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Final report

DROP-IN THE TANK OR A NEW TANK?

Comparison of costs and carbon footprint

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 48361-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

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The project has been supported by a reference group which is formed by industrial partners representing vehicle producers, fuel producers, fuel distributors, as well as duel users. The reference group have been an active part of the project from the idea formulation until the finalization of this report and other output. The experience and support of our industrial partners have been very valuable for the project. Without any internal order:

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EXECUTIVE SUMMARY

Biofuels may play an important role to mitigate climate change and reduce emissions from the transport sector in Sweden and globally. There is however an uncertainty regarding what role different biofuels may have in the future transportation system. Different pathways include different fuels which may require different vehicles and infrastructure. The biofuels may be categorized as either i) drop-in fuels possible to blend in conventional fossil transport fuels or ii) single molecule fuels requiring new vehicles and infrastructure.

This study has compared 12 forest biomass-based biofuels in terms of economic and climate performance as well as resource efficiency (8 drop-in fuels and 4 single molecule fuels) from a Swedish perspective. The cost estimations include costs for feedstock, production, distribution, and vehicles and represent mature costs (i.e., when the biofuels are commercial). The comparison considers the entire chain from biomass feedstock to use as transportation fuel and the use in both cars and trucks are included. A comparison with some electrofuels (fuels produced by electricity, water, and CO_2) is also included. This report is intended as policy decision support.

Single molecule fuels require adapted vehicles and refueling infrastructure (a new tank) which implies additional investments. The included single molecule fuels are ethanol, DME, methane, and methanol. Single molecule fuels may however have a higher resource efficiency and better overall economic performance, which may justify investments in new vehicles and infrastructure. However, methane and ethanol have the advantage of semi-established infrastructure in Sweden also including available vehicles serving a limited vehicle fleet, whereas a distribution infrastructure for DME or methanol would have to be built up basically from scratch and adapted vehicle production initiated.

Drop-in fuels have the obvious advantage of being able to use existing vehicles and infrastructure. This may be an advantage in the short to medium term and should be evaluated together with possibly lower resource efficiency and economic performance. The included drop-in fuels are: gasification-based gasoline; FT-diesel; diesel and gasoline from lignin pre-treatment and upgrading; diesel and gasoline from pyrolysis and hydrotreatment upgrading; bio oil-based diesel and gasoline from hydropyrolysis.

This study is based on a literature review and by updating existing studies when needed and possible and was also performed in discussion with industry. Some fuels currently have higher technology readiness level (TRL) than others. In this study the biofuel pathways are compared for a future situation when they are mature and have reached the commercial phase and with costs that are representative for the Swedish case. The evaluation of alternative pathways, from forest biomass to transport fuels, is relative, meaning that we have tried to show which fuel has a better performance than another.

No clear winner in terms of drop-in versus single molecule fuels has been identified although some advantages associated with different fuels and can be seen. These advantages also vary between cars and trucks:

For cars we find that drop-in fuels in the form of gasoline based on lignin and hydropyrolysis perform well on all three included assessment aspects. However, gasoline based on lignin or hydropyrolysis currently has a low TRL, implying somewhat larger uncertainties in the cost estimates. Furthermore, GHG performance is uncertain for the lignin-based processes and the other hydrotreatment-based biofuels and depends on the final process set-up. Other good options when considering the three assessment criteria, closely following the top are single molecule fuels in the form of methanol, DME, methane and drop-in fuels in the form of gasoline based on fast pyrolysis as well as diesel based on all three hydrotreatment upgrading tracks. Ethanol (E85) currently has the highest TRL among the evaluated fuels for cars, but its overall performance is lower than the mature situation of other fuels.

For trucks we find that drop-in fuels in the form of methanol, DME, and drop-in fuels in the form of diesel based on lignin pre-treatment and upgrading and based on hydropyrolysis turns perform well on all three included assessment aspects. Other interesting fuel options for trucks are LBG in diesel engines (single molecule fuel) and diesel based on fast pyrolysis and hydrotreatment upgrading (drop-in fuels). Like for cars the GHG performance of the hydrotreatment- based fuel pathways are uncertain, which is partly due to the relatively low TRL which may also indicate more uncertain cost estimates for these fuels. The uncertainty may also affect the actual GHG performance.

For cars the fuel cost is between 15-22 % of the total cost and for trucks is between 27–38 %. The vehicle cost is always larger than fuel production cost and for both cars and trucks the distribution and infrastructure related costs are always small in comparison to the costs for vehicles and fuels. The cost for refueling infrastructure is higher for single molecule fuels than drop-in fuels however, the cost is by far compensated by the lower production cost for DME, methanol and methane as compared to the production cost of the drop-in fuels.

The biomass supply potential i.e., forest residues is large for all studied biofuels except the lignin-based pathway that is constrained by the recovery and supply of lignin from kraft pulping.

Based on our assessment and included assessment criteria it is not possible to clearly state if drop-in or single molecule fuels are the preferred strategy for the Swedish case since there is no clear winner from these perspectives. However, as indicated above the assessment highlights which drop-in and single molecule fuels that are most promising in terms of total cost, GHG performance and resource efficiency. The choice of a new tank (single molecule fuels) or drop-in fuels depends also on other aspects (not evaluated in this study), such as, the time frame, socio-technical aspects such as current market situation, the development of the included biofuels (in particular those with currently low TRL) and the development of other alternatives such as electric vehicle and fuel cell-powered vehicles, as well as what choices the industries make since new fuel, however superior its performance, requires a collaboration between fuel producers, fuel distributors, vehicle manufacturers, and policy makers.

There are several good options to produce biofuels with good climate and economic performance from forest biomass.

SAMMANFATTNING

Biodrivmedel kan spela en viktig roll för att minska klimatförändringen och utsläppen från transportsektorn, i Sverige och globalt. Det råder dock en osäkerhet om vilken roll olika biodrivmedel kan ha i det framtida transportsystemet. Olika tekniska spår och vägval inkluderar olika drivmedel som kan kräva olika fordon och infrastruktur. Biodrivmedel kan kategoriseras som antingen i) drop-in-bränslen som går att blanda i konventionella fossila bränslen eller ii) enmolekylära bränslen som kräver nya fordon och ny infrastruktur.

I denna studie ingår tolv biodrivmedel producerade från skoglig biomassa (åtta drop-in bränslen och fyra enmolekylära bränslen). Dessa har jämförts avseende ekonomisk prestanda och klimatprestanda samt resurseffektivitet ur ett svenskt perspektiv. Kostnadsberäkningarna inkluderar kostnader för råvaror, produktion, distribution och fordon och representerar mogna kostnader, dvs då teknikerna för att framställa biodrivmedel är kommersiellt mogna. Jämförelsen tar hänsyn till hela kedjan – från råmaterial till användning som drivmedel i både bilar och lastbilar. En jämförelse med vissa elektrobränslen (bränslen som produceras med el, vatten och koldioxid) ingår också. Denna rapport är avsedd som politiskt beslutsunderlag.

Enmolekylära drivmedel kräver anpassade fordon och tankningsinfrastruktur (en ny tank) vilket innebär ytterligare investeringar. De enmolekylära drivmedel kan dock innebära högre resurseffektivitet och bättre övergripande ekonomisk prestanda, vilket skulle kunna motivera investeringar i nya fordon och infrastruktur. De studerade enmolekylära drivmedlen är etanol, DME, metan och metanol. I Sverige finns det en semi-etablerad infrastruktur för metan och etanol samt en begränsad fordonsflotta för dessa bränslen. Distributionsinfrastruktur för DME eller metanol, däremot, skulle behövas byggas upp i princip från grunden och anpassade fordon skulle också behöva utvecklas.

Drop-in bränslen har den uppenbara fördelen att de kan användas i befintliga fordon och infrastruktur. Detta kan vara en fördel på kort till medellång sikt, dock kan resurseffektiviteten och den ekonomisk prestandan vara lägre. De studerade drop-in drivmedlen är: förgasningsbaserad bensin; FT-diesel; diesel och bensin från förbehandling och uppgradering av lignin; diesel och bensin från uppgradering av pyrolys och vätebehandling; biooljebaserad diesel och bensin från hydropyrolys.

Denna studie baseras på en litteraturgenomgång. Befintliga studier har uppdaterats vid behov och en dialog har också förts med industrin. Vissa bränslen har för närvarande högre teknisk mognadsgrad (TRL efter engelskans Technology Readiness Level) än andra. I denna studie antas att de studerade biodrivmedlen uppnått kommersiell mognad. Dessutom används kostnader som är representativa för Sverige. Utvärderingen av biodrivmedel som görs är relativ, vilket innebär att vi har försökt visa vilket bränsle som har bättre prestanda än ett annat.

Ingen tydlig vinnare har identifierats mellan drop-in och enmolekylära drivmedel, även om vissa fördelar kan associeras med vissa drivmedel. Dessa fördelar varierar dessutom för bilar och lastbilar.

För bilar finner vi att drop-in bränslen så som bensin från lignin och hydropyrolys presterar väl på alla tre kriterierna i bedömningen (ekonomi, klimat och resurseffektivitet). Bensin från lignin eller

hydropyrolys har dock för närvarande en låg TRL, vilket medför något större osäkerheter i kostnadsberäkningarna. Dessutom är klimatprestandan osäker för de ligninbaserade processerna och de andra vätebehandlade biodrivmedlen. Prestandan avgörs av den slutliga processdesignen.

Andra bra alternativ när man överväger de tre bedömningskriterierna, är enkelmolekylära bränslen i form av metanol, DME och metan samt drop-in-bränslen i form av bensin baserat på snabbpyrolys samt de tre slags dieselbränslen som baseras på vätebehandling och uppgradering. Etanol (E85) har för närvarande den högsta TRL bland de utvärderade bränslen för bilar men dess totala prestanda är lägre än för de andra bränslena i jämförelsen (då man antagit prestanda vid kommersiellt mogen teknik även för de andra bränslena).

För lastbilar finner vi att enmolekylära bränslen i form av metanol, DME och drop-in-bränslen i form av diesel baserad på lignin och baserat på hydropyrolys presterar väl på alla tre kriterierna i bedömningen. Andra intressanta bränslealternativ för lastbilar är LBG i dieselmotorer (enmolekylärt bränsle) och diesel baserad på snabbpyrolys och vätebehandling (drop-in bränslen). Liksom för bilar är växthusgasprestandan för de vätebehandlade drivmedlen osäkra, vilket delvis beror på den relativt låga TRL som också kan indikera mer osäkra kostnadsberäkningar för dessa bränslen vilket även kan påverka den faktiska växthusgasprestandan.

För bilar ligger bränslekostnaden mellan 15–22 % av den totala kostnaden och för lastbilar ligger den mellan 27–38 %. Fordonskostnaden är alltid högre än bränsleproduktionskostnaden för både bilar och lastbilar. Dessutom är distributionskostnader och infrastrukturrelaterade kostnader alltid små jämfört med kostnaderna för fordon och bränslen. Kostnaden för tankning av infrastruktur är högre för enmolekylära bränslen än drop-in-bränslen, men kostnaden kompenseras överlägset av de lägre produktionskostnaderna för DME, metanol och metan jämfört med produktionskostnaden för drop-in-bränslen.

Tillförselpotentialen av biomassa, dvs. skogsrester, är stor för de olika biodrivmedlen som studerats, förutom för det ligninbaserade spåret som begränsas av återvinning och tillförsel av lignin från sulfatmassa.

Baserat på vår samlade bedömning och de bedömningskriterier som ingått i vår analys – ekonomi, klimat och resurseffektivitet – så är det inte möjligt att tydligt ange drop-in eller enmolekylära drivmedel är den föredragna strategin för Sverige eftersom det inte finns någon tydlig vinnare utifrån dessa olika perspektiv. Vår analys belyser dock vilka drop-in respektive enmolekylära drivmedel som är mest lovande gällande total kostnad, växthusgasprestanda och resurseffektivitet. Valet mellan en ny tank (enmolekylära bränslen) eller drop-in-bränslen beror också på andra aspekter som inte utvärderats i denna studie, t.ex. tidsram, sociotekniska aspekter som nuvarande marknadssituation, den tekniska utvecklingen för de drivmedel som för tillfället har låg TRL, utvecklingen av andra alternativ såsom elfordon och bränslecellsdrivna fordon, samt vilka val industrin gör eftersom ett nytt drivmedel, oavsett hur bra det är, kräver ett samarbete mellan drivmedelsproducenter, drivmedelsdistributörer, fordonstillverkare och beslutsfattare.

Sammantaget kan vi säga att det finns flera bra alternativ för att producera drivmedel från skogsbiomassa med bra klimat och ekonomiska resultat.

CONTENTS

INTRODUCTION

1.1 BACKGROUND

Biofuels for transport may significantly contribute to Sweden´s climate goals of reducing emissions from the transport sector (Trafikutskottet, 2018). Biofuels may also contribute on a European and global level to reduced emissions of greenhouse gases (IEA, 2018). There is however an uncertainty regarding what role different biofuels for transport may play in the future energy system (due to e.g., differences in supply potential and development stage, sustainability, acceptance, and policy issues). Different pathways and choices of production chains, distribution infrastructure and vehicles may have varying societal economic impacts. For example, so-called drop-in fuels possible to blend in conventional fossil transport fuels are often discussed in relation to so-called single molecule fuels. The term drop-in fuels originally stems from the interest to find biofuels that could be dropped into fossil diesel and gasoline without changing anything in the refuelling infrastructure and vehicles. In practice there is however several aspects that may limit the possibility for higher blends such as density requirements and oxygen levels etc.

Single molecule fuels require adapted vehicles and refueling infrastructure. Examples of these fuels are methane, methanol, and dimethyl ether (DME). Single molecule fuels have shorter molecular chains and may be easier and cheaper to produce from e.g., forest biomass. In addition, factors such as a higher conversion efficiency may signify that these fuels have a better climate performance than so called drop-in fuels when evaluated according to well-to-wheel LCA (Furusjö & Lundgren 2017; Jafri et al. 2019a; Jafri et al. 2019b). However, single molecule fuels are, in general, not compatible with dominant distribution infrastructure in transport sector, nor compatible with conventional vehicles and may in some cases lead to lower engine conversion efficiency. This implies additional costs compared to the drop-in fuels that are compatible with existing infrastructure and vehicles adapted for gasoline and diesel.

It is important to highlight the total cost for different biofuel pathways including the entire value chain, i.e., feedstock, production, distribution, and vehicles. There may thus be transport fuel value chains for which single steps, e.g., distribution infrastructure, may imply additional costs, but still imply a lower total cost. At the same time, the international perspective is important since vehicles adapted for a certain fuel, e.g., DME or methanol, may never be developed exclusively for a small market like the Swedish one (the importance of the international perspective is discussed further in section 6). There may be a societal interest to support the development of certain transport fuel chains, including infrastructure and vehicles given that they for example contribute to greenhouse gas (GHG) emission reductions at a relatively low cost. To motivate such policy support reliable data and literature providing clear policy decision support is needed.

There are several previous studies of individual transport biofuels and their costs or climate performance along the value chain, e.g., Börjesson et al. (2016) that evaluated methane from a well-to wheel perspective. There are also several other studies that have evaluated climate performance and/or costs for different conversion technologies (and the purpose is often to compare different fuels as end-products), e.g., Holmgren et al. (2017) focusing on gasification-based fuels and Anheden et al. (2016) comparing different value chains with different intermediary products. In addition, the use of electricity, hydrogen and other electrofuels as transportation fuels from a cost perspective has been studied with a German focus by FVV (2018). For Swedish conditions, Holmgren et al. (2021) have recently quantified costs for different fossil-free propulsion techniques for heavy long-distance trucks (including e.g., fuel production, distribution and vehicles) and Grahn and Jannasch (2018) have made a comparative study of electrofuels, both in the applications as transportation fuels and in chemical industry. Sartini et al. (2017) have made knowledge compilation regarding vehicles and infrastructure for electricity and hydrogen in heavy transport. Finally, there are a number of studies that compare climate impact and cost for several transport biofuels, such as Furusjö and Lundgren (2017) that analyze the so-called reduction cost for different biomass-based transport fuel value chains. These studies (with a few exceptions) normally have a focus on fuel production and may exclude both cost and aspects concerning infrastructure and vehicles.

There is also the 5th WTW study of the JEC collaboration (Prussi et al 2020a, 2020b) which focuses on energy use and greenhouse gas emissions of a wide range of potential future fuels and powertrains for the road transport sector, including both cars and trucks. This study does not include cost-estimates.

Thus, there is a lack of studies that take a broader approach and that in a systematic manner compare and synthetize total costs and climate impact along the whole value chain, i.e., feedstock, production, distribution and vehicles for several single molecule fuels and compare these with drop-in fuels. This report aims to fill that gap by providing a comparison that include both costs and climate impact for these fuels that may serve as a decision support for policy makers.

1.2 OBJECTIVE

The aim of this project is to compare forest biomass-based fuels1: single molecule fuels and drop-in fuels, that are relevant from a Swedish perspective. A comparison with some electrofuels (fuels produced by electricity, water, and CO_2) is also included and in terms of costs fossil diesel and gasoline are included for comparison too. Estimations of resource efficiency, climate impact, and total cost are made. The cost estimations include feedstock, production, distribution, and vehicles represent mature costs i.e., the case when these technologies have reached a commercial position on the market. The comparison of all three aspects considers the entire value chain from biomass feedstock to use as transportation fuel. The intention is to give an overall picture with pros and cons for single molecule fuels versus drop-in fuels in the transition of the transport system.

1.3 SYSTEM DELIMITATIONS

The transportation fuels included in the study are listed in Table 1 and presented in more detail in section 3.1.

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1 Fuels based on other biomass feedstocks are not included, e.g. so called first generation ethanol or diesel produced from crops; conventional HVO from waste fats and oils; nor biogas from anaerobic digestion.

Table 1: Transportation fuels included in the study.

Drop-in fuels	Fuels that require adapted vehicles and refueling infrastructure
Gasification-based gasoline (represented by methanol to gasoline – MTG)	Methanol
FT-Diesel	Dimethyl ether (DME)
Diesel and gasoline (lignin pre-treatment and upgrading) (“lignin diesel/gasoline”)	Methane (in the form of compressed biogas CBG and liquefied biogas LBG)
Bio oil-based diesel and gasoline (fast pyrolysis and hydrotreatment upgrading) (“pyrolysis diesel/gasoline“)	Ethanol from cellulose in the form of E85 and ED95
Bio oil-based diesel and gasoline (hydropyrolysis) (“hydropyrolysis diesel/gasoline“)	

For practical reasons the term “hydrotreatment based” is used for the following fuels: lignin diesel/gasoline; pyrolysis diesel/gasoline; and hydropyrolysis diesel/gasoline.

The specific fuel-vehicle combinations included in the assessment are listed in Table 2. These combinations may differ between trucks and cars, as specified in the table.

Table 2: Specific fuel-vehicle combinations.

Fuel	Truck/car
Methanol	Truck: MD95[2] Car: M85
DME	Truck Car
Methane	Truck LBG (two kinds, compression ignition engine and spark ignited engine) Truck CBG Car: CBG
Gasification-based gasoline (MTG)	Car: Drop-in
FT-Diesel	Truck: Drop-in Car: Drop-in
Ethanol from cellulose	Truck: ED95 Car: E85
Bio oil-based diesel and gasoline (fast pyrolysis and hydrotreatment upgrading)	Truck diesel: Drop-in Car diesel: Drop-in Car gasoline: Drop-in
Bio oil-based diesel and gasoline (hydropyrolysis)	Truck diesel: Drop-in Car diesel/Car gasoline: Drop-in
Diesel and gasoline (lignin pre-treatment and upgrading)	Truck diesel: Drop-in Car diesel/Car gasoline: Drop-in

This study is geographically focused on Sweden. The biofuels that have been evaluated, see Table 2 above, are relevant for a Swedish context. The raw material costs are representative for northern

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[2] Methanol for trucks can be applied using different engine technologies, see section 3.3.

Europe including Sweden. Distribution cost have been calculated for Swedish circumstances, see section 3.2 for further details.

In terms of costs, the estimates in this study are assumed to represent mature costs i.e., the case when these technologies have reached a commercial position on the market. Thus, the biofuel pathways are compared for the situation when they are commercial, which is considered a fair comparison base. The authors have refrained from specifying a specific year when this may occur due to the uncertainties linked to this. The assumption of mature technologies further means that in our cost estimates e.g., learning effects are to a large extent accounted for.

2 OVERALL APPROACH

The analysis includes: 1) costs, 2) resource efficiency and 3) climate impact. The cost assessment covers cost for fuel production (including feedstock cost), distribution, and vehicles, which are synthesized. For all aspects, existing studies are mapped and updated when needed. The assessment covers the fuels listed in Table 1, and the specific fuel-vehicle combinations listed in Table 2.

2.1 COSTS

Fuel production costs, cost of new infrastructure, and vehicle costs have been evaluated for each included fuel. The cost estimates are based on a literature review of scientific papers and reports covering cost estimates for production of relevant biofuels, relevant vehicles, and distribution/ infrastructure. The existing cost estimates have been updated with new information when needed. The most important update has been the cost of biomass that has been adjusted to reflect Swedish, and northern European, conditions. See section 3.1.2 for more details.

For vehicle costs there is less documented data available. For this case data has been discussed with, and been collected from, vehicle manufacturers, see section, 3.3.

In general, we have tried to use studies that include assessment of different processes/fuels/vehicles in a uniform way, using homogeneous assumptions, as far as possible. Using separate studies for different technical options can lead to larger difficulties in obtaining a relevant comparison, due to the use of different assumptions and system boundaries.

2.2 LITERATURE REVIEW OF COSTS

An overview of the initial literature review covering cost estimates for production of relevant biofuels, relevant vehicle and distribution/infrastructure is presented in Table 3. The cost estimates covered in the identified publications divided as fuel production cost, vehicle cost and distribution/infrastructure cost are indicated. The fuel and vehicle types as well as the type of infrastructure/distribution included in the studies are also indicated in the table. Most of the identified studies included estimates of the fuel production cost and some included estimates of infrastructure and/or distribution costs. On the other hand, there is a lack of studies covering estimates for vehicle costs. Detailed cost information for distribution and infrastructure from selected reports used as background for this study is presented in Table A1 in Appendix 1.

Table 3. Overview of the results from the initial literature review. It is indicated which publications included cost estimates or cost information for fuel production, vehicle and distribution/infrastructure. Fuels and vehicle types covered as well as type of distribution/infrastructure included in the studies are also indicated. BEV - battery electric vehicle, SNG – synthetic natural gas, LBG – liquified biogas, O&M - operation and maintenance cost.

Reference	Estimates of production cost for fuel included	Estimates on vehicle cost included	Estimates on distribution/ infrastructure cost included	Fuels included	Vehicles included	Distribution/ infrastructure included
Holmgren et al., 2021	X	X	X	Ethanol, methanol, methane (CBG and LBG), DME, FT diesel, biodiesel (HVO and RME), electric vehicles (BEV), electric roads, hydrogen driven fuel cells vehicles and electrofuels.	Heavy-duty trucks	Distribution and filling stations (investment and O&M costs)
Hannula & Reiner, 2019	X	X (only for BEVs and then represented by battery cost)		Fischer Tropsch fuels, electrofuels and electricity in BEVs	Conventional and BEVs	
Kollberg, 2019	X	X		Ethanol, methanol, HVO, RME, electricity, gasoline and diesel (fossil)	A standard passenger car is used for the comparisons	
Pettersson et al., 2019	X	X	X	SNG (from gasification integrated with pulp and paper mill), methanol, ethanol, renewable diesel and gasoline, electricity	Car, distribution truck and long-distance truck	Distribution and filling stations (investment and O&M costs)
Thunman et al., 2019	X			Biomethane		
Trafikanalys, 2019		X (additional vehicle costs)		LBG, electricity and ethanol	Heavy trucks	
Concawe, 2018	X	X	X	Ethanol, FAME, HVO, biomass-based gasoline, syndiesel, electrofuels, electricity	Light duty vehicles	Network and charging infrastructure
FVV, 2018	X	X	X	Hydrogen, electricity, electrofuels. Does not include biofuels.	Includes cars for all the assessed fuels and reference truck	Electricity grid, transport of electrofuels, conversion of filling pumps etc.

