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Sustainable aviation fuels – Options for negative emissions and high carbon efficiency

Johan Ahlström [a,*], Yawer Jafri [b], Elisabeth Wetterlund [b,c], Erik Furusjö [a,b]

[a] RISE Research Institutes of Sweden, Stockholm, Sweden
[b] Department of Energy Science, Division of Energy Engineering Technology, Luleå University of Technology, Luleå, Sweden
[c] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

A B S T R A C T

Mitigating the climate impact from aviation remains one of the tougher challenges in adapting society to fulfill stated climate targets. Long-range aviation cannot be electrified for the foreseeable future and the effects of combusting fuel at high altitude increase the climate impact compared to emissions of green-house gasses only, which further limits the range of sustainable fuel alternatives. We investigate seven different pathways for producing aviation biofuels coupled with either bio-energy carbon capture and storage (BECCS), or bio-energy carbon capture and utilization (BECCU). Both options allow for increased efficiency regarding utilization of feedstock carbon. Our analysis uses process-level carbon- and energy balances, with carbon efficiency, climate impact and levelized cost of production (LCOP) as primary performance indicators.

The results show that CCS can achieve a negative carbon footprint for four out of the seven pathways, at a lower cost of GHG reduction than the base process option. Conversely, as a consequence of the electricity-intensive CO_2 upgrading process, the CCU option shows less encouraging results with higher production costs, carbon footprints and costs of GHG reduction. Overall, pathways with large amounts of vented CO_2, e.g., gasification of black liquor or bark, as well as fermentation of forest residues, reach a low GHG reduction cost for the CCS option. These are also pathways with a larger feedstock and corresponding production potential. Our results enable a differentiated comparison of the suitability of various alternatives for BECCS or BECCU in combination with aviation biofuel production. By quantifying the relative strengths and weaknesses of BECCS and BECCU and by highlighting cost, climate and carbon-efficient pathways, these results can be a source of support for both policymakers and the industry.

1. Introduction

Global CO_2 emissions from aviation amounted to 1.9% of the total green-house gas (GHG) emissions in 2020 (Ritchie, 2020). However, owing to the presence of the so-called high-altitude effect, aviation fuels create an additional global warming effect, and aviation is therefore responsible for 3.5% of the effective radiative forcing (Lee et al., 2021) (Lund et al., 2017). Although these numbers might appear small in relation to emissions from other parts of the society, technical limitations entail that aviation is one of the more complex sectors to readjust towards reduced climate impact. If the climate obligations specified in the Paris Agreement are to be reached, emissions from all sectors need to become net zero by 2050 (Schleussner et al., 2016).

Several complex mechanisms contribute to the high-altitude effects, which are caused by the combustion of fuel at high altitudes. The most prominent warming mechanism is the formation of contrail cirrus, which are essentially high-altitude clouds made up of ice crystals that are formed when steam condenses on the aerosols caused by the combustion of jet fuel (Jungbluth and Meili, 2018 Nov 19). To further complicate the overall mechanisms, several of the mechanisms cause both a cooling and warming effect, depending on temperature, time, and other factors. Although some of the high-altitude effects have a short lifetime, research also suggests that the long-term effects are severe. For instance, studies have shown that contrail cirrus also remains an important part of the long-term climate impact, at around 15% over a 100-years' time span (Lund et al., 2017).

Abbreviations: ATJ, Alcohol-to-Jet; BECCS, Bioenergy Carbon Capture and Storage; BECCU, Bioenergy Carbon Capture and Utilization; BL, Black liquor; CAPEX, Capital Expenditure; CCS, Carbon Capture and Storage; CCU, Carbon Capture and Utilization; DFB, Dual Fluidized Bed; EU ETS, European Emission Trading System; FR, Forest Residues; FT, Fischer-Tropsch synthesis; GHG, Green House Gas; GWP, Global Warming Potential; HDO, Hydro deoxygenation; HEFA, Hydro processed Esters & Fatty Acids; HP, hydropyrolysis; IEA, International Energy Agency; IPCC, International Panel on Climate Change; LCA, Life-Cycle Assessment; LCOP, Levelized Cost of Production; LPG, Liquefied Petroleum Gas; OPEX, Operational Expenditure; RED II, European Renewable Energy Directive; RFI, Radiative Forcing Index; RWGS, Reversed water-gas shift; SAF, Sustainable Aviation Fuel; SD, Sawdust.

* Corresponding author.
E-mail address: johan.m.ahlstrom@ri.se (J. Ahlström).

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While large parts of the transport system are expected to transition towards fulfilling climate obligations by increased electrification, e.g., battery electric vehicles (Schiffer and Manthiram, 2017 Sep 6), this option is not currently available for commercial aviation (Moua et al., 2020). Limitations in battery capacity essentially leaves only one option for aviation to decrease its climate impact, namely renewable liquid fuels, produced either from biological feedstock (biofuels) or from electricity (electro-fuels/power-to-fuels, including liquidized hydrogen), such fuels can be commonly called sustainable aviation fuels (SAF) (Chiaramonti, 2019 Feb 1). The International Energy Agency (IEA) estimates that the share of SAF in aviation needs to be more than 15% by 2030 if we are to fulfill announced policy pledges (net zero emissions scenario) (International Energy Agency (IEA) 2021).

Besides avoiding fossil GHG emissions, an additional benefit with SAF is the potentially lower high-altitude effect. The combustion chemistry of aviation biofuels and aviation electro-fuels is different from their fossil counterparts and some recent findings indicate that combustion of aviation biofuels generates fewer particles and aerosols that contribute to high-altitude effects. Voight et al. compared the formation of contrail cirrus from operation of an Airbus A320 (short to mid-range flights) on standard jet fuel and on low aromatic sustainable aviation fuel blends (Voigt et al., 2021). Their results show that burning sustainable aviation fuels can lower the formation of soot and ice concentrations with 50–70%, which, in turn, will lower the high-altitude climate impact. Similar conclusions were drawn by Tran et al. (2020); Narcisoand de (2021) and Grewe et al. (2017).

Owing to the political complexity of cross-border policy, aviation is one of the sectors of transportation least affected by current policy incentives. In the EU, jet fuels up until now have been completely exempt from taxation. The European Emission Trading System (EU ETS) has covered aviation since 2012, although the impact on emission mitigation through demand-side reductions has been insignificant (The European Commission 2021; Oesingmann, 2022). Under its 'Fit for 55′ package, the European Commission has recently set out a draft of new plans for reducing aviation emissions (Von der Leyen, 2021; European Commission 2021). Specific measures include the ReFuelEU aviation proposal for accelerating the uptake of SAF, a revision of the EU ETS scheme intended to progressively phase out the free allocation of allowances, and the introduction of a minimum tax rate on fossil jet fuels for intra-EEU passenger flights, responsible for 40% of the EU's aviation emissions (EUROCONTROL 2021). Some individual member states have implemented national policy measures to accelerate the phase-out of fossil jet fuels. In Sweden, an emission reduction obligation was introduced in 2021, which stipulates a gradual phase-in of SAF in blends with fossil jet fuels, starting at 0.8% GHG reduction in 2021, and gradually increasing to 27% by 2030 (The Swedish Government 2021). To provide additional support for SAF, landing and takeoff tariffs have also been adjusted according to the climate impact of the used fuel (the Swedish Confederation of Transport Enterprises (Transportföretagen) 2021).

The rather modest policy incentives for development of fossil-free aviation have entailed that the development of aviation biofuels has been slower than the development of road biofuels. However, by 2040 it is likely that biomass will be used for production of SAF (Fosilfritt Sverige 2021). According to the IEA World Energy Outlook 2021, total aviation biofuel will have to amount to 3 mboe/day (million barrel of oil equivalent, 126 TJ/day) by 2050 in order to reach the net zero emission scenario (International Energy Agency (IEA) 2021). Bauen et al. estimated that, depending on growth scenarios, between 3 and 13 million tons (130–561 TJ) of SAF can be produced globally by 2030 (Bauen et al., 2018). They pointed out that to achieve this development, production and use of aviation biofuels must have overcome technical and market entry barriers by 2030.

The current discussion regarding how much biomass can be sustainably procured and used highlights the need for high conversion and carbon efficiency; ensuring that the carbon atoms in the biomass are used to as large a degree as possible (see e.g. (Emma, 2020), (f3 The Swedish knowledge center for renewable transportation fuels 2021)). In thermochemical biofuel production processes a part of the feedstock is generally combusted to generate heat for the biomass conversion; hence part of the feedstock carbon is vented as CO_2. Likewise, in fermentation-based biofuel production processes, CO_2 is generated as a consequence of the fuel conversion process. A clear opportunity to address this issue is through capture and utilization of vented CO_2 (CCU), where additional biofuel product is generated through the reaction of electrolysis hydrogen with the CO_2. Furthermore, separation and storage of the vented CO_2 (BECCS) (Vergragt et al., 2011) creates an opportunity to balance the additional global warming attributed to the high-altitude effect (Lund et al., 2017). Using BECCS to compensate for the climate impact of contrails has been highlighted, e.g., by (Åkerman et al., 2021). There is a multitude of techno-economic studies on aviation biofuel production from waste streams, crops and biomass (e.g., (Dahal et al., 2021), (Atsonios et al., 2015)). In the literature, the need for both BECCS, electro-fuels/CCU as well as a large-scale production of SAF from renewable feedstock has been emphasized. However, to our knowledge, no extensive comparison of different production pathways combined with either CCS or CCU has to date been performed.

This work presents an assessment of seven different technology pathways for producing SAF by combining aviation biofuel production with CCS or CCU. The technologies include conventional as well as novel processes, where SAF are produced through processes such as Fischer-Tropsch (FT) and alcohol-to-jet (ATJ) syntheses. When CCS is used, the CO_2 generated in the processes is captured and stored permanently. Under the CCU option, the CO_2 generated is captured and upgraded to biofuels through a process based on reversed water-gas shift (RWGS) and FT synthesis (König et al., 2015). Process models from the literature are adapted for this study and used to compile the mass and energy balances of the considered processes. Thereby, it is possible quantify the increase in carbon utilization and how production costs and climate impact are affected when adopting the processes with CCS or CCU.

The primary aim is to compare the specific pathways' suitability for CCS and CCU from a carbon efficiency, cost and climate perspective. Secondary, the aim is to, in a more general sense, study different aspects of cost and GHG performance, such as the possibility to produce negative emissions biofuels while accounting for high-altitude effects on global warming. The results also enable a more general discussion and comparison between BECCS and BECCU integrated with SAF production, where the eventual possibility of negative emissions from BECCS can be put in relation to efficient use of carbon for fuel production. Finally, this research quantifies the cost and climate performance of several SAF production routes with coherent assumptions to allow for comparison. To the best of our knowledge, no such study has been published previously.

2. Methodology

2.1. Examined aviation biofuel production pathways

A list of the aviation biofuel pathways examined in this work is presented in Table 1. An overview with information on biomass feedstock types, biofuel products and principal conversion steps is provided in Fig. 1.

Three different categories are used to classify the pathways based on their main conversion technology: *Gasification based pathways, hydrotreatment based pathways* and *Fermentation based Pathways.* The first parts of the abbreviations are based on the feedstock type, **BL** for black liquor, **Bark, FR** for Forest Residues, **Tallow, Wheat**, and **SD** for sawdust. The second part of the abbreviation describes the final upgrading technology, **FT** for Fischer-Tropsch, **HP** for hydropyrolysis, **HDO** for hydrodeoxygenation and **ATJ** for alcohol-to-jet. Except for Wheat-ATJ all pathways use feedstocks that can be considered residual.

Table 1
Abbreviations and descriptions of the aviation biofuel production pathways considered.

Abbreviation	Description
Gasification based pathways	
1a (BL-FT)	Synthetic jet kerosene from black liquor gasification and FT synthesis
1b (Bark-FT)	Synthetic jet kerosene from bark by circulating fluidized bed gasification and FT synthesis
Hydrotreatment based pathways	
2a (FR-HP)	Synthetic jet kerosene from forest residues by hydropyrolysis
2b (Tallow-HDO)	Synthetic jet kerosene from tallow by hydrodeoxygenation
Fermentation based pathways	
3a (Wheat-ATJ)	Synthetic jet kerosene from wheat by fermentation to ethanol and ATJ
3b (SD-ATJ)	Synthetic jet kerosene from sawdust by fermentation to ethanol and ATJ
3c (FR-ATJ)	Synthetic jet kerosene from forest residues by fermentation to isobutanol and ATJ

2.2. Study overview

This study evaluates the performance of seven pathways towards the production of SAF under three process options, each signifying a different approach to the treatment of residual carbon streams. Pathways that met one or both of the following conditions were prioritized: (a) based on feedstocks with significant potentials in a northern European context, with a particular emphasis on residues and by-products of the forestry industries, (b) where the principle conversion steps are at a relatively high TRL levels, with a particular emphasis on pathways that are currently certified for drop-in SAF production in accordance with ASTM requirements. Performance was defined in terms of *carbon efficiency* as a measure of biogenic resource utilization performance, *climate impact* as a measure of climate performance, *biofuel production cost* as a measure of economic performance, and *GHG reduction cost* as a combined measure of climate and economic performance.

