The development of CAF price is shown in Figure 10. The average price is expected to increase at a 2.7% annual growth rate. (Wei, et al., 2019) The price of CAF is highly dependent on the crude oil price. The price drop in early 2020 can be explained by the Covid-19 pandemic. The resulting economic crisis and lockdowns within several member states led to CAF being cheaper than crude oil. Prices are expected to rise again, but further development is unclear.

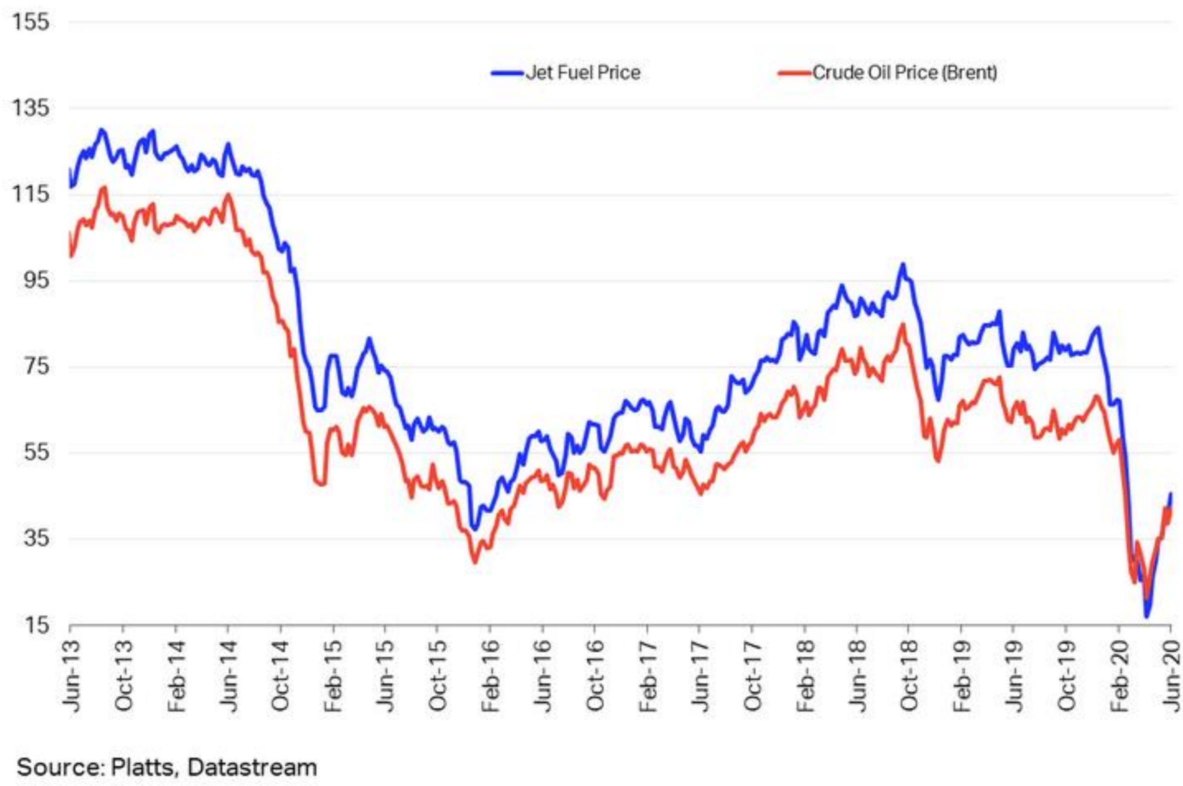

Figure 10: Aviation fuel and crude oil price development (in $/barrel)[5]

<u>Sweden</u>

Sweden has a large number of airports. Stockholm Arlanda, Stockholm Bromma, Göteborg Landvetter and Malmö are the most important ones. Jet-A1 is imported through major ports, such as Gävlehamn (Port of Gävle) and further delivered by train to Arlanda. The Swedish airline industry employs 44,000 people and contributes 2.77 billion € to the Swedish GDP. Sweden is export dependent and therefore air freight is important for the economy. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) In Sweden, CAF demand in 2014 was about 1,196 million litres (equal to 964 kt), about 99% of it was Jet-A1. A long-term traffic forecast by Swedavia (Swedish aviation infrastructure company) indicates annual passenger growth of about 2.1% over the next three decades in Sweden. The total increase of departing

[5] https://www.iata.org/en/publications/economics/fuel-monitor/

passengers is estimated to be 27% between 2017 and 2030. The number of departing passengers in 2030 is estimated to be about 29.65 million, compared with 23.37 million in 2017. (Statens Offentliga Utredningar, 2019)

A projection of future demand was made by the Danish Energy Agency and the PRIMES model of the EU, using EUROSTAT data, among others. According to this projection Sweden will have a CAF demand of about 1,199 million litres (equal to 966.4 kt) in 2050 (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) However, due to the current Covid-19 pandemic, the resulting economic crisis and the drop of oil prices, predictions of future demand are expected to become less accurate.

6.1.2 EU bioethanol market

The EU produced about 3.53 million t of bioethanol in 2017. The production capacity is estimated to be about 7.07 million t. 81% of the bioethanol produced is used in the transport sector. (EurObserv'ER, 2019) Figure 11 shows the development of first-generation bioethanol production and consumption in the EU from 2007 to 2018. One can see the formation of a market equilibrium, through an alignment of supply and demand. (Naumann, et al., 2019)

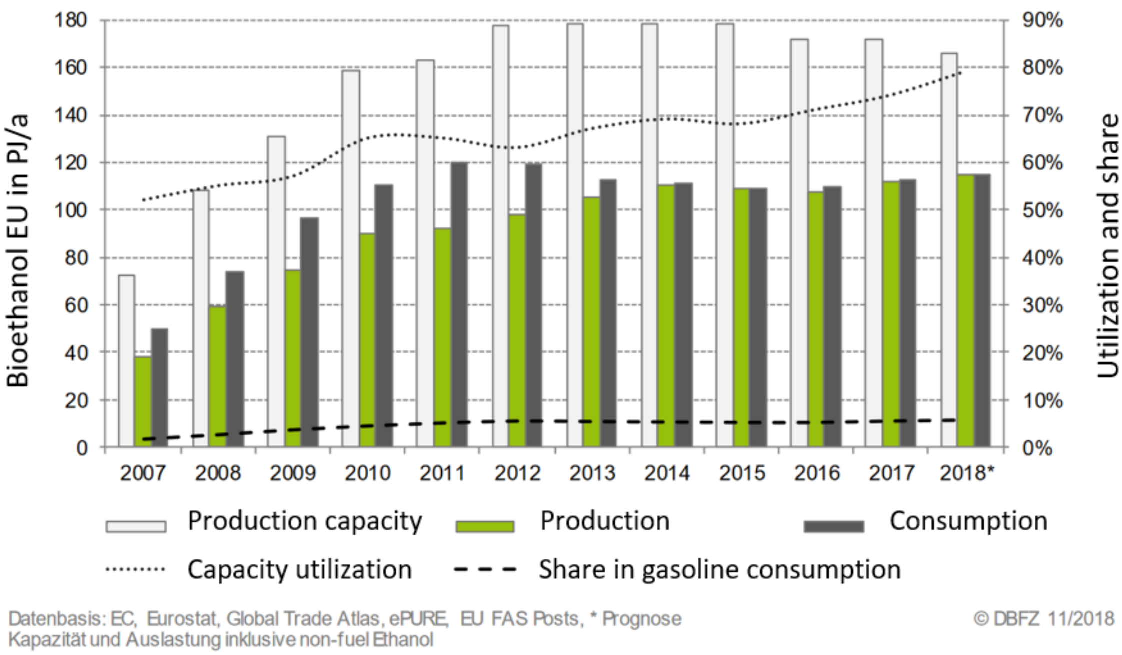

Figure 11: Development of EU bioethanol market (Naumann, et al., 2019)

