Datum
2023-11-21

Dnr
2021-200253

Projektnr
P2021-00091

Energimyndighetens titel på projektet – svenska	
Kostnader för att reducera utsläpp av växthusgaser från väg- och flygtransporter med biodrivmedel och elektrobränslen	
Energimyndighetens titel på projektet – engelska	
Costs for reducing GHG emissions from road and air transport with biofuels and electrofuels	
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Nyckelord: 5-7 st	
biofuels, electrofuels, power-to-X, aviation, road transport, cost, greenhouse gas emissions, carbon abatement cost	

Förord

The authors gratefully acknowledge financial support from the Swedish Energy Agency [Project no. P2021-00091 carried out within the Bio+ program (https://bioplusportalen.se/en/).

En referensgrupp bestående av relevanta aktörer (inkluderandes Ebba Tamm, Drivkraft Sverige; David Hild, Fly Green Fund; Monica Johansson, Volvo Technology, Tomas Ekbom, Svebio, tillika Sveriges representant i IEA Bioenergy Task 39 (Commercializing Conventional and Advanced Transport Biofuels from Biomass and Other Renewable Feedstocks), Jonas Lindmark, Energimyndigheten) från SPBI, Svebio, Energimyndigheten, har bidragit till arbetet via referensgruppsmöten och andra diskussioner.

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Sammanfattning

Förnybara drivmedel för transporter behövs för att nå framtida klimatmål. Den potentiella framtida rollen för olika biobränslen, vätgas och elektrobränslen (producerade av el, vatten och CO_2) i olika transportsektorer är dock fortfarande osäker. Ökad kunskap om förutsättningarna för olika förnybara drivmedel för väg- och flygtransporter att bidra till omställningen av transportsektorn behövs för att säkerställa att omställningen sker på ett klimat- och kostnadseffektivt sätt.

CO_2-reduktionskostnaden, det vill säga kostnaden för att minska en viss mängd utsläpp av växthusgaser (GHG) är central ur både ett samhälls- och företagsperspektiv, det senare delvis på grund av utformningen av det svenska reduktionspliktssystemet. Minskningskostnaden för en specifik bränslekedja beror på bränsleproduktionskostnaden och den minskning av växthusgaser som bränslet ger. Denna rapport ger en uppdaterad sammanställning av CO_2-reduktionskostnaderna för olika typer av biobränslen och elektrobränslen för vägtransporter och flyg, relevanta i ett svenskt sammanhang. Bränsleproduktionskostnader och växthusgasprestanda (well to wheel) för de valda förnybara bränslevägarna kartläggs baserat på publicerade data.

Den beräknade kostnaden för CO_2-reduktion varierar från -0,37 till 4,03 SEK/kg CO_2-ekvivalent. Metan från anaerob rötning av avloppsslam och etanol från jäsning av sockerrör och majs får negativa CO_2-reduktionskostnader givet de antaganden som gjorts, vilket innebär att det är mer ekonomiskt fördelaktigt att använda dessa än deras fossila motsvarighet.

Elektrobränslevägar (särskilt diesel och flygbränslen) har å andra sidan relativt höga kostnader för att minska koldioxidutsläppen. Dessutom har så kallade bioelektrobränslen som produceras av överskott av biogen CO_2 från biobränsleproduktion och el, kopplad till biobränsleproduktion generellt sett högre kostnader för CO_2-reduktion än motsvarande skogsbiomassabaserade biobränslevägar. För skogsbiomassabaserade biobränslen, bioelektrobränslen och elektrobränslen har metanol- och metanvägar i allmänhet något lägre kostnader för CO_2-reduktion än kolvätebaserade bränslen (bensin, diesel och flygbränsle).

Eftersom de flesta av de bedömda förnybara bränslevägarna uppnår en betydande minskning av växthusgasutsläppen jämfört med fossila bränslen, är bränsleproduktionskostnaden i allmänhet viktigare än växthusgasprestandan för att uppnå en låg kostnad för att minska koldioxidutsläppen. Produktionskostnaden för fossila bränslen påverkar också kostnaden för att minska koldioxidutsläppen i stor utsträckning. Fler uppskattningar av kostnader och växthusgasprestanda för förgasning av avfallsbaserade vägar behövs och för vissa vägar under utveckling (t.ex. hydropyrolys).

Energimyndigheten

Summary

Renewable fuels for transport are needed to reach future climate targets. However, the potential future role of different biofuels, hydrogen, and electrofuels (produced by electricity, water, and CO_2) in different transportation sectors remains uncertain. Increased knowledge about the preconditions for different renewable fuels for road and air transport to contribute to the transformation of the transport sector is needed to ensure the transformation is done in a climate- and cost-effective way.

The CO_2 abatement cost, i.e., the cost of reducing a certain amount of greenhouse gas (GHG) emissions is central from both a societal and business perspective, the latter partly due to the design of the Swedish reduction obligation system. The abatement cost of a specific fuel value chain depends on the fuel production cost and the GHG reduction provided by the fuel. This report provides an updated summary of the CO_2 abatement costs for various types of biofuels and electrofuels for road transport and aviation, relevant in a Swedish context. Fuel production costs and GHG performance (well to wheel) for the selected renewable fuel pathways are mapped based on published data.

The estimated CO_2 abatement cost ranges from -0.37 to 4.03 SEK/kg CO_2-equivalent. Methane from anaerobic digestion of sewage sludge and ethanol from fermentation of sugarcane and maize end up with negative CO_2 abatement cost given the assumptions made, meaning it is more economically beneficial to use than its fossil counterpart. Electrofuels pathways (particularly diesel and aviation fuels) have, on the other hand, relatively high CO_2 abatement costs. Also, so-called bio-electrofuels produced from biogenic excess CO_2 from biofuel production and electricity linked to biofuel production generally have higher CO_2 abatement costs than the corresponding forest biomass-based biofuel pathway. For forest biomass-based biofuels, bio-electrofuels and electrofuels, methanol, and methane pathways in general have somewhat lower CO_2 abatement costs than hydrocarbon-based fuels (gasoline, diesel, and aviation fuel).

Since most of the assessed renewable fuel pathways achieve substantial GHG emission reduction compared to fossil fuels, the fuel production cost is, in general, more important than the GHG performance to achieve a low CO_2 abatement cost. The production cost for fossil fuels also influences the CO_2 abatement cost to a large extent. More estimates of cost and GHG performance for gasification of waste-based pathways are needed and for certain pathways under development (e.g., including hydropyrolysis).

1 Introduction

A combination of electrification and renewable fuels for transport, such as biofuels, hydrogen and electrofuels (produced using electricity, water, and carbon dioxide, CO_2 or nitrogen), is required to achieve both the targets of a 70% reduction in greenhouse gas (GHG) emissions in the transport sector to 2030 and for net zero GHG emissions by 2045 in Sweden (Andersson & Börjesson, 2021; Morfeldt et al., 2021). For air transport, technology for electrification and hydrogen is being developed, but neither is expected to have any impact on emissions from aviation in the short and medium term (Trafikanalys, 2020). Biofuels are therefore the most important measure in this sector (in a longer perspective possibly in combination with electrofuels).

In 2018, the Swedish government introduced a mandate for fuel distributors to reduce GHG emissions from petrol and diesel by gradually increasing the blending of renewable fuels (also called reduction quota/mandate). For 2022 and 2023, the requirement was that the climate impact should be reduced by at least 7.8 percent from gasoline and 30.5 percent from diesel, compared to if the same product is produced only with fossil raw materials. A gradual increase until 2030 was previously proposed, but the current Swedish government has during spring 2023 agreed that the current level of the GHG reduction mandate will be reduced from January 1, 2024, until 2026 to a reduction of climate impact by 6% for gasoline and 6% for diesel.

The GHG reduction mandate regulates climate performance rather than the proportion of renewable fuels, which means that renewable fuels with low GHG gas emissions are favored, as these can be blended in lower volumes than biofuels with poorer climate performance to achieve the same emissions reduction. However, the fuel production cost also matters. Biofuels and electrofuels, including hydrogen, can be used to meet the GHG reduction mandate.

To reduce GHG emissions from air transport, a GHG reduction mandate for aviation fuel was also introduced in Sweden. The mandate means that suppliers of aviation fuel are obliged to reduce emissions from aviation fuel by blending renewable fuels into fossil aviation fuels. The requirement for blending started at 0.8 percent in 2021 and was proposed to gradually increase to 27 percent by 2030 (though it has been proposed, by the Swedish Energy Agency, to align the Swedish policy to the regulations decided within the EU, see below). However, the proportion of biofuels in aviation fuel is still marginal, and the Swedish Energy Agency has reported that the achieved emission reduction in 2021 was 0.6 percent (Swedish Energy Agency, 2022a). At the EU level, the RefuelEU Aviation proposal has recently been agreed upon and will involve a quota obligation within the EU that sets the minimum share of sustainable aviation fuels to be made available at EU airports (2% in 2025 increasing to 6% in 2030 and 70% 2050 with specific sub-targets for synthetic fuels). The fact that the proposal is designed as a blending obligation rather than a GHG reduction obligation means that it regulates the proportion of renewable fuels rather than the reduction of GHG emissions.

Renewable fuels will thus be needed on a large scale to reach both national and international climate goals and both in road and air transport, at least in the short to medium term. Renewable fuels are also needed in the shipping sector, but that sector is not covered in this report. For a cost-effective transition and to facilitate the achievement of these climate goals, better knowledge is needed about different alternative fuels and production routes. A key parameter for the competitiveness of different renewable fuel pathways is the reduction cost, that is the cost of reducing a specific amount of GHG emissions with a certain fuel, which depends on the combination of production cost and the level of GHG reduction that the fuel pathway provides. With the construction of the reduction obligation in Sweden, this parameter becomes economically relevant on a societal level as well as for distributors of fuels as they, likely, want to achieve the stipulated reduction at the lowest possible cost.

Only a few Swedish studies estimate the climate benefit of different fuels in relation to production cost (for example Furusjö & Lundgren, 2017; Mossberg et al., 2019). Furusjö & Lundgren (2017) illustrated how the GHG performance of different biofuels for road transport related to their economic value in relation to the Swedish reduction obligation system. In that study, the costs for GHG reduction for different types of biofuels in Sweden were also compared.

The overall purpose of this report is to increase the knowledge and understanding of which production technologies and fuel products for road and air transport, from a climate economic perspective, are the most attractive to invest in and support in terms of policy instruments. More specifically, the aim of this report is to contribute with an updated analysis of production costs for different biofuel routes in relation to possible GHG reduction which, in addition to biofuels for road transport, includes selected biomass-based jet fuels and electro-fuels for road and air transport. The report includes a systematic compilation and comparison of the CO_2 abatement costs for many production routes and fuel alternatives for both road and air transport that are relevant from a Swedish perspective.

Projektet pågick mellan januari 2022 och juli 2023.

Compared to other countries, Sweden has a high use of biofuels. 24.7 percent of all fuels were biomass-based in 2021. The renewable share in diesel was 26.8 percent. In parallel, the design of the GHG reduction mandate has significantly improved the climate performance of biofuels included in the mandate, with an average GHG emission of 9g CO_2eq/MJ compared to about 16g CO_2eq/MJ before its introduction (Swedish Energy Agency, 2022b).

1.1 Current use of renewable fuels for transport in Sweden

Currently, hydrotreated vegetable oil (HVO) biofuels dominate the use of biodiesel in Sweden. In terms of energy content, it accounted for approximately 70% of biodiesel use in 2021 (Swedish Energy Agency, 2022b). HVO is often described as the most important fuel in achieving the GHG reduction mandate. It is also the biofuel sold in the largest volumes outside of the GHG mandate (i.e., in pure form, HVO100). However, the dependence on imported feedstocks for HVO production is significant, with only 11% being domestically sourced in Sweden in 2021. Nonetheless, there is significant international competition for both HVO, and the feedstocks used for its production, which will lead to an increased importance of domestically produced biofuels. Such a development means that new feedstocks and production technologies will be used. These production technologies are often not commercially established, and knowledge about the various alternatives and their performance is limited among many actors. This is particularly true for renewable aviation fuels.

2 Methodology

Production costs for renewable fuels that can potentially contribute to the fulfillment of the Swedish reduction obligation until 2030 and beyond, including biofuels and renewable electrofuels for both road and air transport are compiled (Section 2.2). Data for considered fuels, production routes, and feedstocks are compiled from existing publications through a literature review. The costs are expressed per energy unit for road transport and aviation, respectively. GHG performance (well-to-wheel, expressed as CO_2 equivalent per energy unit) of various biofuels, selected pathways for hydrogen and renewable electrofuels for road and air transport is also compiled (Section 2.3), which is also based on a literature review. Based on the compiled data, the carbon (CO_2) abatement cost is then calculated (see more in Section 2.4).

2.1 Assessed fuel pathways

The fuels assessed in this study include different production pathways for methanol, ethanol, methane, renewable diesel including e.g. FAME and HVO, renewable gasoline, aviation fuel, and hydrogen. The specific fuel pathways included in the study are presented shortly in Table 1. Several of the included production pathways can produce biofuels that can be used both for low blending, for example to fulfill the reduction obligation, and as clean fuels or for high-level blending.