Trafikutskottet, 2018	X		X	Ethanol, methanol, FAME, RME, HVO, synthetic diesel, DME, biomass-based gasoline, biogas, electricity		Distribution costs for fuel
Furusjö & Lundgren, 2017	X			Methanol, DME, ethanol SNG/biogas, FT-diesel, HVO, FAME, renewable gasoline and diesel		
Furusjö, E., et. al., 2017	X			Methanol, different pathways for renewable diesel and gasoline		
Holmgren et al., 2017	X		X	SNG, methanol, FT fuels	Passenger cars	Gas distribution
Lantz et al., 2017	X		X	Biogas		Gas distribution (grid) and O&M of filling stations
Millinger et al., 2017	X		X	Methane, ethanol, biodiesel, SNG, FT-diesel		
Mustapha et al., 2017	X			Ethanol, FT-diesel, renewable diesel and gasoline		
Oloffson et al., 2017	X			Ethanol		
Rafati et al., 2017	X			FT fuels		
Börjesson et al., 2016	X	X	X	Methane/biogas, LBG	Light and heavy-duty vehicles	Distribution and filling stations (investment and O&M costs)
Börjesson Hagberg et al., 2016	X			Ethanol, methanol, biogas, DME, biodiesel		
Holmgren et al 2016	X		X	Synthetic naturgal gas, methanol, FT fuels	Passenger cars	Gas distribution
IRENA, 2016	X			FT diesel, biodiesel, methanol, FAME, ethanol		
Holmgren, 2015	X			SNG, Methanol, FT diesel and gasoline		
Volvo, 2015	X		X	Ethanol, methanol, DME, methane, biodiesel, HVO, Syn-diesel, Electricity	Different types of trucks (adapted for the different fuels)	
Tunå and Hulteberg, 2014	X			SNG, methanol, DME, FT diesel and methanol-to-gasoline.	Passenger car	

2.3 SYNTHESIS OF COSTS

The estimated costs of production, distribution and vehicle are summarized in a total cost per studied transport fuel pathway. The total cost is expressed in SEK per vehicle kilometer.

For summarizing the costs for each transport fuel pathway, the concept of "relative mobility cost" and the underlying equations introduced by Holmgren et al. (2021) are used. For this concept, costs assumed to be the same for all the studied pathways or where the difference can be considered negligible are not included (e.g., cost for tires and insurances). The total cost is in our study are calculated as follows:

$$Totalt\ cost = INV\_C + (FP\_C + \ AB\_C + FDI\_C) * ED \qquad \text{Equation (1)}$$

where INV_C represents the annualized investment costs for the vehicle (SEK/vehicle km), FP_C represents the fuel production cost (SEK/MWh), AB_C represent the AdBlue cost, FDI_C represents the fuel distribution and infrastructure cost (SEK/MWh) and ED represents the energy demand of the vehicle (MWh/vehicle km).

The investment cost for the vehicle (INV_C) in equation (1) is based on an annualized cost that considers the acquisition value, the residual value (expressed in net present value), economic lifetime and the discount rate. The investment cost for the vehicle is calculated as:

$$INV\_C = \frac{(Acquisition\ value - Residual\ value * Net\ present\ value\ factor) * Annuity\ factor}{Annual\ mileage} \qquad \text{Equation (2)}$$

The net present value factor and the annuity factor are calculated following equation (3) and equation (4).

$$Net\ present\ value\ factor = \frac{1}{(1 + Discount\ rate)^{Economic\ lifetime}} \qquad \text{Ekvation (3)}$$

$$Annuity\ factor = \frac{Discount\ rate}{(1 - (1 + discount\ rate)^{-Economic\ lifetime})} \qquad \text{Ekvation (4)}$$

Based partly on Holmgren et al. (2021) the following assumptions are made. A discount rate of 10 % is used for trucks and 5 % for cars3 (Trafikverket, 2020). The lifetime for trucks is assumed to be 7 years and for cars 17 years (Trafikverket, 2020). The annual mileage for trucks is assumed to be 125 000 km/year and for cars 12 200 km/year (Trafikverket, 2020). The residual value, expressed as percentage of the acquisition value, is assumed to be 7.27 % for trucks (SÅcalc, 2019) and 5 % for cars[4].

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[3] A lower discount rate has been used for cars, compared to trucks. The 10 % stated by the Swedish Transport Administration was found to be too high when comparing available loans from banks offered to people to finance a car purchase, such as: www.ssab.se or www.danskebank.se. The interest rate that the banks offer may vary with the individual and may even be below 5 %.

[4] We have assumed that most of the depreciation occurs in the beginning of the cars lifetime and that the curve flattens out towards the end. The value of the car by the end of the lifetime is mostly determined by whether it passes an inspection and is legal to drive. Thus, the depreciation at the end of the car's lifetime is small or zero, according to Bilsvar (2021).

The fuel production cost (FP_C) includes the investment cost for the fuel production facility, feedstocks, and inputs. For the cost for AdBlue which is needed as after treatment for fuels used in diesel-like engines see Section 3.1. The fuel distribution and infrastructure cost (FDI_C) includes the cost for transporting the fuel from the production plant to the filling station (distribution) as well as the investment and operation and maintenance costs for the filling station (infrastructure) (see Section 3.2).

For trucks the total cost was also calculated as cost per transported ton per km [SEK/ton km]:

$$Totalt\ cost\ = (INV\_C + (FP\_C +\ AB\_C + FDI\_C) * ED)/L \qquad \text{Equation (5)}$$

Where L represents the average load in ton. The average load is assumed to be 14.29 ton which is the weighted payload from a simulation (considering loaded conditions and the fact that return journeys sometimes are unloaded) in VECTO in the JEC Study (Prussi et al., 2020a). Transported load [SEK/ton km] is more relevant to measure for trucks than e.g., only vehicle distance [SEK/km] since this is the function they deliver. The tractor weighs approximately 7.5 tons, and the trailer and body are also around 7.5 ton. Payload is not 100 % therefor a 40-ton truck does not transport 40 tons of goods and thus 14.29 tons is used in this study. The truck used for the calculation is an EU 40-ton gross vehicle mass rating for use in long haul missions.

The energy demand of the vehicle is the amount of fuel needed per driven kilometer.

Vehicle maintenance costs in the form of costs for service and repairs (i.e., consumption of lubricants, repairs and replacement of spare parts during the use of the vehicle) also differ depending on the fuel used. For example, the vehicle maintenance cost for ED95 is higher than for corresponding diesel driven vehicle partly due to that the fuel evaporates more easily and causes cavitation in the fuel injectors which need to be replaced more often (while for diesel vehicles the injectors last the whole lifetime) (Fröberg, 2021). Methanol driven vehicles will likely run into the same problem and gas driven vehicles with spark ignited engine have higher vehicle maintenance costs due to the need to replace oil and spark plug more often (Ekström, 2021; Fröberg, 2021). According to Holmgren et al. (2021) there is a lack of published information on vehicle maintenance cost for different biofuel options. Holmgren et al. (2021) assumes that the vehicle maintenance cost for ED95 is 10 % higher than for the conventional diesel alternative while the corresponding cost for methanol, DME and FT diesel are assumed to be the same as for the conventional diesel vehicle (estimated at 1.04–1.19 SEK/fkm depending on truck size). However, since the vehicle and maintenance cost has been indicated to be minor compared to the vehicle cost (Holmgren et al., 2021) and due to the lack of data, this cost is not included in the total cost assessment in this study. The sensitivity of important assumptions is also discussed.

2.3.1 Assumptions

General assumptions for technology maturity, biomass price, as well as conversion efficiency and high and low-cost scenario are presented in section 3.1.2 below.

2.4 RESOURCES EFFICIENCY AND CLIMATE IMPACT

As a measure of resource efficiency, the biomass-to-wheel-efficiencies are assessed for the selected transport fuel chains. The main source for the used estimates of fuel consumption of the vehicles is

Prussi et al. (2020a). Energy efficiency of vehicles was estimated using a reference point obtained through discussion with industry experts as well as engine efficiency charts literature. See section 5.1 for details.

Climate impact for the selected transport fuel chains is estimated based on a well-to wheel perspective and given in g CO_2eq/km for passenger cars and in g CO_2eq/ton km for trucks. The assessment of estimated greenhouse gas emissions for fuel production follows the methodology in Prussi et al (2020b) and the estimated fuel consumption of the vehicles uses the same sources as in the resource efficiency estimates.

Prussi et al. (2020b) is the well-to-tank part of the 5th WTW study performed within the JEC collaboration[5]. The well-to-tank part includes GHG emissions associated with raw material production, for most of the biofuel production chains of this study, this includes forest residue collection and seasoning, wood plantation, harvesting, chipping and transport from harvest site to fuel production site. The GHG emissions from the raw material conversion to (bio)fuel is also included: pyrolysis, gasification, SFFC (simultaneous saccharification and co-fermentation) and synthesis, methanation and hydrotreatment processes. The assessed GHG emissions for the conversion processes include emissions associated with other inputs (other than the biomass), e.g., chemicals, hydrogen, electricity etc. Finally, the estimates of the well to -tank emissions also include distribution of the fuels to the filling stations and emissions associated with dispensing.

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[5] JEC (JRC-Eucar-Concawe) is a long-standing collaboration between the European Commission`s Joint Research Centre, EUCAR and Concawe.

3 COST CALCULATIONS

3.1 FUEL PRODUCTION COSTS

3.1.1 Main sources and methodology

Methanol, DME, methane, FT diesel and ethanol from lignocellulose

The cost analysis of the following fuels – methanol, DME, methane, FT-diesel, ethanol from lignocellulose, and synthetic gasoline – started from two reports: Furusjö & Lundgren (2017) and IEA (2020). In the first report the authors compile and analyze biofuel production cost estimates. This experience was a valuable input to this work although data had to be updated (the report was published in 2017). The second report is more recent, published in 2020, and deals with potential cost reductions of advanced biofuels. In our work we have, however, updated the calculations of IEA (2020) with other estimations of biomass prices that are relevant in a North European perspective (see 3.1.2 below). The project has also collaborated with Holmgren et al. (2021) who has realized a similar analysis, although focused on the transport of long haulage trucks. The results from this study are compared to Holmgren et al. (2021). However, that project lacks bio oil-based diesel and gasoline as well as gasification-based gasoline.

Bio oil-based diesel and gasoline

The production of biofuels from liquified biomass (so called bio oil) may take place through different routes. In this work we consider three alternative routes based on 1) fast pyrolysis with upgrading, 2) lignin separation with upgrading and 3) hydropyrolysis.

The IEA (2020) report includes cost data for fast pyrolysis-based technologies but these have been complemented with data from dedicated techno-economic studies (Susanne Jones et al. 2013; Dutta et al. 2015; Furusjö and Lundgren 2017). For the other two tracks, IEA (2020) does not give any data, which is at least partly due to lack of industrial cost estimates. We have used process and cost data from academic studies. Data for the lignin track is mostly based on Jafri et al. (2020) and Wetterlund et al. (2020) while the most important source for data on the hydropyrolysis track is Meerman and Larson (2017).

Gasification-based gasoline

IEA (2020) does not include production technology for gasification-based gasoline although two commercially available (fairly similar) technologies exist (from the technology suppliers Exxon Mobile and Haldor Topsoe, respectively). These processes may start from gasification of biomass. It is also possible to purchase methanol and use as a feedstock to produce gasoline in these processes. This analysis combines data of production cost of methanol – through biomass gasification – with data of gasoline production based on methanol as a feedstock in order to get data that is representative for the entire fuel production pathway (Hannula and Kurkela 2013; Jafri et al., 2020; Udengaard et al., 2015). Hannula and Kurkela (2013) present a production cost for gasification-based gasoline of 10 EUR/MWh fuel, in addition to the cost of purchasing or producing methanol.

Fossil fuels

The production costs of fossil gasoline and diesel have been included for comparison. We have provided a low and high-cost scenario based on different oil prices, 50 and 100 USD/ barrel BRENT oil respectively. We have then used the assumption that gasoline and diesel price, measured in energy content and without any taxes, can be calculated as a percentage of the oil price (Edwards et al., 2011).

3.1.2 General assumptions

The estimates have started from IEA (2020) for most production technologies. However, some assumptions have been altered as presented below.

Biomass price

A biomass price of 20 EUR/MWh has been assumed (Furusjö & Lundgren 2017; Ouraich et al., 2018; Energimyndigheten 2020). This biomass price corresponds to wood chips as well as branches and treetops[6].

This biomass price is in line with SGAB (2018) that assumes 20 EUR/MWh in some cases (but lower for some cases). It is also in the higher end when comparing to IEA (2020) that assumes a range between 10 and 20 EUR/MWh. However, the lower end of that range – 10 EUR/MWh – corresponds to North American conditions, while the upper end – 20 EUR/MWh – rather represents European conditions (IEA, 2020).

Technology maturity

The estimated production costs in this study assume commercially mature technologies, without specifically specifying when that is reasonable to expect. The reason is that it is difficult to predict when technology development will take place and the aim in this study is to compare the technologies in a mature state. Thus, we have refrained from specifying a specific year when this could be achieved. This assumption should be considered when comparing this study to others. For example, IEA (2020) presents “medium term cost reductions” which could be realized within 15 years if the necessary plants are built and “long-term cost reduction” which could be realized beyond 15 years.

For some technologies we have used, and modified, IEA cost estimations (2020) as explained in section 3.1. IEA (ibid) have made certain assumptions regarding cost reductions which are also included in our estimations. We have used the “medium-term cost reduction potential” as explained above. This entails assumptions about cost reductions in plant capital costs and operating costs. It also entails assumptions regarding improved value of co-products.

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[6] So called GROT, short for “Grenar och toppar” in Swedish.

3.1.2.1 Conversion efficiency and high and low-cost scenario

Methanol, DME, methane, FT diesel and ethanol from lignocellulose

IEA (2020) have used an estimated range for the conversion efficiency, with an upper and lower end. The IEA data has been used for several of the technology tracks included in our assessment: methanol, methane, DME, FT-diesel as well as ethanol from cellulose. We have used the entire range in our estimations. Thus, this range is included in the high and low-cost scenario, although the range for conversion efficiencies has a small effect on the range compared to other uncertainties, see example about methanol, DME and methane below. IEA data has been compared to other sources e.g., Hannula and Kurkela (2013).

Gasification-based gasoline

For biofuels pathways not included in IEA (2020) or with inadequate coverage in IEA other sources have been used for conversion efficiency (and costs). Estimations by Jafri et al. (2020), Udengaard et al. (2015), Hannula and Kurkela (2013) have been used to estimate the conversion efficiency for production of gasoline from methanol.

Bio oil-based diesel and gasoline through fast pyrolysis and upgrading

Estimations by Jones et al. (2016), Jones et al. (2013), Dutta et al. (2015) have been used to estimate the conversion efficiency for production of bio oil-based diesel and gasoline through fast pyrolysis and upgrading.

Bio oil-based diesel and gasoline through hydropyrolysis

Estimations by Jafri et al. (2020), Wetterlund et al. (2020), Löfstedt et al. (2016) have been used to estimate the conversion efficiency for production of bio oil-based diesel and gasoline through hydropyrolysis.

3.1.2.2 High- and low-cost scenarios in the report

Fuel production cost intervals are presented in Table 4, Figure 1 and Figure 2 to illustrate uncertainties regarding estimations of future production cost. From Figure 7 and onwards an average production cost is instead presented. However, the interval is also presented in form uncertainty interval.

3.1.2.3 Unit and exchange rate

The fuel production costs are based on estimates presented in EUR/MWh while distribution and vehicle costs are based on estimates presented in SEK. To illustrate this and facilitate for the readers more used to fuel production costs expressed in EUR the fuel production costs are presented both in EUR/MWh and SEK/MWh (while distribution and vehicle cost and total cost only in SEK). An exchange rate of 9.5 SEK/EUR is assumed.

3.1.3 Methanol, DME, Methane

Woody biomass is gasified, and synthesis gas (syngas) is produced. The gas can then be further processed to produce a range of products, e.g. methanol, DME and methane (IEA 2020). The conversion efficiency from woody biomass to fuel is assumed to be between 60–65 % corresponding to the range used by IEA (2020). The obtained conversion efficiency in a specific case depends on the combination feedstock type, gasification technology and integration options and can be somewhat higher for methane than for the other product options[7].

The conversion processes for production of methanol, DME and methane from woody biomass have been treated as having similar economic performance in agreement with data provided by IEA (2020). The uncertainty related to different plant specific factors, including logistics and integration possibilities, can be larger than the differences between the choice of fuel product.

DME is an abbreviation for dimethyl ether. This fuel has a boiling point of -25 °C and can be liquefied at 6.1 bar. This fuel requires specific distribution infrastructure as well as specific vehicles (Lönnqvist et al. 2015).

Methanol can be an intermediate step to DME or synthetic gasoline. It can also be used as low and high blend-in to gasoline (Lönnqvist et al. 2015). When used as a high blend-in it requires specific distribution. Methanol was tried out as a low blend-in (M15) in Sweden between 1979 and 1982 (Lönnqvist 2017) and is also allowed in up to 3 % blend in EN228 gasoline even if that is not used widely in Europe.

Methanol is used together with an ignition improver and is then called MD95. The cost of MD95 is calculated as follows:

$$\text{MD95} = \text{blending factor} * (0.94*\text{cost}_{\text{MeOH}}+(1-0.94)*\text{cost}_{\text{diesel}}*2.5)$$

The blending factors is set 1.02 and represents the cost of producing the fuel mix from the components.

Methanol can be used in cars together with a mixture of gasoline. This fuel is called M85 and contains 85 % methanol and 15 % ethanol on volume basis, which corresponds to 73 % methanol and 27 % gasoline on energy basis.

Methane made from biomass is sometimes denoted synthetic natural gas (SNG) or renewable natural gas (RNG). Methane requires specific distribution infrastructure as well as specific vehicles. In compressed form it may be distributed through pipelines or in bottles. Methane may also be liquified, LBG, to facilitate distribution when no pipeline is available. There are also specific vehicles, for example trucks, that use LBG since it is a high energy density fuel.

The production cost has been estimated to 60–105 EUR/MWh. The upper level is higher than the estimation by Holmgren et al. (2021), which reported 60–80 EUR/MWh. Effects of plant localiza-

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[7] A higher efficiency from methane than methanol can be obtained main for gasification technologies that produce a significant amount of methane already in the gasifier, such as indirect fluidized bed gasification.

tion, integration and scale will generally be larger than the differences between the different products. However, for specific set-ups, the costs can be lower for methane than for the other two product options. The feedstock cost varies between 31 and 33 EUR/MWh fuel corresponding to the assumption that the conversion efficiency is between 60 and 65 %. Thus, the uncertainties regarding conversion efficiency, as presented by IEA, has a small impact compared to capital cost or operating costs.

3.1.4 Gasification-based gasoline (MTG)

Technology to convert methanol into gasoline was developed in the 1970s as a response to the oil crisis (Gogate 2019). This technology can be used in combination with gasification-based methanol production, as discussed above, to make gasoline components or drop-in gasoline. Two technologies for converting methanol into gasoline are offered commercially today: Exxon Mobile’s methanol-to-gasoline (MTG) and Haldor Topsoe’s Topsoe Improved Gasoline Synthesis (TIGAS).

Both techniques are based on catalytic methanol conversion to dimethyl ether, which is then converted into hydrocarbons, mainly in the petrol range, using a zeoilite-based catalyst (Exxon Mobil 2020). This production technology typically provides about 85–90 % of the total yield as gasoline and 10-15% as LPG (Jafri et al. 2020). The yield from conditioned synthesis gas to products (gasoline and LPG) is about 70-75 %, with synthesis gas-to-methanol roughly 80% and methanol-to-hydrocarbons roughly 90 % (Jafri et al. 2020). However, Hannula and Kurkela indicate a higher efficiency from methanol to hydrocarbons, at 97 % for MTG (Hannula and Kurkela 2013). The gasoline product has high-octane numbers due to a high proportion of aromatics and isoparaffins (Gogate 2019; Exxon Mobil 2020).

The techno-economics of gasification-based gasoline production has been studied both with the TIGAS process (Udengaard et al. 2015) and the MTG process (Jafri et al. 2020; Wetterlund et al. 2020; Hannula and Kurkela 2013). Udengaard et al. (2015) which assesses the TIGAS process with fluid bed gasification of felling residues, assumes a larger production scale in the calculation compared to the other studies[8].

In order to maintain consistency, the studies cited above has been processed to calculate a production cost for gasoline and LPG using methanol as a feedstock. This allows the previously discussed methanol production cost to be used. The result, which would be approximately valid both for cases where methanol production and MTG/TIGAS are co-located and when they are not, is a production cost of 10 EUR/MWh in addition to the cost of methanol, thus in total 70 -110 EUR/MWh. The higher end of this interval is higher than the cost estimated for a process starting from biomass as estimated by Hannula and Kurkela (2013) to EUR70 -80 /MWh, but the costs estimated in that study are generally somewhat lower than other references used here.

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[8] The study estimates 2900 t/d raw material on a dry basis or about 650 MW higher calorific value. This is similar to a medium-sized pulp mill but can still pose challenges because forestry residues have a more demanding logistics than pulpwood.

3.1.5 FT-Diesel

Fischer-Tropsch diesel (FT-diesel) can be obtained from syngas (Lönnqvist et al. 2015). This process involves several different conversion steps performed at different temperatures and using different catalysts. FT-diesel may also be obtained from natural gas or gasified coal. A conversion efficiency from woody biomass to FT diesel of 40–55 % has been assumed for this analysis (IEA 2020; Hannula and Kurkela 2013). The production cost is estimated to 80–125 EUR/MWh. This can be compared to the estimate by Holmgren et al. (2021) at 95–115 EUR/MWh. The most expensive part of the process is to clean the syngas (Lönnqvist et al. 2015).

3.1.6 Ethanol from cellulose

Ethanol can be produced through hydrolysis and fermentation of woody biomass (Lönnqvist et al. 2015). There are two types of hydrolysis: enzymatic and weak acid. The enzymatic hydrolysis process uses enzymes to catalyze cellulose in lignocellulosic feedstocks into sucrose (saccharification). The sucrose can then be fermented to obtain ethanol (Hahn-Hägerdal et al. 2006). Saccharification and fermentation can be performed in two steps or in one combined step (Lönnqvist et al. 2015). Weak acid hydrolysis and fermentation can also be used to obtain ethanol from woody biomass. Ethanol from hydrolysis is also called second-generation ethanol to distinguish it from first-generation ethanol, which generally is based on energy crops and only includes the fermentation step (ibid). If ethanol production is combined with a process that requires heat, e.g. district heating or pellets production, the overall efficiency can increase (ibid). Combined systems can have a total efficiency of approximately 50–90 % (Staffas et al. 2013) while the ethanol production alone has a conversion efficiency of 35–40 % (Frankó et al. 2016, IEA 2020, Staffas et al. 2013). This work has estimated a production cost of 105 – 130 EUR/MWh which may be compared to Holmgren et al. (2021) who have estimated a somewhat higher production cost, 110–150 EUR/MWh.

Ethanol is blended with an ignition improver and is then referred to as ED95. The cost of ED95 is calculated as:

$$\text{Cost ED95} = \text{blending factor} * (0{,}903*\text{cost}_{\text{ETOH}}+(1-0{,}903)*\text{cost}_{\text{diesel}}*2{,}5)$$

The blending factor represents the cost of producing the fuel from the two components and is assumed to be 1.02.

Ethanol can be used in cars together with a mixture of gasoline. This fuel is called E85 and contains 85 % ethanol and 15 % ethanol on volume basis, which corresponds to 79 % ethanol and 21 % gasoline on energy basis.

3.1.7 Hydrotreatment-based gasoline and diesel

Fast pyrolysis and upgrading

Different variants of fast pyrolysis of biomass are becoming established and technologies for producing pyrolysis oil from some biogenic raw materials, especially sawdust are commercially available. The yield of pyrolysis oil from sawdust is typically about 70 % on mass basis, equivalent to about 65 % on energy basis (Benjaminsson et al. 2103). Technology for fast pyrolysis of more low-grade residues, such as bark, branches and tops (GROT) or straw, is not yet commercial, but development work is ongoing. The higher ash content of these raw materials generally leads to a lower yield of pyrolysis oil compared to the yield of sawdust.

There are two main routes for upgrading of pyrolysis oil to transportation fuels. There is a lot of research into the co-processing of pyrolysis oil with fossil raw materials in a fluid catalytic cracking (FCC) unit. It is an established understanding that it is difficult to go above 5–10 % pyrolysis oil fraction in the feed with good performance in the FCC process. However, a pre-treatment (stabilization) of the pyrolysis oil can allow a blend up to 20–30 % (Pinho et al. 2017; Pinho et al. 2015; Bezergianni et al. 2018; Lindfors et al. 2015).

The other upgrading track is by catalytic hydro-treatment, either by co-processing with fossil feeds or stand-alone processing. In recent years, a consensus has emerged that upgrading of pyrolysis oil by hydrodeoxygenation should be done in two stages, the first step being a so-called stabilization, which takes place at milder conditions. This makes the pyrolysis oil less reactive and reduces problems with the coke formation in the second stage, which removes the oxygen content of the oil more or less complete (so-called deoxygenation) (Han et al. 2019) The maturity of the technology is relatively low and experimental data is available only from lab scale and without long operating times that can provide information on catalyst inhibition etc. Jones et al. (2016; 2013) notes that the life time of the catalyst is a key issue where much research is needed.