The *base option* constitutes a comparative baseline for the other two process options, without capture of residual streams of carbon from the biofuel production. CO_2 is separated out from the main process in concentrated streams in the two gasification and the three fermentation pathways. All pathways also generate streams in which CO_2 is found in dilute form, e.g., in flue gas. Diluted CO_2 streams require investment in additional separation equipment to enable CCS and CCU. The *CCS option* was designed to study the capture of residual CO_2 with subsequent transport to an offshore permanent storage location by ship or by truck and ship. The *CCU option* was designed to upgrade the carbon captured to synthetic jet kerosene, diesel and petrol through a process based on reverse water gas shift and FT synthesis (not optimized for jet fuel yield). The process generates a biofuel mix containing substantial quantities of hydrocarbons in the diesel and petrol range, which must be separated out through distillation. It should be emphasized that for the *CCU option,* secondary CO_2 streams were used to increase the SAF production of a given pathway. BECCU pathways using CO_2 as a primary resource for production of electro-SAF were not considered.

Source references for process data and design choices are provided in Table 2. Note that the feedstock input to each pathway was kept the same under the base, CCS and CCU options, to generate a consistent frame of reference for easier comparison. Further details on the assumptions and data used for modeling the biofuel pathways and the BECCS and BECCU configurations are provided in the next two sections.

2.3. Biofuel pathway process models

Production scales and process configurations for process models were based on a survey of techno-economic literature and were intended to be representative of future commercial implementations. Carbon and energy balances are reproduced in full in the Supplementary Material.

Biofuel pathways are typically composed of multiple processing steps, which can be broadly classified into two stages. The biomass feedstock is, in the first stage, converted to an intermediate product of a type that can easily be upgraded to a biofuel product in a second stage. Where possible, a single source was used for modeling all the steps in a process configuration. When use of multiple sources was required, a standard set of thermochemical and compositional data was used to reduce the inconsistencies created by using different sources.

2.3.1. Gasification based pathways

Simplified schematic overviews of 1a (BL-FT) and 1b (Bark-FT) are shown in Fig. 2.

1a (BL-FT) plant was considered co-located and integrated with a

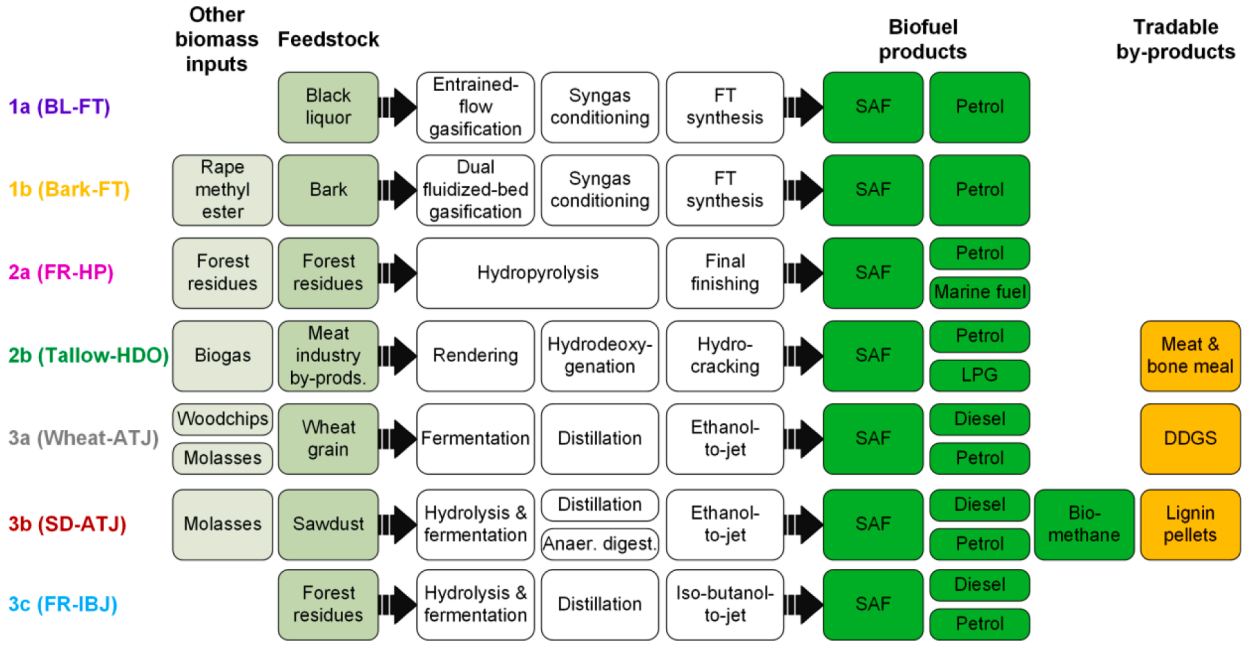

Fig. 1. Overview of the av SAF pathways.

Table 2
Principal references and key design parameters for pathway process models under the base, CCS & CCU options.

	Integration (Type of Industry)	Feedstock Input [LHV MW]	CO_2 Capture Streams Yes/No [Quantity]		CO_2 Transport		Reference Studies
			Concentrated	Dilute	Truck	Ship	
1a (BL-FT)	Yes (Pulp Mill)	92.8[a]	Yes [1]	Yes [1]	No	Yes	(Jafri et al., 2020; RISE Research Institutes of Sweden 2021)[b]
1b (Bark-FT)	No	533	Yes [1]	Yes [1]	No	Yes	(RISE Research Institutes of Sweden 2021; Ahlström et al., 2019)[c]
2a (FR-HP)	Yes (Crude Oil Refinery)	107	No	Yes [1]	No	Yes	(Meerman and Larson, 2017; Jafri et al., 2019)[d]
2b (Tallow-HDO)	Yes (Rendering Plants, Oil Refinery)	1262[e]	No	Yes [1]	No	Yes	(Danish Energy Agency, Energinet 2021)
3a (Wheat-ATJ)	No	240	Yes [1]	Yes [1]	Yes	Yes	(Joelsson et al., 2016; Geleynse et al., 2018)[f]
3b (SD-ATJ)	No	132	Yes [2]	Yes [1]	Yes	Yes	(Geleynse et al., 2018; Haus et al., 2020)[g]
3c (FR-ATJJ)	No	132	Yes [1]	Yes [1]	Yes	Yes	(Geleynse et al., 2018; Tao et al., 1)[h]

[a] The biofuel plant in 1a (BL-FT) would be operated in parallel with a recovery boiler and was sized for a scenario in which the thermal load on the recovery boiler is the same as under normal operation but with an increase of the pulping capacity. See (Jafri et al., 2020) for more information.

[b] Data for black liquor gasification was taken from (Jafri et al., 2020) while data for Fischer-Tropsch synthesis was provided by RISE Research Institutes of Sweden AB (RISE Research Institutes of Sweden 2021).

[c] Data for bark gasification and syngas cleaning was taken from (Ahlström et al., 2019) and for Fischer-Tropsch synthesis from (RISE Research Institutes of Sweden 2021).

[d] Balances in (Jafri et al., 2019) were modified to account for the absence of energy integration, with (Meerman and Larson, 2017) being the original reference. Integration with the crude oil refinery was limited to the delivery of the hydrotreatment products to the refinery for final processing and blending.

[e] Throughput of animal by-products that yield 888 MW LHV of tallow and 375 MW LHV of meat and bone meal.

[f] (Joelsson et al., 2016) for wheat-to-ethanol and (Geleynse et al., 2018) for ethanol-to-jet fuels.

[g] (Haus et al., 2020) for sawdust-to-ethanol and (Geleynse et al., 2018) for ethanol-to-jet fuels.

[h] (Tao et al., 1) for forest residues-to-isobutanol and (Geleynse et al., 2018) for isobutanol-to-jet fuels.

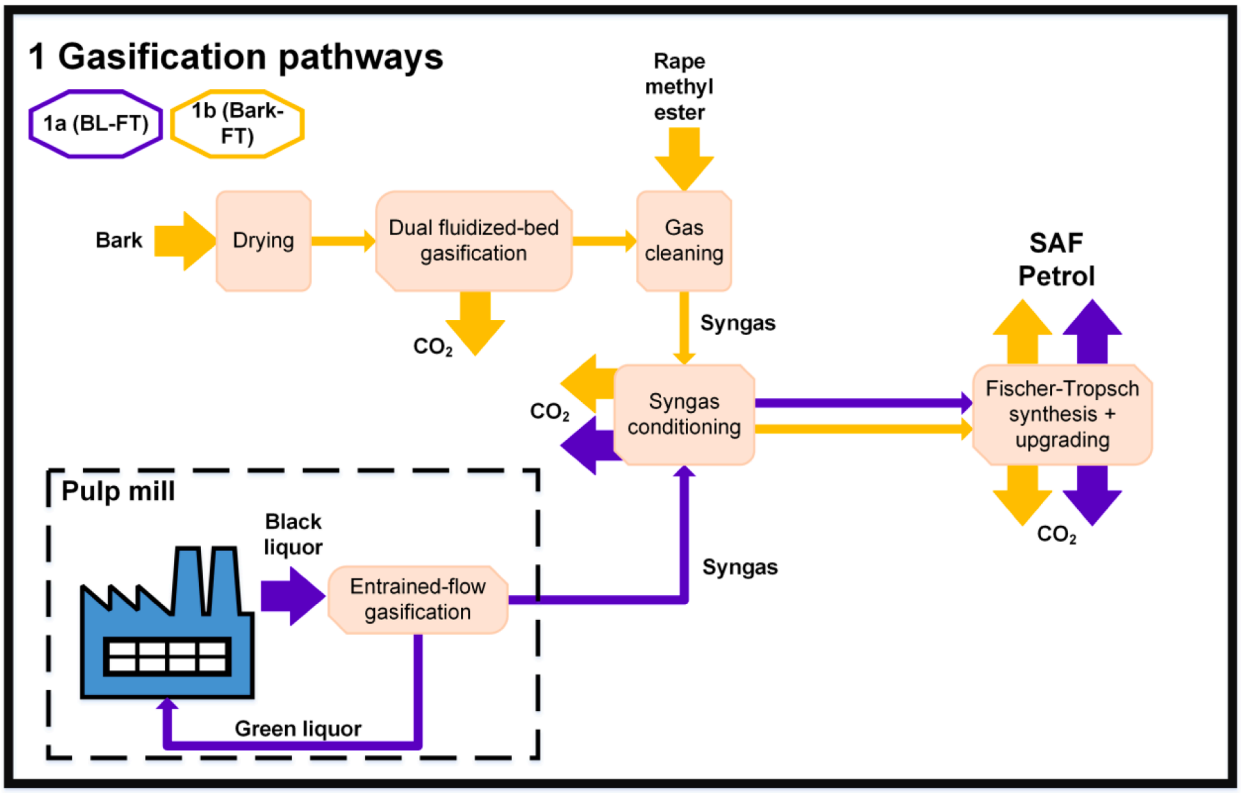

Fig. 2. Simplified schematic overviews of the gasification pathways with biogenic carbon outflows outlined by green arrows. Only biogenic carbon flows are shown. Dashed lines indicate physical boundaries. More details are available in the Supplementary Material.

market pulp mill with access to a sea harbor. Exchange of both material and energy between the plant and the mill is extensive. The pulping chemicals in the black liquor are recovered and returned to the mill for reuse. The BL-FT plant was sized to process 18.5% of the black liquor processed by the recovery boiler of a model state-of-the-art market pulp mill, with a pulping capacity of 2000 t/d. The recovery boiler throughput was kept the same by increasing the pulping capacity (see (Jafri et al., 2020) for more information).

1b (Bark-FT) was modelled as a stand-alone plant with access to a sea harbor and was sized to process approximately 3000 t/d of bark on an as received basis, which was deemed to be the inflection point for feedstock logistics and availability (Thunman et al., 1).

2.3.2. Hydrotreatment based pathways

Simplified schematic overviews of 2a (FR-HP) and 2b (Tallow-HDO) are shown in Fig. 3.