Some fuel pathways based on waste feedstock (referring mainly to household wastes) were also included in the mapping of production costs and GHG performance. However, as there was a lack of data and uncertainties in how to estimate the GHG emissions for some waste-based fuels and sometimes also production costs and difficult to judge the quality and understand the exact approach for the values available, these were not possible to include fully in the comparison and carbon abatement estimates. These pathways are therefore not included in the main results, but some information is presented in Section 3.3.1.

Fuel pathways based on hydropyrolysis of forest based-biomass were also included in the mapping but is not included in the comparison either as it was difficult to verify the capital costs and GHG performance mapped (see Wetterlund et al 2020, Ahlström et al., 2022), see further in Section 3.3.1.

In total, the assessment covers 8 renewable fuel types which are produced from different feedstocks. The assessment covers biofuels that are based on crops and vegetable oil, biofuels that are derived from woody biomass, some waste-based biofuels, hydrogen produced from woody biomass and water (electrolysis), several electrofuels (needing carbon capture technology besides electricity) but also so-called bio-electrofuels produced from biogenic excess CO_2 from biofuel production and electricity linked to the biofuel production (requiring no costly carbon capture technology).

Table 1. Overview of assessed fuel production pathways.

Fuel	Feedstocks	Production pathway
Methanol	Woody biomass	Gasification + methanol synthesis
	Woody biomass + Electricity	Electrolysis + Gasification + methanol synth., Bio-electrofuel (Bio+El)
	Electricity + CO_2	Electrolysis + carbon capture (CC) + methanol synth, Electrofuel (El+CO_2)
Ethanol	Wheat	Fermentation, 1st generation (1G). No carbon capture assumed in the base case)
	Maize	Fermentation, 1G
	Sugarcane	Fermentation, 1G
	Woody biomass	Fractioning + fermentation, 2G
Methane	Waste/sludge	Anaerobic digestion
	Manure/food waste	Anaerobic digestion
	Crops	Anaerobic digestion
	Woody biomass	Gasification
	Substrate + electricity	Anaerobic digestion + electrolysis and methanaton, (Bio+El, bio-electrofuel)
	Woody biomass + electricity	Electrolysis + Gasification + methanation, (Bio+El, bio-electrofuel)
	Electricity + CO_2	Electrolysis + CC + methanation (El+CO_2, electrofuels)
FAME	Rapeseed oil	Transesterification
Diesel	Used cooking oil (UCO)	Hydrotreatment – HVO
	Slaughterhouse waste	Hydrotreatment – HVO
	Tall oil	Hydrotreatment – HVO
	Rapeseed oil	Hydrotreatment – HVO

	Woody biomass	Gasification + Fischer-Tropsch
	Woody biomass + electricity	Electrolysis + Gasification + Fischer-Tropsch: (Bio+El, bio-electrofuel)
	Electricity + CO_2	Electrolysis + CC + Fischer-Tropsch (El+CO_2, electrofuels)
	Woody biomass	Hydrothermal liquefaction (HTL) + Hydrodeoxygenation (HDO)
	Woody biomass	Pyrolysis + HDO
Gasoline	Woody biomass	Gasification + Methanol to gasoline (MTG)
	Woody biomass + electricity	Electrolysis + Gasification + MTG (Bio+El, bio-electrofuel)
	Woody biomass	Isobuthanol fermentation + oligomerization
	Electricity + CO_2	Electrolysis + CC+ MTG (El+CO_2, electrofuels)
Aviation fuel	Woody biomass	Gasification + Fischer-Tropsch
	Woody biomass	Gasification + Methanol to Jet (MTJ)
	Woody biomass + electricity	Electrolysis + gasification + MTJ, (Bio+El, bio-electrofuel)
	Woody biomass + electricity	Electrolysis + gasification + Fischer-Tropsch, (Bio+El, bio-electrofuel)
	Woody biomass	Isobuthanol fermentation + oligomerization
	Electricity + CO_2	Electrolysis + CC + Fischer-Tropsch (representing also the MTJ case[1]) (El+CO_2, electrofuel)
Hydrogen	Woody biomass	Gasification
	Woody biomass	Gasification + CCS (carbon capture and storage) (CO_2 sold)
	Woody biomass	Gasification + CCS (negative emission from CO_2 storage)
	Electricity	Electrolysis + compression
	Electricity	Electrolysis + liquefaction

[1] The MTJ-case is somewhat more costly than the Fischer Tropsch case but the difference and small and these are represented by the same pathway.

For the hydrogen from the Forest-based biomass pathway, three different ways of managing the CO_2-stream were represented. In the first case, the CO_2 is vented. In the second case, referred to as *CO_2 sold,* the generated CO_2 is sold, and the hydrogen is assumed to have the same CO_2 emission as in the first case. The third case referred to as *negative emission from CO_2 storage,* on the other hand, shows the impact on the emissions when the negative emission from direct in-situ CO_2 storage can be credited. For the associated assumptions for the cost estimates, see the next section.

2.2 Production Cost

Reliable, and as up-to-date data sources as possible, were used for production costs for the different pathways. As there is a variation in the current technology maturity for the studied pathways, and to make them comparable, the production costs used in this study are the production costs for a technically mature N^{th} of a kind plant. This implies that the assessed production pathways are deployed at a large scale leading to cost reductions through technology learning. According to IEA (2020) cost reductions could be significant given a large-scale technology deployment, in theory up to 50% compared to the production cost of a first-of-a-kind plant.
Due to the economic developments in recent years resulting in significant cost increases, adjustments to some of the costs taken from older data sources were made. The cost increases can be illustrated by the development of the Chemical Engineering Plant Cost (CEPCI)-index, which in 2022 was more than 40 percent higher than the average index between 2010-2020, see Figure 1.

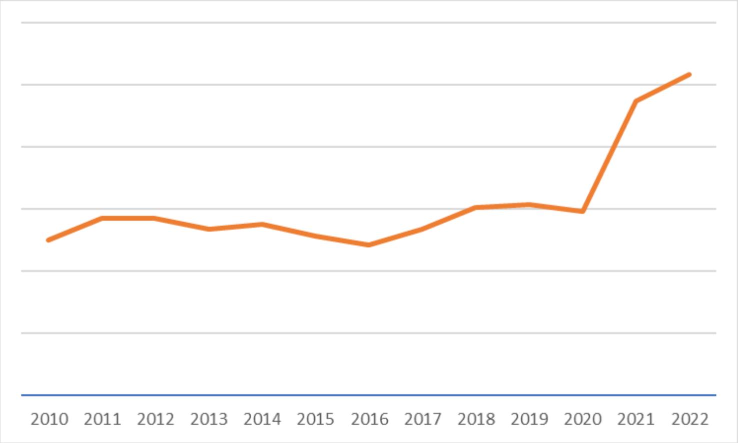

Figure 1. Development of the Chemical Engineering Plant Cost (CEPCI)-index 2010 to 2022.

In the following, the data sources used, and the adjustments made are accounted for.

- ***IEA Bioenergy, 2020****. Advanced Biofuels – Potential for Cost Reduction (Used for 19 pathways)*

The IEA Bioenergy report on advanced biofuels (IEA, 2020) has many advantages. First, it presents both high and low-cost levels depending on feedstock costs, technological learning effects etc. The cost data are also standardized regarding capital return requirements and the different cost elements (capital, feedstock etc.) are fully transparent. This means that relevant adjustments to the costs can easily be made. The IEA Bioenergy report used feedstock costs for biomass in the range of 10-20 €/MWh and -13-0 €/MWh for waste. Here, all production costs were adjusted using a feedstock cost of 20 €/MWh for biomass and 0 €/MWh for waste for both production cost levels. 10 % was added to the production costs to compensate to some extent for the capital cost increases. The IEA Bioenergy report (IEA, 2020) does not cover production costs for biobased hydrogen. However, in this project, it was assumed that the hydrogen production cost via biomass gasification is equal to the costs for gasification-based bio-methanol and bio-methane as presented in IEA (2020). For the bio-hydrogen pathways, three different ways of managing the CO_2-stream were also assumed including:

a) venting the generated CO_2, using the above-mentioned production cost and the CO_2 emission factor of bio-methanol,
b) selling the generated CO_2, using the above-mentioned production cost, but reduced by the net-credits from the sale (4-6 SEK per kg CO_2) and the CO_2 emission factor of bio-methanol and
c) direct on-site storage of the generated CO_2, using the above-mentioned production cost, but with an added cost for CO_2 transport and storage (900 SEK per ton CO_2) and negative CO_2 emissions (see section 3.2).

- ***Grahn et al., 2022,*** *Review of electrofuels feasibility—cost and environmental impact, (used for 14 pathways)*
- ***Furusjö et. Al., 2022****, Bio-electro fuels – hybrid technology for improved resource efficiency (used for 3 pathways)*

These two reports were mainly used for the costs of producing electrofuels and bio-electrofuels. No adjustments were done to the costs, except that the cost for bio-methane liquefaction was removed where relevant. The production costs presented in the two reference reports are comparable, but slightly higher in Grahn et. al (2022) due to assumed higher electricity prices (50 € per MWh). The higher electricity price is the main reason why that report was mostly used.

- ***FFF/Börjesson et al 2016****. Dagens och framtidens hållbara biodrivmedel – i sammandrag (as presented in Furusjö & Lundgren (2017)) (used for 10 pathways)*

The updated summary of the background report from f3 to the governmental investigation on a fossil-free transport fleet (Börjesson et al., 2016) and a report by Furusjö & Lundgren (2017) were used mainly for the production costs for biogas, crop-based ethanol, and FAME. The production costs of FAME (and HVO) were modified using more up-to-date feedstock costs. 20 % was added to the production costs to compensate for cost increases. Due to the earlier date of this study, it was only used as a complement to other data.

- ***Jafri et al., 2021****, Future-proof biofuels through improved utilization of biogenic carbon – Carbon, climate and cost efficiency (used for 2 pathways)*

This report was used for production costs of lignin and pyrolysis oil-based fuels. Here, 10 % was added to the total production costs to compensate for increased costs.

- ***IRENA, 2016****, Innovation Outlook Advanced Liquid Biofuels*

This report was used for comparative purposes and cost data was never used directly in the abatement cost calculations. In the comparison with other cost data, also here 20 % was added to the total production costs to compensate for increased costs.
To illustrate the uncertainty in estimates of the fuel production costs, an upper and lower level was also included based on the literature, ranging from 1% to 30% for the included pathways. The range is both based on cost estimates from different studies and on different assumptions in the same studies. In a few cases where there where a lack of literature no uncertainty range was included.

2.3 Greenhouse gas (GHG) emission performance

GHG emission performance of different biofuels is based on literature including scientific publications where Life Cycle Assessment (LCA) was either performed or reviewed. The approach for calculating the GHG emissions follows the methodology described in the first recast of the Renewable Energy Directive (RED II) which has a scope of well-to wheel i.e., from feedstock extraction, via production to the end-use of the fuel. However, to allow for general comparison, the distribution of biofuels to consumers was excluded from the life cycle stages in the cases where it was included in the estimate. The GHG emission performance from different literature were also chosen preferably from a Swedish perspective and to be consistent and ensure that they represent the same production pathway, when possible, based on the literature chosen for the production cost data.

The mapping of GHG emission performance of each fuel type and production pathway gives a variety of results in the case where several sources were found. For a few pathways, only one GHG emission value from one source was found. Based on the mapping of GHG emissions, one of the collected GHG data was then chosen as a reference value for the calculation of the CO_2 abatement cost. The same reference used for the chosen production cost was chosen also for the reference GHG emission if possible and suitable.

Based on the mapping, an interval of the possible GHG performance was also received for most pathways, with an upper and lower limit, illustrating the uncertainty range. Where several sources were available for different biofuels and pathways, the lowest and highest GHG emissions were generally chosen as the upper and lower value for the interval. However, if the reference for GHG emission chosen for the CO_2 abatement cost provided uncertainty intervals, then those intervals were used. For biofuels with only one reference for GHG performance, the same uncertainty intervals (percentage-wise) as for other biofuels with similar production pathways were assumed. For assumptions on electrofuels and bio-electrofuels see below.

The references used for mapping the GHG emission performance are listed below and are as indicated, often the same as those used for the production cost.

- ***Grahn et al. 2022***, *Review of electrofuel feasibility—cost and environmental* impact (used for 13 pathways)

The assessment by Grahn et al. (2022) provides GHG emissions performances for the electrofuels and bio-electrofuels methanol, methane, gasoline, diesel, and aviation fuel, which corresponds to 13 fuel production pathways. The GHG emissions performances used by Grahn et al. (2022) represent the average of near-term (2030) and long-term (2050) scenarios presented in that study and compiled specifically for this report (the same approach is used for the production cost estimates). The GHG emission factor from the production of electricity applied to the estimates in Grahn et al. (2022) is 7 gCO_2eq./MJ which represents the current Swedish electricity mix. For bio-electrofuels and electrofuels, the lower level of the uncertainty interval was obtained from the case where electricity was assumed to be produced with zero GHG emissions, which can be relevant for some Swedish regions following the delegated acts on renewable fuels of non-biologic origin RFNBOs (see more on this at the end of this section).

- ***FFF/Börjesson et al. 2016 and EM/Swedish Energy Agency 2017, As presented in Furusjö and Lundgren, 2017,*** *(Used for 15 pathways)*

This report was used for various production pathways for methanol, ethanol, methane, diesel, gasoline, and FAME which corresponded to 15 production pathways. The reference reviewed different sources of GHG emission performance where two of them were used in the report: one which was based on Börjesson et al. (2016) (referred to as FFF) and the other based on Swedish Energy Agency (2017) (referred to as EM).