The pyrolysis and catalytic hydro-treatment is predicted to have an energy yield of about 60–70 %[9], (Jones et al. 2016; Jones et al. 2013; Dutta et al. 2015), i.e. using approximately 1.4–1.6 MJ feedstock per MJ of product. This is distributed about 50/50 between petrol and diesel. However, approximately 0.15–0.20 MJ of natural gas per MJ product is also required for the hydrogen treatment, making the energy efficiency about 55–60 % if this is also included.

IEA (2020) reports production costs of 113–139 EUR/MWh for FCC co-processing and 97–127 EUR/MWh for stand-alone hydrotreatment upgrading (after correction of feedstock cost to 20 EUR/MWh). For the hydrotreatment option, other sources of estimated cost of productions are available that are similar or slightly lower. Furusjö & Lundgren (2017) reported 97–108 EUR/MWh for the hydrotreatment route based on Anheden et al (2017). Jones et al (2013) indicates 90 EUR/MWh and Dutta et al (2015) 95 EUR/MWh. Based on these numbers a production cost interval of 90–140 EUR/MWh has been used in this study.

Hydropyrolysis

Pyrolysis in the presence of a catalyst and in hydrogen environment is called hydropyrolysis. This is an area with a lot of recent research and development. Shell (including CRI catalysts) develops and markets a process called IH^2 (Integrated Hydropyrolysis and Hydroconversion) (Shell 2020) based on cooperation with gas technology Institute (GTI) (Marker et al. 2012; 2014). A 5 ton/day

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[9] Corresponding to the possibility of producing approximately 270–320 kg of hydrocarbons per ton of dry biomass. This is not a system-system energy efficiency, but only the relationship between energy in hydrocarbons and biomass feedstock.

pilot plant has been built in Bangalore, India, and has been successfully operated but with a lower capacity than it was designed for (Del Paggio 2018) and is under re-construction (Shell 2019).

The IH^2 process converts the biomass into two stages, hydropyrolysis in a fluidized bed for about 20 bar hydrogen pressure followed by a gas phase upgrade over another catalyst. The process can provide diesel, jet fuel and petrol in different proportions (Urade et al. 2015) with a total liquid yield up to 65 % on energy basis from the raw material (Meerman and Larson 2017; Furusjö et al. 2018b; 2018a) and a slightly lower systems efficiency (Furusjö et al. 2018b; 2018a). Meerman and Larson (Meerman and Larson 2017) indicates a gasoline yield of 2/3 of the total production of liquid fuels and 1/3 diesel yield.

An early techno-economic study from 2013 indicates production costs as low as 40 EUR/MWh (Tan, Marker, and Roberts 2014) but a later study indicates about 70 EUR/MWh with the potential to reach about 55 EUR/MWh with learning effects, however, for a very large scale (Meerman and Larson 2017). On a smaller scale, production is likely to be slightly more expensive but may still be competitive (Furusjö et al. 2018b; 2018a). The Biozin project in Norway has not communicated any expected production cost, but the communicated specific investment cost (Biozin Holding AS 2019) is more than twice the estimate used for a first plant in the academic studies (Furusjö et al. 2018b; 2018a; Meerman and Larson 2017), which will lead to higher production costs. A study with a broader scope for hydropyrolysis indicates a general range of approximately 60–80 EUR/MWh (Nguyen and Clausen 2019). After correction of feedstock costs, an estimated production cost interval is approximately 60–90 EUR/MWh.

Lignin pre-treatment and upgrading

Lignin from pulp mills has recently been widely discussed as a raw material for renewable fuels in a Swedish context but upgrading lignin to fuel has several technical challenges. There are different technical solutions under development, e.g., by the Swedish technology developers SunCarbon and Renfuel. These have in common that they are based on lignin separated from black liquor, which is treated or converted to provide a liquid intermediate that can be fed to a hydrogen treatment process in an oil refinery.

Jafri et al (Jafri et al. 2020; Wetterlund et al. 2020), based on data from SunCarbon and Löfstedt et al (Löfstedt et al. 2016), estimates 82 % energy yield from lignin and 45 % from lignin and hydrogen, without regard to internal hydrogen generation from process gases. The study indicates the production of, in principle, only diesel but this is uncertain due to the low technology maturity.

Furusjö & Lundgren (2017) reported 58–78 EUR/MWh for the hydrotreatment route based on Anheden et al (Anheden et al. 2017). Jafri et al (Jafri et al. 2020; Wetterlund et al. 2020) reports higher production costs: 85–105 EUR/MWh when natural gas-based hydrogen is used for hydrotreatment and 140–155 EUR/MWh when renewable (electrolysis-based) hydrogen is used[10]. All

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[10] The lignin separation process is tightly integrated with the mill and the cost for lignin is calculated based on this integration. It consists mainly of energy-related costs, which is value of decreased electricity sales for an energy surplus pulp mill or replacement fuel for an energy deficient pulp mill. Other costs included are make-up chemicals for pulping, due to effects on pulp mill sodium/sulfur balance, and chemicals used in the lignin separation process (carbon dioxide, sulfuric acid).

cost estimates are uncertain due to low technology maturity. The range 60–100 EUR/MWh has been used since it has been estimated that sustainability criteria of the Renewable Energy Directive can be met also with natural gas-based hydrogen if internal hydrogen generation is used.

3.1.8 Summary biofuels production costs

Table 4 presents a summary of production costs, conversion efficiency, possibility to use as drop-in fuel, and technology readiness level for the different biofuels for transportation included in the assessment.

Table 4: Summary of production costs, characteristics, and conversion efficiencies. The information represent mature costs and conversion efficiencies i.e., the case when these technologies have reached a commercial position on the market (but without specifying a specific year for when this situation might happen).

Fuel	**Production cost for fuel component** [SEK/MWh] [EUR/MWh]	**Conversion efficiency** (only transportation fuel, if not specified)	**Drop-in**	**TRL**[11]
Methanol, DME, Methane	590–990 60–105	60 –65 %	No: DME, Methane, Methanol (but current European standards allow blending up to 3% for methanol)	5,5–7
Gasification-based gasoline (MTG)	670–1050 70–110	54–63 % (producing gasoline and LPG; 9:1) 90–97 % from methanol	Yes	5,5–7
FT-Diesel	770–1190 80–125	40–55 %	Yes	5,5–7
Ethanol from cellulose	990–1230 105–130	35–40 %	Yes (E10), No (E85, ED95)	6–8
Bio oil-based diesel and gasoline (fast pyrolysis and hydrotreatment upgrading)	860–1330 90–140	55–60 % from biomass and hydrogen 60–70 % from biomass	Yes	3–6
Bio oil-based diesel and gasoline (hydropyrolysis)	570–860 60–90	65 %	Yes	3,5–5
Diesel and gasoline (lignin pre-treatment and upgrading)	570–950 60–100	45 % from lignin and hydrogen[a], 82 % from lignin	Yes	3-4
Fossil diesel/gasoline low (Edwards et al 2011)	410 45			
Fossil diesel/gasoline high (Edwards et al 2011)	810 85			
[a] Without consideration of internal hydrogen generation from off gases.				

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[11] Technology readiness level estimates based on Jafri et al (2019) except for ethanol from cellulose. Lower number in range corresponds to TRL for the process step with lowest maturity ("weakest link"). Higher number in range is weighted average TRL for full production chain.

Figure 1 illustrates the range of the estimated biofuel component production costs and also compares them to production costs of fossil transport fuels expressed in SEK/MWh. Figure 2 presents the same data but expressed in EUR/MWh. The resulting costs for the ready-to-use biofuels, i.e. sometimes including additional components, are presented in section 4. A discussion of the results is also presented in section 4.

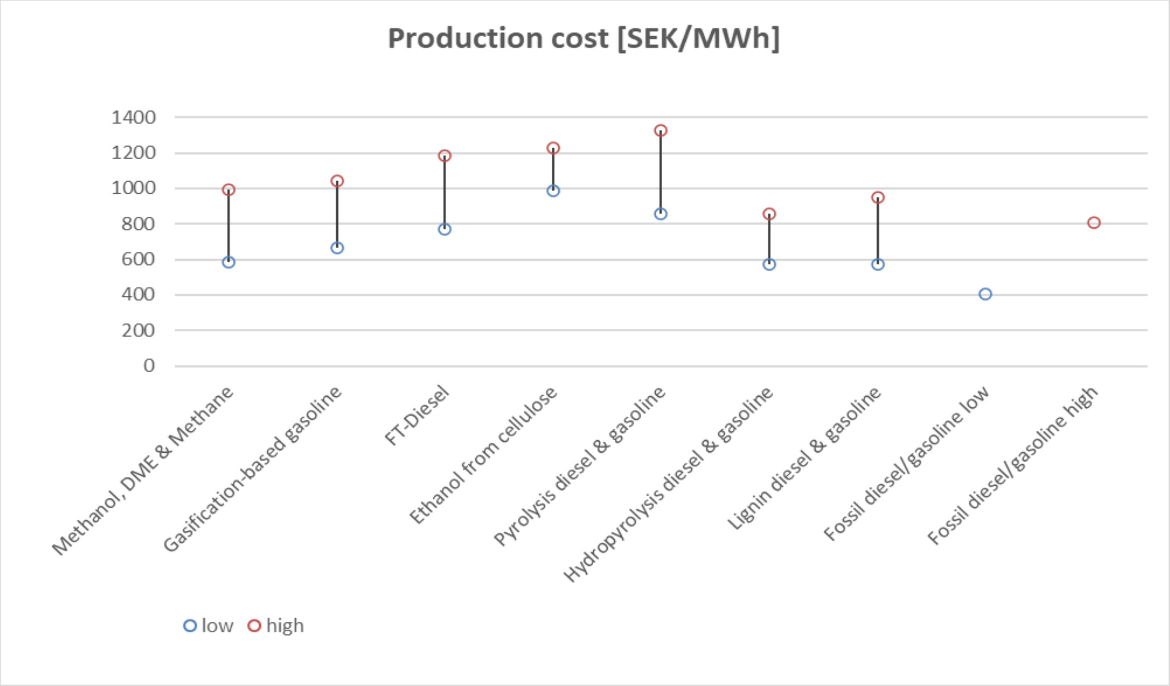

Figure 1: Summary of biofuel component production costs and comparison with fossil transport fuels.

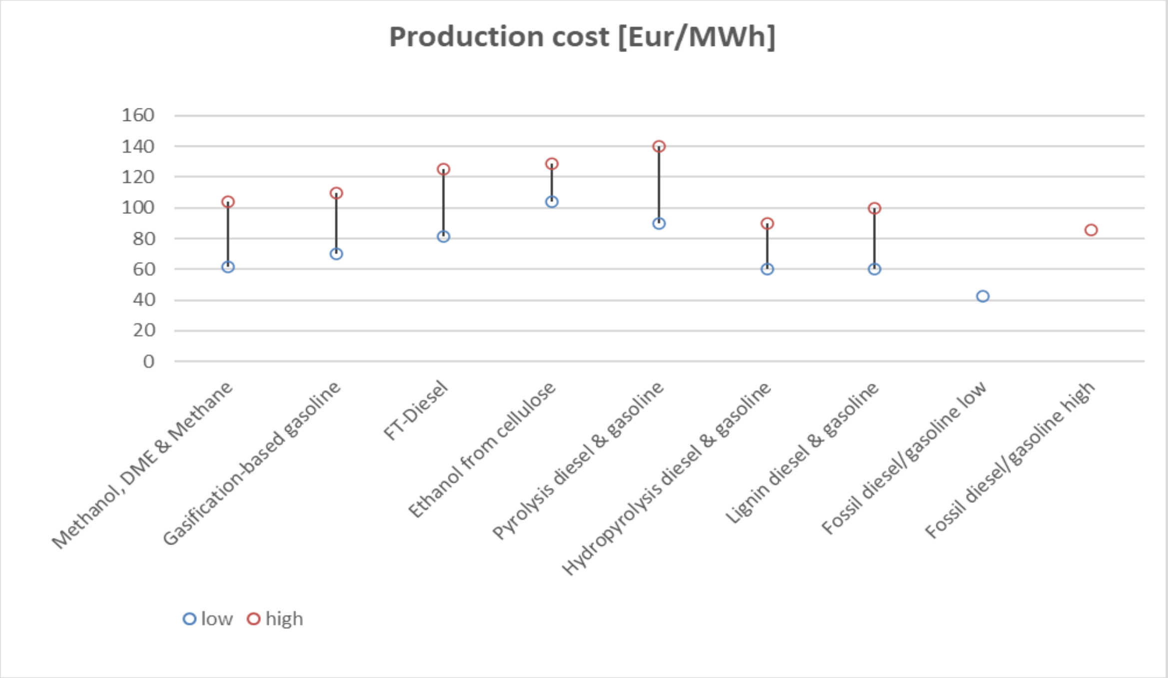

Figure 2: Summary of biofuel component production costs and comparison with fossil transport fuels presented in EUR/MWh.

3.1.9 Electrofuels

Electrofuels represent fuels (and chemicals) produced by electricity, water, and CO_2 (or nitrogen). They can be a variety of end products. In short, electrofuels are produced by combining hydrogen, which is produced by electrolysis of electricity and water, with CO_2 (or nitrogen). Carbon-based electrofuels can be produced from fossil CO_2 sources, biogenic CO_2 sources (e.g., from biofuel production or flue gases from biomass combustion) or from CO_2 from the air by direct air capture.

Two types of electrofuels (following Korberg et al 2021) are of interest for comparison with the forest biomass based fuel pathways in this study (i) electrofuels produced from high concentrated carbon sources as flue gases from power production and industry or from direct air capture (marked with the prefix “e“), and (ii) electrofuels, sometimes called bio-electrofuels, produced from biogenic excess CO_2 from biofuel production and linked to the biofuel production, and thus requiring no costly CO_2 capture technology (marked with the prefix “e-bio”). Cost estimates are included for both these types of electrofuels. However, to not include to many electrofuels options in the result figures on this study and thereby risking losing focus on the core assessment the synthesized results for the bio-electrofuels are only presented in the appendix.

Following the recent estimates of electrofuels production costs in Korberg et al (2021), the following electrofuels are included e-methanol, e-DME, e-methane-LBG[12], e-FT-diesel, e-bio-methanol, e-bio-DME, e-bio-methane-LBG, and e-bio-FT-diesel. The fuel production cost estimates in Korberg et al (2021), presented in Table 5, Figure 3 and Figure 4, is assumed to represent 2030 and commercially mature technologies which make them relevant to compare with the biofuel production cost estimates in this study. However, note that the cost for liquefaction in the case of LBG in Korberg et al (2021) is included in the fuel production cost, whereas for the biofuel pathways in this study this is presented separately and when summarized to total cost included in the distribution cost.

Korberg et al (2021) assume in their base case an average efficiency for electrolysis at 69 % (in lower heating value), a capacity factor for the electrolysis of about 53 %, an electrolysis investment cost at 600 EUR/kW and an electricity cost at 33 EUR/MWh, representing offshore wind power. A total investment cost for CO_2 capture at 400 EUR/ton_CO_2, corresponding to a CO_2 capture cost at approximately 45 EUR/ton_CO2[13], is also assumed in the base case in Korberg et al (2021). The range of costs in Table 5, Figure 3 and Figure 4 represents the sensitivity assessment in Korberg et al (2021) where the electricity cost is varied (reduced and increased), electrolysis cost reduced, efficiency for electrolysis increased and carbon capture cost is increased (to approximately

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[12] Korberg et al (2021) includes two different liquified methane/biogas production pathways. One based on CO_2 from traditional biogas production (digestion, called LBG in their study) and one based on CO_2 from thermal gasification of forest-based biomass (called LMG). The production pathways used in our comparison is the latter one, but it is called LBG to be consistent with the terminology used on our study.

[13] The annualized capture cost is calculated by the authors of this report assuming a lifetime of 25 years and a discount rate of 10 %. For comparison, Brynolf et al (2018) that reviewed the literature reported a short to mid-term costs for CO_2 capture of 20–170 EUR/ton_CO_2.

80 EUR/ton_CO_2). The same conversion factor from EUR to SEK as for the biofuel options are used (i.e., 9.5 SEK/EUR).

As for most technologies that are under development, the future cost for electrofuels is as indicated uncertain. According to Brynolf et al (2018) the most important factors affecting the production cost of electrofuels are the capital cost of the electrolyser and the electricity price, i.e., the hydrogen production cost, but the capacity factor of the unit and the life span of the electrolyser are also important parameters affecting that production cost. As indicated by Brynolf et al (2018) the choice of final energy carrier is not as critical for the electrofuels production cost as the assumption for other costs. In terms of TRL it is assumed that e-methanol and e-DME has TRL 8 while the other electrofuels have TRL 7 (Brynolf et al., 2018).

Table 5. Estimates of production costs for selected electrofuels). Production cost range represents the highest and lowest of the production cost estimates from the sensitivity assessments in Korberg et al (2021). The prefix “e“ refers to electrofuels produced from high concentrated carbon sources as flue gases from power production and industry and the prefix “e-bio” refers to electrofuels produced from biogenic excess CO_2 from biofuel production and linked to the biofuel production. For the LBG cases the production cost includes the cost for liquefaction.

Fuel	Production cost base case [SEK/MWh] [EUR/MWh]	Production cost range [SEK/MWh] [EUR/MWh]
e-methanol	1110 115	930–1400 100–150
e-DME	1160 120	980–1450 100–155
e-methane-LBG	1220 130	1040–1500 110–160
e-FT-diesel	1490 160	1270–1820 135–190
e-bio-methanol	850 90	730–970 80–100
e-bio-DME	860 90	780–1030 80–110
e-bio-methane-LBG	960 100	855–1120 90–120
e-bio-FT-diesel	1090 115	980–1265 100–130

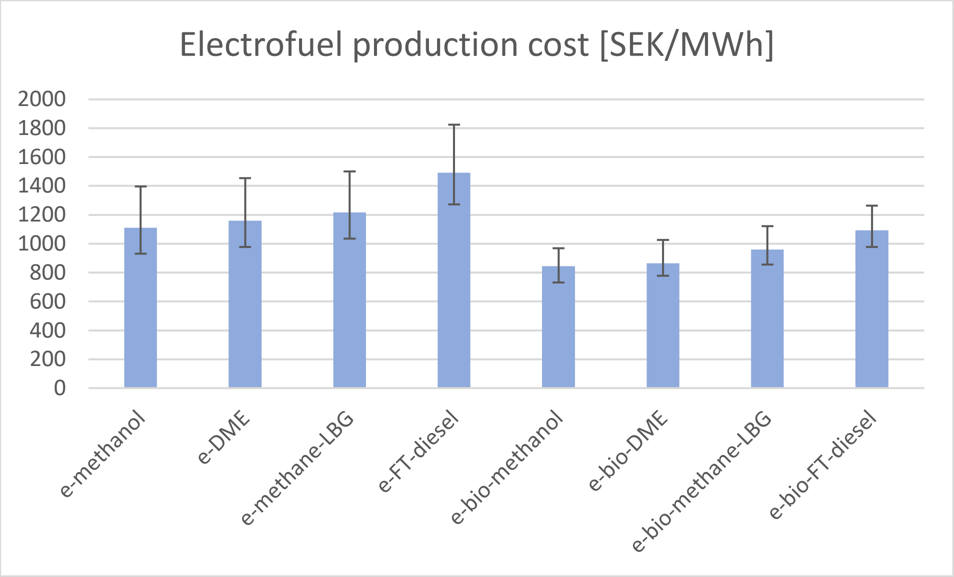

Figure 3: Overview of electrofuel production costs in SEK/MWh (based on Korberg et al., 2021). The range for the production costs represents the highest and lowest of the production cost estimates from the sensitivity assessments in Korberg et al (2021). The prefix "e" refers to electrofuels produced from high concentrated carbon sources as flue gases from power production and industry and the prefix "e-bio" refers to electrofuels produced from biogenic excess CO_2 from biofuel production and linked to the biofuel production.

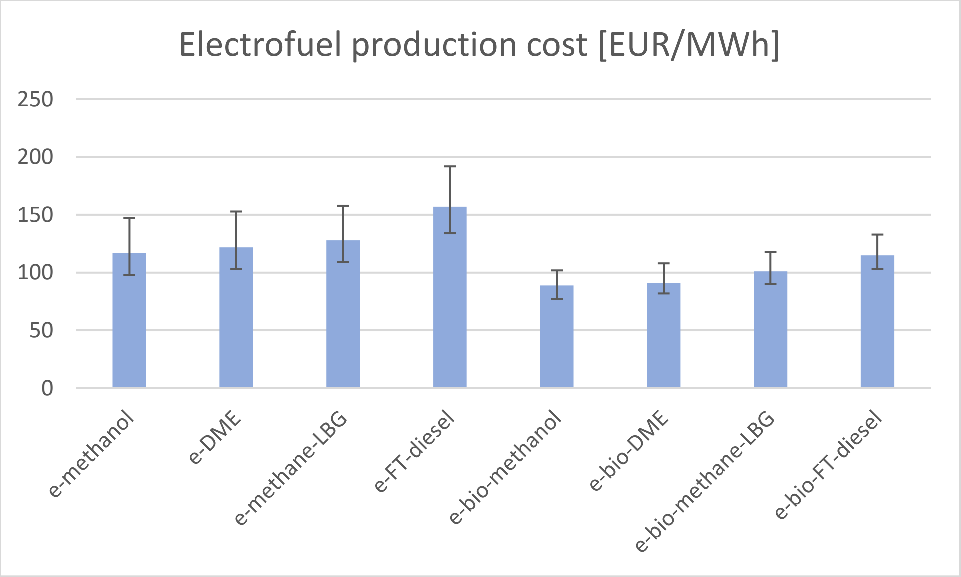

Figure 4: Overview of electrofuel production costs in EUR/MWh (based on Korberg et al., 2021). The range for the production costs represents the highest and lowest of the production cost estimates from the sensitivity assessments in Korberg et al (2021). The prefix "e" refers to electrofuels produced from high concentrated carbon sources as flue gases from power production and industry and the prefix "e-bio" refers to electrofuels produced from biogenic excess CO_2 from biofuel production and linked to the biofuel production.

3.1.10 Costs for AdBlue for diesel-like fuel options

For the diesel-like fuel options, emission requirement calls for after-treatment in the form of addition of so-called AdBlue (for the conversion of NOx in a selective catalytic reduction, SCR catalyst). The amount of AdBlue needed is directly related to the fuel use. Following Holmgren et al. (2021) the cost for AdBlue will, when summarising the costs, therefore be added to the fuel cost for the relevant fuels in this study (i.e., FT-Diesel, DME, methanol, ED95, bio-oil and lignin based diesel and for LBG in case of a compression ignition engine). The costs for AdBlue for trucks are based on Holmgren et al. (2021) who base their costs partly on Röck et al. (2018) but with adjustments based on input provided by Swedish vehicle and fuel producers. The consumption of AdBlue per energy unit of fuel is assumed to be 0.009 liter/kWh_fuel for fuels in compression ignition (CI) engines and for gas fuels in high-pressure direct injection (HPDI) CI engines (LBG). For trucks (mainly used by haulage contractors) the cost for AdBlue is assumed to be 2.5 SEK/liter and assumes that refueling takes place at a storage tank in own depots (Holmgren et al., 2021). This corresponds to an AdBlue cost for trucks at 22.5 SEK/MWh_fuel, see Table 6.

Also, for cars the diesel-like fuel options require addition of AdBlue. The need for AdBlue is assumed to be about 1liter/1000km (based on estimates from Volvo cars, Hanarp, 2021) which roughly corresponds to 0.0028 liter/kWh_fuel (assuming a fuel use at about 130 MJ/100 km based on Prussi et al., 2020). For cars the cost for AdBlue is assumed to be 10 SEK/liter (based on market prices, for example by Biltema (2021), i.e., about 1.05 EUR/liter, at filling stations it is usually somewhat lower about 7 SEK/liter[14]). This corresponds to an AdBlue cost for cars at about 28 SEK/MWh_fuel, see Table 6.

Table 6: Estimated AdBlue cost for the concerned biofuel pathways

Vehicle	Fuel pathways	AdBlue cost (SEK/MWh_fuel)
Trucks	Methanol, DME, FT-Diesel, ED95, LBG (in the case with a compression ignition engine), hydrotreatment-based diesel (lignin, pyrolysis and hydropyrolysis diesel)	22.5
Cars	DME, FT-Diesel, bio oil-based diesel, hydrotreatment-based diesel (lignin, pyrolysis and hydropyrolysis diesel)	28

3.2 DISTRIBUTION AND INFRASTRUCTURE COSTS

For all the studied transportation fuel options distribution and infrastructure costs have been estimated. These costs are represented by the cost for fuel distribution and infrastructure cost represented by the investment as well as operation and maintenance cost of the filling stations. A cost for liquefaction of biogas in the case of LBG and for compression in the case of CBG have also been included.