More than 50% of bioethanol produced in the EU comes from Germany, France and the UK. (EurObserv'ER, 2019) In 2016, Sweden had a bioethanol production capacity of 178 kt and produced 172.6 kt. 3.1 kt of bioethanol were imported to Sweden. (Calderón, Gauthier, & Jossart, 2018) In 2018, Sweden consumed 206.4 kt bioethanol. (EurObserv'ER, 2019)

The current production of advanced bioethanol in the EU is estimated at around 50 million litres. (Flach, Lieberz, & Bolla, 2019) This is equivalent to 39,700 t/y, assuming a density of 0.794 kg/l. Most advanced bioethanol producers utilize agricultural residues, such as wheat straw or corn stover. Borregaard, Domsjö Fabriker and AustroCel Hallein are utilizing brown liquor from wood pulping for their production. St1 is fermenting organic wastes to bioethanol. (ETIP Bioenergy, 2020)

Table 3 lists operational advanced bioethanol production facilities in Europe. The joint capacity amount to 63,420 t/y. This indicates a current capacity utilization of about 60%.

Table 3: Operational advanced bioethanol production facilities[6]

Company	Country	City	TRL	Start-up year	Capacity (t/y)
Borregaard Industries ChemCell Ethanol	Norway	Sarpsborg	9	1938	15,800
Domsjö Fabriker	Sweden	Ornskoldsvik	8	1940	19,000
St1 Cellulonix Kajaani	Finland	Kajaani	6-7	2017	8,000
St1 Etanolix Jokioinen	Finland	Jokioinen	9	2011	7,000
Chempolis Ltd. Biorefining Plant	Finland	Oulu	6-7	2008	5,000
St1 Etanolix Gothenburg	Sweden	Gothenburg	9	2015	4,000
Clariant Sunliquid	Germany	Straubing	6-7	2012	1,000
St1 Etanolix Hamina	Finland	Hamina	9	2008	1,000
St1 Etanolix Vantaa	Finland	Vantaa	9	2009	1,000
St1 Etanolix Lahti	Finland	Lahti	9	2009	1,000
IFP Futurol	France	Bucy-Le-Long	6-7	2016	350
SEKAB Biorefinery Demo Plant	Sweden	Ornskoldsvik	8	2004	160
Borregaard BALI Biorefinery Demo	Norway	Sarpsborg	6-7	2012	110

Table 4 lists advanced bioethanol production facilities, which are currently under construction. The joint capacity amounts to 96,000 t/y. (ETIP Bioenergy, 2020)

[6] http://www.etipbioenergy.eu/images/ETIP-B-SABS2_WG2_Current_Status_of_Adv_Biofuels_Demonstrations_in_Europe_Mar2020_final.pdf

Table 4: Advanced bioethanol production facilities under construction

Company	Country	City	TRL	Start-up year	Capacity (t/y)
Clariant Romania	Romania	Podari	8	2021	50,000
AustroCel Hallein	Austria	Hallein	8	2020	30,000
ArcelorMittal Ghent Steelanol	Belgium	Ghent	9	2020	16,000

Following advanced bioethanol production facilities, with a joint capacity of 380,000 t/y, are planned for the next years (see Table 5).

Table 5: Planned advanced bioethanol production facilities

Company	Country	City	TRL	Start-up year	Capacity (t/y)
Kanteleen Voima Nordfuel biorefinery	Finland	Haapavesi	6-7	2021	65,000
INA	Croatia	Sisak	8	-	55,000
Enviral Leopoldov Site	Slovakia	Leopoldov	9	-	50,000
St1 Cellulonix Kajaani 2	Finland	Kajaani	8	2024	40,000
St1 Cellulonix Pietarsaari	Norway	Pietarsaari	8	2024	40,000
St1 Cellulonix Follum	Norway	Ringerike	8	2024	40,000
Versalis Crescentino restart	Italy	Crescentino	8	2020	40,000
ORLEN Poludnie Jedlicze Site	Poland	Jedlicze	9	-	25,000
Sainc Energy Limited Cordoba	Spain	Villaralto	8	2020	25,000

The current production capacity of advanced bioethanol in Europe amounts to 63,420 t/y. A further capacity of 96,000 t/y is currently under construction. Additionally, a capacity of 380,000 t/y is planned, most of it by 2024. If all of the planned plants are constructed, the total advanced bioethanol production capacity of Europe will be 539,420 t/y (see Figure 12).

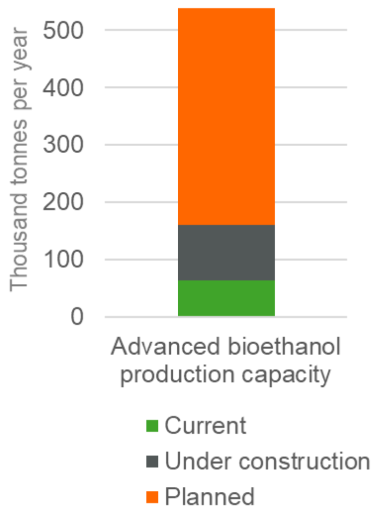

Figure 12: Advanced bioethanol production capacity in Europe (in thousand tonnes per year)

Sweden is already investing in advanced biofuels production. Currently there are three advanced bioethanol production plants in Sweden, with a joint capacity of 23,160 t/y..

Based on the data of the EU Reference Scenario and considering the 7% cap and the ILUC Directive, 10-15 Mtoe (equal to 15.7-23.5 million t) of advanced bioethanol production is feasible by 2030. About the same amount of advanced renewable diesel (HVO) is feasible by 2030. These amounts of advanced biofuels would represent 6% to 9% of the total energy use in the European transport sector, without double counting. In order to realize this scenario for advanced bioethanol, each year 5-10 plants would need to be installed. According to SGAB, there would be enough biomass, waste streams and residues available to reach this scenario. (Maniatis, Landälv, Waldheim, van der Heuvel, & Kalligeros, 2017)

The main barriers for cellulosic bioethanol are high research and production costs and regulatory uncertainties. (Flach, Lieberz, & Bolla, 2019) Feedstock availability, quality and price variations are not seen as a burden for an increase in advanced bioethanol production. (IRENA, 2019) It is estimated that lignocellulosic bioethanol will find suitable conditions for market development considering RED II. (Chiaramonti & Goumas, 2019)