- ***Lönnqvist et al. 2021****, En droppe i tanken eller en ny tank? (Used for 8 pathways)*

This report was used for forest biomass-based methanol, methane, ethanol, gasoline, and diesel corresponding to 8 pathways (as well as for the mapping of electrofuels. Lönnqvist et al. (2021) provided uncertainty intervals for the GHG emission values for the included biofuels. Carbon capture is not assumed for any of the biofuel pathways.

- **Furusjö, E., et. al., 2022.** Bio-electro fuels – hybrid technology for improved resource efficiency. *(Used for 10 pathways)*

This report was used for bio-electro- and electrofuels of methane, methanol, ethanol, diesel, gasoline, and aviation fuel, which corresponds to 10 pathways.

- ***Ahlström et al. 2022,*** *Climate-positive and carbon efficient bio-jet fuels, are they possible? (Used for 6 pathways)*

This report was used for most aviation fuels, corresponding to 6 pathways. The report also provides estimates for the effect of high altitude, but this has not been taken into consideration in this project.

- ***Jafri et al. 2021,*** *Future-proof biofuels through improved utilization of biogenic carbon (Used for 8 pathways)*

This report provides the GHG emission performance of methane, ethanol and diesel based on crops, waste and woody biomass, corresponding to 8 pathways.

- ***Swedish Energy Agency, 2022b,*** *Drivmedel 2021*

This report was used for the mapping of the GHG performance of ethanol, FAME and diesel, in total 5 pathways. The publication is the most recent update on transportation fuel used in Sweden. However, the GHG emissions from this report were not used as reference values (with the exception of FAME) as the origin of the feedstocks for Swedish consumptions of biofuels are mostly not from Sweden.

- ***Trinh et al. 2022****, Fossil-free Airborne Search and Rescue Services*

This report provides GHG emissions for one of the woody biomass-based aviation fuels and was used only for comparison of the GHG emissions performance (not as the reference value).

- ***Haus et al., 2020,*** *Lignocellulosic Ethanol in a Greenhouse Gas Emission Reduction Obligation System—A Case Study of Swedish Sawdust Based-Ethanol Production*

This report was used for the comparison of GHG performance for the woody biomass-based ethanol (but not chosen as the reference value).

- ***Directive (EU) 2018/2001*** *(REDII) (Used for 1 pathway)*

Default values provided in REDII were included in the mapping of GHG emissions for methanol, ethanol, methane, FAME, gasoline and diesel. However, this reference was only used for ethanol from maize.

Table 2 includes a summary of the references mapped.

Table 2. Summary of references used for the mapping of GHG emission performance of studied fuels. The reference for the GHG performance chosen for the abatement cost estimation is indicated in bold.

Fuel	Feedstocks	Production pathway	
Methanol	Woody biomass	Gasification	**Lönnqvist et al. (2021),** FFF, Furusjö & Lundgren (2017), REDII
	Woody biomass + Electricity	Electrolysis + Gasification, Bio-electrofuel (Bio+El)	**Grahn et al. (2022)**, Furusjö et al. (2022)
	Electricity + CO_2	Electrolysis + carbon capture (CC), Electrofuel (El+CO_2)	**Grahn et al. (2022)**, Furusjö et al. (2022), Lönnqvist et al. (2021)
Ethanol	Wheat	Fermentation	**FFF, Furusjö & Lundgren (2017)**, Jafri et al. (2021), Swedish Energy Agency (2022b)

	Maize	Fermentation	**REDII**, Swedish Energy Agency (2022b)
	Sugarcane	Fermentation	**FFF, Furusjö & Lundgren (2017)**, REDII, Swedish Energy Agency (2022b)
	Woody biomass	Fractioning + fermentation	**Furusjö & Lundgren (2017)**, REDII, Haus et al. (2020)
	Woody biomass +electricity	Electrification+ fermentation[a]	Furusjö et al. (2022)
Methane	Waste/sludge	Anaerobic digestion	**FFF, Furusjö & Lundgren (2017),** EM Furusjö & Lundgren (2017), Jafri et al. (2021)
	Manure/food waste	Anaerobic digestion	**FFF, Furusjö & Lundgren (2017),** EM Furusjö & Lundgren (2017), Jafri et al. (2021)
	Crops	Anaerobic digestion	**FFF, Furusjö & Lundgren (2017),** EM Furusjö & Lundgren (2017)
	Woody biomass	Gasification	**Lönnqvist et al. (2021),** FFF, Furusjö & Lundgren (2017), Jafri et al. (2021)
	Substrate + electricity	Electrolysis + Anaerobic digestion, (Bio+El)	**Grahn et al. (2022)**
	Woody biomass + electricity	Electrolysis + Gasification, (Bio+El)	**Furusjö et al. (2022)**
	Electricity + CO_2	Electrolysis + CC (El+CO_2)	**Grahn et al. (2022),** Furusjö et al. (2022), Lönnqvist et al. (2021)
FAME	Rapeseed oil	Transesterification	**Swedish Energy Agency (2022b),** FFF, Furusjö & Lundgren (2017), EM Furusjö & Lundgren (2017), REDII
Diesel	Used cooking oil (UCO)	Hydrogen treatment - HVO	**EM, Furusjö & Lundgren (2017)**, REDII, Swedish Energy Agency (2022b)
	Slaughterhouse waste	Hydrogen treatment - HVO	**EM, Furusjö & Lundgren (2017)**, REDII
	Tall oil	Hydrogen treatment - HVO	**EM, Furusjö & Lundgren (2017)**, Jafri et al. (2021)
	Rapeseed oil	Hydrogen treatment - HVO	**EM, Furusjö & Lundgren (2017)**, REDII
	Woody biomass	Gasification + Fischer-Tropsch	**Furusjö et al. (2022),** Lönnqvist et al. (2021), REDII

	Woody biomass + electricity	Electrolysis + Gasification + Fischer-Tropsch: (Bio+El)	**Grahn et al. (2022)**
	Electricity + CO_2	Electrolysis + CC (El+CO_2)	**Grahn et al. (2022),** Furusjö et al. (2022)
	Woody biomass	Hydrothermal liquefaction (HTL) + Hydrodeoxygenation (HDO)	**Furusjö et al. (2022)**
	Woody biomass	Pyrolysis + HDO	**Lönnqvist et al. (2021),** Jafri et al. (2021)
	Woody biomass	Hydropyrolys[a]	Lönnqvist et al. (2021)
Gasoline	Woody biomass	Gasification + Methanol to gasoline (MTG)	**Lönnqvist et al. (2021)**, REDII
	Woody biomass + electricity	Electrolysis + Gasification + MTG	**Grahn et al. (2022)**
	Woody biomass	Isobuthanol + oligomerization	**Ahlström et al. (2022)**
	Electricity + CO_2	Electrolysis + CC (El+CO_2)	**Grahn et al. (2022),** Furusjö et al. (2022)
	Woody biomass	Hydropyrolys[a]	Lönnqvist et al. (2021)
Aviation fuel	Woody biomass	Gasification + Fischer-Tropsch	**Ahlström et al. (2022)**, Trinh et al. (2022)
	Woody biomass	Gasification + Methanol to Jet (MTJ)	**Ahlström et al. (2022)**
	Woody biomass + electricity	Electrolysis + gasification + MTJ, (Bio+El)	**Grahn et al. (2022)**
	Woody biomass + electricity	Electrolysis + gasification + Fischer-Tropsch, (Bio+El)	**Grahn et al. (2022)**, Ahlström et al. (2022)
	Woody biomass	Isobuthanol + oligomerization	**Ahlström et al. (2022)**
	Electricity + CO_2	Electrolysis + CC + Fischer-Tropsch (El+CO_2)	**Grahn et al. (2022)**
	Woody biomass	Hydropyrolysis[a]	Ahlström et al. (2022)
	Woody biomass	Ethanol-to-jet (ETJ)[a]	Furusjö et al. (2022)
Hydrogen	Woody biomass	Gasification	**Lönnqvist et al. (2021)**
	Woody biomass	Gasification + CCS (carbon capture and storage) (CO_2 sold)	**Lönnqvist et al. (2021)**
	Woody biomass	Gasification + CCS (negative emission from CO_2 storage)	Calculation based on expert knowledge
	Electricity	Electrolysis + compression	**Grahn et al. (2022)**
	Electricity	Electrolysis + liquefaction	**Grahn et al. (2022)**

[a] This production pathways was included in the mapping of GHG emissions but not included in the calculation of the CO_2 abatement cost due to lack of reliable data.

2.3.1 Selected assumptions

As there is a lack of data and the detailed approach for calculating GHG emission performance according to REDII was not available at the time of estimation for the hydrogen pathways the following assumptions were made. The GHG emissions from hydrogen from woody biomass were assumed to be the same as

for methanol from the same feedstock for two of the ways of handling the CO_2 streams.
For the third case with CCS, the negative emissions due to carbon storage were estimated assuming that 1 kg of hydrogen (LHV = 120 MJ/kg) releases 15 kg of CO_2. See section 3.2 for the result.

In the case of woody biomass-based gasoline via isobuthanol+oligomerization, no GHG emission were found. However, it was assumed that the GHG emissions for this pathway is the same as for aviation fuel via the same pathway.

Here follows a motivation for having zero emissions from electricity for the lower case for electrofuels and bio-electrofuels expected to be produced in Sweden. The EU Commission proposed in delegates acts on RFNBOs and recycled carbon under the REDII-directive (published spring 2023) that the GHG emissions from electricity production should be counted as zero in the production of hydrogen and other RFNBOs if it meets the criteria for being counted as fully renewable (European Commission, 2023c). These criteria can, according to the delegated acts, either be met if the production is located within a bidding zone where at least 90 percent of the electricity production is renewable (which seems to be the case for at least the northernmost zone in Sweden) or if the used energy is additional. For this reason, it is justified to include a scenario where GHG emissions from electricity production in Sweden are assumed to be zero when estimating the GHG emission performance of hydrogen and electrofuels.

In terms of gasification of household waste for producing renewable fuels, there was a lack of GHG emission estimates in the literature. The references found did not follow the REDII approach and the production was not representing the Swedish case. Therefore, biofuels based on household waste could not be covered like other fuel pathways. However, some data for GHG performance and production cost for methanol via gasification was found. The GHG emission performance was estimated based on Yang & Chen (2022) where the production was based in the USA. The average of the GHG emission performance interval presented in that study (32.9-62.3 gCO_2eq/MJ) was used to illustrate the potential GHG performance of this pathway (which is higher than the studied woody biomass -based biofuels, bioelectrofuels and electrofuels). The production cost was taken from IEA (2020) with an assumed cost increase of 10%. Estimates for the GHG emission for aviation fuel via gasification of waste and Fischer-Tropsch was based on Prussi et al. (2021). The GHG emission was an average of the reported GHG emissions of household waste with biogenic content of 0% and 40%, respectively (5.2 and 73.4 gCO_2eq/MJ respectively, which is also higher than the studied woody biomass-based biofuels, bioelectrofuels and electrofuels). The production cost was taken from IEA Bioenergy report (IEA, 2020) with an addition of cost adjustment of 10%. See further in Section 3.3.1.

2.4 CO_2 abatement cost

The CO_2 abatement cost is a measure of how cost-efficient different fuel types are regarding decreasing climate impact from the transport sector. It is calculated according to the following equation.

$$\mathrm{CO2\ abatement\ cost} = \frac{(Fuel\ production\ cost - fuel\ production\ cost\ fossil\ reference)}{(CO_2 emissions\ fossil\ fuel\ reference - CO_2 emissions\ fuel)}$$

The biofuel products are, based on their specific characteristics, assumed to replace fossil diesel, fossil gasoline, fossil aviation fuel, or hydrogen produced from natural gas. The applied fossil reference costs and emissions are presented in Table 3.

Table 3. Carbon footprint, energy content expressed as lower heating value (LHV) and reference cost of fossil reference fuels. For references see the text.

	GHG footprint	LHV	Reference cost (2021)	Reference cost (2021)
	gCO2eq/MJ	MJ/kg	SEK/liter	SEK/MJ
Diesel	94	42.6	7.0	0.20
Gasoline	94	43.4	5.62	0.18
Aviation fuel	94	43.0	7.0	0.20
Hydrogen	94	120	0.11	0.09

The physical data (density and energy content in LHV) is taken from the Engineering toolbox (The Engineering ToolBox, 2023). Reference costs for diesel and gasoline are based on the price-data presented by the Swedish industry organization for fuels (Drivkraft Sverige, 2023), recalculated by the Swedish Energy Agency (Swedish Energy Agency, 2021) to represent pure fossil gasoline and diesel and to remove the gross-margin to apprehend the product cost. For lack of better data, aviation fuels are assumed to have the same costs per volume as fossil diesel. The reference cost for hydrogen production from natural gas is based on data from the International Energy Agency (IEA) for the year 2020 (IEA, 2022. An exchange rate of 10.3 SEK/$ was used.