More specifically the cost for fuel distribution includes the estimated cost for distribution of the fuel from production facility to filling station. The costs for infrastructure include the estimated annualized investment costs for the filling station and the estimated operation and maintenance cost of the filling stations. In terms of costs for infrastructure for drop-in fuels it is assumed that also

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[14] https://www.shell.se/foretagskund/listpriser/listpriser-shell-truckdieselkort.html

these fuels are associated with a cost for the investment in filling stations (besides the cost for operation and maintenance of the filling stations) despite that they can use available filling stations without any significant modifications. The reason is that assuming no investment cost for these fuels would be unfair since the continued use of existing infrastructure in terms of filling stations is also associated with a cost for renovation and potential upgrading needs. As the infrastructure cost for all studied biofuel pathways turns out to be minor in relation to the fuel production and vehicle costs a more refined way of handling the investment cost for filling stations for drop-in fuels would not have had a significant influence on the comparison of the studied fuel options whereby the assumption used was assumed good enough for this study. This assumption is also in line with the assumption made in the underlying references used for data collection (see next paragraph).

For the distribution and infrastructure of the different fuels, the following assumptions have been made, based on Pettersson et al. (2019) and Holmgren et al. (2021) but with some modifications based on input from the biofuel industry (specified in the text below). Pettersson et al. (2019) represent a well-to-tank cost study for forest-based biofuels and include a relatively detailed compilation of distribution alternatives for the included fuels. Holmgren et al. (2021) compile cost and risks for different fuel choices for trucks and include several biofuel options. The distribution and infrastructure costs in Holmgren et al. (2021) are mainly based on Pettersson et al., (2019) but with a few updates, primarily to adapt them to heavy transport.

3.2.1 Distribution cost

The liquid fuels are assumed to be distributed from the production facility or refinery to various depots by truck or ship and then distributed by truck from the depot to filling stations. For liquid fuels the transport to depots is assumed at an estimated cost of 0.15 SEK/liter (based on Pettersson et al., 2019) and an average cost of transport of 0.1 SEK/liter (Pettersson et al., 2019) is assumed for the transport from depot to filling station (based on an assumed average distance of 200 km for truck transport in both cases and for ship transport using the distance by sea from Göteborg/Lysekil to Stockholm as the average distance following Pettersson et al., 2019). The energy density of the different fuels is then considered to express the distribution cost per energy unit (following Holmgren et al., 2021). In the case of DME the distribution cost is assumed to be 20% higher in order to represent transport in liquid state at 5 bar (Holmgren et al., 2021). The estimated costs for fuel distribution for the included liquid fuels are presented in Table 7. That all liquid biofuels are assumed to be transported via depot is a difference compared to what is assumed in Pettersson et al. (2019) and Holmgren et al. (2021) (that assumes only direct transport from production facility to filling station). Based on input from biofuel producers this judged to be a realistic assumption for a case with large-scale production of biofuels as in this study (Blackenfelt, 2021; Gundberg, 2021; Tamm, 2021).

For gaseous based fuels the distribution from the production plant to filling station is assumed to use adapted trucks and is based mainly on the assumptions in Pettersson et al., (2019) and Holmgren et al. (2021) but with modifications for the total transport cost to better correspond to large-scale production also for the gaseous biofuels (like in the case of the liquid fuels). For CBG this results in a distribution cost of 0.039 SEK/kWh and for LBG 0.028 SEK/kWh. This is based on an assumed distribution cost of 0,38 SEK/Nm3 for CBG and for LBG a distribution cost of about 0.2 SEK/kg is assumed (Pettersson et al., 2019). Cost for compression (0.012 SEK/kWh) is then added for CBG following Pettersson et al. (2019) and Holmgren et al. (2021) (see Table 7). For LBG the cost for liquefaction (at about 0.087 SEK/kWh following Pettersson et al. 2019 and Holmgren et al. 2021) is also included here. The estimated costs for fuel distribution for the included gaseous based fuels are presented in Table 7.

3.2.2 Infrastructure cost

Filling stations for liquid biofuels (including DME) is assumed to have a capacity of 40 GWh/year for the biofuel in the case of trucks (following the capacity of LNG stations, Holmgren et al., 2021) and 30 GWh/year in the case of cars (Pettersson et al., 2019). The investment cost for filling stations assumed is 6 million SEK for both cases following Pettersson et al., (2019) for cars and following Holmgren et al., (2021) for trucks (which is based on Pettersson et al., 2019)) and is assumed to be valid also for the future case. The reason for the lower investment cost per energy unit fuel supplied for filling stations for trucks is the lower complexity for a truck filling station compared to a filling station for cars and light trucks. For simplicity and since we focus on the case where all fuels are used in relatively large-scale (and since the infrastructure cost turns out to represent a minor cost of the total cost in this study) all forest based biofuels, except for the methane based (see below) are assumed to have the same investment cost for the filling station, following Holmgren et al 2021 and Pettersson et al. 2019 (i.e., no major cost difference for different pumps is assumed when the fuels are used in large-scale). Also, biofuels compatible with existing infrastructure are assumed to have the same yearly infrastructure cost for the filling station (but the associated operation and maintenance cost is lower due to the higher energy content of these fuels), see Table 7.

To calculate the annual investment cost for filling stations a lifetime of 15 years is assumed and discount rate of 10% (corresponding to an annuity factor of about 0.13), following Holmgren et al. 2021. To express the annual investment cost per fuel unit the assumed yearly capacity is used. Thus, it is assumed that the filling stations supply fuels corresponding to the capacity. The cost for operation and maintenance of a filling station is assumed to be about 0.1 SEK per distributed liter (based on Pettersson et al., 2019 for cars and following Holmgren et al. 2021 for trucks) and thus differ due to the energy content of the fuel when expressed per energy unit. The estimated costs for investment and operation and maintenance of filling stations for the included liquid fuels are presented in Table 7.

Filling stations for gaseous based fuels are assumed to have a capacity of 25 GWh/year for CBG and 40 GWh/year for LBG which is assumed to represent a case with large-scale use of these fuels (similar to the case of liquid fuels), following Holmgren et al. 2021. The investment cost for CBG and LBG fillings stations for the capacity chosen and in the short term is estimated to be 7.5 million SEK and 13 million SEK respectively (based on Holmgren et al., 2021). However, cost reductions due to continued learning is expected for LBG and CBG filling stations. Following Holmgren et al. (2021) a learning rate of 10% is assumed and using a market increase factor of 2 the cost reductions correspond to 10 %. This results in investment cost for CBG and LBG filling stations at 6.75 million SEK and 11.7 million SEK, respectively. The annual investment cost is calculated as in the case of liquid biofuels. The cost for operation and maintenance of a CBG and LBG filling station is assumed to be about 0.05 SEK per distributed kWh (based on Holmgren et al., 2021). The estimated costs for investment and operation and maintenance of filling stations for the included gaseous based fuels are presented in Table 7.

Table 7: Cost assumptions for fuel distribution and infrastructure represented by filling stations. For references and assumptions see the text. The costs are assumed to represent the situation in Sweden when the included fuels are mature and commercially available on the market.

Fuel	**Vehicle**	**Fuel distribution costs**	**Infrastructure costs**			
			Investment cost and capacity for filling station			**Operation and maintenance cost for filling station**
		(SEK/kWh)	Total investment cost (MSEK)	Capacity/sales volume (GWh/year)	Investment cost per fuel supplied (SEK/kWh)	(SEK/kWh)
Diesel	Truck	0.026	6	40	0.02	0.010
	Car			30	0.026	
Gasoline	Truck	0.027	6	40	0.02	0.011
	Car			30		
Methanol	Truck	0.057	6	40	0.02	0.023
	Car			30	0.026	
DME	Truck	0.057	6	40	0.02	0.023
	Car			30	0.026	
Methane- CBG	Truck	0.051[a]	6.75[b]	25	0.039	0.055
	Car			25	0.039	
Methane- LBG	Truck	0.028[a] Liquefaction cost: 0.09	11.7[b]	40	0.043	0.053
Gasification-based gasoline	Truck	0.027	6	40	0.02	0.011
	Car			30	0.026	
FT-Diesel	Truck	0.026	6	40	0.02	0.010
	Car			30	0.026	
Ethanol from cellulose (ED95 for trucks and E85 for cars)	Truck	0.043	6	40	0.02	0.017
	Car	0.038		30	0.026	0.015
Hydrotreatment-based diesel (lignin, pyrolysis and hydropyrolysis)[d]	Truck	0.026[c]	6	40	0.02	0.010
	Car			30	0.026	
Hydrotreatment-based gasoline (lignin, pyrolysis and hydropyrolysis)[d]	Truck	0.027[c]	6	40	0.02	0.011
	Car			30	0.026	

[a] For CBG this includes costs for compression (0.012 SEK/kWh). For LBG a cost for liquefaction at 0.087 SEK/kWh is assumed. The costs for compression and liquefaction include investment and maintenance of the facility and are based on the estimates in Pettersson et al., (2019) and Holmgren et al (2021). For compression 0,18 kWh_{el}/Nm^3 is assumed.

[b] For CBG and LBG filling stations a cost reduction of 10% due to the potential for continued learning is assumed.

[c] The final energy density for bio oil based gasoline and diesel is uncertain but is here assumed to have the same energy content as fossil diesel and gasoline, just like gasification based gasoline.

[d] Include the three studied hydrotreatment-based gasoline and diesel pathways i.e., lignin pre-treatment and upgrading, fast pyrolysis and hydrotreatment upgrading, and hydropyrolysis.

The infrastructure and distribution costs for trucks and cars is presented in Figure 5 and Figure 6, respectively. The costs of CBG and LBG is higher than for the other liquid fuels. The infrastructure and distribution costs for electrofuels are assumed to be the same as for the corresponding biofuel.

It should be noted that there are important uncertainties also linked to future distribution and infrastructure costs and this section presents estimations for a future case with large-scale use of all the included options based on the current literature where the main focus has been on having a fair relative representation of the costs. Given that the decarbonization of the future transport system continues for example the actual distribution cost may increase or decrease somewhat compared to the current estimates and the assumed distances used for estimating the costs are also uncertain.

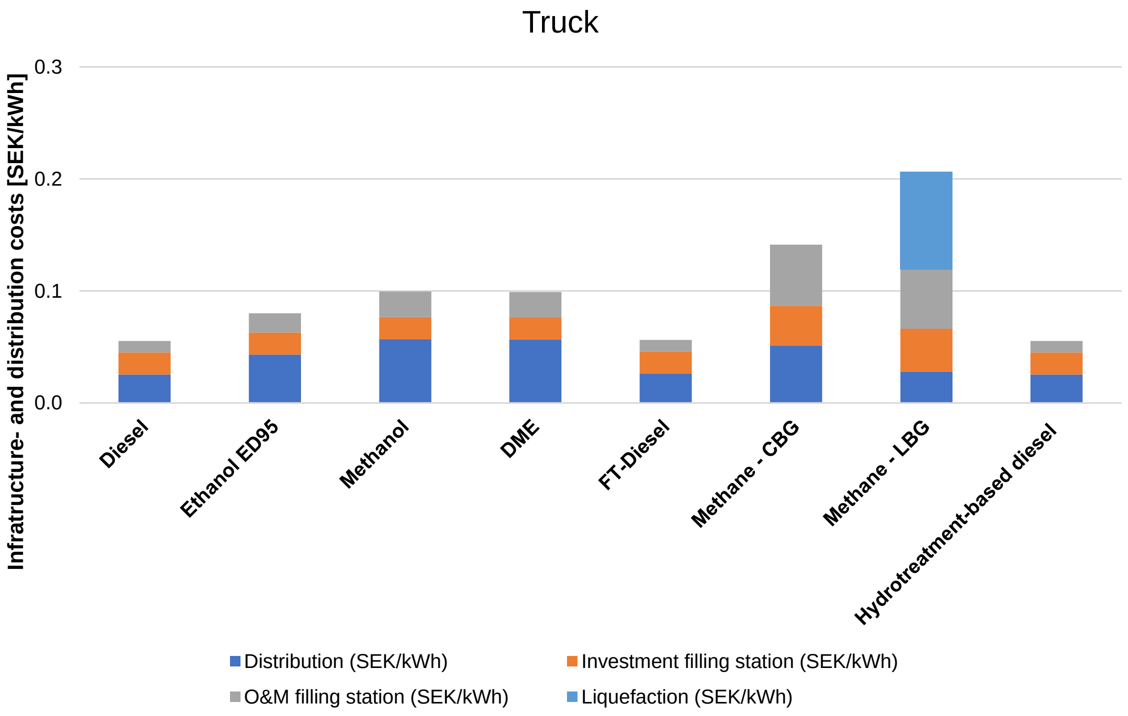

Figure 5 The estimated cost for fuel distribution, and investment and, operation and maintenance of filling stations for the included fuels when used in trucks. The terms “Hydrotreatment-based gasoline and diesel” represent the three studied hydrotreatment-based gasoline and diesel pathways i.e., lignin pre-treatment and upgrading, fast pyrolysis and hydrotreatment upgrading, and hydropyrolysis. For assumptions and references see the text. Investment filling station refers to the annual investment cost for filling stations per energy unit of fuel supplied per year.

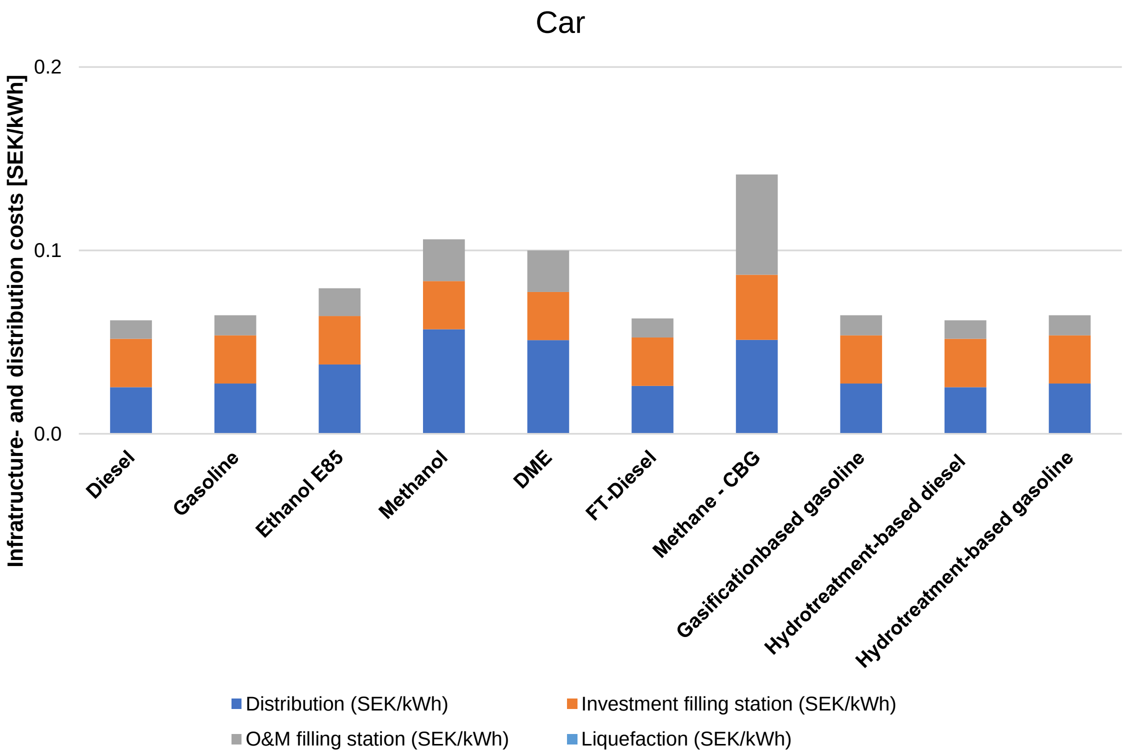

Figure 6 The estimated cost for fuel distribution, and investment and, operation and maintenance of filling stations for the included fuels when used in cars. The terms "Hydrotreatment-based gasoline and diesel" represent the three studied hydrotreatment-based gasoline and diesel pathways i.e., lignin pre-treatment and upgrading, fast pyrolysis and hydrotreatment upgrading, and hydropyrolysis. For assumptions and references see the text. Investment filling station refers to the annual investment cost for filling stations per energy unit of fuel supplied per year.

3.3 VEHICLE COSTS

The cost of vehicles is often protected data since it is of very competitive nature. Market prices of products reflects that the cost can be higher for certain technologies however the "economy of scale" has significant impact. For trucks, this study relies on data from Holmgren et al (2021) where cost of heavy-duty trucks has been compiled together with original equipment manufacturers (OEM´s) in different scenarios. The cost for heavy trucks used in this study represents the 40-ton EU standard vehicle in 2030. The costs are expected prices on the market thus not the true cost. The reference cost of a diesel fueled 40-ton truck in 2030 is 1 126 600 SEK. It is judged that a truck for liquefied biogas (LBG) with a compression ignition engine has an additional cost of 420 000 SEK and a truck with LBG and a spark ignited engine has an additional cost of 195 000 SEK and finally a truck with a spark ignition engine and a compressed biogas (CBG) tank has an additional cost of 15 000 SEK (Holmgren et al., 2021). Besides Holmgren et al (2021) which includes data for trucks, data has also been gathered through interviews with the passenger car vehicle industry (Personal communication with Per Hanarp, Volvo Cars 2021).

Regarding specific combinations of fuels and vehicles that are included in this study please see Table 2 that also shows which fuels are so-called drop-in fuels and which fuels that demand dedicated vehicles.

Trucks fueled with methanol and DME is not assessed in detail in Holmgren et al (2021) and judged to be the same as for the reference diesel truck in the case where these technologies have reached a commercial position on the market. Reaching market maturity for these technologies is a challenging task that is not the scope of this report, but it is discussed briefly in the summary and conclusions. Earlier detailed studies and analysis of DME and methanol driven trucks (e.g., AB Volvo input to the governmental investigation on fossil fuel independence in the Swedish transport sector, the so-called FFF-utredningen, Swedish Government Official Reports, 2013) have pointed in this direction as cost of more complex tank systems is offset by less complicated exhaust after-treatment systems for these vehicles.

Methanol for trucks can be applied using different engine technologies with either adding ignition improvers in a diesel process MD95 or as M100 in a stochiometric otto engine. In addition, it is possible to use methanol in a dual fuel system similar to diesel engines fueled with methane using a small amount of diesel fuel to initiate compression ignition. The most likely scenario today would be to use methanol in the same ways as ethanol in trucks (ED95) i.e., by adding ignition improvers to burn the fuel in diesel engines. The main benefit with this concept, called MD95, is the relatively high energy efficiency of the diesel process and less complicated technologies on the engine. Methanol for trucks is therefore assessed as MD95 in this study.

Vehicle costs for passenger cars are based on the list in Skatteverket (2021) presenting vehicle purchases prices, but, in this study, VAT is removed. The statistics for vehicle sales from BIL Sweden show three different Volvo Car models as the most registered vehicles followed by VW Golf as number four on the list. For the VW Golf there is also a biogas/natural gas version available. VW Golf is chosen as the reference for this study as it is the vehicle with the widest range of driveline technologies.

To get a complete set of cost for the trucks and passenger cars the following principles are applied.

- Methanol driven cars are estimated to have the same cost as E85 vehicles. During the E85 years in Sweden passenger car OEM Saab often mentioned that their E85 vehicles were in principle ready to accept methanol as well. Gasket material and some metallic components might need attention, but it is judged to have minor impact on cost. Previous statements from OEM´s and price aspects of ethanol vehicles support this judgement.

- Methanol for trucks is estimated to have the same cost as diesel used with ignition improver in a similar way as ED95. However, there is some uncertainty here since methanol can be used in many engine concepts in a similar way as methane. Methanol is a traditional Otto-engine fuel for spark ignited engines however a compression ignited methanol engine is also possible using a small amount of diesel fuel to trigger compression ignition.

- DME fueled vehicles are estimated to have the same cost as diesel driven vehicles. Tanks for DME are more expensive but the exhaust aftertreatment system is simpler. Judged to be cost neutral to diesel in the same way as Holmgren et al (2021). Similar reasoning from AB Volvo in the governmental investigation on fossil fuel independence in the Swedish transport sector, the so-called FFF-utredningen (SOU, 2013:84).

- Biogas for passenger cars is limited to one technology alternative which is spark ignited engines with compressed methane at 200 bars. This is a well-known technology that is mature in the market. Liquified methane is not relevant for passenger cars since the tank would vent during stand still.
- Ethanol as E85 has an additional cost of 5000 SEK compared to gasoline cars. This is the historic price difference and is also the difference for new E85 vehicles from Ford introduced on the Swedish market in 2021.
- Biogas for trucks is evaluated with three different technologies, spark ignited compressed gas, spark ignited liquefied gas and compression ignited liquefied gas.
- Ethanol for trucks used as ED95 in diesel engines is estimated to have the same cost as a diesel truck.

Trucks (40 ton EU Long haul truck) excluding VAT. Cost for long haul trucks is for the tractor. The trailer and any other auxillary equipment are not included in the base case. It is important to note that auxillary equipment sometimes represent a significant investment for trucks. Some examples are cranes, bulk tanks etc. To illustrate a more complete vehicle cost for trucks, the total cost for trucks when a cost for a trailer and a body is presented in the end of Table 9. The data and assumptions regarding vehicle costs for cars and trucks are summarized in Table 8 and Table 9.

Table 8: Car costs based on sales prices on the market

Car model	Fuel option	Cost [SEK, excluding VAT]
Golf TDI 115	Diesel	219 920
Golf TGI 130	Methane	222 400
Golf TSI 150 Edt	Gasoline	210 320
Assumed same as gasoline but with additional cost	E85, M85	214 320
Assumed same as diesel	DME	Assumed same as diesel

Table 9: Truck costs Tractors

Truck model (only tractor)	Fuel	Cost [SEK, excluding VAT]
Diesel engine	Diesel, DME	1 126 600
Spark ignition compressed	Methane	1 141 600
Spark ignition liquefied	Methane	1 321 600
Compression ignition liquefied	Methane	1 546 600
Compression ignition	ED95	1 126 600
Compression ignition	MD95	1 126 600
Additional units		
Trailer and body	Same for all models	2 466 600

4 SYNTHESIS OF COSTS

In this section the cost estimates are synthesized in a stepwise manner. First, the fuel component production costs presented in section 3.1 are converted to distributed fuel costs by using a combination of components (when relevant) and including distribution. Then, vehicle capital costs and fuel efficiency are included to give a transport cost. Cars and trucks are treated separately throughout the discussion.

The total fuel related cost – including fuel production cost, fuel distribution and infrastructure cost (for CBG including compression cost), AdBlue cost and for LBG liquefaction cost – is presented in Figure 7 and Figure 8 for trucks and cars, respectively. The fuel production cost (represented by the average value of the cost range presented in Section 3.1.8 but including uncertainty intervals based in the full range) dominates the total fuel related cost for both cars and trucks for all biofuel production pathways. In most cases, the uncertainty intervals for fuel production costs are larger than the costs for distribution etc. This does not make inclusion of these costs and comparison pointless but rather pinpoints the importance of optimizing fuel production and production costs. In essence, it tells us that cost-efficient fuel production is more important than differences in infrastructure and distribution costs. The fuel distribution costs are, still, somewhat higher for methanol, DME, ED95, E85 and CBG (for which the compression cost is included) compared to other fuels. These fuels and LBG are also estimated to have a somewhat higher infrastructure cost.

Overall, the fuels produced based on hydropyrolysis and lignin separation and upgrading have the lowest total fuel related costs, both for cars and trucks. It should, however, be noted that these have the lowest fuel production technology maturity which means a large uncertainty and potentially a downward bias in estimated production costs. The more mature alternatives for gasification-based production of methane, methanol and DME have only slightly higher costs that are not necessarily significantly different given the relatively large production cost uncertainties.

Lignocellulosic ethanol-based fuels (ED95 and E85) and have high production costs. As noted above, this is partly due to the low efficiency which may be changed by on-going technology development that enables valorization of the lignin by-product. The drop-in alternatives FT diesel, FT gasoline and pyrolysis oil-based gasoline and diesel have higher overall fuel-related costs, despite lower distribution and infrastructure costs.