2a (FR-HP) was modelled as a plant with access to a sea harbor located by an existing crude oil refinery without energy integration, but with certain material integration. It was assumed that the final refining and blending of the liquid hydrocarbon products from the hydropyrolysis process could take place at the crude oil refinery in existing units. Aviation fuel was approximated as petrol, due to lack of specific data. The 2a (FR-HP) plant was sized for a forest residue throughput of 1000 t/d on an as received basis, based on the size of the planned hydropyrolysis-based biorefinery in Åmli in Aust-Agder, Norway (International, 2019).

The process configuration in the source reference (Meerman and Larson, 2017) was based on the IH_2 (integrated hydropyrolysis and hydroconversion) concept described by Marker et al. (2013). The share of synthetic jet kerosene in the hydrocarbon product pool was based on the operation of the IH_2 technology in the so-called "jet mode" as presented by Bauldreay (Bauldreay, 2018). 40–50% of the hydrocarbon product in the "jet mode" consists of a naphtha cut, which for this work was treated as petrol, 35–40% of a jet cut, which for this work, was treated as synthetic jet kerosene, and 10–20% of a marine distillate cut, which for this work was treated as marine fuel. The shares of petrol, synthetic jet kerosene and marine fuel were here set at 50%, 30% and 20%, respectively. The shares were cross-checked against the ASTM D2887 boiling curves for the hydropyrolysis products in (Roberts et al., 2015) and were found to be in reasonable agreement.

The 2b (Tallow-HDO) plant was modelled as a large facility co-located and integrated with a crude oil refinery with access to a sea harbor. It was designed to be similar in size to future commercial plants based on the ranges provided in (Danish Energy Agency, Energinet 2021). The hydrocarbon product mix is dominated by jet fuels (76.3% on mass basis) with petrol (9.6%) and LPG (14.1%) as by-products. The excess energy gasses and 15% of the heat produced in the hydrotreatment processes at the biofuel plant were assumed to replace an equal amount of heat from the combustion of natural gas in the refinery (Danish Energy Agency 2017) (Jafri et al., 2020).

2.3.3. Fermentation based pathways

Simplified schematic overviews of 3a (Wheat-ATJ), 3b (SD-ATJ) and 3c (FR-ATJ) are shown in Fig. 4.

Ethanol plants were considered to be set up as stand-alone plants in an inland location, to maximize local uptake of feedstock (wheat, sawdust, or forest residues), with synthetic jet fuel, petrol and diesel as the final products from the ATJ process. The input of wheat grain to 3a (Wheat-ATJ) was set to 1417 t/d on an as received basis, in accordance with the source reference and Lantmännen Agroetanol's commercial facility near Norrköping, Sweden (Andersson, 2015). The input of sawdust to 3b (SD-ATJ) at 1200 t/d on an as received basis corresponds to ~10% of the Swedish sawdust potential and was the same as that in the source study (Haus et al., 2020).

The 3c (FR-ATJ) plant was modelled with two boilers – a biomass boiler for the forest-residue to isobutanol stage, and an electric boiler for the isobutanol to jet fuel stage, with the latter also supplying the heat requirements of CO_2 capture under the CCS option. The input of forest residues to 3c (FR-ATJ) was scaled to be the same as the input of sawdust to the 3b (SD-ATJ) plant, on an energy basis. The electric boiler was not needed under the CCU option since the excess heat generated during the upgrading of CO_2 to synthetic jet kerosene was enough to meet the heat requirement.

The forest residue-to-isobutanol stage in 3c (FR-ATJ) was modelled with data from the upgrading of cellulosic corn stover by Tao et al. (2014). Their study was deemed to provide the best compromise

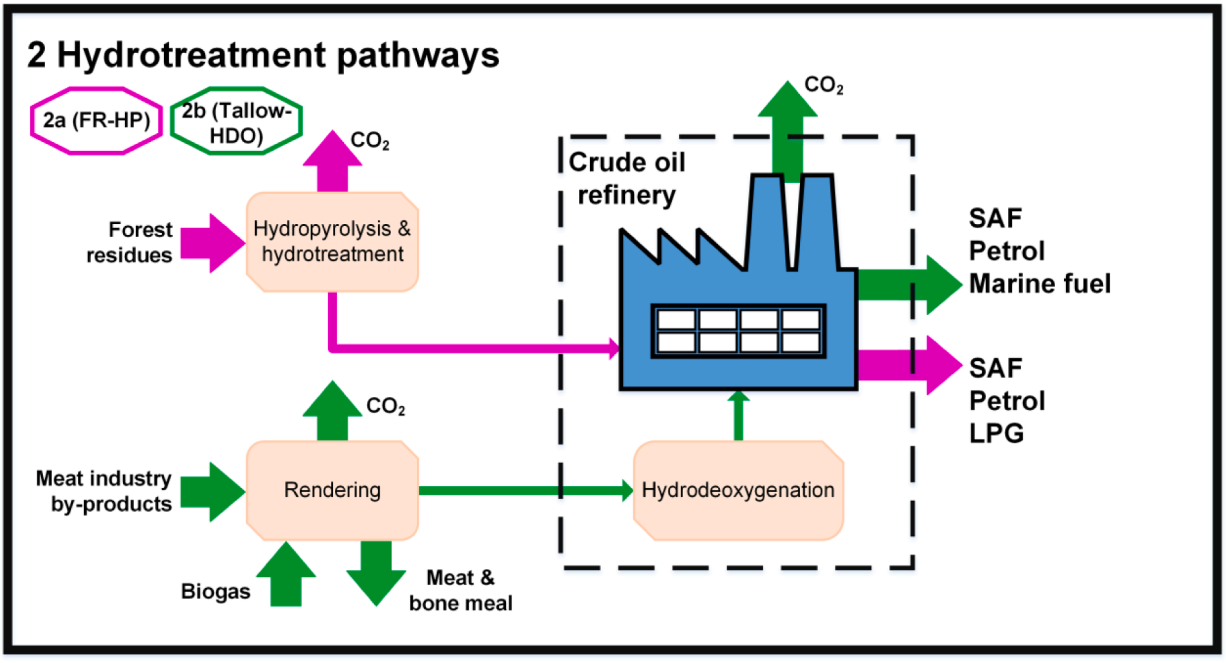

Fig. 3. Simplified schematic overviews of the hydrotreatment pathways with biogenic carbon outflows outlined by green arrows. Only biogenic carbon flows are shown. Dashed lines indicate physical boundaries. More details are available in the Supplementary Material.

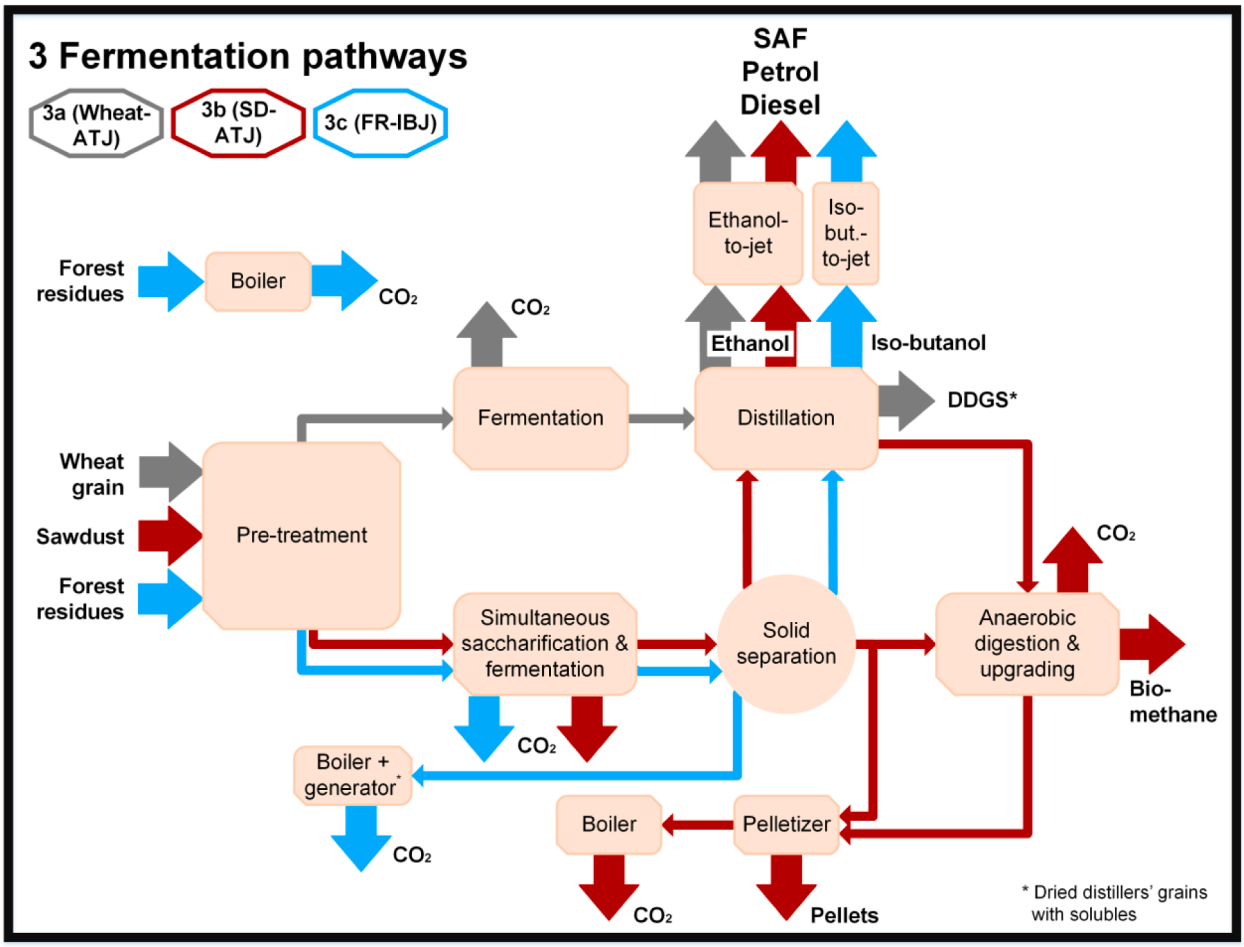

Fig. 4. Simplified schematic overviews of the fermentation pathways with biogenic carbon outflows outlined by color coded arrows. Gray arrows represent the 3a pathway, red arrows the 3b pathway, and blue arrows the 3c pathway. Only biogenic carbon flows are shown. More details are available in the Supplementary Material.

between completeness and fullness of process data on the one hand, and closeness of the feedstock (forest residues) on the other. The CO_2 produced in the isobutanol production step was here estimated following a simplified approach, where approximately two-thirds of the isobutanol obtained was assumed to originate from the glucan fermentation route, and one-third from the xylan fermentation route. The resulting CO_2 yields are consequently uncertain and only appropriate as a first approximation.

2.4. *Modelling assumptions for CO_2 capture, transport & upgrading*

The modeling assumptions for CO_2 capture and transport were developed jointly with a study on BECCS and BECCU for road biofuels by the authors (Jafri et al., 2021). A summary of the most important assumptions is provided below, and readers are directed to the aforementioned study for further details and references.

The CO_2 streams produced during the conditioning of syngas, the upgrading of biogas, and during fermentation were classified as high purity 'concentrated' streams. The concentration of CO_2 in these streams was assumed to be 100% and they could therefore be processed for storage or for upgrading without the need for separation or further treatment. Low purity or 'dilute' CO_2 streams were divided into three categories for the purpose of estimating the utility demand of carbon capture, as summarized in Table 3. The capture rate was set at 85% for all types of streams. The utility demand for carbon capture was primarily satisfied with excess heat and/or electricity from the biofuel processes. Where this was not possible, electricity imported to the plant was used.

As shown in Table 4, the share of diluted CO_2 flow in relation to the total flow differs significantly between the processes, with 12% diluted CO_2 for the BL-FT process and 100% diluted CO_2 for the FR-HP and Wheat-ETJ pathways. Capturing CO_2 from diluted streams requires investing in process equipment, which in turn increases the investment

Table 3
Electricity and heat demand for capturing dilute CO_2 streams using monoethanolamine (MEA) as solvent.

Dilute Stream	Electricity [MJ/kg CO_2]	Heat [MJ/kg CO_2]	Capture Rate [%]	CO_2 Concentration [% mol]	References
Biomass boiler	0.0870 (Pröll and Zerobin, 2019)	3.76 (Sagues et al., 2020; Onarheim et al., 2015)	85 (Onarheim et al., 2015)	15.5	Post-combustion (Pröll and Zerobin, 2019; Sagues et al., 2020; Onarheim et al., 2015)
Refinery fuel gas	0.341 (IEAGHG 2017)	4.00 (Onarheim et al., 2015)	85	8	Post-combustion (Onarheim et al., 2015; IEAGHG 2017; Roussanaly et al., 2017)
Methane reforming	0.126 (IEAGHG 2017)	3.60 (Onarheim et al., 2015)	85	24	Mixed (Onarheim et al., 2015; IEAGHG 2017)

Table 4
Share of diluted CO_2 in relation to the total amount of available CO_2 for each pathway, under the CCS and CCU options. .