According to the updated Renewable Energy Directive (RED II) methodology, fuel production emissions for both biofuels and so-called renewable fuels of non-biologic origin (RFNBO) including electrofuels should be compared to a fossil reference of 94 gCO_2eq./MJ (European Commission 2023a, European Commission 2023b). Production of hydrogen from biomass for use in the transport sector is according to the delegated acts published during spring 2023 defined as biomass fuels and not RFNBO and should, as per the interpretations of the authors of this report, be compared to the same fossil reference as carbon-based biofuels (Zhou and Baldino, 2022). This emission level also compares well to the real emissions from hydrogen production from natural gas with a low methane slip (Bauer et al. 2021).

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The CO_2 abatement cost is presented as a span based on the upper and lower values for production cost and GHG emission performance (see paragraphs 2.2 and 2.3). To calculate the span, the highest cost is combined with the lowest CO_2 emission reduction and vice versa, to thereby obtain the maximum possible solution space

3 Results

3.1 Production cost

A compilation of the mapped production costs (expressed in SEK per MJ) for the considered fuels based on the different feedstocks and production pathways is shown in

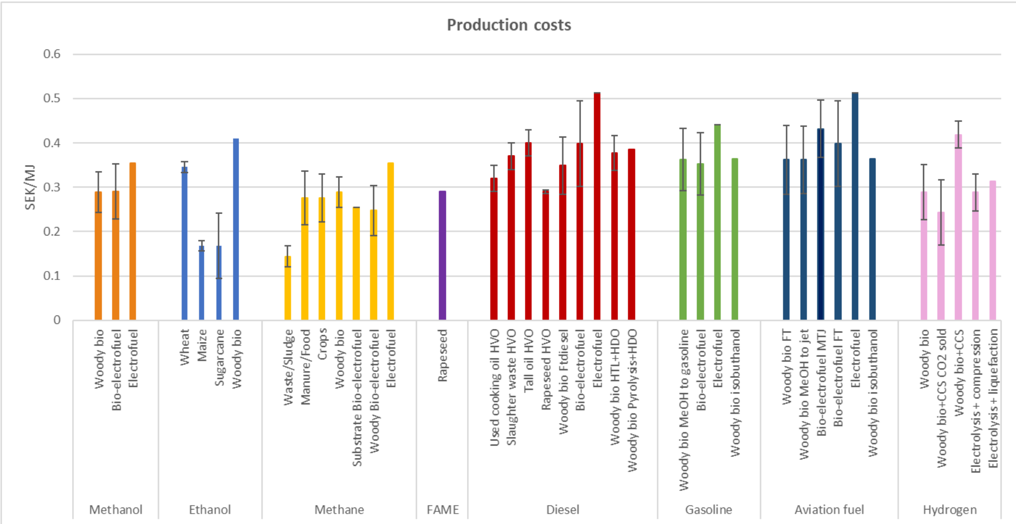

Figure 2. For most production chains, data is only available from one or two of the sources used. In the cases where there is data from several sources, they are in most cases consistent with each other, see

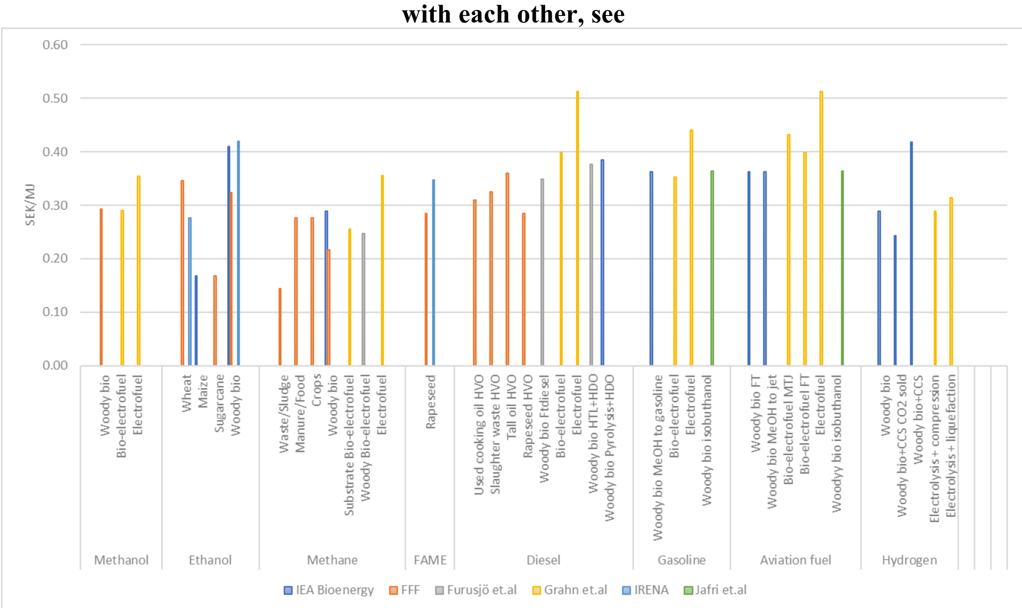

Figure 3.

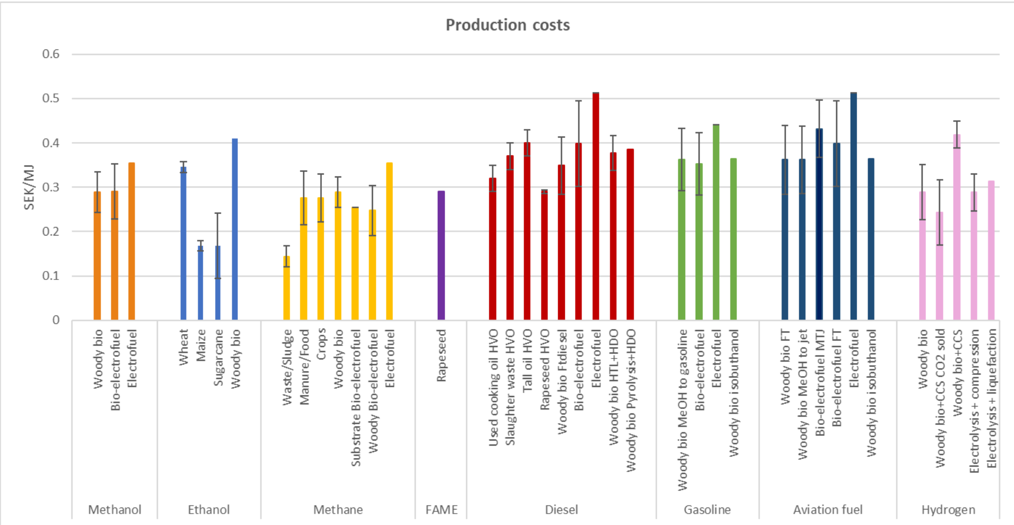

Figure 2. Mapped production costs for all considered fuels and production pathways with the range from different sources indicated. These values are used for the CO_2 abatement cost estimate.

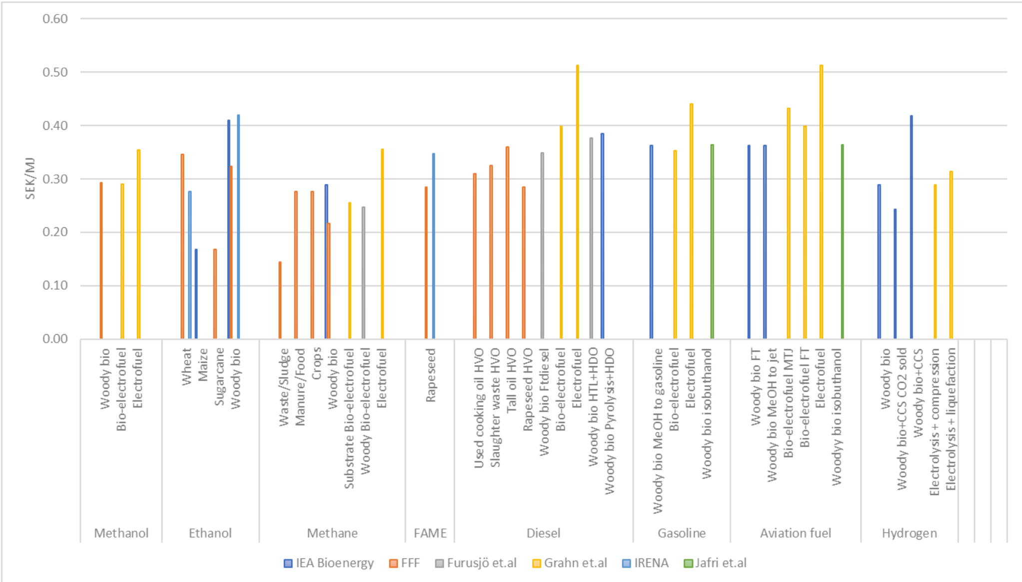

Figure 3. Summarized production costs from the mapped data sources. For full references see the text.

3.2 GHG emission performance

The mapping of the GHG emission performances of the considered fuels pathways is presented in this section. Figure 4 illustrates the GHG emission performances for the considered fuels and production pathways including uncertainty intervals, that are used for the carbon abatement cost estimate. **Error! Reference source not found.**However, note that the GHG performance of the pathway hydrogen from gasification of biomass plus CCS assuming negative emissions from CO_2 storage which resulted in -116 gCO2eq/MJ, is not included in the figure since it was difficult to accommodate in the same figure without reducing the readability of GHG performance for the other pathways.

Energimyndigheten

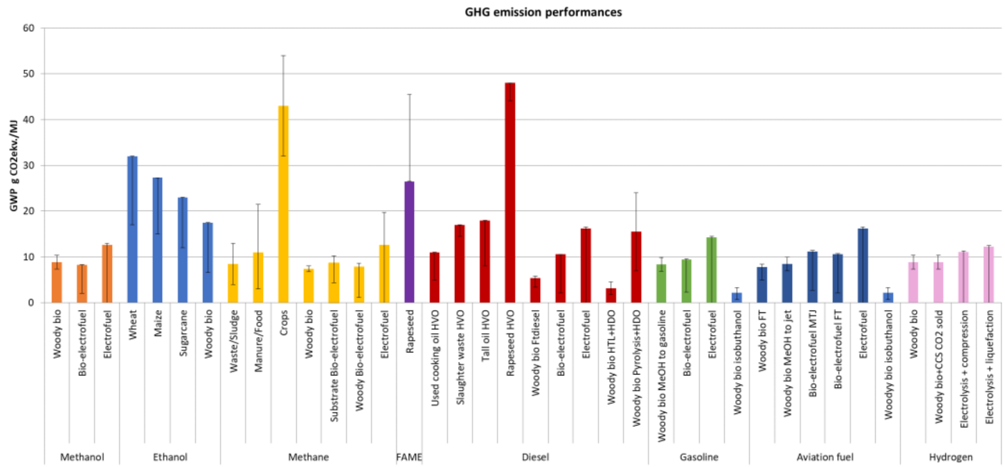

Figure 4. GHG emission performances for the studied fuels and production pathways including uncertainty intervals, used for the carbon abatement cost estimate. The GHG performance for the pathway hydrogen from gasification of biomass plus CCS assuming negative emissions from CO_2 storage (-116 gCO2eq/MJ) is not included with a bar. The pathways are described in Table 1.

The GHG emission performances including the uncertainty intervals for the studied are also presented in Table 4.

Table 4. Detailed GHG emissions performance for the studied fuel pathways including uncertainty intervals used for the CO2 abatement cost estimate.

Fuel	Feedstocks	Production pathway	Reference GHG emission (gCO_2eq/MJ)	GHG emission intervals (gCO_2eq/MJ)
Methanol	Woody biomass	Gasification	8.9	7.4 – 10.4 [a]
	Woody biomass + Electricity	Gasification	8.3	2.05 – 8.4 [b]
	Electricity + CO_2	Electrolysis + CC	12.7	0 – 13.0 [b]
Ethanol	Wheat	Fermentation	32.0	17.0 - 32.0[a]
	Maize	Fermentation	27.3	15.0 – 27.3[a]
	Sugarcane	Fermentation	23.0	12.0 – 23.0[a]
	Woody biomass	Fractioning + fermentation	17.5	6.6 - 17.5[a]
Methane	Waste/sludge	Anaerobic digestion	8.5	4.0 - 13.0[a]
	Manure/food waste	Anaerobic digestion	11.0	3.0 – 21.5[a]
	Crops	Anaerobic digestion	43.0	32.0 – 54.0[a]
	Woody biomass	Gasification	7.4	6.8 – 8.0[a]
	Substrate + electricity	Electrolysis + Anaerobic digestion, (Bio+El)	8.7	4.4 – 10.3[b]
	Woody biomass + electricity	Electrolysis + Gasification, (Bio+El)	7.9	1.2 – 8.7[c]
	Electricity + CO2	Electrolysis + CC (El+CO2)	12.7	0 – 19.74[b]
FAME	Rapeseed	Transesterification	26.5	26.5 – 45.5[d]
Diesel	Used cooking oil (UCO)	Hydrogen treatment - HVO	11.0	5.0 - 11.0[a]
	Slaughterhouse waste	Hydrogen treatment - HVO	17.0	14.5 – 17.0[a]
	Tall oil	Hydrogen treatment - HVO	18.0	8.0 – 18.0[a]
	Rapeseed oil	Hydrogen treatment - HVO	48.0	44.1 – 48.0[a]
	Woody biomass	Gasification + Fischer-Tropsch	5.4	3.4 – 5.8[c]