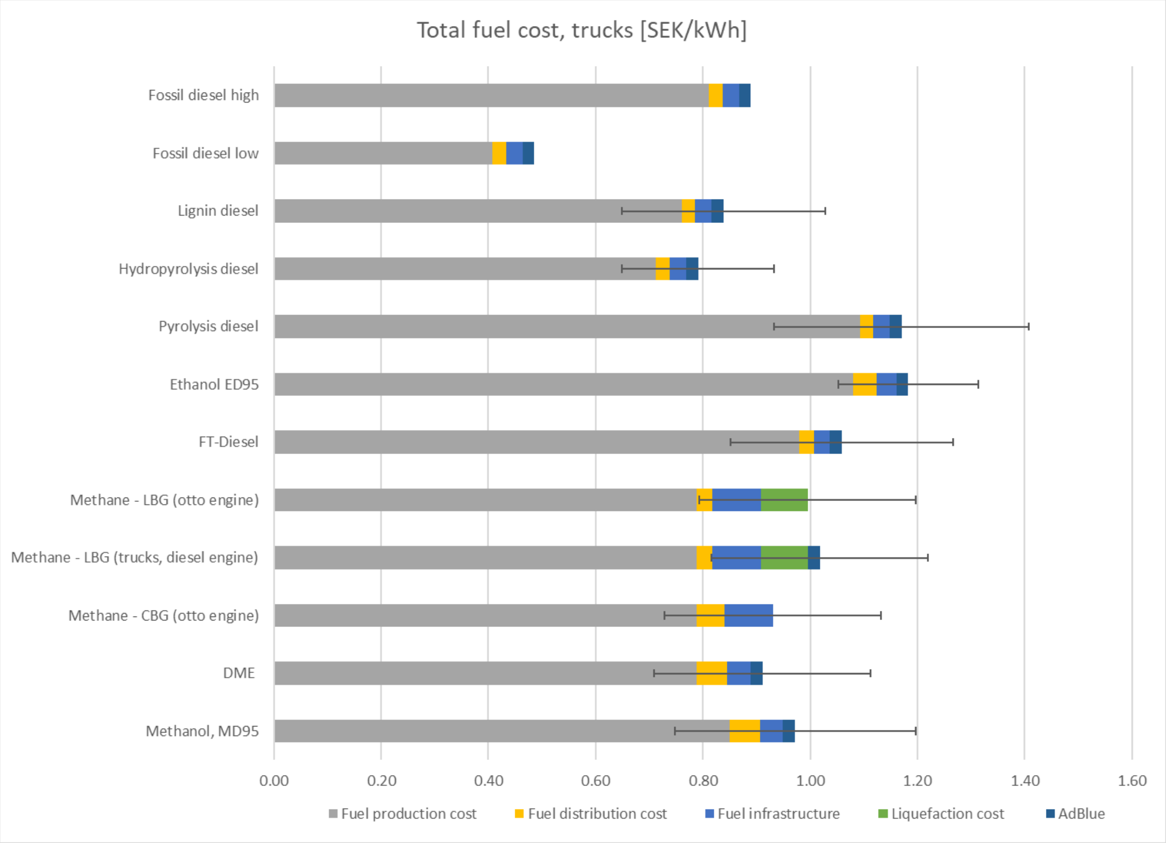

Figure 7: Total fuel related cost for trucks including fuel production cost, fuel distribution and infrastructure cost (for CBG including compression cost), AdBlue cost and for LBG liquefaction.

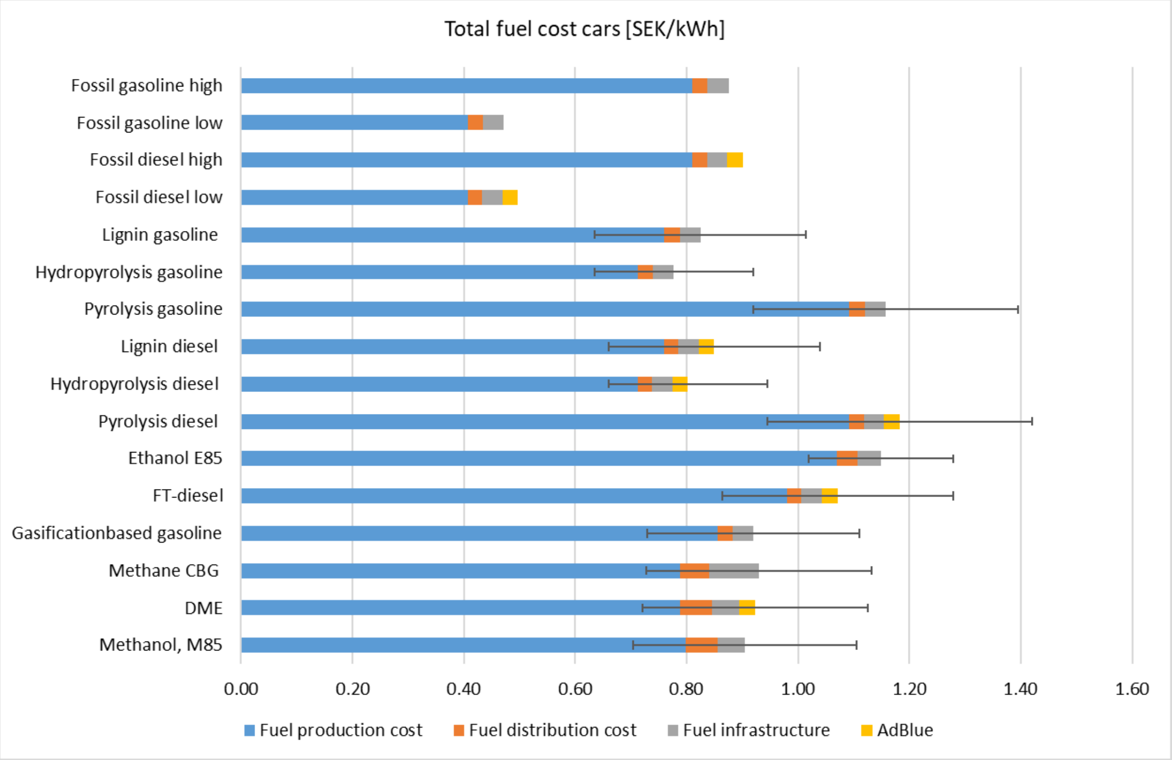

Figure 8: Total fuel related cost for cars including fuel production cost, fuel distribution and infrastructure cost (for CBG including compression cost) and AdBlue cost.

The total cost per studied forest biomass-based fuel pathway (including total fuel related cost and vehicle cost) for trucks (expressed in SEK/km and SEK/ton km) are summarized in Figure 9 and Figure 10, respectively. For LBG the liquefaction cost is in these figures included in the fuel distribution cost. Figure 11 and Figure 12 also show the total cost for the studied fuel pathways but in these figures the costs for a trailer and a cabinet have been added to the vehicle cost. These figures are included for comparison and for the reader to understand that the vehicle related costs could be higher. However, there are still other important costs that are not included such as costs for the driver and for insurances, service etc. As seen in the figures the cost of the trailer and cabinet are slightly larger than the cost of the rest of the vehicle, thus affecting the total cost significantly.

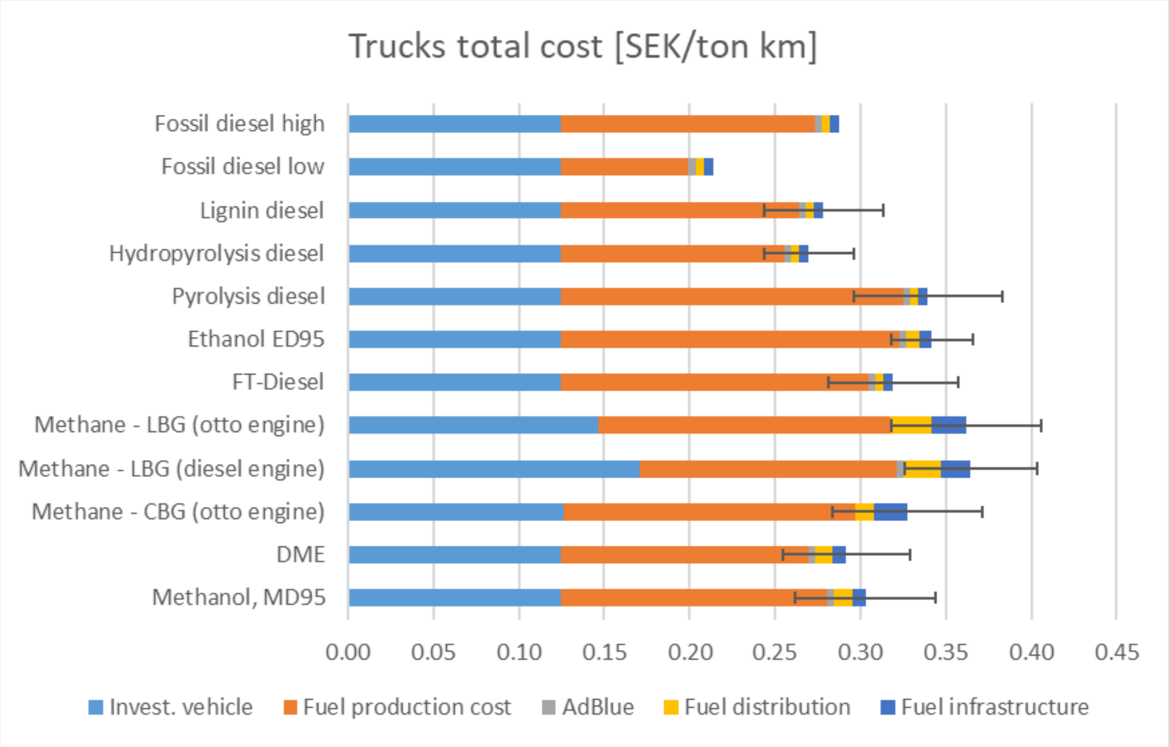

Figure 9: The total cost per studied forest biomass-based fuel pathway (including total fuel related cost and vehicle cost) for trucks (expressed in SEK/ton km). For LBG the liquefaction cost is included in the fuel distribution cost.

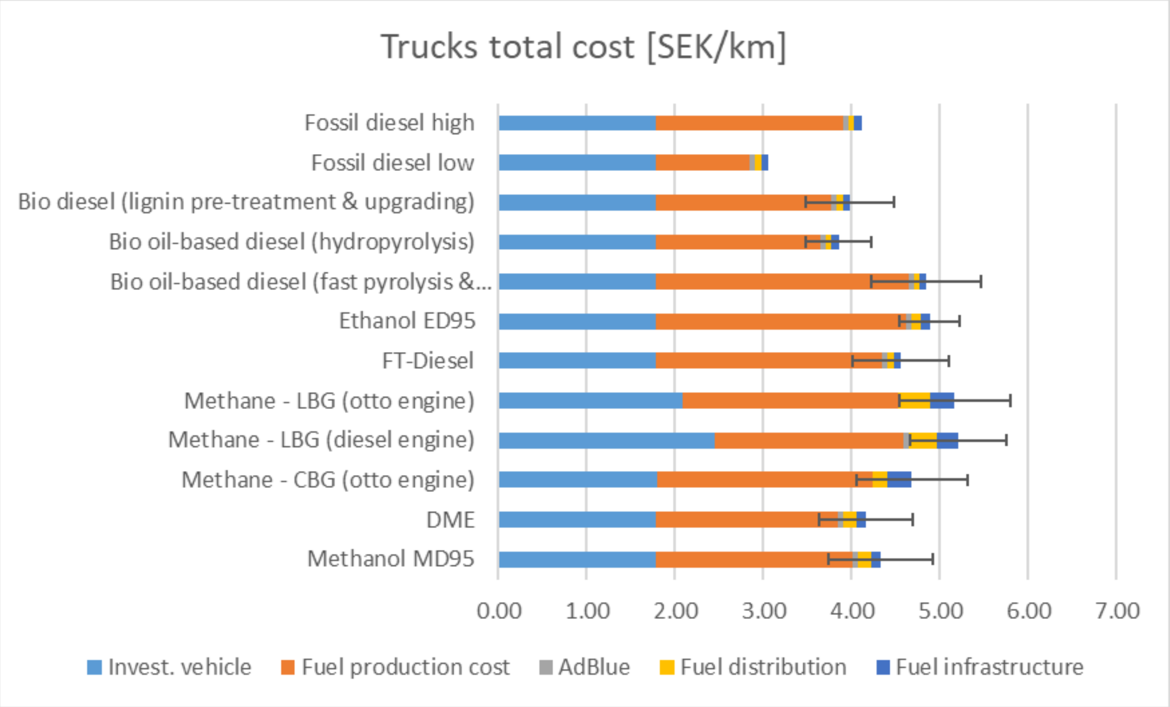

Figure 10: The total cost per studied forest biomass-based fuel pathway (including total fuel related cost and vehicle cost) for trucks (expressed in SEK/km). For LBG the liquefaction cost is included in the fuel distribution cost.

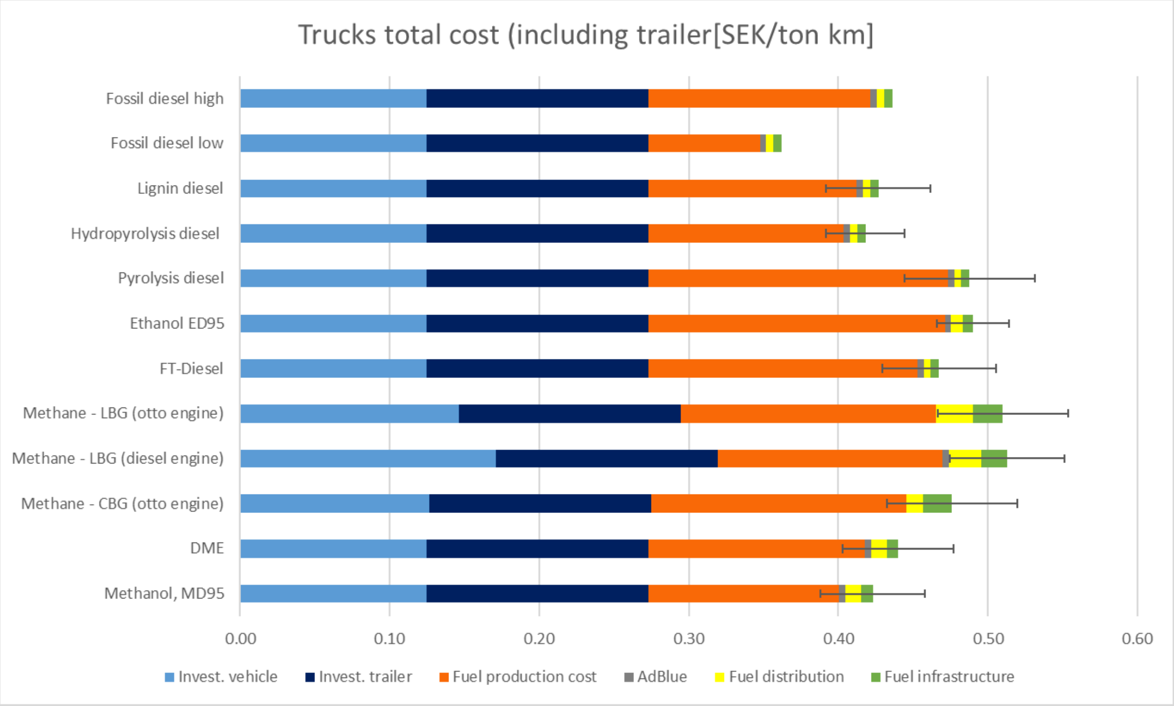

Figure 11: The total cost for trucks (expressed in SEK/ton km) per studied forest biomass-based fuel pathway when also the investment cost for trailer and cabinet are included.

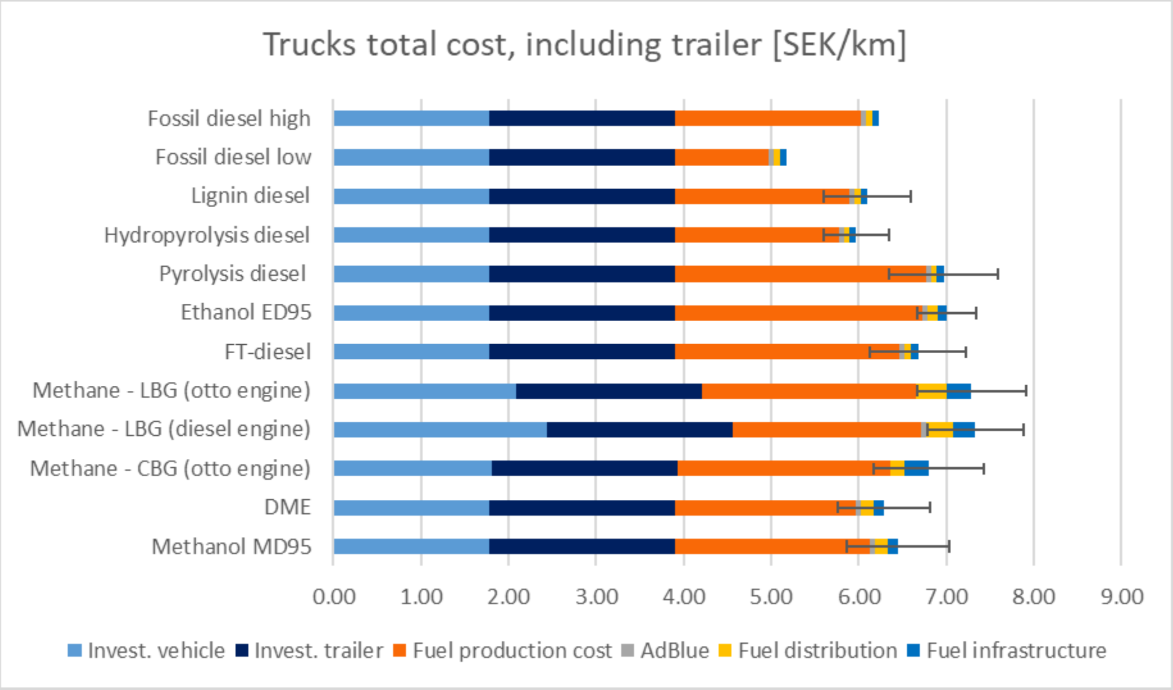

Figure 12: The total cost for trucks (expressed in SEK/km) per studied forest biomass-based fuel pathway when also the investment cost for trailer and cabinet are included.

The total cost per studied forest biomass-based fuel pathway for cars (expressed in SEK/km) are summarized in Figure 13.

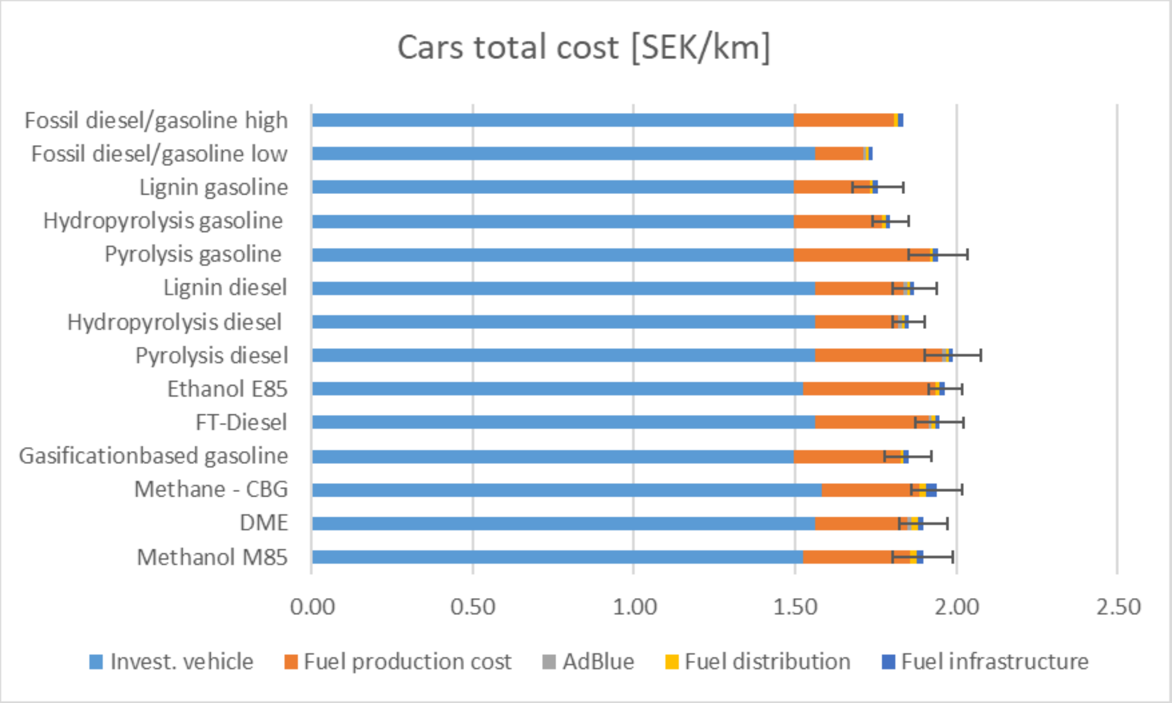

Figure 13: The total cost per studied forest biomass-based fuel pathway (including total fuel related cost and vehicle cost) for cars (expressed in SEK/km).

4.1.1 Comparison with electrofuels

In this section we compare the total cost for the forest biomass-based fuels with the corresponding cost for so-called electrofuels (produced based on captured CO_2). The total cost for the studied forest biomass-based fuel pathway and for the included electrofuels pathways (including total fuel related cost and vehicle cost) for trucks and cars, respectively are summarized in Figure 14 and Figure 16. Figure 15 shows the total cost for trucks when also the cost of trailer and cabinet is included. Note, that for the electrofuels the cost for liquefaction for LBG is included in the fuel production cost (as in the original reference) while for the biofuel pathways it is included in the distribution cost.

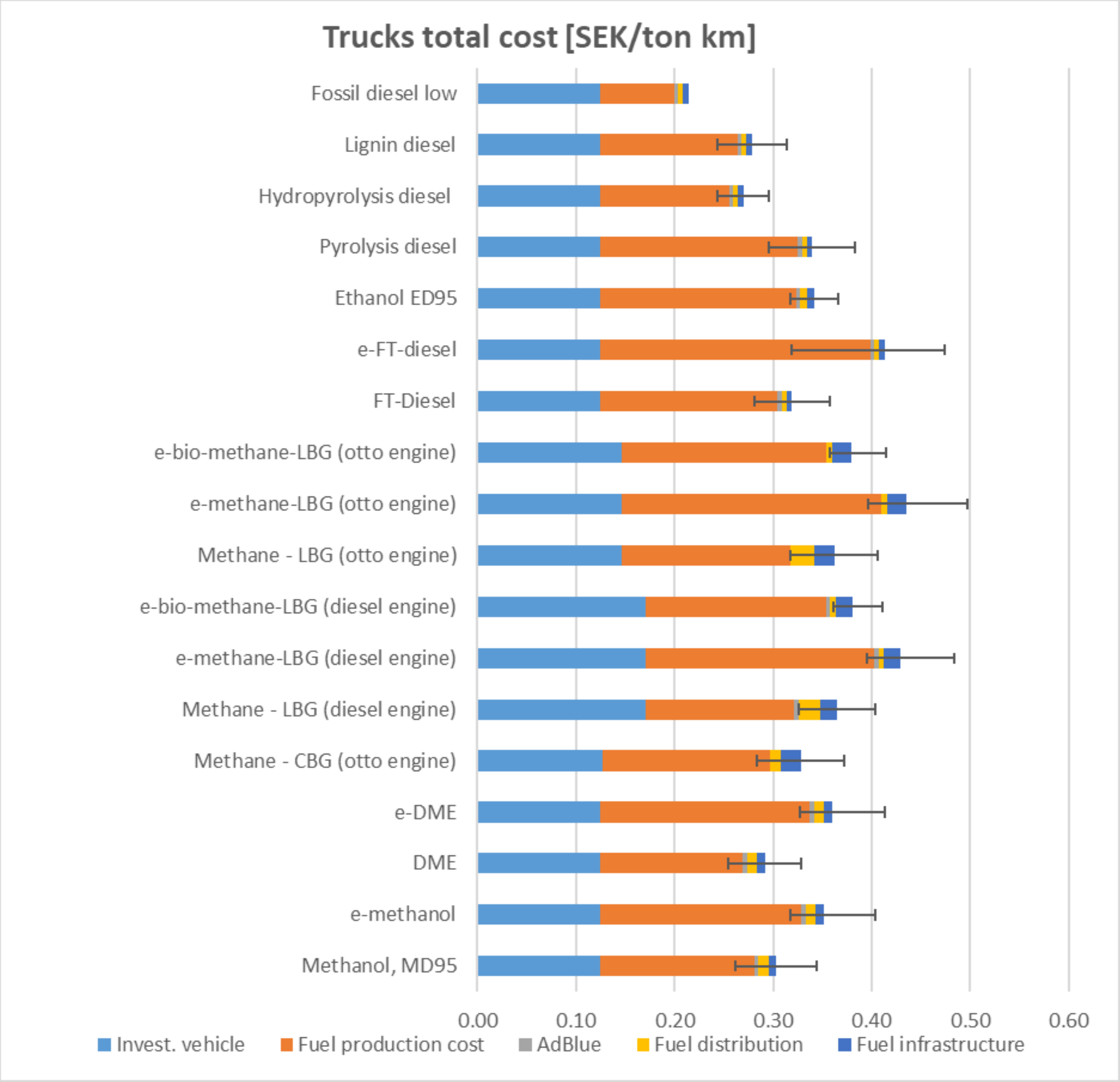

Figure 14: The total cost per studied forest biomass-based fuel pathway in comparison to the corresponding cost for the studied electrofuels pathways (including total fuel related cost and vehicle cost) for trucks.