Currently, there is no global trade in advanced bioethanol. A scenario of a study conducted by E4tech estimates a supply of advanced bioethanol outside of the EU of about 3.6 billion litres (equal to 2.9 million t) by 2030. Half of it is expected to be produced in the USA. It is further estimated that only about 0.9 billion litres (equal to 0.7 million t) would be available for import to the EU. This is due to incentives for advanced bioethanol within the USA. It is estimated that there would be enough lignocellulosic waste and residues to produce up to 718 billion litres (equal to 570.1 million t) advanced bioethanol worldwide by 2030. This indicates that feedstock availability is not limiting future EU imports. (E4tech, 2019)

6.1.3 Advanced bioethanol production costs

In general, biofuels are more expensive than fossil fuels. A main part of biofuel production costs is the feedstock cost. Therefore, biofuels based on waste streams seem to be the most competitive, except if an intensive pre-treatment of the waste stream is necessary. It is expected that in the mid to long-term, competitiveness of advanced bioethanol will increase, due to economies of scale and learning curve effects. (Festel, Würmseher, Rammer, & Boles Eckhard, 2014) However, production costs of advanced biofuels have not decreased in recent years. On average, feedstock costs represent 33-39% of total costs and operation costs represent 33-42%. (Witcover & B. Williams, 2020) Table 6 shows total lignocellulosic bioethanol production costs in low, medium and high cost scenarios. According to that, production costs vary between 85 and 158 €/MWh (equivalent to about 630 €/t and 1,180 €/t). Considered are: capital costs, costs for feedstock, enzymes and operation and maintenance. (Landälv, Waldheim, Maniatis, van den Heuvel, & Kalligeros, 2017) The report "Advanced Biofuels – Potential for Cost Reduction"[7], published by IEA Bioenergy Task 39 in 2020, confirmed that these cost estimations are still reasonable.

Table 6: Production costs of lignocellulosic bioethanol (Landälv, Waldheim, Maniatis, van den Heuvel, & Kalligeros, 2017)

	LOW	MEDIUM	HIGH
	Low (2570 EUR/kW) Capital 20y/8% Feed at 10 EUR/MWh EUR/MWh	Low (2570 EUR/kW) Capital 15y/10% Feed at 13 EUR/MWh EUR/MWh	High (3650 EUR/kW) Capital 15y/10% Feed at 20 EUR/MWh EUR/MWh
Capital	32	42	60
Feedstock	25	33	50
Enzymes	15	15	30
Other O&M	13	13	18
Total	85	103	158

6.1.4 EU sustainable aviation fuels (SAF) market

In EU28 the production capacity of pure SAF amounted to 1,000 t/y from 2015 to 2017 and increased to 7,000 t/y in 2018, according to EUROSTAT. Since 2011, 22 airlines were performing more than 3,000 commercial passenger flights, using SAF blends (up to 50%). In 2016, 4.5 million litres (equal to 3,600 t/y) of SAF were produced globally. Which is double the amount of 2015. (Wei, et al., 2019)

Figure 13 shows a scenario analysis conducted by ICAO. The low scenario would replace 4% of CAF. For that, an annual SAF production of 20 million t/y would be needed by 2050. The

[7] http://task39.sites.olt.ubc.ca/files/2020/02/Advanced-Biofuels-Potential-for-Cost-Reduction-Final-Draft.pdf

maximum scenario of 100% SAF would require the construction of about 170 new biorefineries every year from 2020 to 2050. Both scenarios would require a production of SAF of 5 million t/y by 2025. However, off-take agreements only covered 0.9 million t/y in 2017. (Chiaramonti & Goumas, 2019) It is expected that low quota obligations of SAF will have a negligible effect on demand for air travel services and aviation fuels. Example: A blend-in ratio of 20% is causing a price increase of 16% for fuel, which increases ticket prices by 4.8%. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016)

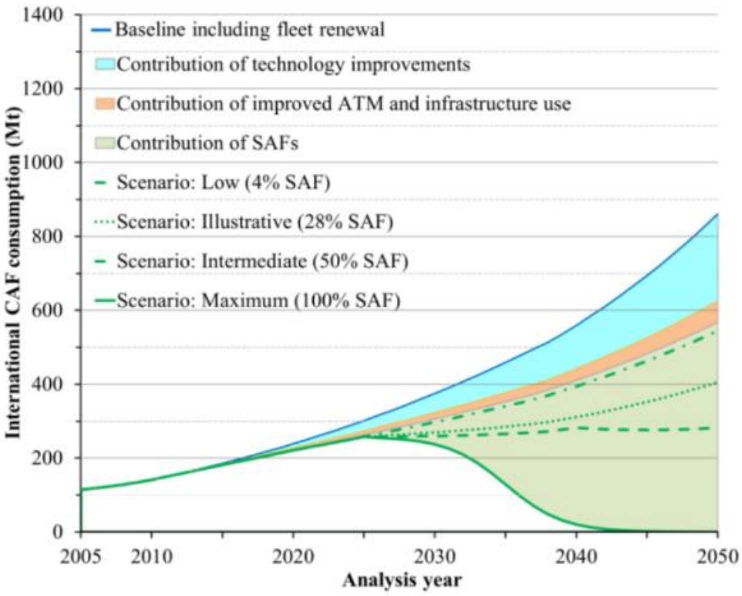

Figure 13: Expected aviation fuel consumption (ICAO)[8]

Global aviation fuel consumption will increase to 22.88 EJ (equal to 532.6 million t) in 2040. The global potential of energy from residual lignocellulosic biomass was 42.54 EJ/y in 2005. Global SAF production could reach (estimated) 21.46 EJ (equal to 499.1 million t), which would be about 94% of global aviation fuel consumption in 2040. (Wei, et al., 2019)

Demand for SAF is rising, but there are still challenges. The main challenges are feedstock availability, economics and sustainability. (Wei, et al., 2019) SAF can be produced in a price range of 0.8-2.2 €/l. In comparison CAF production costs are about 0.25 €/l. The costs of SAF are about 3 to 9 times higher compared to CAF. Also, the current ETS carbon price (about 24€/tCO_2) is not sufficient to fill this gap. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016)

Sweden

The current market share of SAF in Sweden is still small, but there are some initiatives, such as the Fly Green Fund Initiative and ongoing research. The aviation industry in Sweden shows

[8] https://www.icao.int/Meetings/CAAF2/Documents/CAAF.2.WP.006.4.en.Revised.pdf

great interest and the potential for increasing SAF in Sweden is promising. SAF demand in Sweden is assumed to be 160 million litres (equal to 129 kt) by 2030, and 450 million litres (equal to 362.7 kt) by 2050, according to (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016). Sweden already has a production capacity of 23,160 t/y advanced bioethanol production, which could be further processed to SAF. Additionally, there is the PREEM refinery in Gothenburg, currently co-processing tall oil to produce diesel with renewable content for road transport. This refinery could also produce SAF in future, using existing infrastructure. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) SAF can be produced with various feedstocks via various production pathways. Therefore, future SAF production is hard to estimate.