	Woody biomass + electricity	Electrolysis + Gasification + Fischer-Tropsch: (Bio+El)	10.6	2.2 – 10.7[b]
	Electricity + CO2	Electrolysis + CC (El+CO2)	16.2	0 – 16.5[b]
	Woody biomass	Hydrothermal liquefaction (HTL) + Hydro-deoxygenation (HDO)	3.2	1.8- 4.6[e]
	Woody biomass	Pyrolysis + HDO	15.5	7.0 – 24.0[a]
	Woody biomass	Hydropyrolys	17.6	11.6 – 23.6[a,n]
Gasoline	Woody biomass	Gasification + Methanol to gasoline (MTG)	8.4	6.9 – 9.9[a]
	Woody biomass + electricity	Electrolysis + Gasification + MTG	9.4	2.3 – 9.6[b]
	Woody biomass	Isobuthanol + oligomerization	2.2	0.73 – 3.3[f]
	Electricity + CO2	Electrolysis + CC (El+CO2)	14.3	6.8 – 8.0[b]
	Woody biomass	Hydropyrolysis	17.6	9.1 – 26.1[a,n]
Aviation fuel	Woody biomass	Gasification + Fischer-Tropsch	7.8	4.9 – 8.5[g]
	Woody biomass	Gasification + Methanol to Jet (MTJ)	8.5	6.9 – 10.0[h]
	Woody biomass + electricity	Electrolysis + gasification + MTJ, (Bio+El)	11.2	2.8 – 11.4[b]
	Woody biomass + electricity	Electrolysis + gasification + Fischer-Tropsch, (Bio+El)	10.6	2.2– 10.8[b]
	Woody biomass	Isobuthanol + oligomerization	2.2	0.7 – 3.3[i]
	Electricity + CO2	Electrolysis + CC + Fischer-Tropsch (El+CO2)	16.2	0 – 16.5[b]
	Woody biomass	Hydropyrolys	1.7	1.0 – 2.4[l,n]
	Woody biomass	Ethanol-to-jet (ETJ)	5.1	1.9 – 5.1[m]
Hydrogen	Woody biomass	Gasification	8.9	4.9 – 8.5[j]
	Woody biomass	Gasification + CCS (carbon capture and storage) (CO2 sold)	8.9	6.9 – 10.0[j]
	Woody biomass	Gasification + CCS (negative emission from CO2 storage)	-116	-158 to -116[k]
	Electricity	Electrolysis + compression	11.1	0– 11.3[b]
	Electricity	Electrolysis + liquefaction	12.3	0 – 12.5[c]

[a] An uncertainty interval is provided in the references used.
[b] The lower part of the interval is based on the assumption that the electricity is produced with zero GHG emissions, while the higher end represents the near-term scenario in the reference used (Grahn et al., 2022) but adapting it with 7 gCO_2eq/MJ for the electricity.
[c] The lower part of the interval represents a case where the electricity is produced with zero GHG emissions, the higher end represents a similar pathway alternative presented in Furusjö et al. (2022).
[d] The lower and upper limits represent the range of all the references mapped.
[e] Uncertainty range assumed to be the same as the average percentage increase and decrease for the case of woody biomass-based diesel via pyrolysis+HDO (55%) and via hydropyrolysis (34%) based on Lönnqvist et al (2021).
[f] The uncertainty interval was assumed to be the same as for gasoline via hydropyrolysis (in percentages). The hydropyrolysis pathway was not included in the calculation of abatement cost.
[g] Uncertainty interval in percentages was assumed to be the same as for woody biomass-based diesel via gasification+Fischer-Tropsch (-37% and +8%)
[h] Uncertainty interval was assumed to be the same as for woody biomass-based gasoline via gasification+methanol+MTG (±18%)
[i] Uncertainty interval was assumed to be the same as for woody biomass-based gasoline via isobutanol+oligomerization (-67% and +48%).
[j] Uncertainty interval was assumed to be the same as for woody biomass-based methanol (±17%)
[k] The lower limit was calculated when the CO_2 storage is increased from 15 to 20 kg CO_2/kg H_2
[l] Lowest and highest interval was assumed to be the same as an average of percentage increase and decrease for the case of woody biomass-based diesel and gasoline via hydropyrolysis (34% and 48%)
[m] Uncertainty interval was assumed to be the same as for woody biomass-based ethanol.
[n] This pathway was not included in the main estimate of the CO2 abatement cost.

3.3 CO_2 abatement cost

The CO_2 abatement cost interval for all pathways with sufficient cost and emission data quality is presented in Figure 5. Overall, the carbon abatement cost ranges from -0.4 to 4.0 SEK/kgCO_2eq, depending on the specific pathway. The average value is 1.9 SEK/kgCO_2eq and the median is 2.0 SEK/kgCO_2eq. All but five of the considered pathways end up within an interval ranging from 0.8 to 3.3 SEK/kgCO_2eq.

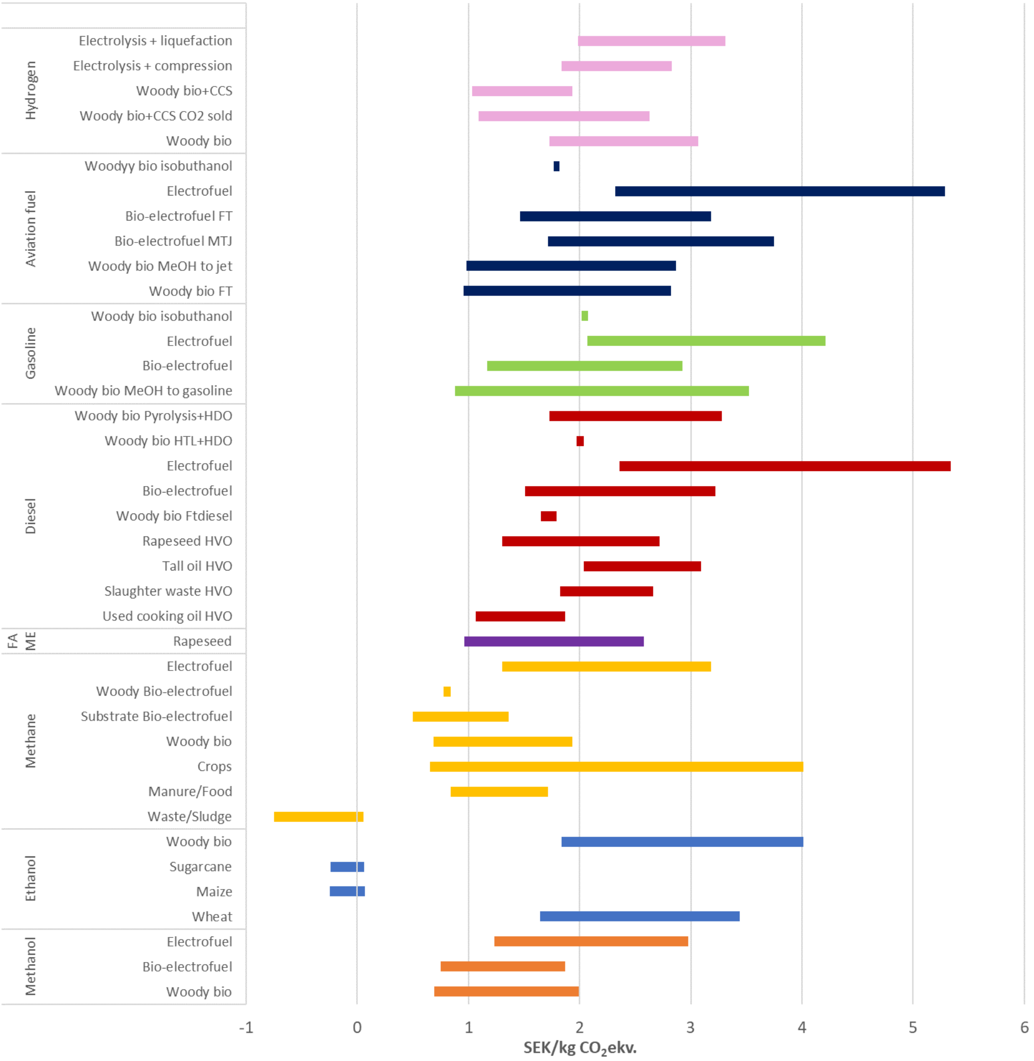

Figure 5. Estimated carbon dioxide abatement cost interval for all considered pathways in SEK per kg of CO_2 equivalents. The pathways are described in Table 1.

The large variations in result intervals, highlight how the data availability varies substantially between different pathways. The CO_2 abatement cost varies largely for different value chains also with the same fuel type (with different feedstocks). But some trends can nevertheless be observed.

Currently, commercial pathways have, in general, lower CO_2 abatement costs than pathways that are not yet deployed in large scale. Pathways for HVO and biogas based on residues including used cooking oil (UCO), talloil, sludge, manure, and food waste have a CO_2 abatement cost between about -0.4 and 2.2 SEK/kgCO2eq. First generation ethanol has a CO_2 abatement cost between -0.1 and 2.7 SEK/kgCO2eq with the lower range representing maize and sugarcane.

Forest biomass-based biofuels have a CO_2 abatement cost of 1.3 to 3.1 SEK/kgCO2eq. Bio-electrofuels have a CO_2 abatement cost of 1.3 to 2.8 SEK/kgCO2eq and electrofuels between 2.2 and 4.1 SEK/kgCO2eq. For these, methanol and methane in general has somewhat lower CO_2 abatement cost than hydrocarbon-based fuels (gasoline, diesel, and aviation fuel).

Three pathways are estimated to have low enough production costs to achieve a negative CO_2 abatement cost (methane from anaerobic digestion of sewage sludge and ethanol from fermentation of sugarcane and maize). A negative carbon abatement cost means that, given that the production cost of the fossil diesel and gasoline compared to is correct, is currently more economically beneficial to use the biofuel option rather than its fossil counterpart.

In Figure 6 the average production cost is plotted against the CO_2 abatement cost for all considered biofuel pathways. The data is color-coded based on end-product. Also in this figure, it is hard to make any clear distinctions between different end-products. However, most methane pathways (yellow) achieve relatively low production costs and CO_2 abatement costs. Likewise, hydrogen production (pink) stands out with a relatively high CO_2a batement cost compared to other pathways with similar production costs. The main reason for this result is the, relatively, low cost of the reference, fossil hydrogen, produced from natural gas.

Two pathways also stand out with high production and CO_2 abatement cost: production of diesel and aviation fuel from carbon dioxide and electricity (electrofuel). Thus, the included biobased aviation fuels (and to some extent also bio-electrofuels for aviation) seem more promising in this perspective.

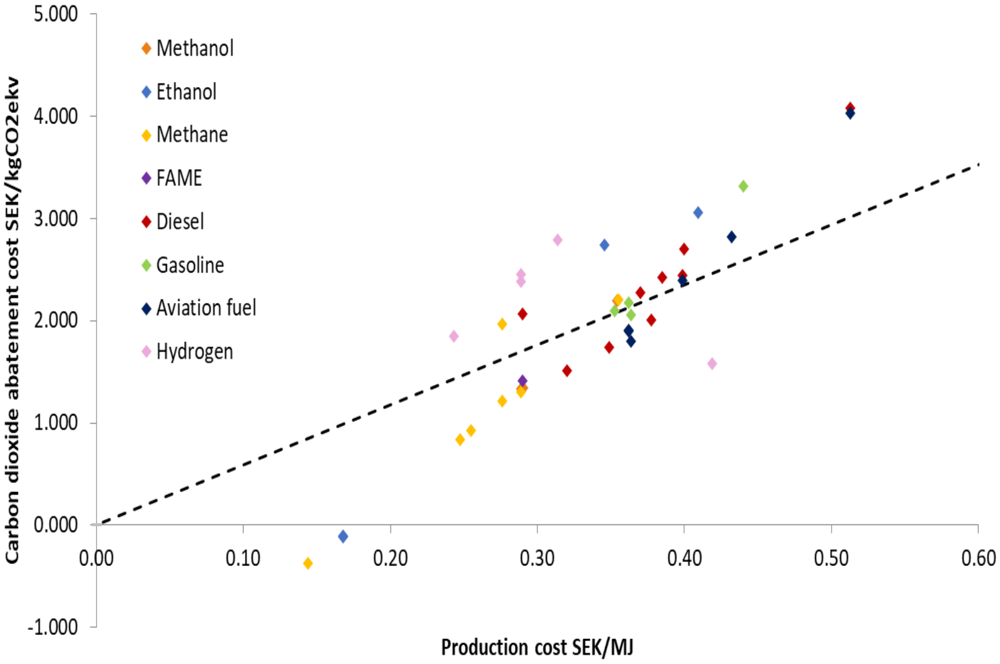

Figure 6. Scatter plot of carbon dioxide abatement cost against production cost for all considered pathways sorted per type of end-product. Note that the three methanol pathways are hidden behind two of the methane pathways (the methanol pathways have a production cost of 0.29 and 0.35 SEK/MJ and CO_2 abatamenet cost of 1.3 and 2.2 SEK/kg CO_2eq respectivley).