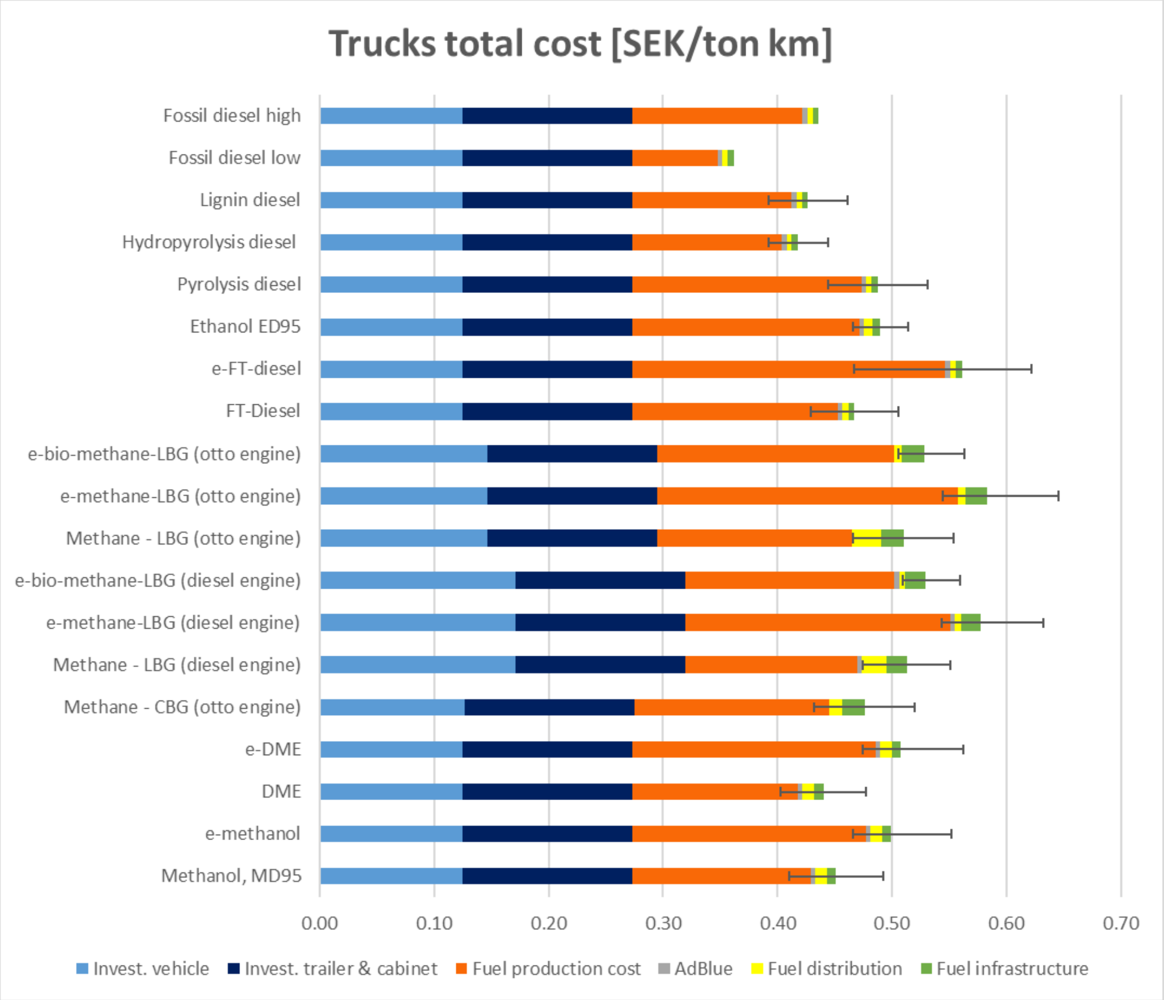

Figure 15: The total cost per studied forest biomass-based fuel pathway in comparison to the corresponding cost for the studied electrofuels pathways (including total fuel related cost and vehicle cost) for trucks, including vehicle as well as trailer and cabinet.

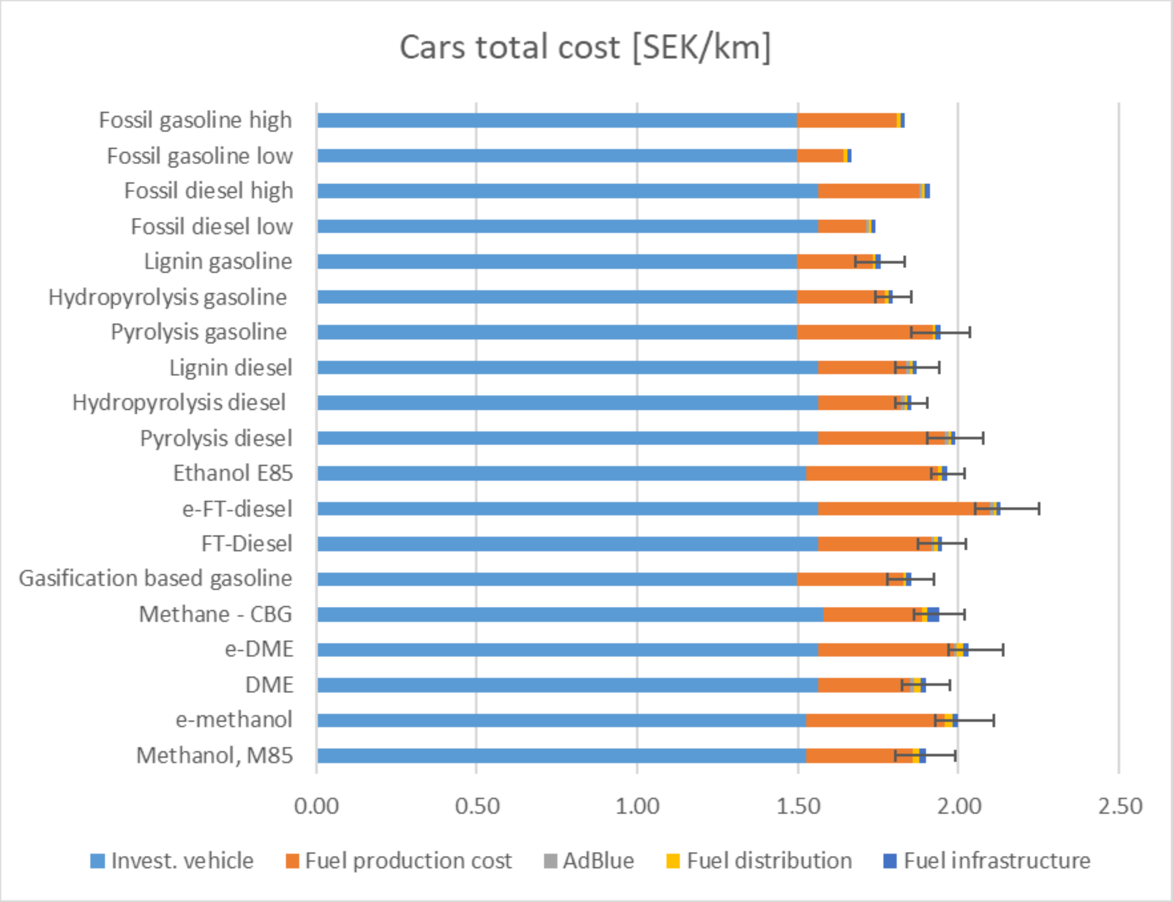

Figure 16: The total cost per studied forest biomass-based fuel pathway in comparison to the corresponding cost for the studied electrofuels pathways (including total fuel related cost and vehicle cost) for cars.

As seen in the figures all the forest biomass-based fuels have a lower fuel production cost than the corresponding electrofuel. The total cost for the studied biofuels and electrofuels in comparison also to the total cost of so-called bio-electrofuels (i.e., electrofuels produced from CO_2 from biofuel production without carbon capture cost) is presented in Figures A1 and A2 in Appendix 2. for trucks and cars respectively. The total cost of the bio-electrofuels falls between the total cost for the corresponding biofuels and electrofuels.

4.1.2 Findings from the cost synthesis

For cars the total cost is estimated to be lowest for the bio oil-based diesel based on hydropyrolysis, and the biogasoline and biodiesel based on lignin pre-treatment and upgrading production pathways (which are also the pathways having the lowest TRL), while the cost is highest for the CBG, FT-diesel, E85 and bio oil-based diesel based on fast pyrolysis and hydrotreatment upgrading (and even higher for the electrofuels if they are also included). For cars, the difference in cost for the lowest and highest pathways is 12 % when not including electrofuels and 18 % when including electrofuels.

For trucks the total cost is estimated to be lowest for the methanol, DME, FT-diesel, bio oil-based diesel (hydropyrolysis) and diesel (lignin pre-treatment and upgrading) while the cost is highest for the LBG options (and even higher for the electrofuels if they are included). For trucks, the difference in cost for the lowest and highest pathways is 18 % when not including electrofuels and 31 % when including electrofuels.

For cars, the vehicle cost clearly dominates the total cost (corresponding to 77–85 % for the studied biofuels and 73–85% for the included electrofuels) while the distribution and infrastructure cost only represent a minor part of the total cost. For both trucks and cars, the fuel distribution and infrastructure related cost only corresponds to a minor share of the total cost estimated in this study for all the studied fuel options (about 1–3 % for cars and 2–9 % or 3–12 % for trucks, with or without the trailer and cabinet cost).

For trucks the fuel distribution and infrastructure related cost for the fuel and vehicle combinations that include methane[15] corresponds to between 6 % and 9 % of the total cost (when trailer and cabinet is included). For DME, methanol and ED95 the corresponding share is 3–4% and for the drop-in fuels the share is 2 %. Also, for cars, the distribution and infrastructure cost represent a somewhat higher share of the total cost for methane, DME and methanol than for E85 and all the drop-in fuels.

For trucks using the studied biofuels the included vehicle costs represent 25–33 % of the total cost (56–65 % if also the cost for trailers and cabinets are included). The corresponding share for electrofuels the range is somewhat lower.

For trucks, the biofuel production cost represents a larger share of the total cost than for cars (27–41 % for trucks including trailer and cabined compared to 15-22% for cars). For the electrofuels cases the fuel production cost corresponds to a somewhat higher share.

As indicated earlier there are also other costs linked to vehicles (e.g., vehicle maintenance costs) that are not considered in this study (see Section 2.4) but that would affect the total cost and the percentages given here if included.

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[15] This is partially explained by the fact that liquefaction of methane is included in the distribution cost for LBG.

5 RESOURCE EFFICIENCY AND CLIMATE MITIGATION

5.1 RESOURCE EFFICIENCY

Resource efficiency is an important component for the cost calculations as described in section 3. This section presents the total system efficiency for the studied fuel and vehicle combinations building on the previous assessment. In general, there are larger differences for trucks compared to passenger cars as Otto engines for cars is expected to be close to Diesel engines in the driving conditions for cars. Trucks which operate with otto engines have lower energy efficiency compared to diesel engines.

The energy consumption for long haul trucks in 2025 is summarized in Table 10 and the energy consumption for cars in Table 11.

Table 10: Expected energy consumption for long haul trucks in 2025, based on Prussi et al. (2020a).

Trucks: Fuel	**l/100km kg/100 km**	**MJ/ton km**
MD95	62,4	0.66
DME	49.5	0.66
Methane CBG, Otto	24.7 (kg)	0.78
Methane, LBG, Diesel	18.4 (kg)	0.68
Methane LBG, Otto	24.2 (kg)	0.78
FT-Diesel	27.5	0.66
ED95	45.3	0.66
Bio oil-based diesel Fast pyrolysis and hydrotreatment upgrading	27.5	0.66
Bio oil-based diesel Hydropyrolysis	27.5	0.66
Diesel, lignin pre-treatment and upgrading	27.5	0.66

Table 11. Expected energy consumption for passenger cars in 2025, based on Prussi et al. (2020a).

Passenger cars: Fuel	l/100km kg/100 km	MJ/100 km
Methanol (as M85)	8.2	140.3
DME	6.9	130.6
Methane CBG, Otto	2.9 (kg)	138.5
FT-Diesel	3.8	129
Ethanol (as E85)	6.3	140.3
Bio oil-based diesel Fast pyrolysis and hydrotreatment upgrading	3.8	129
Bio oil-based diesel Hydropyrolysis	3.8	129
Diesel, lignin pre-treatment and upgrading	3.8	129
Bio oil-based gasoline Fast pyrolysis and hydrotreatment upgrading	4.3	139.2
Bio oil-based gasoline Hydropyrolysis	4.3	139.2
Gasoline, lignin pre-treatment and upgrading	4.3	139.2
Gasification-based gasoline (represented by methanol to gasoline – MTG)	4.3	139.2

Energy efficiency of vehicles was estimated using a reference point obtained through discussion with Staffan Lundgren at AB Volvo and Magnus Fröberg from Scania with specific values for methane fueled otto engines as well as engine efficiency charts in the JEC study (Prussi et al., 2020a). Today a heavy-duty diesel engine has an energy efficiency of around 47% in the best case. Some energy is lost while transferring the power to the wheels of the engine ending up with around 4 percentage units lost. This figure is used comparing the different drivelines and the energy efficiency is then calculated with the differences found in the JEC study (Prussi et al., 2020a), see Table 12. This is a simplification since energy efficiency will be affected depending on the specific situation. For example, transient conditions for trucks gives disadvantages for otto engines fueled with methane. The total resource efficiency for the studied forest biomass-based fuel and vehicle combinations represented by the biomass to wheel efficiency are presented in Table 12.

Table 12: Total resource efficiency represented by the biomass to wheel efficiency for the studied forest biomass-based fuel and vehicle combinations.

Fuel	Conversion efficiency		Vehicle efficiency	Total efficiency	
	low	high		low	high
Methanol, trucks	60%	65%	44%	26%	29%
Methanol, cars	60%	65%	41%	24%	26%
DME (trucks & cars)	60%	65%	44%	26%	29%
Methane - CBG (trucks, otto engine)	60%	65%	36%	22%	24%
Methane - LBG (trucks, diesel engine)	60%	65%	42%	25%	28%
Methane - LBG (trucks, otto engine)	60%	65%	36%	22%	24%
Methane - CBG (cars)	60%	65%	41%	25%	27%
Gasification-based gasoline (cars)	54%	63%	41%	22%	26%
FT-Diesel (trucks & cars)	40%	55%	44%	18%	24%
Ethanol from cellulose (trucks ED95)	35%	40%	44%	15%	18%
Ethanol from cellulose (cars E85)	35%	40%	41%	14%	16%
Bio oil-based diesel (fast pyrolysis and hydrotreatment upgrading) (trucks & cars)	60%	70%	44%	26%	31%
Bio oil-based gasoline (fast pyrolysis and hydrotreatment upgrading) (cars)	60%	70%	41%	25%	29%
Bio oil-based diesel (hydropyrolysis) (trucks & cars)	65%	65%	44%	29%	29%
Bio oil-based gasoline (hydropyrolysis) (cars)	65%	65%	41%	27%	27%
Diesel (lignin pre-treatment and upgrading) (trucks & cars)	82%	82%	44%	36%	36%
Gasoline (lignin pre-treatment and upgrading) (cars)	82%	82%	41%	34%	34%

5.2 CLIMATE CHANGE MITIGATION

The GHG emissions associated with the production, distribution and dispensing of the studied biofuels (well-to-wheel) are presented in Table 13 and are mainly based on Prussi et al.(2020b).

In the appendices to Prussi et al. (2020b), the CO_2 combustion emissions of the fuels are considered when comparing the fossil fuels that they replace, which is the case also in the rightmost column of Table 13 of this report.

Some adjustments have been made to the GHG estimates presented by Prussi et al. (2020b). In Table 13 these adjustments are indicated, and the general adjustments are explained here:

- Prussi et al. (2020b) use an emission factor for electricity corresponding to European average electricity mix in 2016 being 106.3 g CO_2eq/MJ for medium voltage and 110.1 g CO_2eq/MJ for low voltage. This study has a Swedish perspective, and the emission factor of Swedish electricity mix of 13.0 g CO_2eq/MJ has been used in fuel chains where electricity has a significant impact on the overall emissions. The used emission factor for the Swedish electricity mix (considering imports and exports)[16] is to be used by the Swedish Energy Agency in the reporting according to e.g., the EU Directive 2015/652.

- In several of the production pathways, hydrogen is used, and in Prussi et al. (2020b) hydrogen is assumed to be produced by conventional steam reforming of natural gas. In this report an emission factor for hydrogen production based on electrolysis using a Swedish electricity mix is also used.
- The energy balances and biomass conversion efficiencies of the gasification-based fuel production processes differs for the different fuels (DME, methanol, SNG and FT-diesel production) in Prussi et al. (2020b). Efficiency for DME/methanol by Prussi et al. (2020b) 51.1 % (net zero electricity balance) and 45.1 % for FT-diesel (however, with a net electricity surplus from the process, accounted for by a “wood-credit”[17]). The efficiency for the SNG process is estimated to 66.4 % and requires a net input of electricity and LPG according to Prussi et al. (2020b). For SNG, the GHG emissions from production were adjusted based on the energy balances and inputs required for the process according to Heyne and Harvey (2013). There is no LPG utilization and a small net electricity output from the process according to Heyne and Harvey (2013) For methanol/DME the energy balance is here based on the process performance of the proven gasification processes and synthesis according to Hannula and Kurkela (2013), which includes a biomass to methanol conversion of 60.6 %. Except for the adjusted energy balances of the gasification processes, the rest of the production chains use the estimates given in Prussi et al. (2020b).

For ethanol, the estimated emission factor is based on Prussi et al. (2020b), and the process has a net surplus of electricity but, requires process chemicals (for the SSCF process) that have a significant impact on the process GHG emissions.

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[16] The methodology for the calculation is presented in Moro and Lonza (2018).

[17] Prussi et al (2020b) credits excess electricity by wood assuming electricity production in a combined heat and power (CHP) plant.

Table 13 Assessed GHG emissions for fuel production, distribution and dispensing, and estimates of GHG reduction compared to fossil fuels (including CO_2 emissions from combustion). Prussi et al. (2020b) is the main source, adjustments and other sources are indicated.

Fuel	GHG emissions of fuel production	GHG emissions of fuel distribution and dispensing	GHG mitigation[a]
	g $CO_{2eq.}$/MJ	g $CO_{2eq.}$/MJ	[%]
Methanol/DME (solid biomass gasification)[b]	8.9 ± 1.5	1.8 (Methanol) 1.7 (DME)	87–90
MD95[c]	17.1	1.8	78-81
Methane (CBG, LBG) (compression & liquefaction are included in distribution and dispensing)[d]	7.4 ±0.6	CBG: 0.3 (Swe el.), 2.4 (EU el.) LBG: 0.8 (Swe el.), 6.7 (EU el.)	CBG: 89–92 LBG: 84–92
Gasification-based gasoline (MTG)[e]	8.35 ± 1.5	1.1	88–91
FT-Diesel (gasification based)	10.4 ± 2.2	1.0	85–90
Ethanol from (forest-based) cellulose	21.4± 0.3	1.4	75–75
ED95 [f]	31.8	1.4	65
Bio oil-based diesel and gasoline (fast pyrolysis and hydrotreatment upgrading)[g]	15.5 ± 6.0	1.0 (diesel) 1.1 (gasoline)	76–89
Bio oil-based diesel and gasoline (hydropyrolysis/HTL)[h]	17.6± 8.5	1.0 (diesel) 1.1 (gasoline)	71–89
Diesel and gasoline (lignin pre-treatment and upgrading)[i]	23.5 ± 11.5	1.0 (diesel) 1.1 (gasoline)	62–86
Electrofuels (Methanol/ DME/ CBG, LBG)[j]	13.0 ±13.0	1.8 (methanol) 1.7 (DME) 0.3 -2.4 (CBG) 0.8- 6.7 (LBG)	64–98

[a] Compared to an average of the WTW GHG emissions for fossil diesel and gasoline based on Prussi et al. (2020b) (91 g CO_{2eq}/MJ). This comparison includes WTW emissions.

[b] The values for the gasification processes were adjusted based on the energy balances for gasification methanol production given by Hannula and Kurkela (2013).

[c] According to Larsson and Persson (2020) the fuel additives in MD95 is the same as in ED95, and. MD95 is assumed to be 94 % methanol and 6 % function-enhancing additives by energy content.

[d] The fuel production values (energy balance and inputs to gasification process) have been adjusted from the ones given by Prussi et al. (2020b). In this study the energy balance of gasification-based methane is based on Heyne and Harvey (2013) which differs by not requiring LPG, having a net power surplus, and using CLR and scrubbing with water instead of scrubbing with RME. The distribution and dispensing of the fuels were adjusted by using the emission factor for Swedish electricity mix for compression and liquefaction of the gas.

[e] The GHG emission estimates for the MTG production pathway is based on the process performance given in Hannula and Kurkela (2013) and on the values for methanol given in this table. The MTG production pathway is not included in Prussi et al. (2020b).

[f] The mixture of the fuel additives is based on Prussi et al (2020b); station a composition (on energy basis) of 90.3 % ethanol, 4.6 % PEG, 3 % MTBE, 0.6 % i-butanol and 1.6 % lubricants. For the calculations in this study, it was assumed that the constituents of the ignition improver are fossil based.

[g] This is based on the process performance used in Prussi et al. (2020b) but includes both hydrogen production by steam reforming and by electrolysis (with and Swedish electricity mix).

[h] The value is based on Prussi et al. (2020b) but the range has been extended by calculating values using a Swedish electricity mix for hydrogen production and other electricity demand.

[i] Entirely based on Furusjö et al. (2018a), these pathways are not included in Prussi et al. (2020b). The uncertainty range is mainly due to assumptions regarding H_2 production (steam reforming or electrolysis using Swedish electricity mix). Note that these calculations do not credit oil replacement in the refinery.

[j] Based on electricity demands as estimated by Prussi et al. (2020b) but using an upper value for the emission factor for the electricity of 13 g CO_{2eq}/MJ (as for the Swedish electricity mix in 2016) and the lower value to be zero (as in Prussi et al. (2020b). The electrofuels are only included for comparison and **are** not included in the further comparisons of the biobased fuels. Note that it assumes a biobased source of the flue-gas CO_2.

The GHG emissions for the fuel and vehicle combinations included in this study for trucks and cars (per kilometer or ton kilometer) are presented in Figure 17 and Figure 18, respectively. This assessment is based on the GHG emissions factors in Table 13 and the fuel consumption of trucks based on Prussi et al. (2020a), see Table 10 and for cars according to Table 11. It was assumed that the fuel consumption is the same (in MJ/tonkm) for MD95 and pure methanol for trucks. The comparison includes emissions from a WTW-perspective.

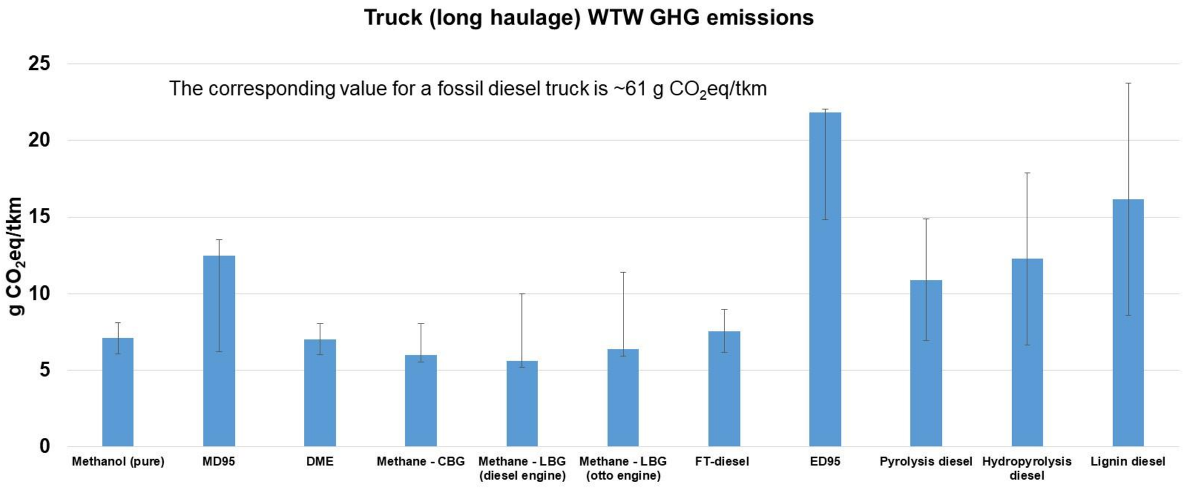

Figure 17 GHG emissions for a long haulage truck (Group 5) using the different fuels considered in this study based on VECTO.