	1a (BL-FT)	1b (Bark-FT)	2a (FR-HP)	2b (Tallow-HDO)	3a (Wheat-ETJ)	3b (SD-ETJ)	3c (FR-ATJ)
Share diluted CO_2	12%	65%	100%	100%	44%	67%	70%

cost of the plant. However, previous research by the authors indicates that the increased CAPEX of capturing dilute CO_2 might be offset by lower CO_2 distribution costs, entailing a lower cost of GHG reduction (Jafri et al., 2021). It should be mentioned that these are theoretical process designs. To fully determine the most economic option of each pathway requires a more detailed assessment, which was left out of the scope of this work.

Under the CCS option, the captured CO_2 was liquefied with a propane-based refrigeration unit at −30 °C, 15 bar(g) (Element Energy 2018). The biofuel plants for the fermentation pathways were assumed to be located 50 km inland from a harbor capable of handling CO_2 transporting ships. The CO_2 captured in these pathways was transported to the harbor in liquefied form in 40 t trucks and stored in 4500 t tanks before shipment to the storage site. The total cost of transport by truck was calculated as an annual cost, by multiplying the total number of annual trips by a specific cost per km (0.86 EUR/km, as applicable to a Swedish case developed by (Mikhelkis and Govindarajan, 2020)). The biofuel plants for all other pathways were treated as being located by a CO_2 transport harbor.

The choice of ship size was found to have a substantial impact on economic performance under the CCS option. Since both the production scales and the shares of feedstock carbon in residual streams varied significantly between pathways, there was a large variation in the quantities of CO_2 that were available for capture – from ~41 kt/y for 2b (Tallow-HDO), to ~911 kt/y for 1b (Bark-FT). An overview of CO_2 transport parameters e.g., ship sizes is provided in Table 5. The reference capital cost for the 20 kt ship was from (Kler et al., 2015) and the remaining from (Element Energy 2018) and is provided in the supplementary material. Pathways able to utilize their assigned ship for 4,000 h/y or more were assumed to have their own dedicated ship. Pathways that do not produce enough CO_2 to do so were assumed to instead share the costs with other same-sized plants. A similar approach was used for allocating the costs of the platform and the storage tanks (40,000 t) moored adjacent to the storage well. The storage site was an 80% depleted offshore gas and the storage depth 1000 m (Neele et al., 2017). The mid-point estimate in (Kler et al., 2015) was used as the reference cost of the injection platform and the 40 kt temporary CO_2 storage (including offshore transport and installation).

Under the CCU option, the CO_2 captured was upgraded to a biofuel product mix made up of synthetic jet kerosene, petrol and diesel with electrolysis H_2 through reverse water gas shift and FT synthesis based on data from König et al. (2015). H_2 was considered to be produced by polymer electrolyte membrane (PEM) electrolysis with a nominal system efficiency of 60% on LHV basis (Buttler and Spliethoff, 2018; Rego de Vasconcelos and Lavoie, 2019). A summary of product yields and utility consumption is provided in Table 6. Owing to the heating demands of the FT-unit, part of the off-gasses from the separation sequence are used as fuel for heating, instead of being recirculated to the RWGS-reactor. Therefore, part of the carbon entering the FT-process is lost as flue gas. The overall carbon efficiency of the RWGS+FT process is ~75%.

Table 5
Overview of CO_2 transport parameters.

Pathway	Transported CO_2 [kt/y]	Ship Size/CO_2 Capacity [kt]	Annual Utilization [hour/y][a]
1a (BL-FT)	173	4000	5365
1b (Bark-FT)	911	20,000	5658
2a (FR-HP)	149	2000	4613
2b (Tallow-HDO)[b]	41	2000	2565
3a (Wheat-ATJ)	360	8000	5589
3b (SD-ATJ)	183	4000	5673
3c (FR-ATJ)	247	8000	3827

[a] Transport distance was set at 1200 km and the total time at sea at 128 h.
[b] The total quantity of CO_2 transported from a crude oil refinery is likely to be significantly higher since a realistic CCS implementation would be built around the capture of fossil CO_2, with the biogenic CO_2 only making up a very minor fraction. The resulting economies of scale and their impact on CO_2 transport costs were not estimated since the impact on the levelized cost of biofuel production would be minimal.

2.5. Greenhouse gas footprint

The standards specified in RED II were used to calculate the GHG footprint of each pathway from well-to-wheel (usage in jet engine) (The European Commission 2021). Following the RED II standard, pathway emissions were allocated to the products of each pathway according to the refinery principle. This means that allocations are made on energy-basis until the point where streams diverge. Hence for pathways with more than one product (all studied pathways), emission allocation diverges at the part in the process where the process streams are separated. Thereby, emissions from the electricity used for H_2 production for the CO_2-to-jet process (CCU) are only allocated to the fuels produced through that process (SAF, petrol, and diesel); different emission factors are also applied for distribution of the final products. Unlike for CCU, negative emissions from CCS were allocated, on an energy basis, to all biofuel products.

An overview of the most important emission factors is presented in Table 7. In six of the pathways the feedstock is classified as a residue and therefore emissions linked to land use change and carbon accumulation from improved agricultural management were omitted.

Due to the complexity of showing the GHG footprint of every specific product of all seven pathways under all three process options, the GHG footprint is reported either as only the share of GHG emissions attributed to the aviation biofuel product, or as an average GHG footprint (on energy basis) of all biofuel products of each pathway. See the

Table 6
Product yields and utilities for CO_2 upgrading under the CCU option. Reworked from König et al. (2015)).

Stream	[a]		Notes
Hydrogen consumption	[kg/kg CO_2]	0.132	
Synthetic jet kerosene	[kg/kg CO_2]	0.105	
Petrol yield	[kg/kg CO_2]	0.075	
Diesel yield	[kg/kg CO_2]	0.060	
Electricity (Internal Use)	[MW/ $kgCO_2$]	0.740	
Steam (Internal Use)	[MW/kg CO_2]	3.44	
2.3 bar steam	[MW/kg CO_2]	0.709	Excess. Used for process demands, e.g., for heat for CO_2 capture.
8.8 bar steam	[MW/kg CO_2]	0.488	Excess. Used for process demands, e.g., for heat for CO_2 capture.
20 bar steam	[MW/kg CO_2]	2.85	Excess. Used for process demands, e.g., for heat for CO_2 capture.

[a] Presented in terms of 1 kg of CO_2 upgraded.

Table 7
Overview of GHG emission factors.

	Value	Unit	Reference [Notes]
Electricity	46.8	kg CO_2eq/MWh	(Pool, 2021) [Swedish mix]
GWP methane	32	g CO_2eq/g CH_4	(International Energy Agency 2010)
Forest biomass outtake	1.03	kg CO_2eq/MWh	(Eliasson and Johannesson, 2014)
Forest biomass transport	0.02	kg CO_2eq/MWh,km	(Åkerman et al., 2021)
Jet fuel distribution	1.51	kg CO_2-eq/MWh	(Pettersson et al., 2019)
Bio-Methane distribution	2.49	kg CO_2-eq/MWh	(Pettersson et al., 2019)
Petrol distribution	1.55	kg CO_2-eq/MWh	(Pettersson et al., 2019)
Diesel distribution	1.45	kg CO_2-eq/MWh	(Pettersson et al., 2019)
CO_2 distribution, truck	108	g CO_2eq/ton*km	(The European Commission 2021)
CO_2 distribution, ship (LNG fuel)	38	g CO_2eq/ton*km	(Brynolf et al., 1)
Wheat cultivation	50.4	kg CO_2-eq/MWh	(Börjesson et al., 2010) [Wheat-ATJ only]
Average fossil fuel footprint	333	kg CO_2eq/MWh	Used for estimating GHG reduction costs (see text)

Supplementary Material for a full breakdown of the GHG footprint evaluation.

2.5.1. *High-Altitude effect*

Although the effects of high-altitude emissions clearly have an impact on the GHG footprint of bio jet fuels, we have not been able to find specific GWP factors concerning the different bio jet fuels considered in this work. Owing to the lack of consistent data for how to handle the GWP of high-altitude effects, several LCA studies of bio jet fuels simply do not account for them at all, e.g. (Lokesh et al., 1; Budsberg et al., 2016). As mentioned in the introduction, recent literature has concluded that it is likely that the GHG footprint caused by high-altitude effects is lower for bio jet fuels than for fossil jet fuel. However, little is said about long-term effects. Therefore, specific representation of the GWP of high-altitude effects from bio-jet fuels has not been included in this work. Rather, a sensitivity analysis was carried out to account for high altitude effects without specifically assessing the combustion of the fuel generated in the different pathways. Thereby, a broader perspective on the climate impact of SAF has been provided and examined.

The central assumption here assumed GWP values corresponding to an increase in the GHG footprint of FT and hydrotreatment-based aviation biofuel with 69.8 g CO_2eq/MJ and alcohol-based aviation biofuel with 70.9 g CO_2eq./MJ (Cavalett and Cherubini, 2018). As no specific value for hydrotreatment-based aviation fuels was provided in Cavalett and Cherubini (2018), it was assumed that their fuel chemistry more resembles that of FT-based fuels, than that of fermentation-based fuels. The sensitivity case assumed a 30% reduction in the GWP values. It is important to acknowledge that the GWP of the high-altitude effect is dependent on the usage of the fuel product and should not be attributed to production of the fuel in itself. For that reason, the term climate impact was used to describe the combined GWP from production of the fuel and the high-altitude effect from using it.

Naturally, the total high-altitude effect will differ between flight routes, depending on the time spent at high altitude. The share of total flight time spent above an altitude where there is an additional warming effect will differ depending on, e.g., length, speed, and flight planning. It is also important to emphasize that there are other options to decrease the high-altitude effect of aviation, for instance implementation of route optimization strategies. To evaluate aviation biofuels taking such effects into account would require detailed scenario analysis outside the scope of this work. The emission factors attributed to the high-altitude effect represent an average for long-distance aviation and might be both higher and lower for specific cases. Thereby, the calculations presented in this work provide an indication of the scale of the high-altitude effect in relation to the total climate impact of SAF; they should not be viewed as exact data.

2.6. *Economic evaluation*

There are companies, at various stage of development, that work on production of aviation biofuels with BECCU (see e.g. (gevo [Internet] 2022; LanzaTech [Internet] 2021)), already captured carbon can also, as well, be stored in a BECCS concept. However, large-scale commercial production is currently not available and therefore the economic assessment was carried out for an energy market scenario for the year 2030. The prices of central energy carriers such as electricity and biomass were estimated with the energy price and carbon balance scenario (ENPAC) tool (Harvey and Axelsson, 2010). Potential revenue from the sequestration of CO_2 under the CCS option was not included in the main scenario, but the impact of a CO_2 sequestration credit of 100 EUR/tCO_2 on biofuel production costs was included as a sensitivity case in the overall assessment. All prices were denominated in EUR_{2020} using exchange rates of 0.88 EUR/USD, 0.095 EUR/SEK, and 1.13 EUR/GBP. All energy flows were computed in MW_{LHV}.

Table 8
References for estimating capital expenditure.

Pathway	References	Notes
1a (BL-FT)	(Jafri et al., 2020; RISE Research Institutes of Sweden 2021)	Oxygen for gasifying black liquor was purchased on the market under the base and CCS options but was taken from the PEM electrolyzer under the CCU option. The same reference was used for the process modeling and CAPEX estimation of the gasification stage. The CAPEX for the FT stage was based on scaling the costs of individual process units.
1b (Bark-FT)	(RISE Research Institutes of Sweden 2021; Thunman et al., 1)	The same reference was used for the process modeling and CAPEX estimation of the gasification stage. The CAPEX for the FT stage was based on scaling the costs of individual process units.
2a (FR-HP)	(Tan et al., 2014) (Jafri et al., 2020).	Partly different references were used for process modeling and CAPEX estimation. It was assumed the final refining and blending of the liquid hydrocarbon products from the hydropyrolysis process could take place at the crude oil refinery in existing units without additional CAPEX and OPEX requirements.
2b (Tallow-HDO)	(Danish Energy Agency, Energinet 2021)	The same reference was used for process modeling and CAPEX estimation.
3a (Wheat-ATJ)	(Frankó et al., 2016)	The same reference was used for process modeling and CAPEX estimation.
3b (SD-ATJ)	(Haus et al., 2020)	(Haus et al., 2020) is partly based on (Frankó et al., 2016) and was used for both process modeling and CAPEX estimation.
3c (FR-ATJ)	(Geleynse et al., 2018; Tao et al., 1)	The same references were used for both process modeling and CAPEX estimation.