Figure 6 also shows that there is a relatively linear correlation between the production cost and CO_2 abatement cost. This result highlights how production cost, in general, is a more important parameter to achieve a low CO_2 abatement cost than CO_2 emission reduction. Most of the studied biofuel pathways achieve substantial GHG emission reduction compared to their fossil counterparts. In general, the reduction potential is also larger for woody biomass-based biofuels, however, that difference is indicated to have a marginal impact on the CO_2 abatement cost. This conclusion is emphasized by considering the pathway for the production of hydrogen from woody biomass through gasification combined with CCS (the lowest pink dot to the far right in

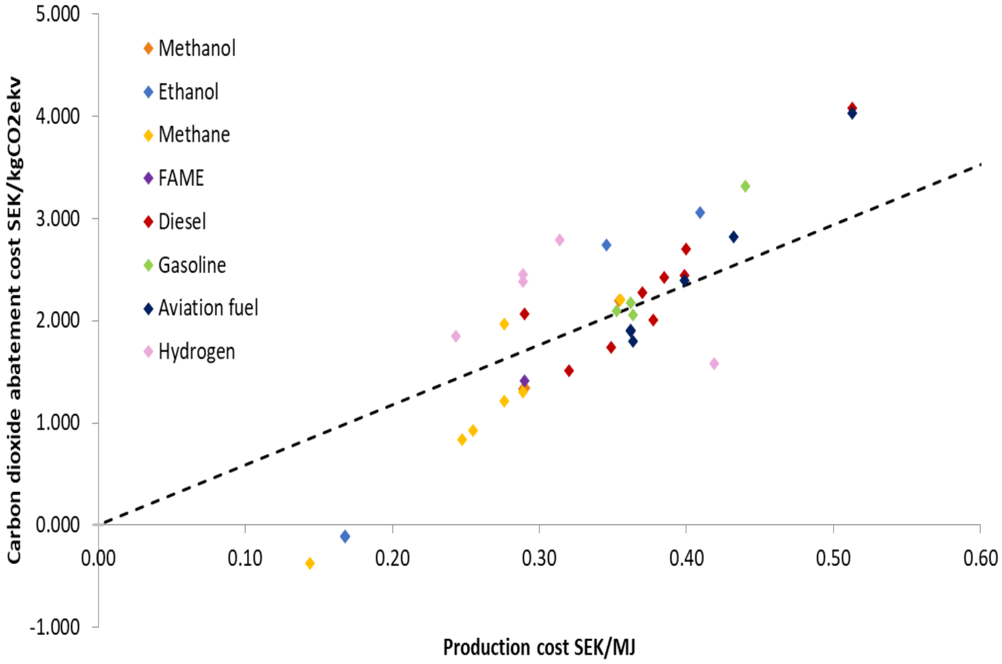

Figure 6). This pathway has, by a margin, the largest carbon dioxide reduction potential (see Chapter 3.2), however, the CO_2 abatement cost is, although lower, within the same range as for the other pathways.

Given that production cost is an important parameter in lowering the CO_2 abatement cost, the fossil reference cost has a large impact on results.

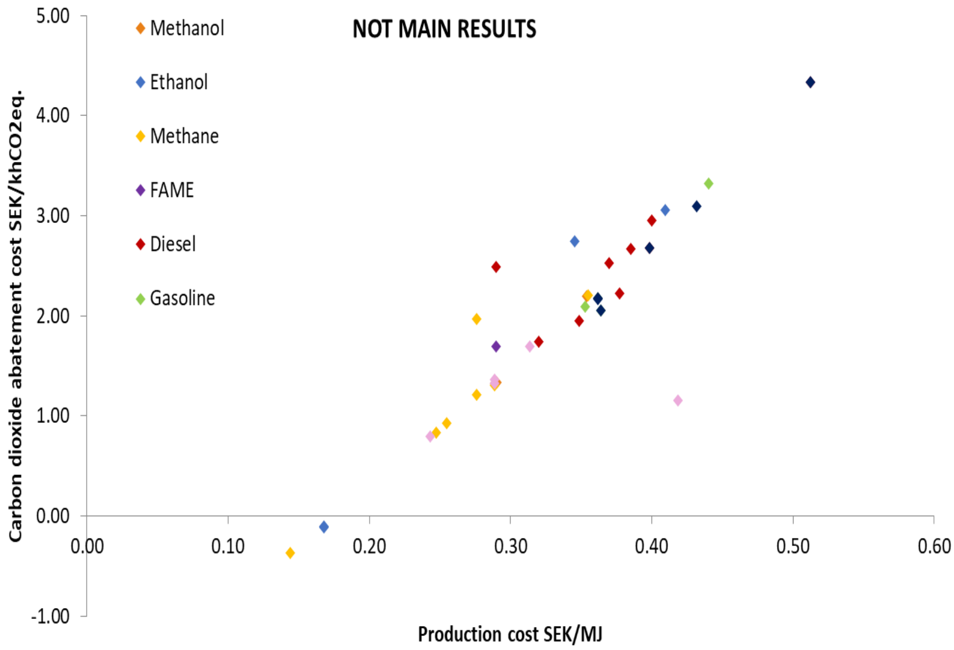

Figure 7 shows the same results as Figure 6 but utilizes the same fossil reference cost for all pathways (18 SEK/MJ, which represent the one used for gasoline). When removing the reference cost as a variable, the results are far less shattered, leaving an almost uniform line, crossing the x-axis at the fossil reference cost (18 SEK/MJ). The remaining deviation from a

completely linear relation is caused by the difference in climate footprint between the pathways. Given the relatively small deviation, the results of

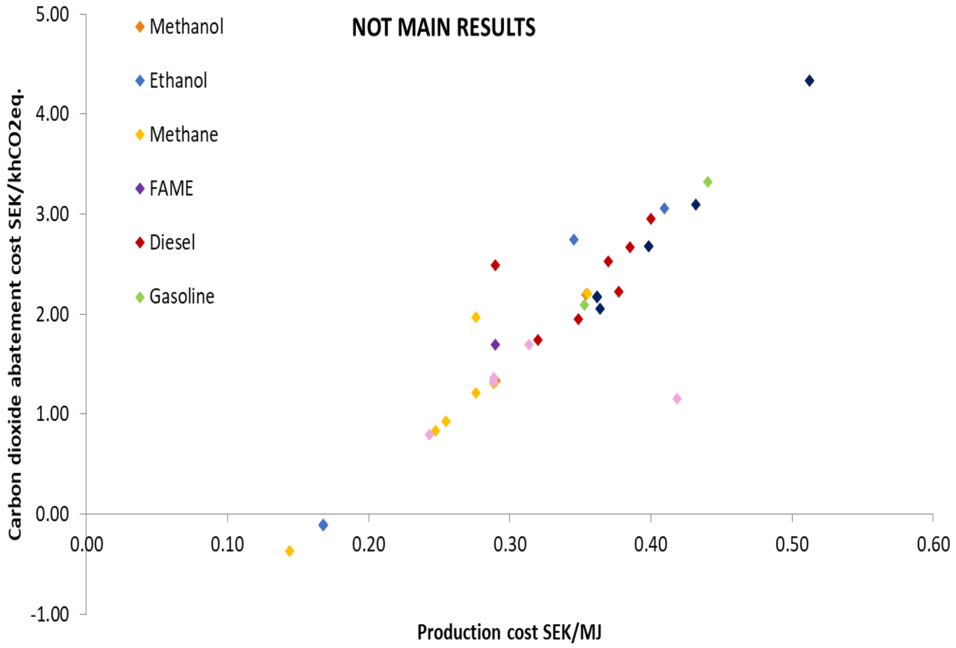

Figure7 highlight what has previously been discussed: GHG emission performance, in general, has a limited impact on the CO_2 abatement cost. There are, however, a few exceptions, caused by a deviating climate impact in relation to the other pathways. This is mainly higher climate footprint for some crop-based fuels or the carbon-negative hydrogen option.

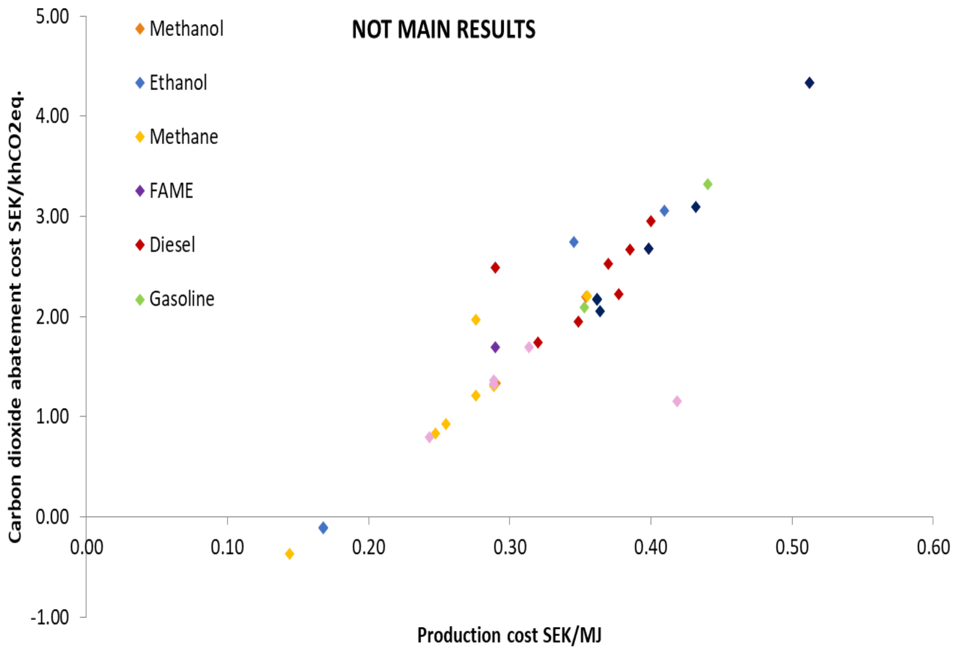

Figure 7. Scatter plot of carbon dioxide abatement cost, with the same fossil reference cost for all pathways, against production cost for all considered pathways sorted per type of end-product. CAC represents CO_2 abatement cost.

The CO_2 abatement cost data is also sorted based on the type of feedstock and the type of replaced fuel. These results are presented in Figure 8, together with a plot of GHG performance in relation to production cost.

Sorting the data based on the feedstock type shows how the first-generation biofuels (crop-based), clearly have a higher carbon footprint compared to the other pathways. It also shows how the impact on the CO_2 abatement cost is limited. Although, many of the first-generation biofuel pathways do have a relatively high cost for CO_2 abatement in relation to their production cost. In general, the woody biomass-based pathways have low carbon footprints but moderately high production costs, which puts them relatively consistently in the middle, compared to other feedstock options, in terms of the CO_2 abatement cost. Although not true for all pathways, the bio-electrofuels and electrofuels pathways have the highest production costs and correspondingly, the highest CO_2 abatement cost. As expected, the pathways based on waste streams, e.g., anaerobic digestion of sewage sludge have low climate impact combined, mostly, with relatively low production costs, which in general puts them among the pathways with the lowest CO_2 abatement cost.

Although not overly clear for all specific pathways, it is easier to distinguish trends when categorizing the pathways according to feedstock type rather than specific end-product. These results suggest that the feedstock cost, in general, may have a larger impact on the CO_2 abatement cost compared to specific end-product. Although, in some cases, the type of end-product is closely related to used feedstock (e.g., methane from anaerobic digestion of sewage sludge or FAME from rapeseed).

By categorizing the results according to the type of replaced fuel, a trend regarding the CO_2 abatement cost is seen. Biofuels that replace the same type of fossil fuel have a clearer linear correlation, except for a few deviations with a substantial difference in climate footprint. This is, according to the reasoning presented in Figure 7, a consequence of the relatively large impact on the assumptions related to fossil fuel reference cost.