The uncertainty ranges in Figure 17 include for methanol/DME, CBG, LBG and gasification-based FT-diesel different transport distance for the raw material (a short distance transport of < 500 km and a long-distance transport also including shipping). For MD95 the uncertainty range also includes the fuel additives, which in our base assumption is assumed to be fossil based. For CBG and LBG there is also an interval given for the transport and dispensing of the fuel, which is the result of using different emission factors for the electricity used in the compression/liquefaction.

For ED95, the uncertainty range includes the greenhouse gas intensity for the fuel additives (with the higher range assumed to be equal to fossil-based components as estimated by Prussi et al (2020), 10.3 g CO_{2eq}/MJ_{fuel}. Also for MD95 the uncertainty range includes the fuel additives.

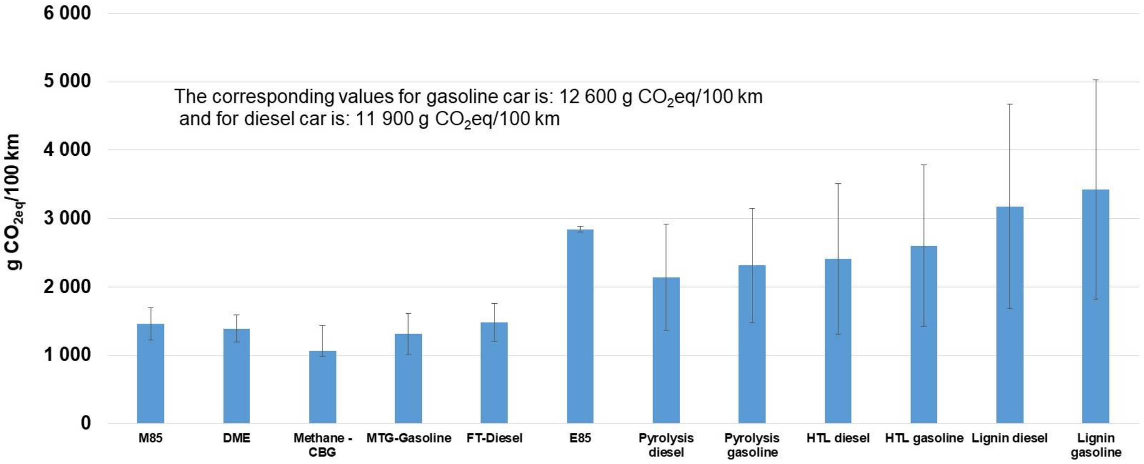

Figure 18 GHG emissions from WTW-perspective for cars using different renewable fuels based on WLTP.

The uncertainty range in Figure 18 are caused by the same factors as those described for Figure 17.

The fuels M85 and E85 consists of 85 % methanol/ethanol and 15 % renewable gasoline by volume, respectively. It was assumed that the fuel consumption for M85 is the same as for pure methanol and for E85 the same as for pure ethanol. The estimated fuel consumptions for the pure alcohols are given in Table 11. Volumetric consumption is higher for alcohols due to lower energy content.

6 DISCUSSION AND OVERALL CONCLUSIONS

6.1 OVERALL COMPARISON AND CONCLUSIONS

An overall summary of the comparison of the selected forest biomass-based fuel pathways for cars and trucks respectively, is presented in Table 14 and Table 15. The assessment of selected electrofuels is also included to broaden the comparison. Besides total cost (including fuel production, distribution and infrastructure and vehicle costs), GHG performance, and total efficiency (including biomass to fuel conversion efficiency and vehicle efficiency), technology maturity for the fuel production pathways is included (based on Table 4 and Section 3.1.8).

The assessments of the included options for use in cars (Table 14) and trucks (Table 15) are shown on a relative scale (--, -, +, ++) i.e., generally using the lowest and highest performance in each category as the highest and lowest end of the scale, and relating all other options to these (strengthening the difference between the studied options). In other words, the grade "- -" on e.g. total efficiency does not necessarily mean an inefficient option, it just means that it is the least efficient option among the compared options. In the same way the grade on total cost "+ +" does not necessarily mean a low-cost option but it is the lowest cost among the compared options. However, for GHG performance the scale is made differently. The scale (+, ++) is used and the assessment is made against the required GHG reduction level in the updated Renewable Energy Directive (REDII) at, at least 65 % for biofuels produced in plants starting operation from 2021. The reason for using this scale in terms of GHG performance is that all studied biofuels (the biofuels share) meets/is expected to meet the required GHG reduction level in REDII, i.e., current policy level, and it might then mislead the reader if minus signs were used to indicate their performance.

Keep in mind that in terms of costs, the estimate in this study is assumed to represent mature costs i.e., the case when these technologies have reached a commercial position on the market (learning effects and potential cost reductions for all options and in particular those with low TRL thus being considered) and is not given for a specific year. The estimates are relevant for the future Swedish context.

Table 14: Overall summary of the comparison of the selected forest biomass-based fuel pathways for cars. The assessment is made on a relative scale (--, -, +, ++) for the included options, except for GHG performance, which is assessed against sustainability criteria in the updated Renewable Energy Directive (using + and ++ if reaching the GHG reduction level at, at least 65%). Technology maturity refers to the fuel production and does not consider vehicle development.

CARS	**Total cost**	**GHG performance**	**Total efficiency**	**Technology maturity (fuel)**
Single molecule fuels				
Methanol	+	++	+	+
DME	+	++	+	+
Methane – CBG	+	++	+	+
Ethanol from cellulose (E85)	-	+	--	++
Drop-in fuels				
Gasification-based gasoline (MTG)	+	++	-	+
FT-Diesel	-	++	-	+
Bio oil-based diesel (fast pyrolysis and hydrotreatment upgrading)	-	+/++[a]	+	-
Bio oil-based gasoline (fast pyrolysis and hydrotreatment upgrading)	+	+/++[a]	+	-
Bio oil-based diesel (hydropyrolysis)	+	+/++	+	-
Bio oil-based gasoline (hydropyrolysis)	++	+/++	+	-
Diesel (lignin pre-treatment and upgrading)	+	+/++[a]	++	-
Gasoline (lignin pre-treatment and upgrading)	++	+/++[a]	++	-
Electrofuels				
e-methanol (single molecule fuel)	-	+/++[b]		++
e-DME (single molecule fuel)	--	+/++[b]		++
e-FT-diesel (drop-in fuel)	--	+/++[b]		+

[a] For the diesel and gasoline pathways based on lignin pre-treatment and upgrading, and pyrolysis and upgrading the GHG performance is relatively uncertain due the range of process and integration possibilities which will affect the actual GHG performance. For example, the origin of the hydrogen used and to what extent the gases produced is assumed to be used internally and replace other fuels in the refinery (the latter leading to an improved GHG performance if assumed to take place to a large extent). To capture this uncertainty the GHG performance is represented by a range for these options illustrating the potential outcome in terms of GHG performance when different assumptions are made for the production processes (see also Section 5.2). For comparison, with the assumptions made in Furusjö et al (2018 a,b) (i.e., assuming natural gas based hydrogen) it is indicated that these biofuel production pathways may not reach the GHG limit in REDII which imply that the actual process configuration chosen as well as methodology for estimating GHG performance is key.

[b] Please note that in the updated Renewable Energy Directive, REDII, there is no final guidance on how to calculate the appropriate minimum thresholds for GHG emissions savings of recycled carbon fuels (i.e., electrofuels). The Commission will adopt a delegated act on this by 31 December 2021. Therefore, the GHG emissions saving level for biofuels have been used here.

Table 15: Overall summary of the comparison of the selected forest biomass-based fuel pathways for cars. The assessment is made on a relative scale (--, -, +, ++) for the included options, except for GHG performance, which is assessed against sustainability criteria in the updated Renewable Energy Directive (using + and ++ if reaching the GHG reduction level at least 65 %). Technology maturity refers to the fuel production and does not consider vehicle development.

TRUCKS	**Total cost**	**GHG performance**	**Total efficiency**	**Technology maturity (fuel)**
Single molecule fuels				
Methanol	++	++	+	+
DME	++	++	+	+
Methane - CBG (otto engine)	+	++	-	+
Methane - LBG (diesel engine)	+	++	+	+
Methane - LBG (otto engine)	+	++	-	+
Ethanol from cellulose (ED95)	+	+	--	++
Drop-in fuels				
FT-Diesel	+	++	-	+
Bio oil-based diesel (fast pyrolysis and hydro-treatment upgrading)	+	+/++[a]	+	-
Bio oil-based diesel (hydropyrolysis)	++	+/++	+	-
Diesel (lignin pre-treatment and upgrading)	++	+/++[a]	++	-
Electrofuels				
e-methanol (single molecule fuel)	+	+/++[b]		++
e-DME (single molecule fuel)	+	+/++[b]		++
e-methane-LBG (otto engine) (single molecule fuel)	--	+/++[b]		+
e-methane-LBG (diesel engine) (single molecule fuel)	--	+/++[b]		+
e-FT-diesel (drop-in fuel)	-	+/++[b]		+

[a] For the diesel and gasoline pathways based on lignin pre-treatment and upgrading, and pyrolysis and upgrading the GHG performance the GHG performance is relatively uncertain due the range of process and integration possibilities which will affect the actual GHG performance. For example, the origin of the hydrogen used and to what extent the gases produced is assumed to be used internally and replace other fuels in the refinery (the latter leading to an improved GHG performance if assumed to take place to a large extent). To capture this uncertainty the GHG performance is represented by a range for these options illustrating the potential outcome in terms of GHG performance when different assumptions are made for the production processes (see also Section 5.2). For comparison, with the assumptions made in Furusjö et al (2018 a,b) (i.e., assuming natural gas based hydrogen) it is indicated that these biofuel production pathway may not reach the GHG limit in REDII.

[b] Please note that in the updated Renewable Energy Directive, REDII, there is no final guidance on how to calculate the appropriate minimum thresholds for GHG emissions savings of recycled carbon fuels (i.e., electrofuels). The Commission will adopt a delegated act on this by 31 December 2021. Therefore, the GHG emissions saving level for biofuels have been used here.

In general, the GHG reduction potential of the studied pathways is high with some uncertainties for low TRL technologies (Table 14-15). There are larger variations when it comes to cost and resource efficiency (Table 14-15).

For cars, drop-in fuels in the form of gasoline based on lignin and hydropyrolysis have the lowest cost. Lower vehicle costs are a contributing reason that gasoline alternatives rank highest, compared to diesel options that have similar fuel costs. In terms of total resource efficiency (i.e., resource efficiency represented by the biomass to wheel efficiency) drop-in fuels in the form of gasoline and diesel based on lignin pre-treatment and upgrading is indicated to have the potential to perform best but is followed by both single molecule fuels (such as methanol, DME and methane in the form of CBG for cars and LBG in diesel engines for trucks) and other drop-in fuels (the other hydrotreatment-based gasoline and diesel options). In terms of GHG emissions all fuel options have the potential to contribute to considerable reductions for both cars and trucks even if the uncertainties are larger for the hydrotreatment-based gasoline and diesel options.

In terms of total cost for trucks, both some of the single molecule fuels (methanol and DME) and some of the drop-in fuels (diesel based on lignin pre-treatment and upgrading and based on hydropyrolysis) present the lowest cost.

For cars, when considering the three main developed assessment criteria (the three perspectives) drop-in fuels in the form of gasoline based on lignin and hydropyrolysis turns out as promising options when assuming the highest GHG performance. However, the technology maturity level for fuel production is currently low for these pathways implying increased uncertainties in the cost estimates. In addition, GHG performance is uncertain for the lignin-based processes and depends on the final process set-up (see discussion below). Other interesting options for cars (closely following the top), when considering the three main developed assessment criteria, are single molecule fuels in the form of methanol, DME, methane (CBG), and drop-in fuels in the form of gasoline based on fast pyrolysis as well as diesel based on all three hydrotreatment upgrading tracks. However, the cost differences between the options are relatively small and the low technology maturity for some of the drop-in options should be kept in mind since it implies that the cost estimates can be regarded somewhat more uncertain for these options. E85 and two of the electrofuels are the only fuels with a relatively high maturity level.

For trucks, when considering the three main developed assessment criteria (the three perspectives) both single molecule fuels in the form of methanol, DME, and drop-in fuels in the form of diesel based on lignin pre-treatment and upgrading and based on hydropyrolysis turns out as promising options, followed by single molecules fuels in the form of methane in the form of LBG in diesel engines and drop-in fuels in the form of diesel based on fast pyrolysis and hydrotreatment upgrading. Also, for trucks the technology maturity level and the uncertainties in GHG performance should be kept in mind since it implies uncertainties.

In terms of GHG performance (as indicated in a footnote to the tables), for the diesel and gasoline pathways based on lignin pre-treatment and upgrading, and pyrolysis and upgrading, the GHG performance is relatively uncertain due the range of process and integration possibilities which will affect the actual GHG performance. For example, the origin of the hydrogen used and to what extent the gases produced is assumed to be used internally and replace other fuels in the refinery. In addition, the process conditions, e.g., the hydrogen demand for these low TRL technologies are very uncertain and this has a significant impact on the greenhouse gas emissions. Thus, it is difficult to assess the actual GHG performance for these pathways as it will depend on the actual process set up and system boundaries used in the GHG assessment.

Linked to conversion efficiency, and the relatively poor outcome for the lignocellulosic based ethanol pathway, the current state of technology for lignocellulosic ethanol production only allows the cellulose fraction of the wood feedstock to be converted into liquid fuel. A large fraction of the feedstock, mainly lignin, is typically used either as internal energy or exported as fuel pellets. There is technology development in progress that aims to develop technology that can also convert the lignin by-product into transportation fuel, but that is still quite immature and not included in our calculations. Resides from ethanol production can also be used for biogas production which increases the total conversion efficiency but is not considered here. For ED95 the fuel additives would also contribute significantly to the total GHG impact. At current they are assumed to be completely fossil-based, but the possibility to produce them from biomass-based sources would reduce this impact.

For cars and trucks, based on the developed assessment criteria, we find that electrofuels produced from captured CO_2 cannot be motivated from only a cost perspective (when represented by the total cost in this study) in the mid-term due to the relatively higher fuel production cost (see section 4.1.1). However, e-DME and e-methanol have a relatively high TRL and potentially good GHG performance (like the rest of the electrofuels). The policy implications linked to the prospects for electrofuels for road transport, is that they will depend on the guidelines for how to calculate the GHG performance of electrofuels (linked to REDII) in relation to the GHG performance of forest-based biofuels under development and the cost development for these options (i.e., if the cost can be decreased substantially more compared to the biofuels than assumed in this study). Producing electrofuels from biogenic excess CO_2 from biofuel production and linked to the biofuel production results in somewhat lower fuel production costs for electrofuels (see Appendix 2) but requires the continued production of biofuels and has a more limited production potential than electrofuels from other CO_2 sources in Sweden (Hansson et al., 2017). The potential for this fuel pathway has not been in focus in this project and need to be further studied in other projects.

For passenger cars the results on total cost are more even with smaller differences compared to the differences for trucks. For cars, the difference between the highest and the lowest total cost (lignin gasoline) is 16 % when including electrofuels, and 11 % if excluding electrofuels. For trucks the corresponding difference is somewhat larger; 33 % and 20% with and without electrofuels. One of the reasons for this is that the more expensive vehicles such as methane stored under liquid form is not included for cars since this fuel is not suitable for passenger cars. The cost for vehicles is also rather similar for the included technologies. Energy efficiency of passenger cars is also similar for the technologies, and it is also a smaller gap foreseen between diesel and otto engines in the future. Since passenger cars have lower use rates than trucks the investment in the vehicle is a larger part of the total cost. Thus, for trucks, the fuel production cost represents a larger share of the total cost than for cars.

There are however large variations and uncertainties in the fuel production cost estimates in this study (which is due to the technologies being under development) and the uncertainties in fuel production cost are larger than the total estimated cost for distribution and infrastructure. The different TRL levels also likely indicate that uncertainty is higher for some pathways.

To summarize and conclude, based on the comparison of drop-in fuels and single molecule fuels made in this study focusing on a mature situation and the Swedish context and considering the three main developed assessment criteria:

- There is no clear winner, and it is not possible to point out either drop-in fuels or single molecule fuels as concepts neither for cars nor trucks. For example, for trucks both single molecule fuels (in the form of methanol, DME), and drop-in fuels (in the form of diesel based on lignin pre-treatment and upgrading and based on hydropyrolysis, when assuming the highest GHG performance) turn out as the most promising options. For cars, the most promising drop-in fuels are closely followed by both single molecule fuels options and other drop-in fuels options (see next point).
- Among the drop-in fuels all the hydrotreatment based pathways seem promising for cars and trucks (but the fast pyrolysis and hydrotreatment upgrading pathways is somewhat less promising). For cars, the gasoline pathways are generally more promising than the diesel pathways. Among the single molecule fuels methanol and DME are the most promising pathways for trucks followed by LBG in diesel engines and, for cars it is methanol, DME and methane (CBG) that are the most promising singe molecule fuel pathways.
- The total costs are dominated by the vehicle costs for both analyzed vehicle types. The dominance is stronger for cars and less strong for trucks. Costs for fuel distribution and infrastructure constitute a small part of the total costs.
- It can be observed that resource efficiency for gasification-based fuels used in diesel engines is around 30 % lower for FT-Diesel compared to DME and methanol. This is significant in comparison to the estimated savings from e.g., hybridization 7.4 % for truck and -16.5 % for passenger cars according to Prussi et al. (2020a, b). Thus, choosing DME or methanol before FT-diesel will give significant gains in resource efficiency in the production step that by far outweigh gains like hybridization in the use phase. DME and methanol could therefore contribute significantly to increased resource efficiency.
- The uncertainty range of the GHG performance is greater for fuel production pathways with lower TRLs. Additives used in some applications contribute significantly to the total climate impact but, could potentially also be produced from biomass-based sources in the future (and is not considered in the GHG reduction requirements in REDII). All investigated fuels show potential for good GHG performance. However, ethanol from wood has low conversion efficiency to fuel and requires chemicals with significant climate impact. To also use residues from this process or the possibility to use a higher fraction of the feedstock e.g., lignin for biofuels would improve this pathway.

In addition to the uncertainties in cost estimates and GHG performance there are several other aspects that will influence the prerequisites for different fuel pathways. These are discussed in the next section.

6.2 DISCUSSION OF TRADE-OFFS AND UNCERTAINTIES

For production cost we rely mainly on IEA as this study includes many pathways assessed under uniform conditions. The rather wide uncertainty in terms of cost somewhat limits the possibility to draw strong conclusions however several relative differences can be observed between pathways. There are sometimes exemptions where a pathway may have lower cost due for example unique integration possibilities or access to low-cost feedstocks. Thus, the cost results are of general nature and should be seen as an indication with the system boundaries of this study.

The included fuel options which are not existing on the market today have major hurdles to reach the volumes where economy of scale sets in (and thus the cost estimated in this study). As already indicated, the current TRL (which represent one key aspect) also to some extent indicate the uncertainty in terms of cost estimates and GHG performance (where lower TRL as in the case of the hydrotreatment-based gasoline and diesel options implies more uncertain cost estimates and GHG performances) The current and future use in the rest of the world will also influence the prerequisites for different options. Alternatives with such challenges are DME and methanol (which are not used to a significant extent in the EU market), where the “chicken and egg” dilemma is also a problem as ramp up of vehicle and fuel production must be synced timewise. It is likely hard to introduce these fuels without a coordinated market pull from several use sectors in different countries at the same time. In addition, it is key to ensure that a fuel is applicable and introduced on the world market and that standards and procedures are available to introduce it on the market.

The cost for refueling infrastructure is higher for single molecule fuels however the cost is by far compensated by the lower production cost for DME, methanol and methane as compared to the production cost of the drop-in fuels. For both trucks and cars, the fuel distribution and infrastructure related cost only corresponds to a minor share of the total cost estimated in this study. However, there is always costs for introducing new technologies and hurdles to overcome before being fully established on the market, aspects not considered in our cost analysis. The current situation in terms of infrastructure and distribution is therefore a factor of importance, which might also influence the prerequisites for different options in different countries. Refueling infrastructure for DME and methanol is not existing in Europe today. Due to the need for denser refueling infrastructure for passenger cars compared to trucks it is more likely that DME or methanol would be applied in trucks before cars. This is basically the same way as diesel was introduced in a historic context, first being used in trucks with refueling infrastructure meeting this segment and then later also developed for cars. Most of the fuels included in this study has either a large refueling network (gasoline/diesel/E85) or a partly established network (CBG/LBG/ED95) while some as already indicated thus not yet have refueling network in place. In order to fuel trucks a rather low number of refueling locations are needed in comparison to cars. One example is the BioDME project where five filling stations was set up to fulfill the need for a small number of trucks operating long ranges in Sweden. As the refueling infrastructure is a small part of the overall cost it is not an economical question however it is significantly uneconomical if the infrastructure is not used and a significant challenge in a startup phase.

On the cost side for trucks the least favorable option in this comparison (focusing on a mature market for all options) turns out to be the methane fueled truck with the fuel stored in liquid form in a cryogenic tank. To provide a viable business case for these alternatives, when using forest based LBG, compared to a truck fueled with drop-in variants or methanol or DME the future LBG price (for LBG from forest biomass) must be significantly lower. However, this is assuming that the methane is produced solely from forest-based biomass. The cost for producing biogas from waste and residues is lower than the production cost for methane from forest-based biomass and the use of biogas from these resources increases the cost-competitiveness of the LBG driven trucks but is outside the scope of this study.

For GHG emissions the results are rather similar for the alternatives except for ethanol and primarily diesel and gasoline based on lignin pre-treatment and upgrading which has been indicated to have somewhat higher emissions. For both MD95 and ED95 the fossil-based fuel additives also contribute to somewhat higher GHG emissions. However, this can be mitigated either by engine technologies that tolerate pure alcohols or production of biobased fuel additives.

Having high efficiency means less cost for the users and more transport work done for the same amount of biomass. As stated in the conclusions, the resource efficiency of using biomass-based FT-diesel in diesel engines is significantly lower as compared to using DME and methanol. A relevant question from this observation is whether it is worth to sacrifice 30 % energy efficiency to keep the existing vehicle and infrastructure compared to investing in the separate infrastructure for DME and methanol. This observation is important going forward and the scale of future markets and other market mechanisms such as development of alternative technologies will impact the direction. The growth of battery-electric solutions and later possibly hydrogen for the long-haul segment might hamper the market development of alternatives to drop-in diesel and gasoline fuels as these markets is likely to shrink significantly in order to meet climate targets.

One additional important aspect not covered in the current assessment (summarized in Table 14 and 15) is the biofuel production potential. All biofuel production pathways except the diesel and gasoline from lignin pre-treatment and upgrading use forest residues and, thus, have a relatively large biomass supply potential. The lignin-based pathway is constrained by the recovery and supply of lignin from kraft pulping. Furusjö et al (2018a, b) estimate the practical potential for lignin-based biofuels in Sweden corresponds to roughly 4–8 TWh biofuels per year. However, all the assessed biofuel production pathways use forest-based biomass resources that are linked to the current use of the forest and thus are not expected to contribute to increased deforestation and associated issues.

Another constraint, that is not the main focus, is that some of the fuels have lower energy content compared to traditional fuels and therefore impacts the tank systems of vehicles since those tanks have to be significantly larger in order to cover the same range as traditional ones. This is especially relevant for compressed biogas and somewhat relevant for DME, methanol and LBG. In principle it means that some fuels are less suited for parts of the transport system. If a fuel has challenges for any of the three aspects in this report a low energy content would impact the market potential further.

Socio-technical aspects such as actors, networks, resource mobilization, legitimation, lock-in effects, incumbent actors etc. are also important for the development of different pathways but has not been considered specifically in this project as it is outside the scope of this study. However, for insights on their importance for Swedish biorefinery development the reader is referred to publications such as Hellsmark et al. 2016; Söderholm et al., 2019; Mossberg et al. 2021.

This study could not pick the winner of the drop-in fuels or the single molecule fuels for the Swedish case. Thus, there are two different strategies, either to use the existing fuel infrastructure as long as it is available with more blending (i.e., for cars until it is scrapped and replaced with electricity) or due to the uncertainties in less known technologies, at least for trucks, invest in single molecule fuels such as methanol and DME. For cars where electrification is progressing fast there seem to be no strong reason to switch to single molecule fuels. However, which strategy to choose also depends on several factors that have not been investigated in this study, but that should be assess in future work. The choice of a new tank (single molecule fuels) or drop-in fuels depends on time frame, socio-technical aspects such as current market situation and actors, the development of the included biofuels (in particular those with currently low TRL) and the development of other alternatives such as electric vehicles and fuel cell-powered vehicles (hydrogen), as well as what choices the industries make since new fuel, however superior its performance, requires a collaboration between fuel producers, fuel distributors, vehicle manufacturers, and policy makers.

A final reflection is that if society started from scratch today without all of the lock-in effects and vested interests, the fuel mix in the market would be different.