The ATJ pathway for SAF production has a good chance to enter the commercialization stage, once adequate economic conditions are available. (Chiaramonti & Goumas, 2019) The price of SAF produced from the market available ethanol (ATJ-SKA produced from Swedish Biofuels) is expected to be three to five times higher than that of Jet A-1, which is a CAF. The price of the feedstock is the main factor for the production cost of SAF. Using the ability of Swedish Biofuels ATJ technology to convert syngas, SAF production costs can be decreased by using 90% syngas and 10% alcohol. If additionally, wood waste is used as feedstock, the ATJ SAF price will come close to that of Jet A-1. (Zschocke, 2012)

Swedish Biofuels currently runs a small production plant, which produces around 5 l/h, 24 h a day of mixed product. Around half of it is SAF, with an annual production of SAF of about 16 t. A future production capacity of 20,000 t/y of fuels is planned. The volume of SAF from such production is about 1% of jet fuels consumed by Arlanda airport.

In 2018, the Swedish Government appointed a special inquiry to describe and quantify supplementary measures to reach national climate targets. If a reduction obligation is introduced, the inquiry assumes the following results for total SAF demand and associated costs. The total amount of SAF will be 10.9 kt by 2021, 56.4 kt by 2025 and 341.7 kt by 2030. The total additional costs of SAF utilization is expected at 162 million SEK in 2021, 560 million SEK in 2025, reaching 2,544 million SEK in 2030. More details of the inquiry can be found in chapter 6.2. The total additional costs will affect ticket prices for passengers. It is estimated that the price for a domestic one-way ticket from Sweden will increase by 3 SEK in 2021, 10 SEK in 2025 and 41 SEK in 2030. For European flights these additional costs are expected to double (6 SEK in 2021, 19 SEK in 2025 and 78 SEK in 2030). And for intercontinental flights the prices will increase by 19 SEK in 2021, 61 SEK in 2025 and 250 SEK in 2030 (Statens Offentliga Utredningar, 2019).

Additional costs for SAF will be a burden for passengers. Their willingness to pay is estimated to be insufficient, which makes policy measures to promote an increase of SAF, even more important. The lowest production cost for SAF is estimated to be about 8-10 SEK/l. In comparison, fossil jet fuel costs about 6 SEK/l. Selling price of SAF, taking supply and demand, growing production capacities and a certain profit margin into consideration, is estimated at 18 SEK/l by 2021, 14 SEK/l by 2025 and 12 SEK/l by 2030. (Statens Offentliga Utredningar, 2019)

Possible co-products of the SB ATJ process are other transport fuels or biochemicals, which are of interest to the chemical industry. Currently companies operating naphtha crackers are interested in buying bio-based naphtha from companies like NESTE or UPM, in order to add green feedstock to its chemical production processes. Adding high value chemicals to SAF production output can improve the overall business case.

6.2 Legal and political framework for sustainable aviation in the EU and Sweden

Aviation is a policy-driven area, where the political framework determines the development of markets, research and investments. Policy can provide significant support. EU emission targets alone only lead to minor increase in SAF production. Additional subsidies are necessary in order to reach the 14% target, and the 0.2% advanced biofuels target by 2022 of the RED II. Most of the Member States have more than enough sustainable feedstock to meet these targets, however incentives for advanced biofuels and SAF are small. E.g. RED II includes a 1.2 multiplier for replacing fuel in the aviation sector. However, EU aviation industry would prefer full double-counting in order to achieve economic sustainability. (Chiaramonti & Goumas, 2019)

The RED II established the framework that will drive the market of SAF. However, follow-up actions from EU and MS are still necessary. Investments can only occur in stable, long-term, and well-defined policy framework, in particular for the aviation sector, given the procedural and technical complexity. RED II policy provisions have to be implemented quickly and in an economic and doable way in order to develop a market for SAF in Europe. Therefore, scaling up the production capacities of SAF will be required and large investments (demonstration, certification, plants) have to be taken. (Chiaramonti & Goumas, 2019)

The International Civil Aviation Organization (ICAO) is developing a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). ICAO set the ambitious target of 50% GHG emission reduction until 2050 (compared to 2005). CORSIA aims to implement that each airline has to compensate its emissions, above a baseline. A first pilot phase, is planned for 2021-2023, followed by a voluntary phase from 2024-2016 and, finally by a mandatory phase from 2027-2035. This scheme aims for offsetting 80% of the air traffic growth after 2020. (Chiaramonti & Goumas, 2019)

Coordination of RED II and CORSIA will be crucial for the aviation sector. Key components of both policies are minimum sustainability criteria and how these are ensured and certified. Mandates for SAF were already announced by some Member States. It is likely that Sweden also has such plans. SAF volumes produced must be registered, they have to be accounted under both, RED II and CORSIA. CO2 savings calculation need particular attention, since there are differences in national emission counting. It must be ensured that the transposition of these two schemes in MS legislation takes this into account to avoid carbon counting conflicts. However, GHG emission reduction requirements are quite different (10% for CORSIA, 65% for RED II). (Chiaramonti & Goumas, 2019)

In 2011, the European Commission, in coordination with airlines and biofuel producers, launched the "European Advanced Biofuels Flightpath"[9] initiative to develop and promote a roadmap targeting a production of 2 million tonnes of SAF by 2020. During the life time of the initiative and over more than ten years, the Flightpath core team, of which Swedish Biofuels was an active member, contributed a significant amount of time to support the SAF value chain development and promote the production, storage and distribution of SAF. Despite the production target of 2020 not being reached, a number of significant achievements have been made including seven ASTM certified pathways for SAF production, longer term policies, implementation of mandates and other SAF incentives at a national level. Furthermore, a number of substantial obstacles related to economics, policy and market related issues, were identified and addressed.

The current projects and initiatives, such as "Bioport Holland"[10] or IATA[11] also aim for supporting SAF production in Europe. For example, IATA introduced three emission targets for the whole aviation industry. One is to cut net emissions in half by 2050 compared to 2005. Examples for European airlines, with long-term contracts for SAF are Lufthansa and KLM. (Wei, et al., 2019)

The price of CAF is much lower than that of SAF. Therefore, incentives or compensation mechanisms are needed to overcome the price gap for airlines and to create a market, attract investors and to reduce risks. Efforts for further cost reduction should be focused (feedstock productivity, cheap catalyst, equipment, reaction conditions, etc.) (Wei, et al., 2019) Supporting policies and research are key for large-scale deployment of SAF, e.g. for sustainable feedstock production. Innovative feedstocks, which require minimum resources in terms of land, water quality and nutrients should be developed. E.g. the USA`s Renewable Fuel Standard (RFS) increases the availability of price-competitive SAF with support and incentives for agriculture and technology providers. (Wei, et al., 2019)

Carbon pricing would increase the competitiveness of SAF (Wei, et al., 2019) The price gap between fossil fuels and biofuels in aviation is even higher than in road transport. Additionally,

[9] https://www.biofuelsflightpath.eu/about
[10] https://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=37
[11] https://www.iata.org/

aviation fuels are often tax exempted. This makes policies even more important in order to create a market. (Chiaramonti & Goumas, 2019) Aviation is responsible for about 2% of CO_2 emission induced by humans and about 12% CO_2 emissions in the transport sector. Since 2012, flights entering the EU are required to pay for CO_2 emissions due to the EU Emission Trading System (ETS) (Wei, et al., 2019)

Decarbonization of the aviation sector is a main driver for SAF. However, new SAF has to be certified by ASTM, which is a long and expensive process (3 norms, certification process). The certification process brings technical and financial barriers. Given the estimation that the average certification process needs about four years and that the RED II covers 10 years, the need for stable and long-term policies in order to find investors is even more clear. (Chiaramonti & Goumas, 2019)

ATJ-SPK is already certified by ASTM. Possible feedstocks are: biomass used for starch and sugar production and cellulosic biomass for isobutanol and ethanol production. ATJ-SPK can be blended up to 50% (ICAO, 2018). Once it is certified, it is suggested that SB-SKA can be used as 100% neat fuel for flights (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016).