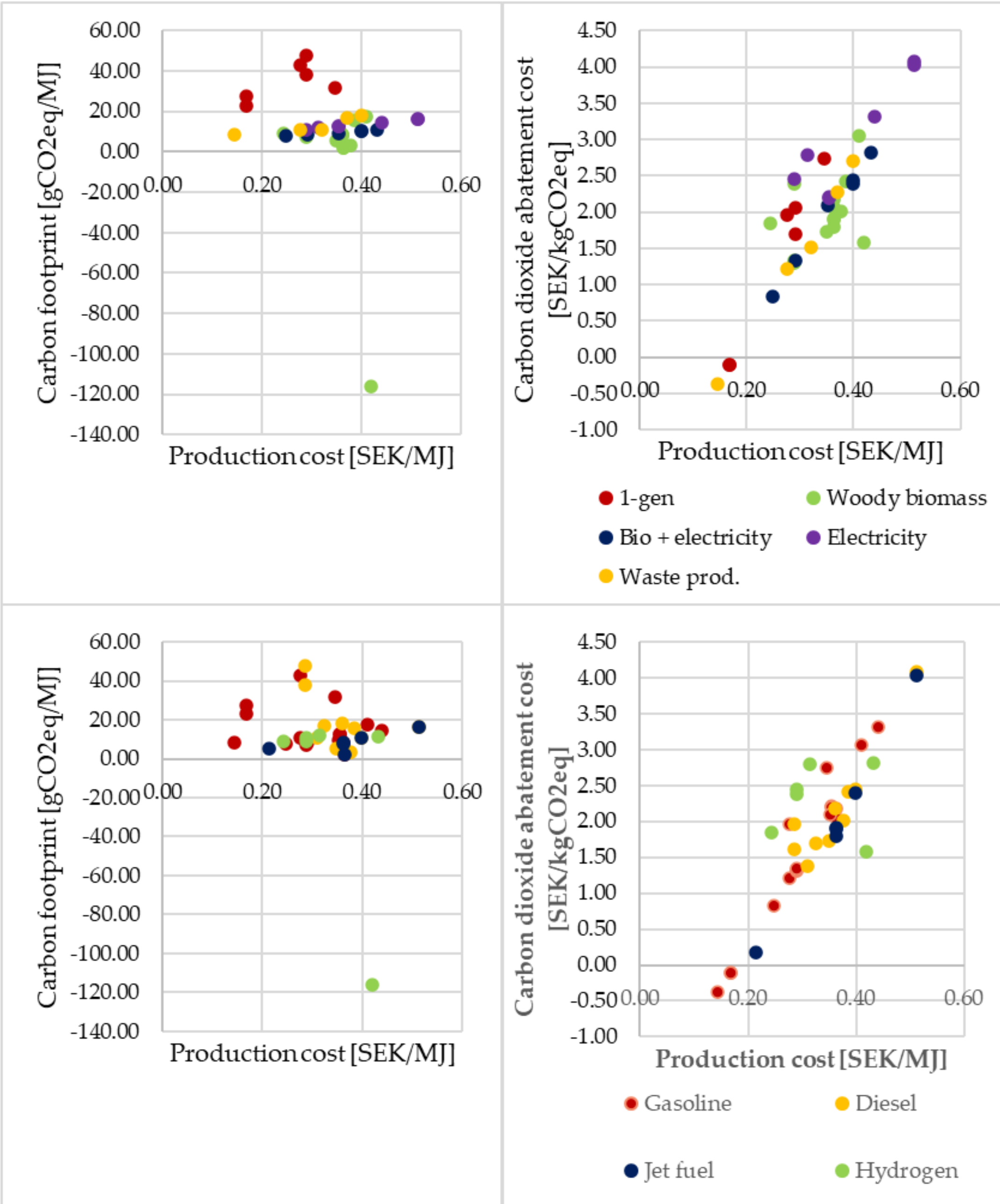

Figure 8. Scatter plots of carbon footprint (i.e., GHG emission performance) as a function of production cost (left), as well as CO_2 abatement cost as a function of production cost (right), for all considered pathways sorted by feedstock type (top) and replaced fuel (bottom).

In Sweden, the recent political debate has put the question of carbon abatement cost for different technology pathways on the agenda. With the reduced levels of GHG reduction mandates for gasoline and diesel, Sweden will likely not be able to reach the target for reduced climate impact from the vehicle fleet by 70% by 2030 and may also fail to meet climate obligations made to the EU[1]. To promote

[1] https://www.energimyndigheten.se/nyhetsarkiv/2022/reduktionsplikten-ar-avgorande-for-att-na-sveriges-energi--och-klimatmal/

other GHG reduction measures, the current government has launched support for large-scale investments in bioenergy applications with carbon capture and storage (BECCS). The idea is that negative GHG emissions will compensate for increased emissions from the transportation sector.

Beiron et al (2022) assessed the cost for integrating BECCS at 110 biomass or waste fired combined heat and power (CHP) plants in Sweden. It was found that the cost for CO_2 separation and transportation via truck to intermediate storage hubs is in the range of 45–125 EUR/tonCO_2 for most CHP plants. Around 10.6–13.6 MtonCO_2/year could be available for capture at a cost of <100 EUR/tonCO_2, excluding the costs for ship transport and storage. Adding a cost for ship transport and end-storage (estimated at 35-55 EUR per ton CO_2) gives a total cost for BECCS in the range of 80-180 EUR/tonCO_2 with the majority achieving a cost of less than 155 EUR/tonCO_2 (Andersson et al.2021).

For comparison, the estimated CO_2 abatement cost of the fuel production pathways considered in this work is in the range of -50 to 400 EUR/tonCO_2, but 100-300 EUR/tonCO_2 for the majority of the assessed pathways. Several of the considered fuel pathways reaches a CO_2 abatement cost that is within the same range as the estimated cost of BECCS or lower. The CO_2 abatement cost presented in this work should, however, mainly be used to compare different renewable fuels for transport, with the same application. To reach the long-term climate goals the emissions in all sectors need to be substantially reduced.

3.3.1 Separate pathways

As previously mentioned in Section 2, it has not been possible to find reliable data for all considered pathways. To avoid misinterpretation and misuse of the data, these pathways are not presented together with the others. For some of the pathways, e.g., hydropyrolysis-based production of aviation fuels from woody biomass, the capital costs that were possible to apprehend are too optimistic for a reasonable estimation of the CO_2 abatement cost. Therefore, these numbers are not included in the report. For many of the waste-based pathways it is, however, possible to find data, but hard to judge the quality and if the correct methods have been applied to estimate it. The CO_2 abatement cost for the two waste-based pathways where it was possible to find both cost and carbon footprint data that seems relatively reliable (based on Ahlström et al., 2022, Wetterlund et al., 2022, IEA, 2020, Yang & Chen (2022)) is presented in Table 5.

Table 5. Carbon abatement cost, with upper and lower values for two waste-based pathways.

Fuel	Technology	Carbon dioxide abatement cost (SEK/kgCO2eq)	Upper	Lower
Aviation fuels	Gasification + FT	1.45	0.44	5.77
Methanol	Gasification	1,55	0.46	3.04

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Any direct comparison with the other pathways should be viewed with caution, particularly as the uncertainty range is large. It can, however, be concluded that the CO_2 abatement cost for the production of aviation fuels from this pathway (using the chosen value and given that the carbon footprint is correctly estimated) indicates that it might be a promising pathway compared to other pathways for aviation fuel production. However, it depends on the actual performance. For methanol production, the CO_2 abatement cost is within the same range as the other considered methanol pathways.

4 Conclusions

This study presents a thorough and structured review of production costs, GHG emission performance, and corresponding CO_2 abatement costs for different technologies to produce renewable fuels. Included fuels are diesel, gasoline, methanol, ethanol, methane, and hydrogen for road transport and aviation that are available or under development and relevant for Sweden. The main findings from the study are summarized below.

In terms of production cost for the same fuel, biofuels are generally less costly than bio-electrofuels which are somewhat less costly than electrofuels (except for the case of methane). All the assessed renewable fuel pathways achieve substantial GHG emission reduction compared to fossil fuels, in general somewhat less so for crop-based fuels. Hydrogen produced from biomass with CCS of the generated CO2 result in negative emissions.

The estimated carbon abatement cost ranges from about -0.4 to 4.0 SEK/kgCO_2eq, with an average value of 1.9 SEK/kgCO_2eq (median value of 2.0 SEK/kgCO_2eq). In general, processes based on waste feedstock, e.g., anaerobic digestion of sewage sludge, reaches low production costs and related CO_2 abatement cost. On the contrary, electrofuels pathways or bio-electrofuels have relatively high production costs and related CO_2 abatement costs.

Woody biomass-based pathways, in general, have low climate impact, but a moderately high production cost which leads to a moderate performance in terms of CO_2 abatement cost. More in detail, pathways based on residues including used cooking oil, talloil, sludge, manure, and food waste have a CO_2 abatement cost between about -0.4 and 2.2 SEK/kgCO2eq. First generation biofuels have a CO_2 abatement cost between -0.1 and 2.7 SEK/kgCO2eq while woody biomass-based biofuels and bio-electrofuels have a CO_2 abatement cost of 1.3 to 3.1 SEK/kgCO2eq. Electrofuels have the highest CO_2 abatement cost between 2.2 and 4.1 SEK/kgCO2eq.

Compared to a previous report on CO_2 abatement costs from biofuels conducted in 2017 (Furusjö and Lundgren, 2017), where the CO_2 abatement cost on average was 1.44 SEK/kgCO_2eq., the numbers presented in this study are higher. The reason for the relatively large difference is the higher estimated average production cost obtained in this study. In the 2017 report, the average production cost was 0.22 SEK/MJ, compared to 0.33 SEK/MJ for the pathways considered in this report. This is partly explained by the inclusion of pathways that were not considered in the 2017 report, e.g., electrofuels pathways and the production of aviation fuels and hydrogen. It should be noted that in 2017, the fossil reference cost was substantially lower, compared to the numbers applied in this work. Thereby, the difference in CO_2 abatement costs would be even larger if the same fossil reference cost was applied.

If only the same pathways as in the previous report are included in the comparison, the average CO_2 abatement cost in this report is lowered to 1.5 SEK/kgCO_2eq, which is close to the number presented in the 2017 report. However, if lowering the fossil reference cost to the same levels as in the 2017 report, the corresponding number is 2.44 SEK/kgCO_2eq. Thereby, the increase in production cost, owing to high energy prices in general and other factors, has been compensated by increased fossil fuel prices.

The CO_2 abatement cost shows a clear linear relation with production cost for most pathways. This result highlights that the production cost generally has a larger impact on the CO_2 abatement cost compared to GHG performance of the fuel. The reason is that almost all the assessed fuel pathways have relatively low GHG emissions. Although the climate impact differs between pathways, the relative difference is small in relation to the effect of a lower production cost. Except for a few deviating pathways, e.g., hydrogen from biomass gasification with CCS, the climate footprint has a limited impact on the CO_2 abatement cost.

There is not a general correlation between the CO_2 abatement cost and the type of fuel/end-product for all cases. However, for woody biomass-based and woody bio-electrofuels and electrofuels-based methanol and methane pathways, in general, have somewhat lower CO_2 abatement costs than hydrocarbon-based fuels (gasoline, diesel, and aviation fuel). There is a correlation between the CO_2 abatement cost and the type of feedstock; indicating that type of feedstock is also important in reducing costs.

In Sweden, BECCS is currently considered as the main technology pathway to achieve climate obligations on the EU level. Several of the assessed fuel pathways have a CO_2 abatement cost that is in the same range as BECCS and the best performing value chains reaches lower (or even negative) CO_2 abatement cost while the more costly fuel pathways seem to be more costly than BECCS. This study shows that using renewable transport fuels to replace fossil counterparts results in comparable CO_2 abatement costs as BECCS.

More estimates of cost and GHG performance for gasification of waste-based pathways are needed and for certain pathways under development (e.g., including hydropyrolysis).

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Appendix A

The result from the mapping of the GHG emission performance for each fuel pathway for the identified relevant references is presented in detail in Figures A1-A8.

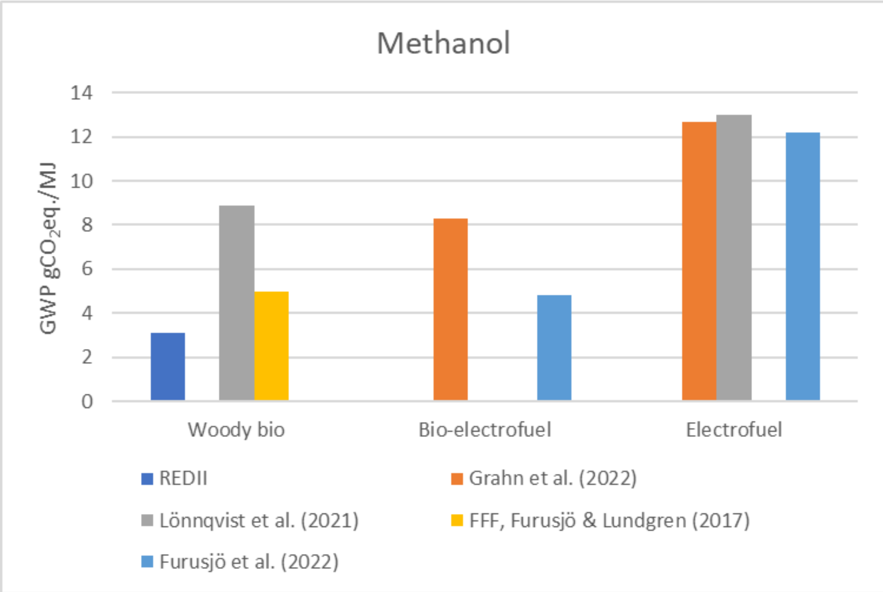


Figure A1. GHG emission performances of methanol for different production pathways according to different references.

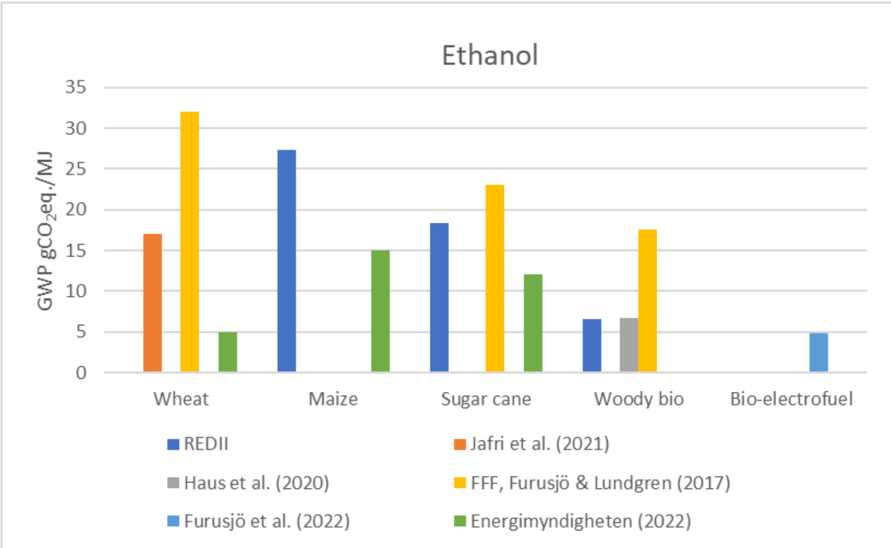


Figure A2. GHG emission performances of ethanol for different production pathways according to different references.