Table 9
Prices for selected energy and material streams. See the Supplementary Material for an expanded, annotated listing.

	ENPAC [EUR/kg]	[EUR/MWh]	Notes
Electricity [Buy]	–	49	
Electricity [Sell]	–	50	Plants exporting renewable electricity were assumed to be eligible for support and the corresponding support level (5 EUR/MWh) was included in the price.
Pellets [Sell]	–	32	Pellets from lignin and other forestry assortments.
Bio-Methane [For Industrial Heating, Producer gate price]	–	43	Based on alternative cost for the consumer, where the biogas was exempted from the energy tax according to current Swedish tax levels and avoided the EU ETS allowances at the cost level of the CO_2 emissions charge. Gate prices were calculated assuming the same distribution costs for natural gas and biogas.
Wood chips & Forest Residue [Buy]	–	29	Forest residue include tops and branches, bark, hog fuel, sawdust etc. Price of wood chips was based on the price relation between wood chips and by-products the last decade.
District Heating Water	–	28	Assuming heat replaces existing Bio-CHP
Natural Gas	–	51	Including CO_2 charge.
Fossil Petrol [Sell]	–	47	Producer gate price.
Fossil Diesel [Sell]	–	54	Producer gate price.
	Other Sources		**Assumptions and references**
	[EUR/kg]	[EUR/MWh]	
Wheat Grain	0.167	–	December 2020 price for the wheat used for ethanol production in Sweden (Niléhn, 2018; Jordbruksverket 2021).
Meat Industry By-Products	0.300	–	AO2 carcass price was chosen as an indicative reference price for tallow feedstock (PRI.EU.MAR 2021; Zagklis et al., 2020)
Bark	–	27	Bark is a forestry by-product and the price was assumed to shadow the price of forestry residue in ENPAC.
Sawdust	–	27	Sawdust is a forestry by-product and the price was assumed to shadow the price of forestry residue in ENPAC.

Estimates of capital expenditure (CAPEX) were taken from the literature. An annotated listing of references is provided in Table 8. The CAPEX calculations should be considered as indicative. Finding reliable estimates from commercial projects is difficult as many of the production pathways currently (2022) only exist in demonstration scale. Where possible, the same references were used for both the process models and the CAPEX estimates. Where such information was available, estimates were used and scaled in accordance with the methodology provided in the source studies. Data granularity and underlying assumptions, such as those related to indirect costs and balance of plant, varied between different studies. Some of the estimates were based on total capital investment (TCI) and variously included cost items such as engineering, construction, and contingency, others were based on estimates of main and auxiliary equipment costs.

PEM CAPEX was calculated with a reference value of 1000 EUR/kW (2018 USD price level) and without economies-of-scale (Jafri et al., 2020). The CAPEX estimates for the RWGS and FT-based CO_2-to-jet step was for a configuration similar to that used as the basis for the carbon and energy balances (Albrecht et al., 2017). The CO_2-to-jet TCIs compiled were modified to exclude the costs of major process either not included in the configuration studied, namely, a turbine, or estimated separately, namely, electrolyzers. The CCU options in 1a (BL-FT), 2a (FR-HD) and 3b (SD-ATJ) were scaled with references costs for the small-sized CO_2-to-jet concept. The remaining pathways were scaled with reference costs for the large-sized concept.

The scaling of costs was carried out as described in Eq. (1) (Remer and Chai, 1990):

$$C = C_0 * \frac{P_0^{SF}}{P} \quad \text{(Eq. 1)}$$

where C is the cost of the process or specific unit operation, C_0 the base cost, P_0 the base scale, and P the scale. SF is the scaling factor, which, unless otherwise specified, was set to 0.67.

The Chemical Engineering Plant Index was applied to update all cost data to 2020 monetary values (Chemical Engineering 2021):

$$C_{2020} = C_x * \frac{CEPCI_{2020}}{CEPCI_X} \quad \text{(Eq. 2)}$$

Where C_{2020} is the equipment cost in 2020 monetary value, C_x the cost at the given year x, and $CEPCI$ the cost index at year 2020 and year x, respectively.

Operational expenditure (OPEX) was classified into $OPEX_{Materials\ \&\ Energy}$ and $OPEX_{O\&M}$. $OPEX_{Materials\ \&\ Energy}$ represented energy and material costs. $OPEX_{O\&M}$ covered maintenance and personnel costs, with costs for process components expressed as a fraction of the capital cost, set at 3% for all cost components apart from intermediate and offshore CO_2 storage units, which were set at 5%, following (Element Energy 2018).

Gross margins for petrol and diesel were added to the OPEX of the FR-HP (2a) pathway, to account for the additional cost of refining bio-products in existing units that are presumed to be operating at full capacity. The Swedish Energy Agency estimated the average gross margin to be 1.52 SEK/l (9.1 kWh/l) for petrol and 1.10 SEK/l for diesel (energy density: 9.8 kWh/l) in the year 2021 (The Swedish Energy Agency 2021).

The ENPAC input data for estimating the prices of energy carriers in the year 2030 was based on the Sustainable Development (SD) scenario from the IEA's World Energy Outlook 2017 (International Energy Agency 2017). A selection of the most important energy and material prices from ENPAC and other sources is presented in Table 9, with further details provided in the Supplementary Material.

More information on the ENPAC inputs, outputs and assumptions, such as representative CO_2 emission charges for Northern Europe as well as prices for crude oil, natural gas and coal specific to this study can be found in the Supplementary Material and in (Jafri et al., 2021). Most were taken or adapted from previous work presented in Pettersson et al. (2020).

2.7. Performance indicators

The efficiency with which each pathway utilizes its feedstock carbon under each of the three process options was measured with Eq. (3):

$$\eta_{Carbon} = \frac{C_{Biofuel\ Product\ (s)} + C_{PermanentStorage}}{C_{Feedstock\ (s)}} \quad \text{(Eq. 3)}$$

Carbon in permanent storage under the CCS option, and carbon in non-aviation biofuel products under all options, was treated in the same manner as the carbon in aviation biofuel products, for the purpose of estimating the efficiency of carbon utilization in this study. This was considered reasonable since increasing the production of biofuels of all types and the sequestration of CO_2 both contribute to the reduction of

GHG emissions. With that in mind, the temporal arc for the carbon deposited in permanent storage is different from that which is upgraded to biofuels. The former is removed from the carbon cycle for millennia, while the later replace fossil equivalents.

The levelized cost of biofuel production was used as the principal measure of economic performance and was calculated as follows:

$$LCOP = \frac{CRF * CAPEX_{Total} + OPEX_{Materials\ \&\ Energy} + OPEX_{O\&M} - Revenue_{By-products}}{p * h} \quad \text{(Eq. 4)}$$

where CRF is the capital recovery factor, $CAPEX_{Total}$ the total capital investment, $OPEX_{Materials\ \&\ Energy}$ the annual operational expenditure on energy and material streams, $OPEX_{O\&M}$ the annual operational expenditure on operational personnel and maintenance, $Revenue_{By\text{-}products}$ the annual revenue from by-product sales, P the biofuel production capacity in MW_{th} with all biofuel products (aviation, road and marine) aggregated, and h the annual plant operating hours, set at 8000 for all pathways under all options. The value for the capital recovery factor (CRF) was set at 0.126, based on a real discount rate of 11% applied to the investments over a time period of 20 years.

The main measure of climate performance was the GHG footprints of aviation biofuel product fractions with and without high-altitude effects, which were quantified by allocating emissions on an energy basis in accordance with the RED II guidelines.

The emission factors taken into account for the GHG footprint consideration are presented in Eq. (5) (see also Section 2.4):

$$E = e_{ec} + e_p + e_{td} - e_{ccs} \quad \text{(Eq. 5)}$$

Where E denotes the total value-chain emissions from the production

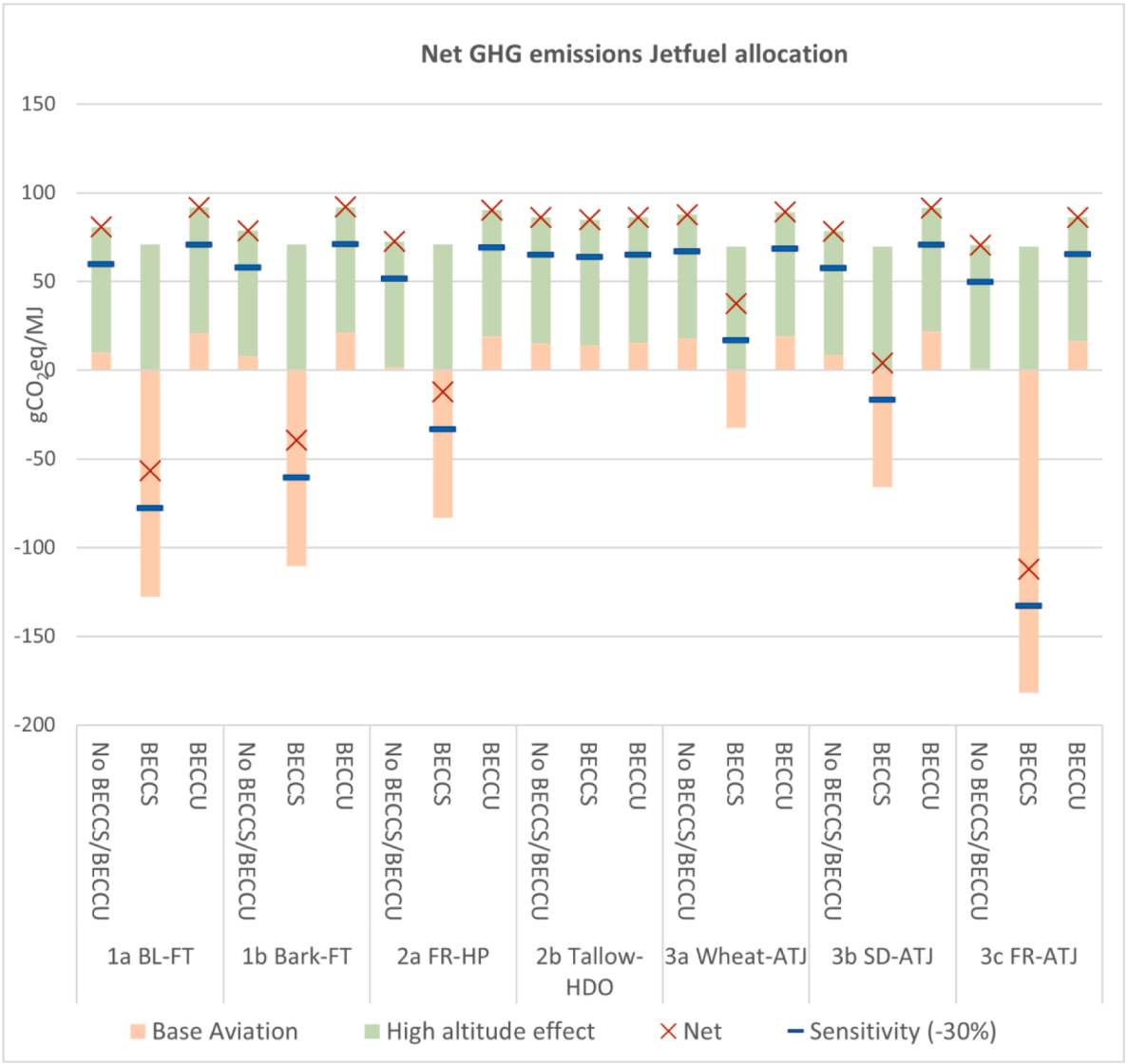

Fig. 5. Climate impact with high altitude effect and sensitivity analysis. Light red bars represent GHG footprints of the biofuels in a well-to-wheel perspective, and green bars the high-altitude effect contributions. The red X marks the net climate impact including the high-altitude effect contribution, and the blue lines the net impact for the sensitivity case (decreasing high-altitude effect with 30%).

and use of the biofuel, e_{ec} emissions from extraction and cultivation of raw materials, e_p emissions from processing the feedstock(s), e_{td} transport and distribution emissions, and e_{CCS} emissions savings from CO_2 capture and geological storage. The climate impact was then calculated according to Eq. (6)

$$Climate\ \ impact = E + ha - effect \quad \text{(Eq. 6)}$$

where E is the total value chain carbon footprint (Eq. 5), and *ha-effect* the high-altitude effect (see Section 2.5.1)

GHG reduction cost was used as a measure of the combined carbon and climate performance as defined in Eq. (7):

$$GHGReductionCost \frac{\left(AnnualProductionCost_{Biofuel} - AnnualProductionCost_{Fossil}\right)}{Climateimpact_{Fassil} - Climateimpact_{Biofuel}} \quad \text{(Eq. 7)}$$

where *Annual Production Cost*$_{Biofuel}$ is the combined annual biofuel CAPEX and OPEX, *Annual Production Cost*$_{Fossil}$ the reference fossil equivalent, calculated by multiplying the annual biofuel production capacity with the average of fossil petrol and diesel gate prices for the year 2030 (50.2 EUR/MWh) in the ENPAC SD 2030 scenario, *Climate impact*$_{Biofuel}$ the biofuel climate impact calculated according to Eq. (6) and *Climate impact*$_{Fossil}$ the reference fossil fuel GHG footprint (92.5 $gCO_2eq./MJ$) plus the aforementioned high altitude effect (same for bio and fossil aviation fuel). In calculating the *Annual Production Cost*$_{Fossil}$, the relatively small difference in the distribution costs of biofuels and fossil fuels was ignored.