Sweden

At the time of writing the report, there were no mandatory measures for increasing the share of SAF in Sweden. E.g. Indonesia has a SAF mandate of 2%, rising to 5% until 2025. However, the option of a fuel quota obligation system has been under investigation by the Swedish Energy Agency and the Swedish Transport Agency. However, the ticket prices would be increased and this would result in Swedish airlines being less competitive. Some voluntary initiatives, such as the Fly Green Fund Initiative mechanism are gaining popularity.

The Ministry of Environment and Energy of Sweden published Sweden`s draft integrated national energy and climate plan (NECP), according to European Regulation. This draft report is a summary of Sweden`s climate change and energy policies. Climate targets are shown in Figure 14. (Ministry of the Environment and Energy)

Target	Target year	Base year
Sweden will not have any net emissions of greenhouse gases into the atmosphere and should thereafter achieve negative emissions	2045	1990
Reduction of -75 percent of emissions from sectors outside the EU ETS	2040	1990
Reduction of -63 percent of emissions from sectors outside the EU ETS	2030	1990
Reduction of - 70 percent of emissions from domestic transport	2030	2010
Reduction of -40 percent of emissions from sectors outside the EU ETS	2020	1990
50 percent share of renewable energy in gross final energy consumption	2020	
100 per cent renewable electricity production (this is a target, not a deadline for banning nuclear power, nor does mean closing nuclear power plants through political decisions)	2040	
Sweden's energy use is to be 50 percent more efficient than in 2005	2030	2005

Figure 14: Overview on Sweden`s climate targets (Ministry of the Environment and Energy)

Domestic aviation is excluded from the reduction of -70% of emissions from domestic transport, since aviation is included in the EU-ETS. However, emissions from domestic flights are included in the zero net-emission until 2045 target. Currently, aviation causes about 1% of Sweden`s GHG emissions. (Swedish Climate Policy Council, 2019)

Additionally, the Ministry of Environment and Energy of Sweden, published "The Swedish climate policy framework[12]", in 2017. It includes the Climate Act (started January 1st, 2018), Sweden´s climate goals and it introduced an independent Climate Policy Council. (Wormslev, Pedersen, Eriksen, Bugge, & Skov, 2016) This independent climate policy council is evaluating policies and the progress to achieve the climate goals. (Ministry of the Environment and Energy, 2017) The report of the Swedish Climate Policy Council, published in 2019[13], summarizes that the progress to achieve the climate goals is too slow. One reason is that sectors included in the EU-ETS (e.g. aviation) account for almost 40% of Sweden´s GHG emissions and there is currently no mechanism to bring these emissions to net zero. However, in April 2018, an excise duty was introduced on air travel and there was also an inquiry[14] into a greater use of biofuels for aviation reported. (Swedish Climate Policy Council, 2019) The tax is on commercial flights and is paid from the airline for passengers travelling from a Swedish Airport. Dependent on the final destination, there are various levels of tax (SEK 61, 255, 408). (Ministry of the Environment and Energy)

12 https://www.government.se/495f60/contentassets/883ae8e123bc4e42aa8d59296ebe0478/the-swedish-climate-policy-framework.pdf

13 https://www.klimatpolitiskaradet.se/wp-content/uploads/2019/09/climatepolicycouncilreport2.pdf

14 https://www.regeringen.se/493238/contentassets/6d591e58fd9b4cad8171af2cd7e59f6f/biojet-for-flyget-sou-201911

Inquiry "Biojet för flyget"

The Inquiry "Biojet för flyget" was published in 2019. Tasks are, analysing how biofuels for aviation can be supported, and finding answers for the questions which policies are suitable and what blending ratio is reasonable. The main proposal for reducing GHG emissions is a reduction obligation for aviation fuels. For that, fuel suppliers would need to blend CAF with SAF. The volume ratio for SAF needs to meet the reduction obligation, depending on GHG emission reduction. In contrast to a blending obligation, a reduction obligation favours SAF with high GHG emission reduction. However, there is no ceiling for total CAF emissions, which could lead to an overall increase in emissions if demand for aviation fuels is increasing drastically.

Reduction levels are set until 2030 (27%), targeting 100% SAF by 2045. If the reduction obligation is unfulfilled, there would be a reduction obligation fee, which is significantly higher than the cost of blending SAF. In order to reach sufficient production capacity, investments of about 5 billion SEK are estimated.[15]

The reduction obligation could impact climate with two different effects, fuel shift (CAF is replaced by SAF) or altered travel patterns (reduced flying, transfer with other mode of transport). Figure 15 shows the climate impact of these effects, calculated with reference scenarios, compared to 2017. GHG emission reduction of fuel shift is expected to be much higher than of reduced flying. (Statens Offentliga Utredningar, 2019)

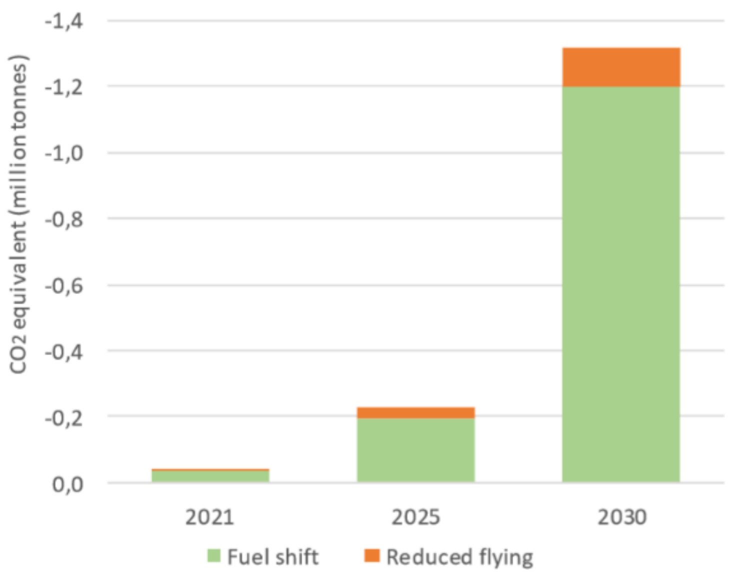

Figure 15: Climate impact - fuel shift, altered travel patterns

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[15] http://fossilfritt-sverige.se/in-english/roadmaps-for-fossil-free-competitiveness/roadmap-the-aviation-industry-summary/

It is estimated that biofuels will contribute as a central part for GHG emission reduction until 2030. Therefore, the requirements on how to produce SAF with high GHG emission reductions were also studied in this case study as part of the sensitivity analyses in the sustainability assessment. However, there are still uncertainties regarding price and supply development due to competing demand for biomass from aviation, shipping and other industries (Swedish Climate Policy Council, 2019) SAF can be only one measure to reduce GHG emissions. Increasing efficiency, electrification etc. are also needed to achieve Sweden`s climate targets. (Statens Offentliga Utredningar, 2019)

Disclaimer: The assessment of the political framework for fossil carbon free aviation in the EU and Sweden was conducted in 2020 and 2021. Some of the details may have changed since the study was done.