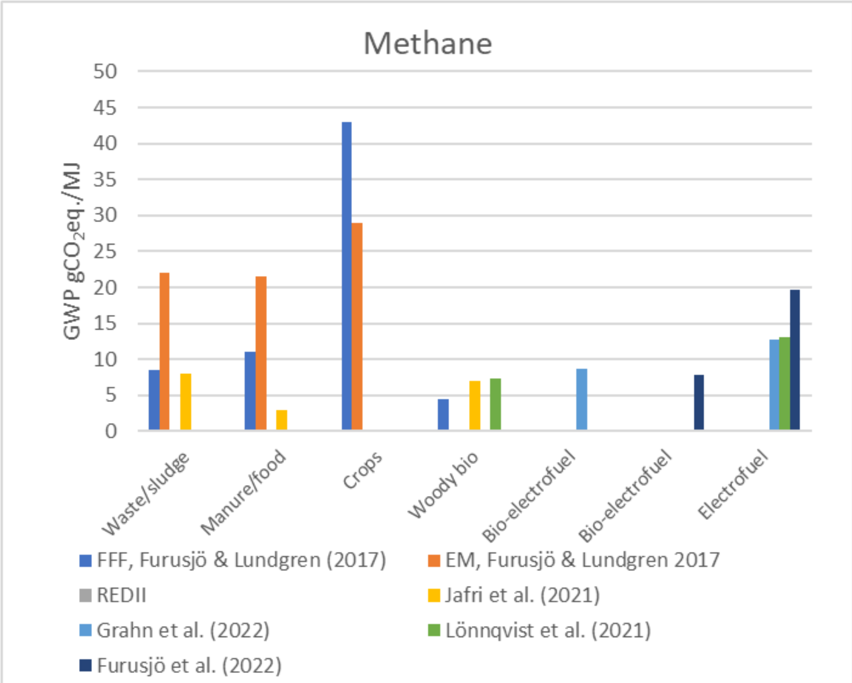


Figure A3. GHG emission performances of methane for different production pathways according to different references. The first bio-electrofuel is based on substrate and the second on woody biomass.

For methanol there are some variations in GHG performance for the bio-electrofuels and woody biomass-based pathways while very similar estimates for the electrofuels pathway. For ethanol there is a large variation which is due to that the GHG emission performances of ethanol from wheat in Swedish Energy Agency (2022) was calculated based on wheat that was produced locally in Sweden in a plant that capture the CO_2 emission (which is not the base case chosen in this assessment as we do not consider this for other pathways either). Also, for methane there is a large variation in GHG emission performance depending on the pathway.

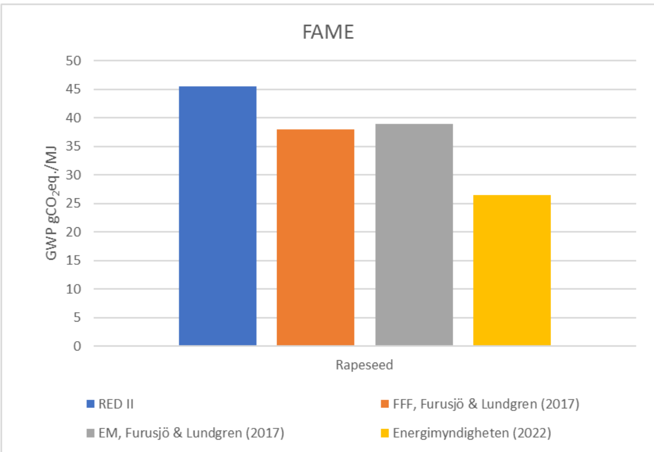


Figure A4. GHG emission performances of FAME for different production pathways according to different references.

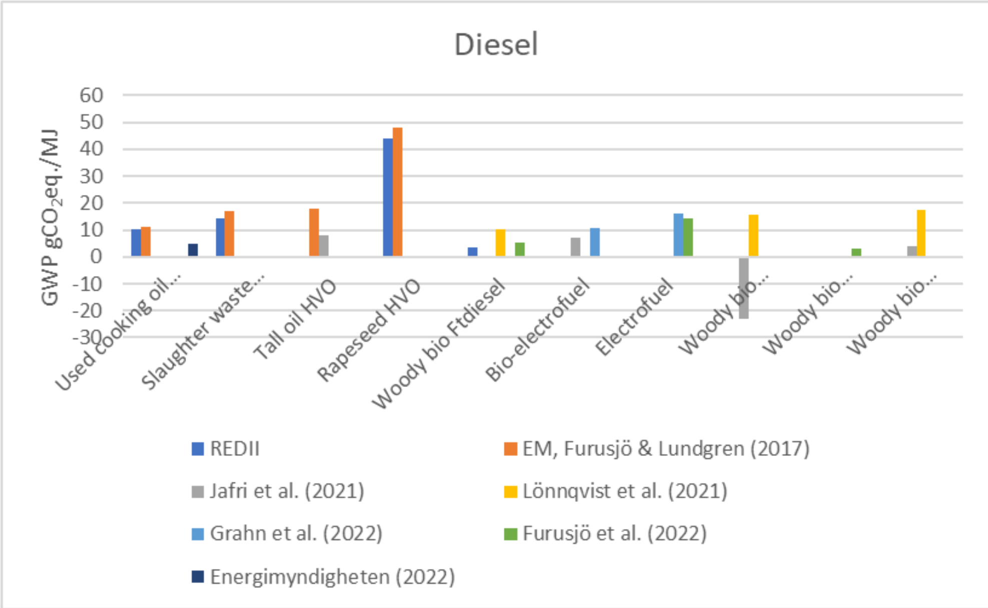


Figure A5. GHG emission performances of diesel for different production pathways according to different scenarios.

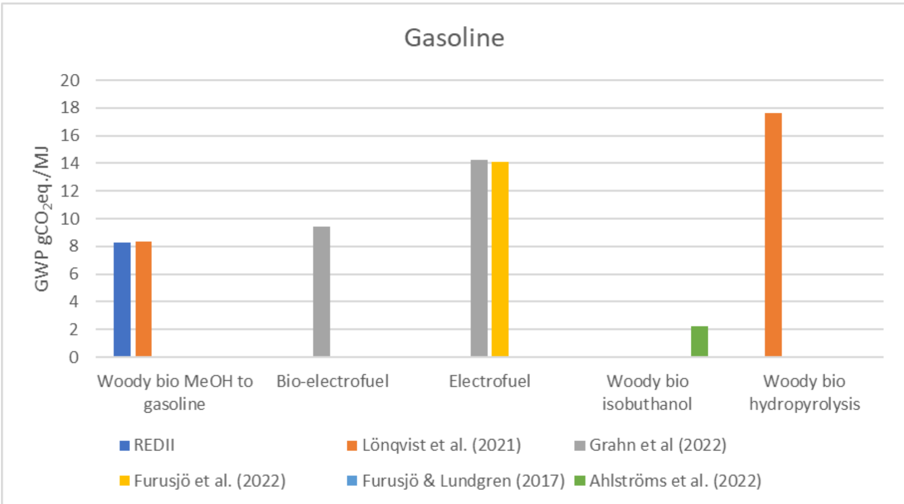
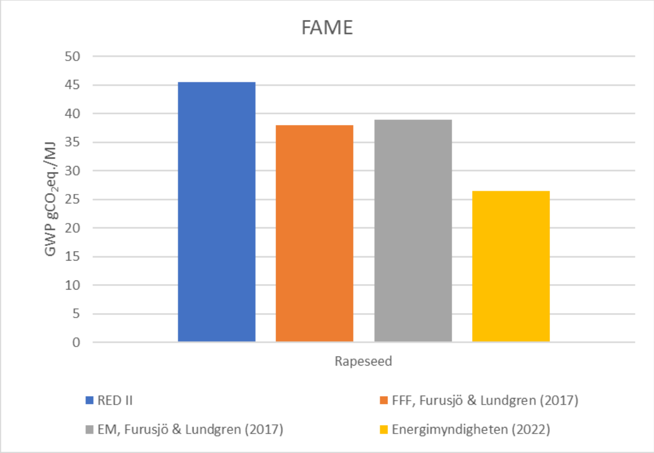


Figure A6. GHG emission performances of gasoline for different production pathways according to different scenarios

The negative GHG emission for diesel via pyrolysis+HDO based on Jafri et al. (2021) is due to that the production pathway has an integrated process where heat waste was used to supply part of the heat demand, resulting in a decrease in fossil methane consumption. It is

not known if this would be accountable according to the RED II methodology.



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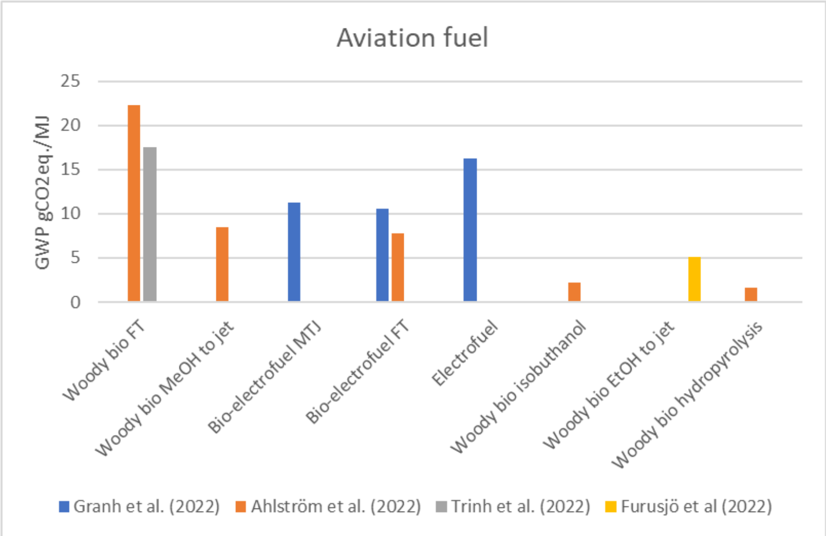


Figure A7. GHG emission performances of aviation fuel for different production pathways according to different scenarios

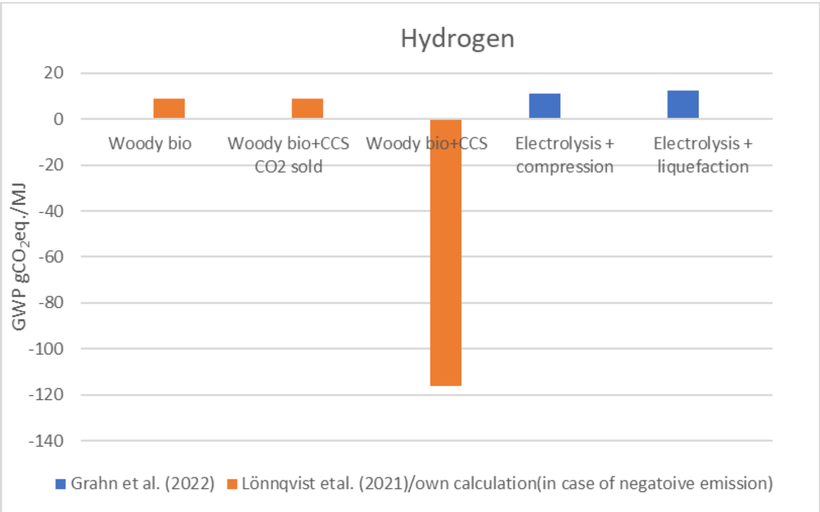


Figure A8. GHG emission performances of hydrogen for two different production pathways according to different scenarios

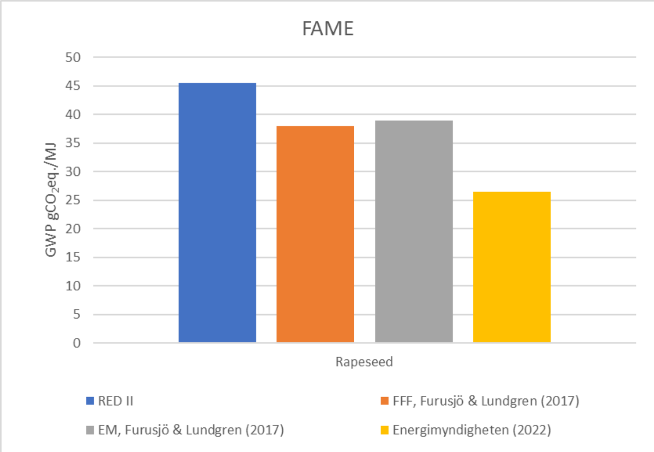
In terms of aviation fuels, 

Figure the pathway for gasification of woody biomass plus Fischer-Tropsch shows the highest GHG emissions followed by the electrofuels pathway. In terms of hydrogen the case when CO_2 is stored, and the pathway credited for this result in negative emissions while the other pathways have similar GHG performance.