3. Results and discussion

The impact of high-altitude effects on climate impact and opportunities for negative emissions SAF is covered in Section 3.1. Carbon and GHG performance under base, CCS and CCU options is shown and discussed in Section 3.2. LCOPs are presented together with climate impact in Section 3.3. Section 3.4 discusses the cheapest alternatives for decreasing GHG emissions, section discusses the LCOP under a carbon sequestration revenue for the CCS option, and Section 3.6 presents a summary of the results.

All figures use the same color scheme and markers for each pathway throughout the results (with the exception of Fig. 5). Circles represent the base option, squares the CCS option and triangles the CCU option.

3.1. Negative emission SAF & high-altitude effects

Fig. 5 displays the net climate impact for the SAF product for every biofuel pathway under all three process options (base, CCS and CCU), when accounting for high altitude effects.

The most important result is that four of the pathways, 1a, 1b, 2a and 3c, can achieve net negative climate impact for the aviation biofuel fraction under the CCS option, with pathway 3b not far off the negative mark. This result makes it clear that it is possible to operate aviation without climate impact, even when factoring in high altitude effects.

Overall, feedstock and processing emissions under the base option are in the range 1–18 g CO_2eq/MJ depending mainly on feedstock type and electricity use. In all pathways, adding the CCU option to the process increases the climate impact due to the large electricity consumption, albeit with non-noticeable levels in the 2b (tallow-HDO) pathway. The main specific contributions to the GWP potential and thus the climate impact is through the high-altitude effect, which however is similar for all pathways.

Iso-butanol to jet from forest residues (3c, FR-ATJ) offers the best possibility for negative emission biofuels with the CCS option. This is partly an effect of low emissions under the base option, but mostly due to the generation of relatively high levels of biogenic CO_2 in relation to the fuel production levels. This pathway is followed by the two gasification-based ones (1a and 1b), where relatively large volumes of CO_2 are generated in concentrated forms. The forest residue hydropyrolysis pathway (2a) also reaches net negative GHG emissions for the CCS option.

The tallow-HDO pathway (2b) is not able to yield climate-neutral SAF. Already under the base option, most of the carbon in the animal by-product feedstock ends up in either the biofuel product, or in the meat and bone meal by-product. Thus, the levels of available CO_2 are too low to make a significant difference in terms of climate impact under the CCS option. The same effect can also be observed in the CCU option, where the climate impact remains almost constant in relation to the base option.

Also for the wheat and sawdust ethanol-to-jet pathways (3a and 3b), the net climate impact remains positive under the CCS option, albeit at low levels for the sawdust pathway (3b). This is a consequence of the fact that a relatively small fraction of feedstock carbon is available in CO_2 for CCS. A substantial amount of the carbon in the feedstock ends up as a pellet by-product. Notably, 3b is the only pathway where the sensitivity analysis for the high-altitude effect has an impact on whether negative emission SAF can be obtained. A high-altitude effect contribution 30% lower than the GWPs used as the reference values would result in the pathway being able to produce negative emission SAF. As stated, (see Sections 1 and 2.5.1), previous research suggests that the high-altitude effect of bio aviation fuels is lower than for their fossil counterparts. Hence, it might be possible to generate climate neutral/positive biofuels through the ethanol-to-jet route.

3.2. Carbon & climate performance

Fig. 6 shows the climate impact (Eq. (6)) as a function of the carbon efficiency (Eq. (3)) for the base, CCS and CCU option for all seven pathways. The climate impact of the base option is relatively uniform among the different pathways, while the carbon efficiency ranges from 25 to 66%. The tallow-HDO (2b) pathway (dark green dot) clearly displays the highest carbon utilization efficiency in the base option.

Under the CCS option, the results tend to display an almost opposite trend; the carbon utilization efficiencies go up to 70–95% while the resulting climate impact become more dispersed. The, for the base option, efficient tallow-HDO process (2b), remains at a similar carbon efficiency and climate impact. Conversely, the processes that exhibit the lowest efficiencies for the base option reach among the highest carbon utilization rates and by far the lowest climate impact when CCS is implemented. The reason is, as mentioned above, that in the tallow-HDO process, most of the feedstock carbon ends up either in the aviation biofuel product, or in by-products, resulting in a negligible amount of generated sequesterable CO_2. For the FR-ATJ (3c, light blue), BL-FT (1a, dark blue) and Bark-FT (1b, yellow) pathways, the opposite is true. The carbon utilization is low in the base option owing to a large part of the feedstock being converted to CO_2 to heat the processes. When that CO_2 is stored, the carbon-utilization reaches levels close to 90%, thus generating a positive climate impact. However, for the FR-HP pathway (2a, magenta, the carbon efficiency is relatively high already in the base case. The FR-HP pathway has the second highest efficiency for the base case and, since the process does not generate any non-fuel by-products, also

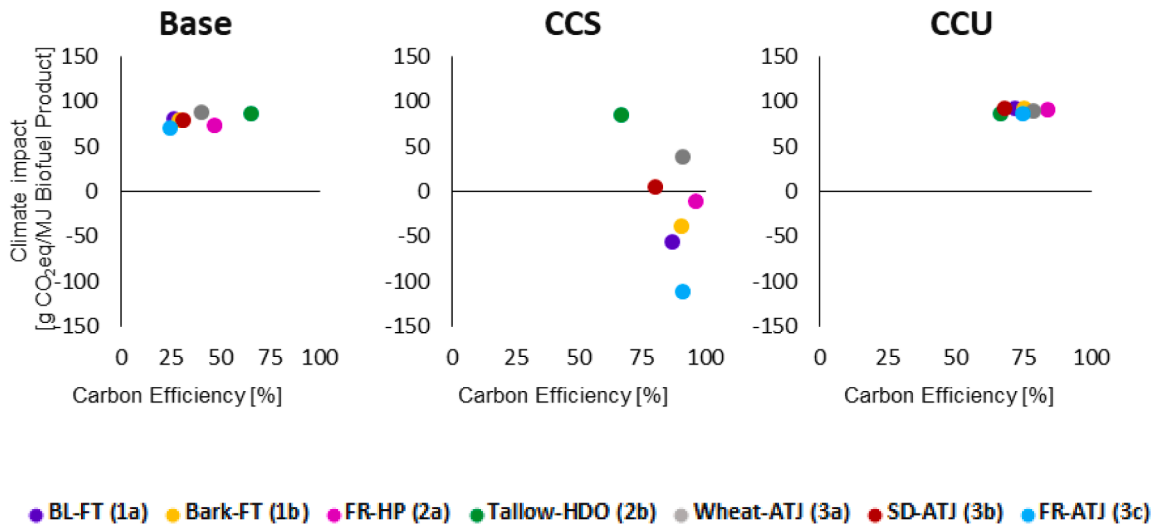

Fig. 6. Carbon efficiencies and climate impact (including the high-altitude effect contribution) under the base (circles), CCS (squares) and CCU (triangles) options.

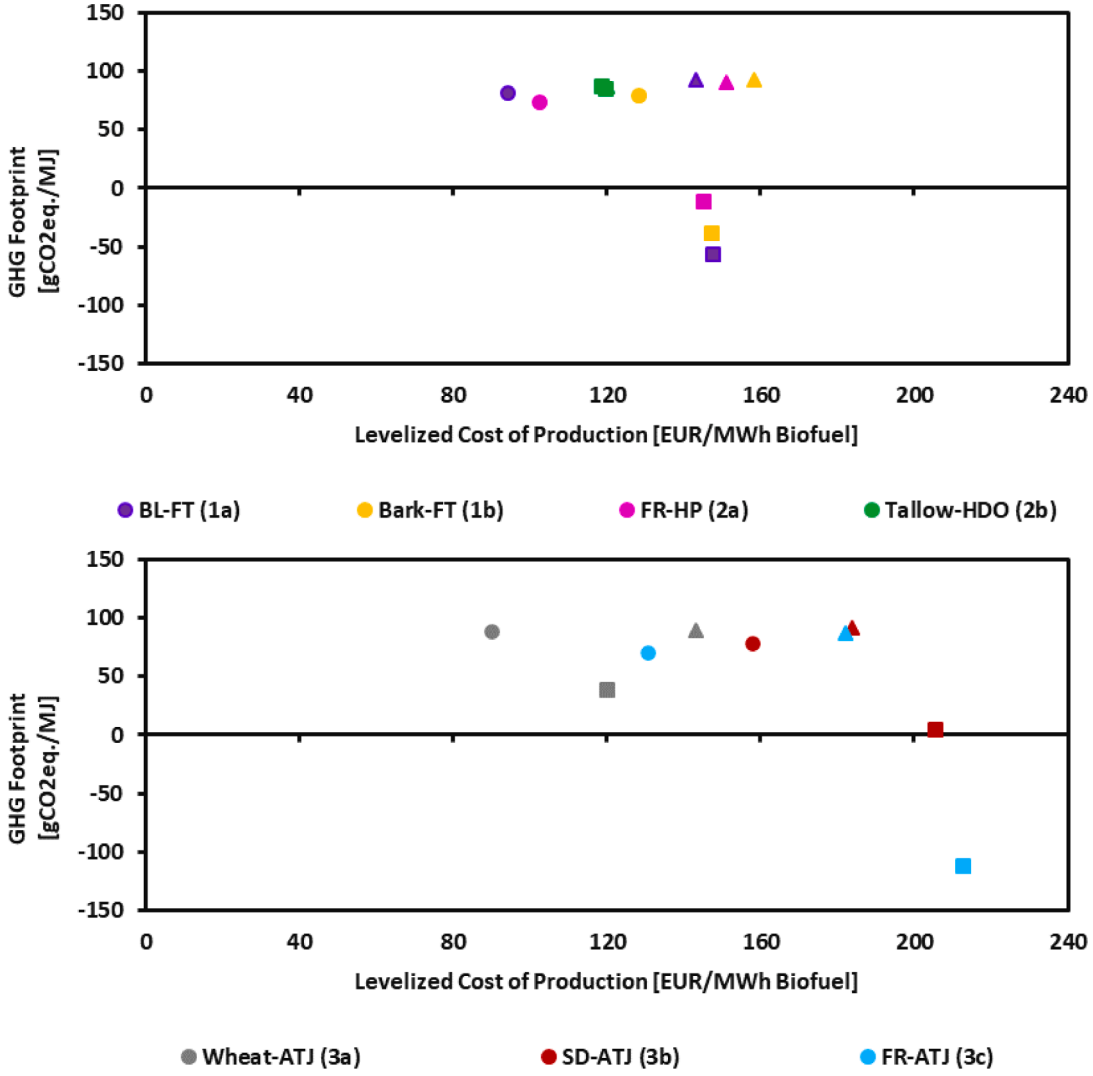

Fig. 7. Levelized cost of production and climate impact of all considered pathways under the base (circles), CCS (squares) and CCU (triangles) options. The top figure presents the gasification and hydrotreatment pathways, 1a, 1b, 2a and 2b. The bottom figure presents the fermentation pathways, 3a-3c.

large quantities of CO_2 available for CCS or CCU.

Under the CCU option, all pathways are clustered at approximately the same climate impact as for the base option, and at a slightly lower carbon efficiency than for the CCS option. The CO_2-to-jet process does have a relatively low carbon efficiency in itself; approximately 27–28% of the ingoing CO_2 is lost as flue gas, which explains the lower carbon efficiency compared to the CCS option.

With relatively high feedstock-to-biofuel conversion rates, and with substantial by-product but small capturable carbon flows, the relative increase in carbon efficiency achieved under the CCS and CCU options is minimal for SAF produced from meat processing by-products (Tallow-HDO). This is explained by the oxygen content in oil and fat feedstocks (~11 wt%). Most of the oxygen is removed as water, resulting in a high carbon and hydrocarbon yields in the hydrotreatment step. On the contrary, the feedstocks for the other pathways (biomass) have high oxygen content (30–40 wt%) with the larger part of the oxygen removed as CO_2, resulting in relatively lower yields.