6.3 Conclusions on market

Even though there is huge interest in SAF from Swedish aviation industry and initiatives, SAF production rises slowly. The projected SAF demand for Sweden by 2030 is higher than current total global SAF production. Main barriers for SAF deployment are economic, policy and market related issues. Biomass feedstock costs vary and have high contribution on SAF production costs. However, research regarding feedstock and production pathways is estimated to decrease costs of SAF significantly. Additionally, European and national climate goals foster the use of advanced biofuels, also in aviation sector. Sweden´s target of fossil free aviation until 2045 is seen as a main driver towards SAF production. Several Member States are already investing in advanced biofuels production and there is a huge increase in capacity and production planned in Europe. Main uncertainty is still regarding long-term policies, which would have major contribution on investments and subsequent market growth.

7 Techno-economic assessment

The economic feasibility of the retrofit was determined by using economic metrics, such as IRR and NPV. In addition, a sensitivity analysis was performed to understand the impact of variation in premium and OPEX on the economic feasibility. Using the current input values and assumptions, the retrofit is economically feasible, with an NPV of 8.6 M€, an IRR of 30.1% and a payback period of 3 years. However, the investment is relatively small compared to the cash flow. For this reason, a small decrease in the premiums for the bio-based fuels, or a small increase in the OPEX will quickly result in negative economic metrics, which decrease rapidly with decreasing premiums or increasing OPEX costs. Should the premium for bio-based jet fuels reach below 1,100 €/t, or the OPEX costs increase by 1.5%, the retrofit becomes economically unfeasible. On the other hand, this also means that small increases in the premium and small decreases in the OPEX will result in very positive economic metrics. For example, an increase in premium for bio-based jet fuel to 1,400 €/t results in an NPV of 52.2 M€, an IRR of 126.8 %, and a payback period of 0.8 years. Moreover, a decrease in OPEX of 2% results in an NPV of 20.5 M€, an IRR of 57% and a payback period of 1.8 years. Overall, the retrofit is economically feasible, however, due to the large impact of small changes in the OPEX or profit, there are high risks associated with the uncertainties.

8 Sustainability

The present work investigated the environmental performance of the integration of the ATJ-SKA process into the existing 1G ethanol plant. A thorough life cycle analysis has been carried out for this purpose employing the REDII and the Impact 2002+ methodology.

The total GHG emissions for the production of 241,670 m^3 of BCyL bioethanol (current situation) are evaluated at 296,831 $tCO_{2eq.}$/y (with CO_2 use.) The relevant GHG emissions figure per 1 MJ of final ethanol is 53.26 $gCO_{2eq.}$/MJ. This value agrees with the value in the RED II Directive, estimating the GHG emissions at 56.80 $gCO_{2eq.}$/MJ. Having addressed the entire life cycle of the BCyL bioethanol production facility, it can be argued that the operation of both the natural gas cogeneration system and the natural gas-fuelled boilers are the most important contributors to GHG emissions, due to the main pollutants emitted (e.g. carbon dioxide (CO_2), nitrogen oxides (NO_x), organic compounds gases, etc.) when burning natural gas.

On the other hand, the GHG emissions related to the ethanol facility retrofitted with the ATJ-SKA process amount to 455,658 tCO_{2eq}/y. The main adverse impact is associated with the grid electricity supply to cover the electricity intensive processes of both productions, with the required electricity being supplied by the Spanish electricity mix, which is still dominated by fossil fuels (oil, gas and coal). The corresponding GHG emissions figure per 1 MJ of final fuels, namely, avgas, jet fuel, diesel, gasoline and condensate products, are estimated at 52.23 gCO_2/MJ. This value is comparable with values in the relevant literature, estimating GHG emissions of renewable jet fuel at 71 gCO_2/MJ[16]. A large-scale penetration of renewables in the electricity generation mix alone, will lead to a more environment-friendly energy production approach, improving the environmental footprint of the retrofitted facility. More specifically, a potential increase of renewable energy – from 37% to 74% - in the electricity mix will cause a decrease in the total global warming potential in the order of 21%. In addition,

[16] De Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A and Junginger M. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. BIOTECHNOLOGY FOR BIOFUELS 10 (64); 2017. JRC106178

when the renewables share in the generation mix is expected to reach 100%, there is going to be a further decrease in the GHG emissions (about 23% as compared to that of 74% RES).

The GHG emissions for the stand-alone ATJ-SKA process (bioethanol delivered by truck to the ATJ plant) are evaluated at 457,379 tCO_{2eq}/y. The relevant GHG emissions figure per final fuel is estimated at 54.56 gCO_2/MJ, including GHG emissions of ethanol. GHG emissions attributed to the standalone ATJ plant result from energy provided by the national grid and needed for pumping and preheating the ethanol.

In order to provide comparable results with the fuel comparator determined by the RED II Directive (estimated at 94 gCO_{2eq}/MJ), the GHG emissions savings, defined as the emissions avoided from the production of biofuels, have been calculated per MJ of energy produced from ethanol. It was found that 43% emissions savings are associated with the current situation with 1G bioethanol production, whilst 44% and 42% are related to the retrofitted facility with the ATJ process and the standalone ATJ plant with BCyL bioethanol as a feedstock, respectively. As expected, future electricity generation mixes with increased penetration of renewables could certainly lead to a further increase on emissions savings. Indeed, in 2030, with 74% share of renewables, the emissions savings are estimated to be about 56% for the retrofitted facility, and 54% for the stand-alone ATJ-SKA process with BCyL bioethanol as a feedstock. In 2050, with 100% share of green electricity, but still using natural gas in the ethanol plant, the emissions savings increase further, reaching about 67% and 63% in cases of the retrofit and the alternative scenario, respectively. It is evident, therefore, that renewable jet fuels from corn-based ethanol can provide significant GHG mitigation, as compared to conventional fossil fuels. It was further shown that the retrofitted facility with the ATJ process exhibits higher GHG emissions savings (67%) than the stand-alone ATJ plant (63%).

In general, sustainability of SAF will improve significantly in the future by the transition to sustainable alternative energy on the national level or locally at the production site. The Swedish Biofuels ATJ technology is GHG emissions neutral; the majority of emissions is associated with the existing 1G ethanol production. It is worth noting that if sustainable local energy sources are implemented for meeting both the electricity and heat requirements of the retrofitted facility and the stand-alone ATJ plant, **the emissions savings will reach 95% and 94.5%, respectively.** These high percentage figures present a major improvement of the environmental impact of the existing 1G bioethanol production plant. The production and use of hydrogen may also play an important role in future jet fuel production towards reducing the emission intensity of jet fuels, especially when produced through electrolysis from renewable electricity. The ability of SB ATJ technology to process the CO_2, produced at the fermentation stage, and green hydrogen as additional feedstocks for SAF production could further increase the GHG emissions savings, potentially leading to **negative carbon emissions**.