From a perspective with relatively low GHG emissions from electricity production (e.g., Sweden), adopting the CCU concept allows for substantial increases in carbon efficiency, while the difference in climate impact is small. However, it is also clear that when producing aviation fuels, both the base and CCU option remains at a climate impact of between 50 and 100 g CO_2eq./MJ; the CCS option is required to deliver bio aviation fuels with both high carbon efficiency and low climate impact.

3.3. Cost performance

Fig. 7 shows the LCOP and climate impact for the gasification (1a and 1b) and hydrotreatment (2a, 2b) pathways in the top figure and for the fermentation (3a-c) pathways in the bottom figure. Circles represent the base option, squares the CCS option and triangles the CCU option. It should be observed that in contrast to other by-products, no economic value was assigned to CO_2 sequestration in these calculations. Starting with the gasification and hydrotreatment pathways (top figure); in all pathways except for BL-FT (1a), the LCOP is lowest for the base option, increases under the CCS option, and is highest under the CCU option. Also for the fermentation pathways (bottom figure), the cost is lowest for the base option, but for both SD-ATJ (3b) and FR-ATJ (3c), the cost is lower for the CCU option than for the CCS option. Wheat-ATJ (3a) displays the same trend as most of the gasification and hydrotreatment pathways.

The Wheat-ATJ (3a) pathway reach the lowest base option cost, at 90 EUR/MWh. However, whereas the 3a pathway also reaches the lowest CCS option cost (120 EUR/MWh, together with 2b), the 1a pathway has similarly low cost for the CCU option (143 EUR/MWh). The difference in cost between the CCS and CCU option is also much larger for the 3a pathway (120 and 143 EUR/MWh respectively) compared to the 1a pathway (148 and 143 EUR/MWh). The reason for this change in trend is the lower specific CAPEX for the CCU option in the 1a pathway, owing to a larger flow of CO_2. The 2b pathway actually has the lowest cost for both the CCU option and the CCS option (together with 3a for the CCS). As was highlighted in previous sections, the Tallow-HDO pathway (2b) has low levels of CO_2 available for both CCS and CCU. This implies small differences in costs between the three options, but essentially no change in climate impact, since very low amounts of CO_2 are stored with CCS and very low amounts of additional fuel are produced with CCU.

The gasification pathways (1a and 1b) in general display a comparably good economic performance under all options, particularly the 1a pathway. BL-FT (1a) has the second lowest LCOPs for the base option as well as for the CCU option, and the fourth lowest cost for the CCS option. The Bark-FT pathway (1b) has the worst economic performance of the gasification and hydrotreatment based pathways but outperforms two of the fermentation-based pathways (3b and 3c).

The hydropyrolysis pathway (2a) has a higher climate impact compared to the gasification pathways for the CCS option. This is explained by the lower levels of CO_2 available in relation to the biofuel produced. Nonetheless, the 2a pathway still achieves among the lowest LCOP for the CCS option, which is explained by the relatively large availability of CO_2 in absolute terms. These results can be put in contrast to the FR-ATJ (3c) pathway which achieves the lowest climate impact of all value chains, but also the, by far, highest cost for the CCS option. The 3c pathway has high levels of CO_2 in relation to the fuel production, explaining the potential for large negative emissions; however, the absolute amounts are low. Low absolute amounts of CO_2 imply that the specific costs of separation and transportation for CCS and separation and upgrading for CCU are high.

Scale of production also explains why the two gasification pathways have more similar costs for CCS and CCU compared to the base options. Although the BL-FT (1a) pathway offers more CO_2 for capture per MWh biofuel produced than the Bark-FT pathway (1b), the quantities available in absolute terms are greater in the latter case. Therefore, the specific cost of capture and upgrading is lower for the 1b pathway, which is particularly evident from a comparison of the LCOPs of the two pathways under their respective CCS options, with the LCOPs being almost equal in value. These results emphasize that scale of production is important for achieving low LCOPs for CCS and CCU, both in absolute terms and in terms of CO_2 availability in relation to biofuel production.

With the exception of Wheat-ATJ (3a), the fermentation-based pathways show among the highest LCOPs for all process options. The overall cost picture of the FR-ATJ (3c) pathway is also dispersed relative to other pathways. The reason is, again, the economy of scale for separation, transportation and upgrading of CO_2. The fermentation pathways are in general smaller than the gasification and hydrotreatment pathways and consequently have lower absolute CO_2 flows. According to the cost model applied in this work, the cost of shipping under the CCS option is to an extent binary. It is assumed that plants with CO_2 availability below a certain minimum threshold can share the storage infrastructure and ships for transporting CO_2. The specific cost of CO_2 transportation is lower for plants with large quantities of CO_2. Therefore, among the fermentation pathways, the cost of CCS is higher for the SD-ATJ and FR-ATJ pathways, which becomes particularly clear when comparing the 3c pathway to the 3a pathway, where the production scale is approximately 100 MW_{th} (60%) larger for the latter.

For three of the pathways, BL-FT (1a), SD-ATJ (3b) and FR-ATJ (3c), the LCOP is, as mentioned above, lower for the CCU than for the CCS option. Common for these pathways is the high amounts of CO_2 available in relation to the base option fuel production, i.e., relatively large volumes of additional product can be produced from the CO_2-to-jet process, in relation to the base product output. Nonetheless, this conclusion is also true for the Bark-FT (1b) and Wheat-ATJ (3a) pathways. However, these two pathways have the, by far, largest absolute flows of CO_2 (911 and 360 kt/year, respectively) and thus the cost of CO_2 transportation and injection is low enough to outweigh the relatively low cost of CCU, resulting in processes where CCS is cheaper than CCU, although the cost increase in relation to the base option is low for both options.

3.4. Cheapest alternatives for reducing ghg emissions & improving carbon utilization

Fig. 8 shows the GHG reduction cost and carbon efficiency for the CCS option (top) and CCU option (bottom) in relation the base option. These numbers can be compared to a highest observed cost for jet kerosene (excluding taxes) in the past five years of approximately 61 EUR/MWh (IATA - Fuel Price Monitor [Internet] 2021). The clearest observation from Fig. 8 is how, while the cost of GHG reduction decreases or remains constant for most pathways with the CCS option, a clear increase in GHG reduction cost can be observed for all pathways with the CCU option. For CCU, the climate impact, as has been discussed, remains broadly the same or increases slightly compared to the base option, for all pathways (Fig. 6). Therefore, with GHG emission savings similar to those achieved under the base option, but with higher

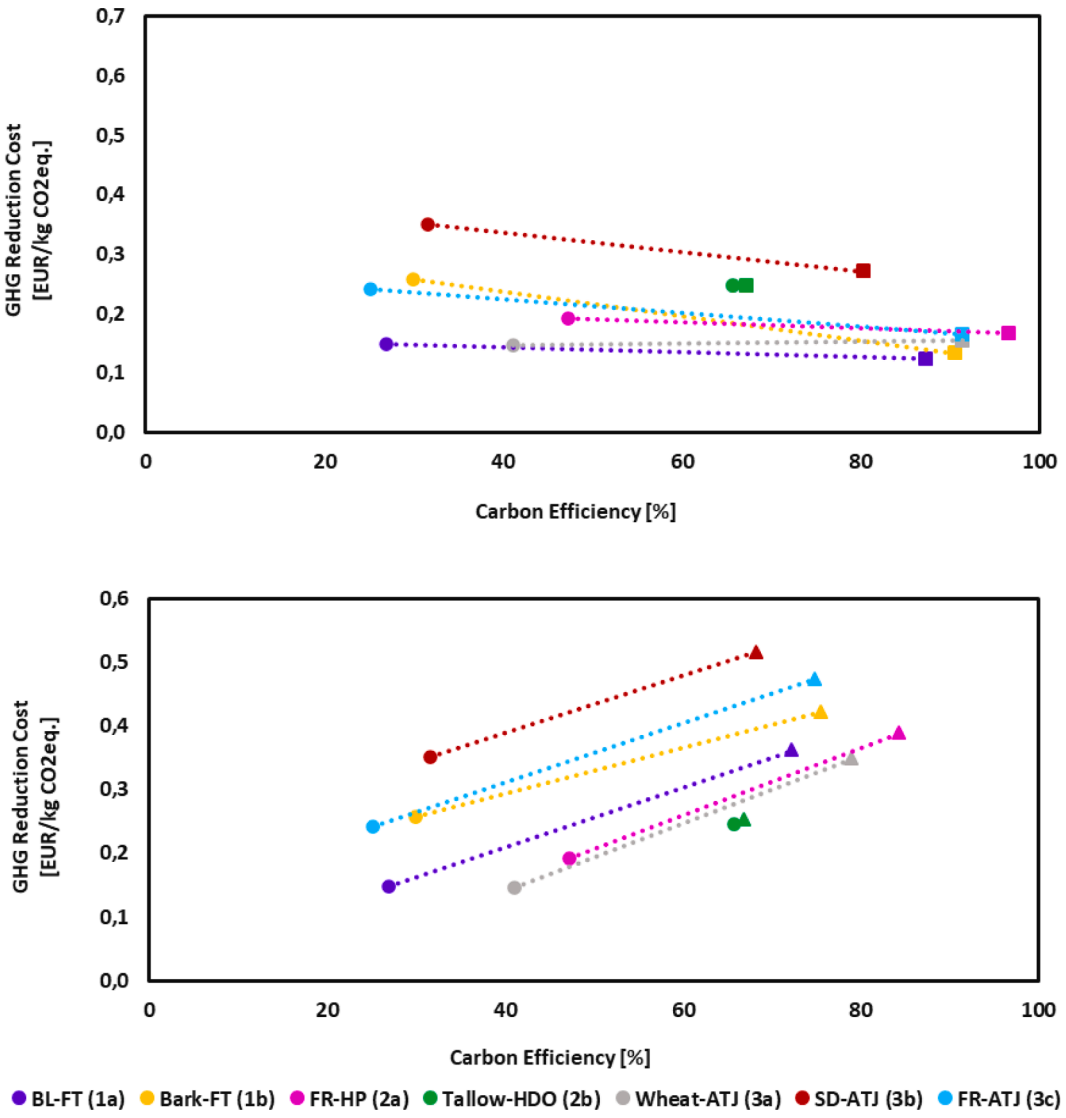

Fig. 8. Cost of reducing 1 kg of CO_2 equivalents and carbon dioxide efficiency for all pathways for both the CCS option (top) and the CCU option (bottom). Circles represent the base option, squares the CCS option and triangles the CCU option.

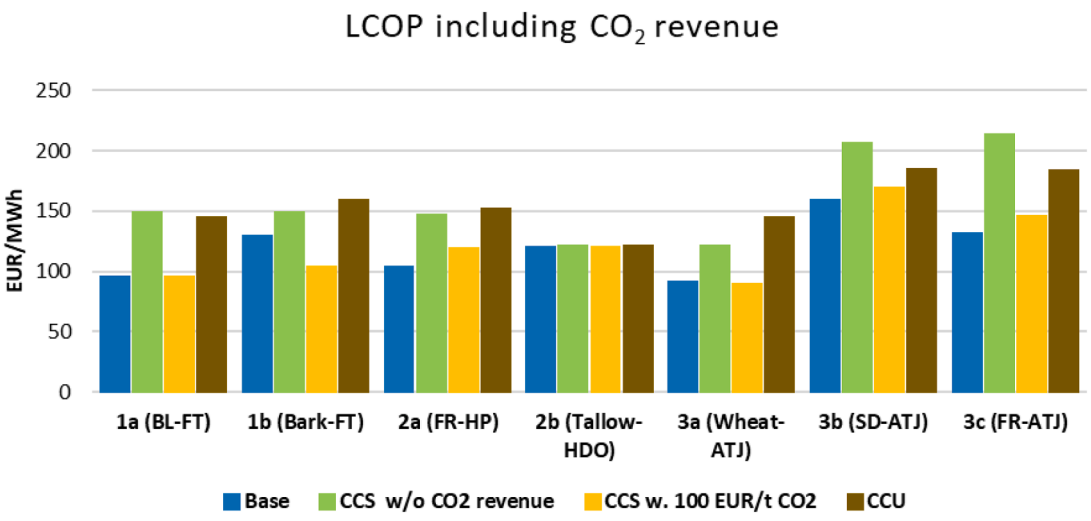

Fig. 9. Carbon sequestration costs of all pathways for the CCS option without CO_2 revenue (green), the CCS option with 100 EUR/t CO_2 revenue (yellow), the base option (blue) and the CCU option (brown).

costs due to the added expenses of the CO_2 upgrading processes, biofuels produced with CCU have higher GHG reduction costs. In contrast, all pathways except Tallow-HDO (2b), exhibit a possibility to decrease the climate impact substantially by adopting CCS, as discussed above. Consequently, CCS both results in generally lower GHG reduction costs, and achieves higher carbon efficiencies, compared to the CCU option considered in this work.

For the CCS option, the two gasification-based pathways, BL-FT (1a) and Bark-FT (1b) have the lowest cost of GHG reduction, closely followed by Wheat-ATJ (3a) and FR-ATJ (3c). However, although the black liquor gasification-based pathway (1a) has slightly lower costs, the largest gain from adding CCS is achieved for the bark gasification process (1b), which can reach very high carbon utilization with competitive GHG reduction costs. On the other hand, the hydropyrolysis pathway (2a) reaches the clearly highest carbon efficiency, although the GHG reduction cost is slightly higher compared to the best performing options. For 2a, the cost of GHG reduction remains almost similar when adopting the process with CCS. This is explained by the fact that although a beneficial climate impact is reached, the negative emissions are relatively small in relation to the gasification and isobutanol pathways. Thereby, the added cost of CCS is almost matched by the increased carbon utilization.

For the CCS option, two of the fermentation pathways (3a and 3c) also reach GHG reduction costs in the same range as the gasification pathways. However, for the Wheat-ATJ pathway (3a) the CCS option comes out as slightly worse than its corresponding base option (0.155 compared to 0.146 EUR/kg CO_2eq.). For Tallow-HDO (2b) the added cost of CCS and any differences in climate impact are almost negligible, therefore CCS and CCU have negligible effects on GHG reduction costs. Excepting the Tallow-HDO pathway, Wheat-ATJ has the highest climate impact of all pathways and, similarly to Tallow-HDO, the small change in climate impact explains why the additional cost of CO_2 separation and storage outweighs the gain of a decreased climate impact.

Interestingly, the pathway with largest negative GHG emission potential when CCS is applied (FR-ATJ, 3c) does not have the lowest GHG reduction cost. This is an effect of the high LCOP for the base process, the low absolute amounts of CO_2 stored, and the resulting high specific costs of CO_2 infrastructure.

SD-ATJ (3b) has the highest GHG reduction costs for all options. This is a consequence of the second highest base option LCOP and a relatively low potential for both CCS and CCU due to a low CO_2 flow. The cost of GHG reduction is significantly improved by adopting CCS, but it is left with the second lowest carbon efficiency after Tallow-HDO (2b), due to the diversion of significant amounts of the feedstock carbon to the pellet by-products.

3.5. Impact of CO_2 revenue

Fig. 9 shows the LCOP of all pathways with CO_2 sequestration revenue of 100 EUR/t under the CCS option, compared to the LCOP for the CCS option without a revenue, as well as to the LCOP of the base and CCU options.

A CO_2 credit of 100 EUR/t for the CCS option, unsurprisingly, has a large impact on the biofuel LCOP for some of the pathways, especially those with large negative emissions. For the FR-ATJ pathway (3c), the LCOP decreases with over 30%, and for the two gasification pathways the corresponding numbers are 36% (1a) and 30% (1b), respectively. For the Bark-FT pathway (2b), as well as for the Wheat-ATJ pathway (3a), the 100 EUR/ton revenue leads to the CCS option exhibiting a lower LCOP than the base option. It is, however, also clear that for several pathways, a larger revenue would be required for the CCS option to be economically competitive to the base option (3b SD-ATJ, 3c FR-ATJ and 2a FR-HP).

It should be observed that while biofuel product costs differ between the different pathways, none of them reach a level where they can be cost competitive with fossil jet kerosene, even with the CO_2 sequestration revenue. According to statistics by the International Aviation Transport Association (IATA), the highest observed cost for jet kerosene (excluding taxes) in the past five years was approximately $95/bbl, which corresponds to 61 EUR/MWh (IATA - Fuel Price Monitor [Internet] 2021). Judging by these results, it is safe to conclude that blending mandates, policy support or taxes are required to see a substantial demand and corresponding production of SAF.

3.6. Result summary

Table 10 summarizes the overall performance of aviation biofuel pathways under the three process options. Besides cost, carbon and climate efficiencies, estimates for Swedish feedstock potentials are provided for context. Feedstock potentials for all feedstocks except black liquor were taken from recently published Swedish estimates (Börjesson, 2021; Potter et al., 2020). For black liquor, estimates from (Jafri et al., 2019) were applied, with the potential presented as a range; the upper limit denotes the entire Swedish black liquor throughput under an annual production increase of 1.3% between 2018 and 2030, while the lower limit denotes black liquor only from pulp mills with recovery boilers built before 1995.

In general, all pathways based on forest biomass assortments have good feedstock availability, while the Swedish feedstock potential of animal by-products is limited. However, the animal by-products-based Tallow-HDO (2b) is the only pathway that is in commercial operation today. Most of the forest biomass-based pathways have technology readiness levels of around 7, and thereby have not yet reached full commercialization (Jafri et al., 2019; van and J, 2021; Fagerström et al., 2021; Cerruti et al., 2020; Bhosale, 2018; ARTFuels 2020). The Wheat-ATJ pathway (3a) is at a similar level of development as the forest biomass pathways. It seems to have limited applicability in a Swedish context and the feedstock potential is therefore not evaluated.

The results in Table 10 emphasize what has already been discussed in earlier sections. Low efficiency of the CO_2-to-jet processes, as well as expensive process equipment, makes an uncompelling case for adding a biofuel-based CCU option to the production of SAF from biomass feedstock. This result is true for all pathways considered, except for Tallow-HDO (2b), where, instead, the added production from the CCU is inconsequential both in comparison to the total production and to all other pathways. Excluding the Tallow-HDO process, the relative increase in LCOPs under the CCU option is 16–59%. It should, however, be noted that while the CCU costs are primarily driven by the cost of electricity, the uncertainty in CAPEX estimates is large, and better estimates together with more carbon-efficient FT process configurations may result in GHG reduction costs that are closer to the base option.

Overall, the Wheat-ATJ (3a), BL-FT (1a) and FR-HP (2a) process pathways have the lowest costs for the base option. The gasification-based pathways (1a, 1b) demonstrate the most compelling cases for the CCS option as they generate large enough amounts of CO_2 to reach low LCOP, while also delivering negative emission SAF. In the Bark-FT pathway, the chosen value of the sequestration credit leads to lower LCOP for the CCS option compared to the base option and for BL-FT, the cost is the same for the base and CCS option when there is a CCS credit. Wheat-ATJ also results in a low biofuel production cost under the CCS option but is penalized by a high climate impact.

4. Conclusions

A techno-economic assessment of seven different pathways for production of SAF has been performed. The aim was to compare the specific pathways suitability for CCS or CCU from a carbon efficiency, cost and climate perspective, but also to, in a more general sense, study different aspects of cost and GHG performance, such as the possibility to produce negative emissions biofuels, while accounting for high-altitude effects on global warming.

The clearest outcome of this work is the distinction between the CCS

Table 10
Overall assessment of aviation biofuel pathways under the base, CCS and CCU options.

	All options	Base Option			CCS Option				CCU Option		
BL-FT (1a)	24-54	27	94	81	87	94	148	-57	72	143	92
Bark-FT (1b)	12.5	30	129	79	91	103	148	-40	76	159	92
FR-HP (2a)	32	47	103	73	97	118	145	-12	84	151	90
Tallow-HDO (2b)	0.55	66	119	86	67	119	120	85	67	120	86
Wheat-ATJ (3a)	n.a.	41	90	88	91	89	120	37	79	143	89
SD-ATJ (3b)	10.2	32	158	78	80	168	206	4	68	184	92
FR-ATJ (3c)	32	25	131	71	91	145	213	-112	75	182	86
	Swedish Feedstock Potential [a] [TWh/y]	Carbon efficiency [b] [% Feed-to-Biofuels]	Biofuel Cost [c] [EUR/MWh]	Climate impact [d] [g CO_2eq./MJ Biofuels]	Carbon efficiency [b] [% Feed-to-Biofuels]	Biofuel Cost [c] [EUR/MWh] CO_2 credit 100 EUR/t	Biofuel Cost [c] [EUR/MWh] w/o CO_2 credit	Climate impact [d] [g CO_2eq./MJ Biofuels]	Carbon efficiency [b] [% Feed-to-Biofuels]	Biofuel Cost [c] [EUR/MWh]	Climate impact [d] [g CO_2eq./MJ Biofuels]

[a] < 10 TWh, 10 – 20 TWh, > 20 TWh. Potentials rounded to two significant figures for classification assignment.

[b] < 33%, 33 – 66%, >66%. Efficiencies rounded to two significant figures for classification assignment.

[c] > 115 EUR/MWh, 75 – 115 EUR/MWh, < 75 EUR/MWh. Represents the levelized cost of biofuel production.

[d] > 103 g CO_2eq./MJ, 103 – 0 g CO_2eq./MJ, < 0 g CO_2eq./MJ. Represents the average value of the footprints of all individual biofuel products. Classification based on a 65% reduction relative to a fossil reference of 92.5 g CO_2eq./MJ. The high-altitude effect contribution of 70.9 g CO_2eq./MJ was assumed to be the same for all fossil fuels and biofuels.

and CCU options' potential to cost-efficiently reduce the climate impact of SAF. The CCS and CCU options both entail increased carbon efficiency, either through CO_2 sequestration, or through additional biofuel production. However, in contrast to road biofuel production, where the climate impact usually is low, **the additional warming effect of combusting fuels at high altitude entails that it is not possible to produce SAF from biomass with CCU and reach a climate impact under 85 g CO_2eq/MJ.** This implies that although a significant improvement compared to fossil fuels is seen both for the base and CCU option, it is only through CCS that the climate impact of aviation can be fully mitigated.

The results presented in this work can be compared to previous work by the authors on 14 pathways for road biofuels with BECCS and BECCU (Jafri et al., 2021), in which the outcomes for the CCU option were found to be more favorable. The critical decision in that case rather concerned whether the investor wants to prioritize negative emissions *or* enhanced biofuel production, with both options being competitive against the base option for cost-efficient GHG emission reduction. In contrast, the results of this work are clearly more challenging for CCU. **A CO_2-to-jet option based on the FT technology is relatively inefficient compared to CO_2-to-road biofuel options based on catalytic methanation, methanol synthesis and MTG technologies.** The lower efficiency in combination with the relatively large investments required and the low relative impact on the GHG balance entails that the cost of GHG emission reduction is high for all pathways with CCU.

When studying the results of the CCS adopted pathways, a more optimistic image emerges. **Four of the seven pathways can reach positive climate impact (net negative emissions), regardless of the high-altitude effect.** Importantly, this can be achieved at GHG reduction costs that are not only low in absolute terms, but that are also an improvement compared to the base option. The uncertainty in estimations of the high-altitude effect can also have an impact on a pathway's estimated climate impact.

Looking at individual pathways, the pathways with large streams of CO_2 both in relation to fuel production and in absolute terms, achieve low LCOPs and larger negative GHG emissions for the CCS option, resulting in lower costs of GHG reduction. **Especially the black liquor and bark gasification pathways with FT-synthesis, the forest residues hydropyrolysis and the wheat fermentation ATJ pathways show low costs of GHG reduction for the CCS option, although the wheat pathway has a negative climate impact (net positive GHG emissions). The lowest climate impact is, notably, clearly achieved by the forest residues fermentation isobutanol-to-jet pathway.** However, this pathway is penalized by the low scale of production and the high CAPEX, resulting in a high LCOP and consequently a cost of GHG reduction slightly higher than previously mentioned pathways. Pathways with small streams of CO_2 are generally less suited for cost efficient production of SAF with CCS or CCU, which is particularly obvious for the tallow hydro-treatment pathway. It might appear contradictory that pathways with low carbon utilization for the base option are the ones that look most interesting from an investment perspective, but **with substantial high-altitude effects, large streams of CO_2 for storage become necessary for attaining climate-neutral SAF.**

Nonetheless, the results are uplifting in that the pathways most suitable for the production of SAF correlate well with the pathways where there is clear room for increased production. Although technologies such as tallow hydrotreatment are well developed and commercialized, most of the available feedstock is already being utilized. Thus, our results indicate that utilizing feedstock such as animal by-products as tools for transitioning the road and shipping sectors rather than for production of aviation fuels is not necessarily bad. **There is a large potential to utilize forest residual streams and sawdust for production of SAF and, when combined with CCS, these pathways are the best candidates for producing biofuels for climate neutral aviation.**

CRediT authorship contribution statement

Johan Ahlström: Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Yawer Jafri:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Elisabeth Wetterlund:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Erik Furusjö:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2023.103886.

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