A summary of the results of the environmental analysis is presented in Table 7.

Table 7. Overview results of environmental assessment in scenarios of Swedish Biofuels case study.

Scenario	Emissions per MJ of fuel (gCO_{2eq}/MJ)	Saving compared to REDII (%)
Baseline Scenario	53.26	43.34
Current retrofit scenario based on existing 1G bioethanol plant	52.23	44.00
Sustainable retrofit scenario	4.93	95.00
Current alternative scenario based on existing 1G bioethanol plant	53.67	40.33
Sustainable alternative scenario	5.13	94.50

KPIs

The results of the environmental KPIs in the retrofit scenario are presented in Table 8.

Table 8. Environmental KPIs results on Swedish Biofuels case study.

KPI	Value Current energy supply	Value Sustainable energy supply
Carbon dioxide Equivalent Emission Reduction of supply chain and operation	44%	95%
Increased efficiency of resources consumption	Not estimated	Not estimated

9 Risks

9.1 Risk assessment for the retrofit

A comprehensive list of risks was compiled by the case study team. Only the risks directly related to the retrofitting and retrofitted situation have been considered. The current situation and alternative were left out of the scope of the risk assessment.

The probability and consequence of each risk was determined in a survey amongst all case study members and mean values are presented in Table 9. By multiplying the results for probability and consequence a total risk was calculated, which allows a ranking of the risks.

Table 9: List of risks, their probability and consequence and the resulting total risk

Nr.	Risk	probability (1 = low, 4 = high)	consequence (1 = little, 4 = severe)	total risk (1-16)
1	ATJ kerosene is not considered advanced biofuel when utilizing maize-based ethanol, EtOH plant has to undergo 2 retrofits (1. from 1G to advanced fuels, 2. to ATJ adaption)	3,1	3,2	10,0
2	Aviation sector is not willing to pay the green premium	2,2	3,2	7,2
3	Competition with other sectors like road transport or chemical market is more attractive to market ethanol than conversion by ATJ	2,4	2,9	7,1
4	Increasing prices for sustainable feedstock for ethanol production	2,9	3,0	8,7
5	Not enough green electricity is locally available to achieve high GHG emissions	1,9	3,2	6,1
6	Unsupportive or only short-term policies frameworks lead to changes in the market (e.g. green premiums)	2,7	3,2	8,6
7	Other biokerosene technologies enter market with cheaper solution	2,5	2,4	5,9
8	By-products contribute less to economic viability than assumed (e.g. because markets are not developed)	1,8	2,8	4,9
9	Increasing electricity prices	2,4	2,7	6,5
10	ATJ-SKA might not pass the ASTM certification process	1,6	3,3	5,3
11	Not sufficient flexibility of the plant to switch between products according to market situation	1,9	2,1	4,0
12	Bankruptcy or change in strategic direction of value chain partners	2,1	3,1	6,6
13	Adverse reactions from the public	1,6	2,4	3,8

According to the ranking and the representation in the scatter plot (Figure 16), special attention has thus been drawn to risks 1, 4 and 6:

- To deal with risk 1, the transfer of the retrofit scenario to a dedicated 2G ethanol plant could be interesting. Many of the results of this case study like the mass and energy balances of the retrofit would be very similar for an integration into 2G ethanol production.
- Risk 4 is difficult to approach and needs measures that are already needed for the existing 1G ethanol production, like increasing flexibility to use different feedstocks and other measures to react to changing markets.

- Risk 6, resulting from changing policy frameworks is a very common risk for bioenergy projects. Possible measures are supporting policy makers with accurate information to guide policy development and mitigate the need for adjustments. Furthermore, although difficult, possibilities to achieve feasibility of the project with minimized dependency on policy support should be aimed for.

The remaining risks can be seen with medium or low urgency. For example, they address the doubts about achievable prices for ATJ kerosene and by-products on the market (2, 7 and 8). Here, negotiations with possible clients is necessary to get a better idea of reasonable prices and long-term offtake agreements to lower the risks for the retrofit project. The availability and the price of renewable electricity is seen as a risk (5 and 9). A possibility to deal with this is cooperation with renewable electricity providers or the development of own renewable electricity production capacities, that would allow the provision electricity to the plant.

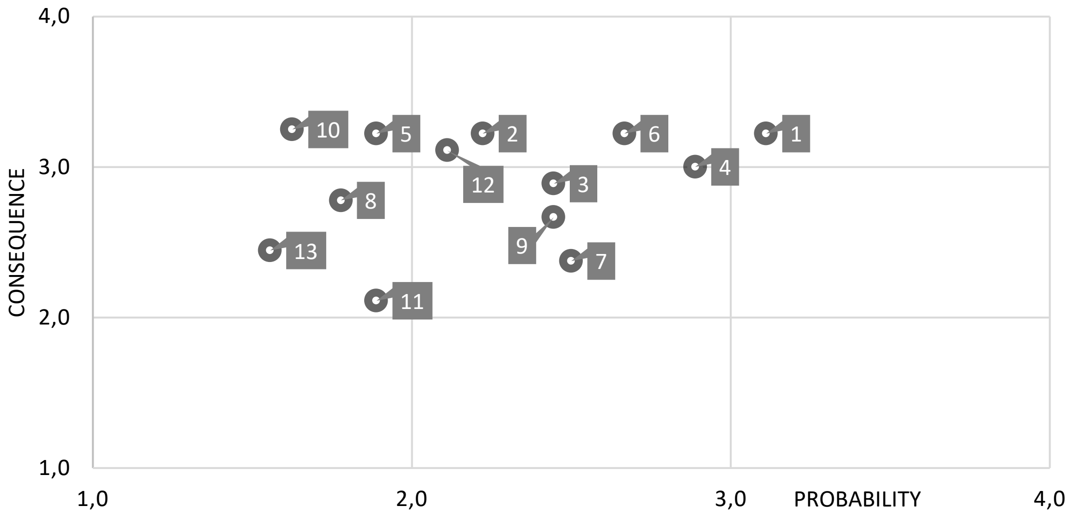

Figure 16 Scatter plot of the risks in Table 9 with consequence vs. probability.

10 Key Performance Indicators (KPI)

The KPIs have been calculated for this retrofit case study including technical KPIs, economic KPIs and environmental KPIs and are discussed below.

KPI	value
Increase in biomass converted per year	0
Increase in bioenergy or biofuel generated per year	-8%
Internal rate of return; IRR	30.1%
CAPEX reduction compared to alternative	N.A.
Carbon dioxide Equivalent Emission Reduction of supply chain and operation	44% - 95% *
Increased efficiency of resources consumption	N.A.

* 44% current case of mainly fossil energy sources in Spain

* 95% for case of sustainable local energy sources

10.1 Technical KPIs

The following technical KPIs were calculated for all case studies in the BIOFIT project. Although presented here, some of the KPIs are more suitable for other case studies.

- **Increase in biomass converted per year**

In this case study there is no direct increase in biomass conversion for the retrofit scenario compared to the current situation. The retrofit aims at producing a more versatile product spectrum with applications in higher value markets. But there is no direct impact on the amount of biomass converted.

- **Increase in bioenergy or biofuel generated per year**

The retrofit that is considered in this case study, could lead to an increase in the production of bio-based jet fuel as a main product and the by-products naphtha and diesel. At the same time, bioethanol, that is currently used as a biofuel in road transport, is consumed for the jet fuel production. Thus, there is a net decrease of 471 TJ/y (8%) in biofuels production in the retrofit scenario. At the same time, 2,507 TJ/y of new types of biofuel are produced.

Table 10: Comparison of amount of biofuel generated per year

	t/y	MJ/kg	TJ/y
Biofuel production in Current situation			
Ethanol	190,919	29.7	5,677
Biofuel production in Retrofit scenario			
Ethanol	90,793	29.7	2,700
Biogas	1,993	59.0	118
Gasoline	25,911	44.2	1,145
Jet fuel	21,716	42.9	932
Diesel	7,164	43.5	312
Total Retrofit scenario			**5,206**
Increase in biofuel generated			**-471**
Increase in biofuel generated (%)			**-8%**

10.2 Economic KPIs

The following economic KPIs are defined:

- **Internal rate of return; IRR**

For assessment of the economic feasibility, among other indicators the IRR of the retrofit scenario was calculated (section 0). The retrofit shows an IRR value higher than the discount rate with an IRR of 30.1% versus a discount rate of 8% per year, which indicates the economic viability of the retrofit. This can be explained by the high value of the green jet fuel product (1,745 €/t), compared to the ethanol, which is valued just below 400 €/t.

- **CAPEX reduction compared to alternative**

The CAPEX reduction can be calculated by subtracting the CAPEX required for the retrofit from the CAPEX required for the alternative scenario. The obtained CAPEX reduction should then be normalised on the annual capacity of the main product. This will result in a reduced CAPEX per GJ/y added capacity.

No detailed CAPEX estimation was made for the alternative scenario. Therefore, this KPI could not be calculated. However, savings in CAPEX are expected from synergies resulting from utilization of infrastructure available at the retrofitted ethanol plant.

10.3 Environmental KPIs

- **Carbon dioxide Equivalent Emission Reduction of supply chain and operation**

Greenhouse Gases (GHGs) are gases in the atmosphere that absorb infrared radiation that would otherwise escape to space; thereby contributing to rising surface temperatures. There are six major GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Emissions of other gases can be converted to CO_2 equivalents through specific methodologies. Since the main sources for CO_2 emissions are combustion processes related to energy generation and transport, CO_2 emissions can therefore be considered a useful indicator to assess the contribution of retrofitting on climate change.

It was found that the retrofit scenario leads to 44% savings of CO_2 emissions compared to fossil jet fuel (section 8). The results for the retrofit scenario were slightly better than for the current practice of ethanol production and the alternative scenario with standalone plants. It is evident, therefore, that renewable jet fuels from corn-based ethanol can provide significant GHG mitigation, as compared to conventional fossil fuels. Through a sensitivity analysis it was demonstrated that the biggest proportion of the AtJ process emissions are related to its electricity consumption. Hence, considering the growth of the proportion of renewable energy (currently 37% in Spain) to 74% in 2030 and 100% in 2050, the retrofitted facility would lead to 56% and 67% savings of CO_2 emissions compared to fossil jet fuel, respectively.

It is worth noting that if sustainable local energy sources are implemented for meeting both the electricity and heat requirements of the retrofitted facility and the stand-alone ATJ plant, **the emissions savings will reach 95% and 94.5%, respectively.** These high percentage figures present a major improvement of the environmental impact of the existing 1G bioethanol production plant. The production and use of hydrogen may also play an important role in future jet fuels production towards reducing the emission intensity of jet fuels, especially when produced through electrolysis from renewable electricity. The capture and storage of the biogenic carbon dioxide from the fermentation process could also further increase the GHG emissions savings and potentially lead to **negative carbon emissions**.

- **Increased efficiency of resources consumption**

The specific KPI “increased efficiency of resources consumption” measures the degree to which renewable fuels have substituted fossil and/or nuclear fuels in the case study, and therefore contributed to the decarbonisation of the European economy. However, in this case study, only renewable corn-based ethanol is used as feedstock in both the retrofit and the alternative scenario; thus, this KPI is not estimated.

11 Conclusions

This case study identifies the benefits of the integration of an alcohol to jet (ATJ) process into an existing 1G ethanol plant from a technical, economic, and environmental perspective. The retrofit of a current maize-based bioethanol plant was studied using Swedish Biofuels ATJ (SB ATJ) technology to produce a sustainable aviation fuel (SAF), namely synthetic paraffinic kerosene with aromatics (ATJ-SKA).

It was found that the combination of SB ATJ with current ethanol production has synergies when waste from the production of ethanol, fusel oils, and hydrated ethanol can be processed, without the need of dewatering in molecular sieves. Further synergies can result from heat and power integration, but would require significant changes in the existing ethanol plant and were not studied in detail.

Furthermore, it was discussed that by using SB ATJ technology, the CO_2, produced at the fermentation stage of the current ethanol plant, and green hydrogen can be used as an additional feedstock to ethanol. This will increase the feedstock for fuel production, reduce the land used for biomass production, increase the GHG emissions reductions and potentially even lead to negative carbon emissions. The use of hydrogen and CO_2 was not part of the current study as there is no green electricity available at the ethanol plant site for the production of hydrogen.

The Techno-economic assessment concluded that in this case study the revenue is much higher than the investment, but there are a number of risks. In particular, the sensitivity analysis showed that small changes in feedstock costs may have a strong effect on the economic feasibility of the retrofit.

Results of the Market assessment evidenced the ambitious plans for use of sustainable aviation fuels, e.g. from European and national authorities as well as ICAO (International Council of Aviation Organization), highlighting the direction of the market development. Feedstock-wise, a significant increase of advanced bioethanol production facilities is planned in the EU. Accordingly, a literature research showed that the feedstock availability for this case study is not a burden.

The Sustainability Assessment showed that the ATJ plant is CO_2, neutral but the current ethanol plant is severely affected by the unavailability of sustainable power for the production process, namely electricity and natural gas. A transition from fossil to sustainable heat and power on the national level will contribute to a significant improvement of GHG emissions savings from the current ethanol plant. A finding was the importance of using renewable energy both in the ethanol production and in the ATJ process. It was shown that, with future electricity generation mixes with an increased proportion of renewables, significant GHG mitigation, up to 67% as compared to conventional fossil fuels, can be reached. With further improvements of replacing the natural gas with a sustainable alternative for the current ethanol production, e.g. producing steam from renewable energy, GHG emission reductions of ~95% can be achieved.

Based on the results of this study, the recommendation is made to encourage retrofitting of existing ethanol production plants with ATJ processes to accelerate the availability of SAF volumes on the European market. Furthermore, the results of the present work are expected to provide useful information to policy makers for developing and proposing appropriate energy and environmental policies that will encourage the implementation of clean energy technologies at a European level, so as to minimize the environmental footprint of the aviation sector.

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