Different assessment criteria or giving different weight to the included assessment criteria would have affected the results and the findings. This could be explored in a follow-up study since it is outside the scope of the current study. The study could also be updated when new cost estimates and GHG performance estimates are available for the hydrotreatment-based gasoline and diesel pathways.

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REFERENCES

Anheden M, Ehn C, Lundberg V, Pettersson K, Fugelsang M, Hjerpe C, Håkansson Å, Gunnarsson I (2016). Value chains for production of Renewable Transportation Fuels Using Intermediates. Report No 2016:05, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

Anheden, Marie, Ida Kulander, Karin Pettersson, Johan Wallinder, Lennart Vamling, Carl Johan Hjerpe, and Åsa Håkansson. 2017. "Determination of Potential Improvements in Bio-Oil Production (ImproOil)." Report No 2017:16., f3 The Swedish Knowledge Centre for Renewable Transport Fuels.

Benjaminsson, Gunnar, Johan Benjaminsson, and Nils Bengtsson. 2013. "Decentraliserad Produktion Av Pyrolysolja För Transport till Storskaliga Kraftvärmeverk Och Förgasningsanläggningar."

Bezergianni, Stella, Athanassios Dimitriadis, Oleg Kikhtyanin, and David Kubička. 2018. "Refinery Co-Processing of Renewable Feeds." Progress in Energy and Combustion Science 68: 29–64. https://doi.org/10.1016/j.pecs.2018.04.002.

Bilsvar, 2021. Depreciation of cars. https://www.bilsvar.se/sv/ordlista/Vardeminskning/

Biltema, 2021. Cost for Adblue products, https://www.biltema.se/soksida/?query=adblue. Accessed 2021-05-05.

Biozin Holding AS. 2019. "Industrial Partners Creating the Way from Forest to Advanced Biofuel Clean Energy from Norwegian Forest." In Zerokonferansen 2019, 6-7 November, Oslo. Oslo: Zero.

Blackenfelt, P., 2021. Personal communication, Pernilla Blackenfelt, Product Manager, Adesso Bioproducts AB, 2021-03-23.

Brynolf, S., Taljegård, M., Grahn, M., Hansson, J., (2018). Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews 81 (2) p. 1887-1905.

Börjesson et al. (2016) Methane as vehicle fuel – A well-to-wheel analysis (MetDriv). Report No 2016:06, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden, available at www.f3centre.se.

Börjesson Hagberg, M., Pettersson, K. and Ahlgren, E. O., 2016. "Bioenergy futures in Sweden – Modeling integration scenarios for biofuel production." Energy 109: 1026-1039

Concawe, 2018. "Impact Analysis of Mass EV Adoption and Low Carbon Intensity Fuels Scenarios – Summary Report."

Dutta, Abhijit, Asad Sahir, Eric Tan, David Humbird, Lesley J Snowden-swan, Pimphan Meyer, Jeff Ross, et al. 2015. "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis Vapors Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Thermochemical Research Pathways with In." NREL/TP-5100-62455. Golden, CO. https://doi.org/10.2172/1215007.

Edwards et al 2011. Edwards R, Larive` J, Beziat J. Well-to-Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context - Report, Version 3c. EUR 24952 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2011. JRC65998Edwards R, Larive` J, Beziat J. Well-to-Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context - Report, Version 3c. EUR 24952 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2011. JRC65998

Ekström, M., 2021. Personal communication, Madeleine Ekström, Senior engineer Emission and fuel requirements, Scania, 2021-04-27.

Energimyndigheten 2020. Energiläget 2020 (Energy in Sweden 2020) Available at: file:///C:/Users/tomas0962/Downloads/Energil%C3%A4get%202020.pdf

European Commission 2020. JEC version 5 – 2020 https://ec.europa.eu/jrc/en/jec/publications/reports-version-5-2020

EU Directive 2015/652. Council Directive (EU) 2015/652 of 20 April 2015 laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels. http://data.europa.eu/eli/dir/2015/652/2018-12-24

Exxon Mobil. 2020. “MTG Fact Sheet.” https://www.exxonmobilchemical.com/en/catalysts-and-technology-licensing/synthetic-fuels.

Fröberg, M., 2021. Personal communication, Magnus Fröberg, Technical Manager Fuels, Scania, 2021-04-26.

Furusjö, E., Lundgren, J., 2017. ”Utvärdering av produktionskostnader för biodrivmedel med hänsyn till reduktionsplikten.” Rapport nr 2017:17, f3 Svenskt kunskapscentrum för förnybara transportbränslen. Tillgänglig på www.f3centre.se.

Furusjö, E. Jafri, Y. Wetterlund, E., Anheden, M., Kulander, I., Wallinder, J. and Håkansson, Å. 2018a. “Techno-Economics of Long and Short Term Technology Pathways for Renewable Transportation Fuel Production - Detailed Report.” f3 2018:09. Göteborg.

Furusjö, E. Jafri, Y. Wetterlund, E., Anheden, M., Kulander, I., Wallinder, J. and Håkansson, Å. 2018b. “Tekno-Ekonomisk Utvärdering Av Kortsiktiga Och Långsiktiga Teknikspår För Integrerad Biodrivmedelsproduktion - Sammanfattningsrapport.” f3 2018:08. Göteborg.

Furusjö, E. Jafri, Y. Wetterlund, E., Anheden, M., Kulander, I., Wallinder, J. and Håkansson, Å. 2020. “IH2 TECHNOLOGY.” 2020. https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-technology.html.

FVV 2018, Defossilizing the transportation sector. Research Association for Combustion Engines. Available at: www.fvv-net.de

Gogate, Makarand R. 2019. “Methanol-to-Olefins Process Technology: Current Status and Future Prospects.” Petroleum Science and Technology 37 (5): 559–65. https://doi.org/10.1080/10916466.2018.1555589.

Grahn, M. & Jannasch, A-K. (2018) Electrolysis and electro-fuels in the Swedish chemical and biofuel industry: a comparison of costs and climate benefits. Report No 2018:02, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

Gundberg, A., 2021. Personal communication, Andreas Gundberg, Business Development, Lantmännen Biorefineries, 2021-03-23.

Han, Yinglei, Mortaza Gholizadeh, Chi Cong Tran, S. Kaliaguine, Chun Zhu Li, Mariefel Olarte, and Manuel Garcia-Perez. 2019. "Hydrotreatment of Pyrolysis Bio-Oil: A Review." Fuel Processing Technology 195 (June): 106140. https://doi.org/10.1016/j.fuproc.2019.106140.

Hanarp, P., 2021. Personal communication, Per Hanarp, Technical Specialist Fuels & Engine Oil Engineering, Volvo cars, 2021-03-26.

Hannula, I., and Reiner, D.M., 2019. "Near-Term Potential of Biofuels, Electrofuels, and Battery Electric Vehicles in Decarbonizing Road Transport." Joule (2019), https://doi.org/10.1016/j.joule.2019.08.013

Hannula, I, and Kurkela, E., 2013. "Liquid Transportation Fuels via Large-Scale Fluidised-Bed Gasification of Lignocellulosic Biomass." VTT TECHNOLOGY 91. Espoo. https://www.vtt.fi/inf/pdf/technology/2013/T91.pdf

Hansson, J., Hackl, R., Taljegård, M., Brynolf, S., Grahn, M., 2017. The potential for electrofuels production in Sweden utilizing fossil and biogenic CO2 point sources. Frontiers Energy Research 5:4, doi:10.3389/fenrg.2017.00004

Hellsmark, H., Mossberg, J., Söderholm, P., Frishammar, J., 2016. Innovation system strengths and weaknesses in progressing sustainable technology: the case of Swedish biorefinery development. J. Clean. Prod. 131: 702–715. https://doi.org/10.1016/j.jclepro.2016.04.109

Heyne, S., Harvey, S., 2013. Assessment of the energy and economic performance of second generation biofuel production processes using energy market scenarios. Appl. Energy 101, 203–212. https://doi.org/10.1016/j.apenergy.2012.03.034

Holmgren et al (2015) Perspectives on investment cost estimates for gasification -based biofuel production systems. Chemical Engineering Transactions, 45, 427-32, DOI: 10.3303/CET1545072.

Holmgren, K., et. al., (2021) KNOGA. Fossilfri framdrift för tunga långväga transporter på väg – Kostnadsfördelning och risker för olika aktörer. Rapport nr FDOS 12:2021. Tillgänglig på https://f3centre.se/sv/samverkansprogram

Holmgren, K., Berntsson, T., Andersson, E., Rydberg, T., 2016. Comparison of integration options for gasification-based biofuel production systems e Economic and greenhouse gas emission implications. Energy 111, p. 272-294

Holmgren, K.M., et al., (2017) Profitability and greenhouse gas emission reduction potential of gasification-based biofuels – comparison to electricity in transport by conventional conversion of biomass. Report No 2017:18, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

IEA (2020) Advanced Biofuels – Potential for Cost Reduction. Brown, A., Waldheim, L., Landälv, I., Saddler, J., Ebadian, M., McMillan, J., Bonomi, A. & Klein, B.

IRENA, 2016. "Innovation outlook advanced liquid biofuels"

Jafri, Y. Wetterlund, E., Anheden, M., Kulander, I., Håkansson, Å., Furusjö, E. 2019a. Multi-aspect evaluation of integrated forest-based biofuel production pathways: Part 1. Product yields & energetic performance, Energy.

Jafri, Y. Wetterlund, E., Anheden, M., Kulander, I., Håkansson, Å., Furusjö, E. 2019b. Multi-aspect evaluation of integrated forest-based biofuel production pathways: Part 1. Product yields & energetic performance, Energy.

Jones, S, L Snowden-Swan, P Meyer, A Zacher, M Olarte, H Wang, and C Drennan. 2016. "Fast Pyrolysis and Hydrotreating: 2015 State of Technology R&D and Projections to 2017." Richland, Washington 99352.

Jones, Susanne, Pimphan Meyer, Lesley Snowden-Swan, Asanga Padmaperuma, Eric Tan, Abhijit Dutta, Jacob Jacobson, and Kara Cafferty. 2013. "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels - Fast Pyrolysis and Hydrotreating Bio-Oil Pathway." Vol. PNNL-23053. Richland, Washington.

Kollberg J., 2019. "Maximal CO_2-reduktion per investerad krona för personbilar: En bred systemanalys." Master thesis. Lund University, Sweden.

Korberg, A., Brynolf, S., Grahn, M., Skov I., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews 142 110861.

Lantz, M., et al., 2017. "An economic comparison of dedicated crops vs agricultural residues as feedstock for biogas of vehicle fuel quality." AIMS Energy 5(5): 838-863.

Lindfors, Christian, Ville Paasikallio, Eeva Kuoppala, Matti Reinikainen, Anja Oasmaa, and Yrjö Solantausta. 2015. "Co-Processing of Dry Bio-Oil, Catalytic Pyrolysis Oil, and Hydrotreated Bio-Oil in a Micro Activity Test Unit." Energy and Fuels 29 (6): 3707–14. https://doi.org/10.1021/acs.energyfuels.5b00339.

Löfstedt, Joakim, Christian Dahlstrand, Alexander Orebom, Gerrit Meuzelaar, Supaporn Sawadjoon, Maxim V. Galkin, Peter Agback, et al. 2016. "Green Diesel from Kraft Lignin in Three Steps." ChemSusChem 9 (12): 1392–96. https://doi.org/10.1002/cssc.201600172.

Lönnqvist, T., Grönkvist, S., Sandberg, T. (2015) How can forest-derived methane complement biogas from anaerobic digestion in the Swedish transport sector? Report No 2015:11, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

Lönnqvist, Tomas 2017. Doctoral thesis, KTH. Biogas in Swedish transport – a policy-driven systemic transition.

Marker, Terry L, Larry G Felix, Martin B Linck, and Michael J Roberts. 2012. “Integrated Hydropyrolysis and Hydroconversion (IH 2) for the Direct Production of Gasoline and Diesel Fuels or Blending Components from Biomass , Part 1 : Proof of Principle Testing.” Environmental Progress & Sustainable Energy 31 (2): 191–99. https://doi.org/10.1002/ep.

Marker, Terry L, Larry G Felix, Martin B Linck, Michael J Roberts, Pedro Ortiz-toral, and Jim Wangerow. 2014. “Integrated Hydropyrolysis and Hydroconversion (IH 2) for the Direct Production of Gasoline and Diesel Fuels or Blending Components from Biomass , Part 2 : Continuous Testing.” Environmental Progress & Sustainable Energy 33 (3): 762–68. https://doi.org/10.1002/ep.

Meerman, Johannes C, and Eric D Larson. 2017. “Negative-Carbon Drop-in Transport Fuels Produced via Catalytic Hydropyrolysis of Woody Biomass with CO 2 Capture and Storage.” Sustainable Energy & Fuels 1: 866–81. https://doi.org/10.1039/c7se00013h.

Millinger, M., et al., 2017. “Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany.” Energy Policy 107: 394-402.

Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transport Research. Part D: Transport and Environment. 64, 5–14. https://doi.org/10.1016/j.trd.2017.07.012

Mossberg, J., Söderholm, P., Frishammar, J., 2021. Challenges of sustainable industrial transformation: Swedish biorefinery development and incumbents in the emerging biofuels industry. Biofuels, Bioprod. Biorefining 1–17. https://doi.org/10.1002/bbb.2249

Mustapha, W.F., et al., 2017. “Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning.” Energy Conversion and Management 149: 368-380.

Müller-Langer, F., Rönsch, S., Weithäuser, M., Oehmichen, K., Seiffert, M., Majer, S., Scholwin, F., Thrän, D., 2009. Erdgassubstitute aus Biomasse für die mobile Anwendung im zukünftigen Energiesystem. DBFZ, Deutsches BiomasseForschungsZentrum gemeinnützige GmbH, Gülzow, Germany. https://mediathek.fnr.de/media/downloadable/files/samples/3/2/3232014_fkz-22031005_dbfz_endbericht_biomethan_2009_rev2.pdf

Nguyen, Tuong Van, and Lasse Røngaard Clausen. 2019. “Techno-Economic Analysis of Polygeneration Systems Based on Catalytic Hydropyrolysis for the Production of Bio-Oil and Fuels.” Energy Conversion and Management 184 (March): 539–58. https://doi.org/10.1016/j.enconman.2019.01.070.

Olofsson, J., et al., 2017. “Integrating enzyme fermentation in lignocellulosic ethanol production: life-cycle assessment and techno-economic analysis.” Biotechnology for Biofuels 10:51.

Ouraich, I., Wetterlund, E., Forsell, N. & Lundmark, R. (2018) A spatial-explicit price impact analysis of increased biofuel production on forest feedstock markets: A scenario analysis for Sweden. Biomass and Bioenergy. https://doi.org/10.1016/j.biombioe.2018.09.029

Paggio, Alan Del. 2018. “IH2 Technology.” In Advanced Biofuels Conference, Gothenburg 18-20 September, 1–22. Stockholm: Svebio.

Pettersson, K., Gåverud, H., Görling M., 2019. “Well-to-wheel cost for forest-based biofuels.” Report No 2019:03, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

Pinho, Andrea De Rezende, Marlon B B De Almeida, Fabio Leal Mendes, Vitor Loureiro Ximenes, and Luiz Carlos Casavechia. 2015. “Co-Processing Raw Bio-Oil and Gasoil in an FCC Unit.” Fuel Processing Technology 131: 159–66. https://doi.org/10.1016/j.fuproc.2014.11.008.

Pinho, Andrea de Rezende, Marlon B.B. de Almeida, Fabio Leal Mendes, Luiz Carlos Casavechia, Michael S. Talmadge, Christopher M. Kinchin, and Helena L. Chum. 2017. “Fast Pyrolysis Oil from Pinewood Chips Co-Processing with Vacuum Gas Oil in an FCC Unit for Second Generation Fuel Production.” Fuel 188: 462–73. https://doi.org/10.1016/j.fuel.2016.10.032.

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, 2020a. JEC Well-To-Wheels report v5. EUR 30284 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20109-0, doi:10.2760/100379, JRC121213.

Prussi, M., Yugo, M., Padella, M., Edwards, R., Lonza, L and De Prada, L. 2020b.JEC Well-to-Tank report v5: Annexes, Hamje, H., editor, EUR 30269 EN, Publications Office of the European Union, Luxembourg ISBN 978-92-76-21707-7, doi:10.2760/06704, JRC119036.

Rafati, M., et al., 2017. “Techno-economic analysis of production of Fischer-Tropsch liquids via biomass gasification: The effects of Fischer-Tropsch catalysts and natural gas co-feeding.” Energy Conversion and Management 133: 153-166.

Röck, M., Rexeis, M., Hausberger, S., 2018. Tank to wheels report - Heavy duty vehicles (No. FVT128/18/Rö EM-I2017/29 from 31.10.2018). JEC JRT.

Sartini, F., Grönkvist, S. & Fröberg, M. (2017). Infrastructure and vehicles for heavy long-haul transports fuelled by electricity and hydrogen – An overview. Report No 2018:02, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SGAB (2018) Technology status and reliability of the value chains: 2018 Update, Landalv, I., Waldheim, L. & Maniatis, K., 2018.

Skatteverket, 2021, Skatteverkets föreskrifter om nybilspriser för bilar med tillverkningsår 2021 vid värdering av bilförmån, www.skatteverket.se

Shell. 2019. “IH2 Technology Fact Sheet.” https://www.shell.com/ih2.

Swedish Government Official Reports, 2013. Fossilfrihet på väg (On its way to fossil fuel independence). SOU 2013:84, 2013. In Swedish

SÅcalc, 2019. Example numbers for reference vehicles obtained from Sveriges Åkeriföretag as reported by Holmgren et al (2021).

Söderholm, P., Hellsmark, H., Frishammar, J., Hansson, J., Mossberg, J., Sandström, A., 2019. Technological development for sustainability: The role of network management in the innovation policy mix. Technological Forecasting & Social Change 138: 309–323. https://doi.org/10.1016/j.techfore.2018.10.010

Tamm, E., 2021. Personal communication, Ebba Tamm, Product & Environmental Expert, Drivkraft Sverige, 2021-03-23.

Tan, Eric C D, Terry L Marker, and Michael J Roberts. 2014. “Direct Production of Gasoline and Diesel Fuels from Biomass via Integrated Hydropyrolysis and Hydroconversion Process — A Techno-Economic Analysis” 33 (2): 609–17. https://doi.org/10.1002/ep.

Thunman H., Gustavsson, C., Larsson, A. et al., 2019. “Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant.” Energy Science and Engineering, 7(1): 217-229, http://dx.doi.org/10.1002/ese3.271.

Trafikanalys, 2019. ”Styrmedel för tunga miljövänliga lastbilar.” (No. 2019:2). Trafikanalys, Stockholm, Sweden.

Trafikutskottet, 2018. Fossilfria drivmedel för att minska transportsektorns klimatpåverkan – flytande, gasformiga och elektriska drivmedel inom vägtrafik, sjöfart, luftfart och spårbunden trafik

Trafikverket, 2020. Analysmetod och samhällsekonomiska kalkylvärde för transportsektorn: ASEK 7.0 (Trafikverket No. ASEK 7.0, version 2020-06-15). Trafikverket, Borlänge, Sverige.

Tunå, P. and Hulteberg, C., 2014. Woody biomass-based transportation fuels – A comparative techno-economic study. Fuel 117: 1020-1026.

Udengaard, Niels;, Richard; Knight, Jesper; Wendt, Jim; Patel, Kip; Walston, Pekka; Jokela, and Cheryl Adams. 2015. “Green Gasoline from Wood Using Carbona Gasification and Topsoe TIGAS Process.” DOE-TOPSOE--EE0002874-F. https://doi.org/10.2172/1173129.

Urade, Vikrant, Madhusudhan Rao, Harish Balam, Laxmi Narasimhan, and Alan Del Paggio. 2015. “Quality of Transportation Fuels from the IH2® Process.” In 4th International Conference on Thermochemical (TC) Biomass Conversion Science, Chicago, USA, 2-5 November. Chicago: Gas Technology Institue.

Volvo, 2015. “Alternative fuels. The way forward.”

Wetterlund, E., et. al., (2020) Drop-in fuels from black liquor part streams – bridging the gap between short- and long-term technology tracks. Report No FDOS 05:2020. Available at https://f3centre.se/en/renewable-transportation-fuels-and-systems

APPENDIX 1. RESULT FROM LITERATURE REVIEW OF INFRASTRUCTURE AND DISTRIBUTION COSTS.

Detailed information for distribution and infrastructure costs from selected reports used as background information for this study is presented in Table A1.

Table A 1. Detailed cost information for vehicles and distributions infrastructure.

Reference	Costs included	Fuels and cost items	Main cost	Unit
Börjesson et al., 2016	Light duty vehicle costs	**CNG/CBG**		
		Running costs	0.14-0.16	SEK/km
		Vehicle cost	275000	SEK
		Additional vehicle cost	25000	SEK
	Heavy-duty vehicle costs	**Methane**		
		Running costs (6% interest rate)	0.14-0.41	SEK/km
		Running costs (10% interest rate)	0.16-0.49	SEK/km
		Vehicle cost	1.1-1.3	MSEK
		Additional vehicle cost	100000-300000	SEK
	Filling station	**CBG - grid**		
		Investment cost	7500000	SEK
		O&M cost	50	SEK/MWh
		CBG - off grid		
		Investment cost	7500000	SEK
		O&M cost	50	SEK/MWh
		LBG		
		Investment cost	15000000	SEK
		O&M cost	50 (assumed same as CBG)	SEK/MWh
	Investment cost for the compression of methane	Local Gas Grid (30 GWh)	1	MSEK
		Transmission Grid (100 GWh)	12	MSEK
		Transmission Grid (520 GWh)	18	MSEK
		Transmission Grid (1600 GWh)	35	MSEK
		CBG (30 GWh)	7	MSEK
		CBG (100 GWh)	12	MSEK

		CBG (520 GWh)	35	MSEK
		CBG (1600 GWh)	75	MSEK
Pettersson et al., 2019	Distribution to refueling station	Ethanol (EtOH)	0.15	SEK/litre
		Methanol (MeOH)	0.15	SEK/litre
		E85	0.02	SEK/kWh
		CBG	0.03	SEK/kWh
		LBG	0.09	SEK/kWh
	Refueling station capital cost	Ethanol (EtOH)	0.1	SEK/litre
		Methanol (MeOH)	0.1	SEK/litre
		E85	0.02	SEK/kWh
		CBG	0.025	SEK/kWh
		LBG	0.04	SEK/kWh
		Total investment cost	7.5	MSEK
	Refueling station O&M cost	Ethanol (EtOH)	0.2	SEK/litre
		Methanol (MeOH)	0.2	SEK/litre
		E85	0.02	SEK/kWh
		CBG	0.07	SEK/kWh
		LBG	0.05	SEK/kWh
	Total annual vehicle cost (excluding fuel)	**SNG/Biogas (CNG/CBG) - Golf 1,4 TGI 110 Blue Motion DSG**		
		Price	196320	SEK
		Costs for O&M (excl. taxes)	13600	SEK
		Vehicle tax	360	SEK
		Purchase bonus/subsidy (excl. VAT)	8000	SEK
		Ethanol/Methanol - Golf 1,4 TSI 125		
		Price	177520	SEK
		Costs for O&M (excl. taxes)	14600	SEK
		Vehicle tax	415	SEK
	Cost for distribution trucks	**Gas (CNG/CBG)**		
		Price	1.55	MSEK
		Costs for O&M (excl. taxes)	83400	SEK
		Vehicle tax	8200	SEK
		Purchase bonus/subsidy (excl. VAT)	175000	SEK

		ED95		
		Price	1.2	MSEK
		Costs for O&M (excl. taxes)	79000	SEK
		Vehicle tax	8200	SEK
	Cost for long-distance trucks	**LBG/LNG**		
		Price	4.55	MSEK
		Costs for O&M (excl. taxes)	339300	SEK
		Vehicle tax	12975	SEK
		Purchase bonus/subsidy (excl. VAT)	525000	SEK
		ED95		
		Price	3.5	MSEK
		Costs for O&M (excl. taxes)	323300	SEK
		Vehicle tax	12975	SEK
Trafikanalys, 2019	Additional costs of trucks compared to traditional diesel driven trucks	LBG	245000-480000	SEK/vehicle
		CBG	145000-200000	SEK/vehicle
		ED95	60000-100000	SEK/vehicle
Trafikutskottet, 2018	Distribution costs for fuel	FT-diesel	1.0-1.5	SEK/litre
		Ethanol/methanol	1.20-1.95	SEK/litre
		SNG	2	SEK/litre gasoline eq.

APPENDIX 2. ADDITIONAL RESULT FIGURES

The total cost for trucks and cars also including the so-called bio-electrofuels is presented in Figure A1 and A2. In this study bio-electrofuels refers to electrofuels that are produced from biogenic excess CO_2 from biofuel production and linked to the biofuel production, and thus requiring no specific CO_2 capture technology (these are marked with the prefix “e-bio” in the figures).

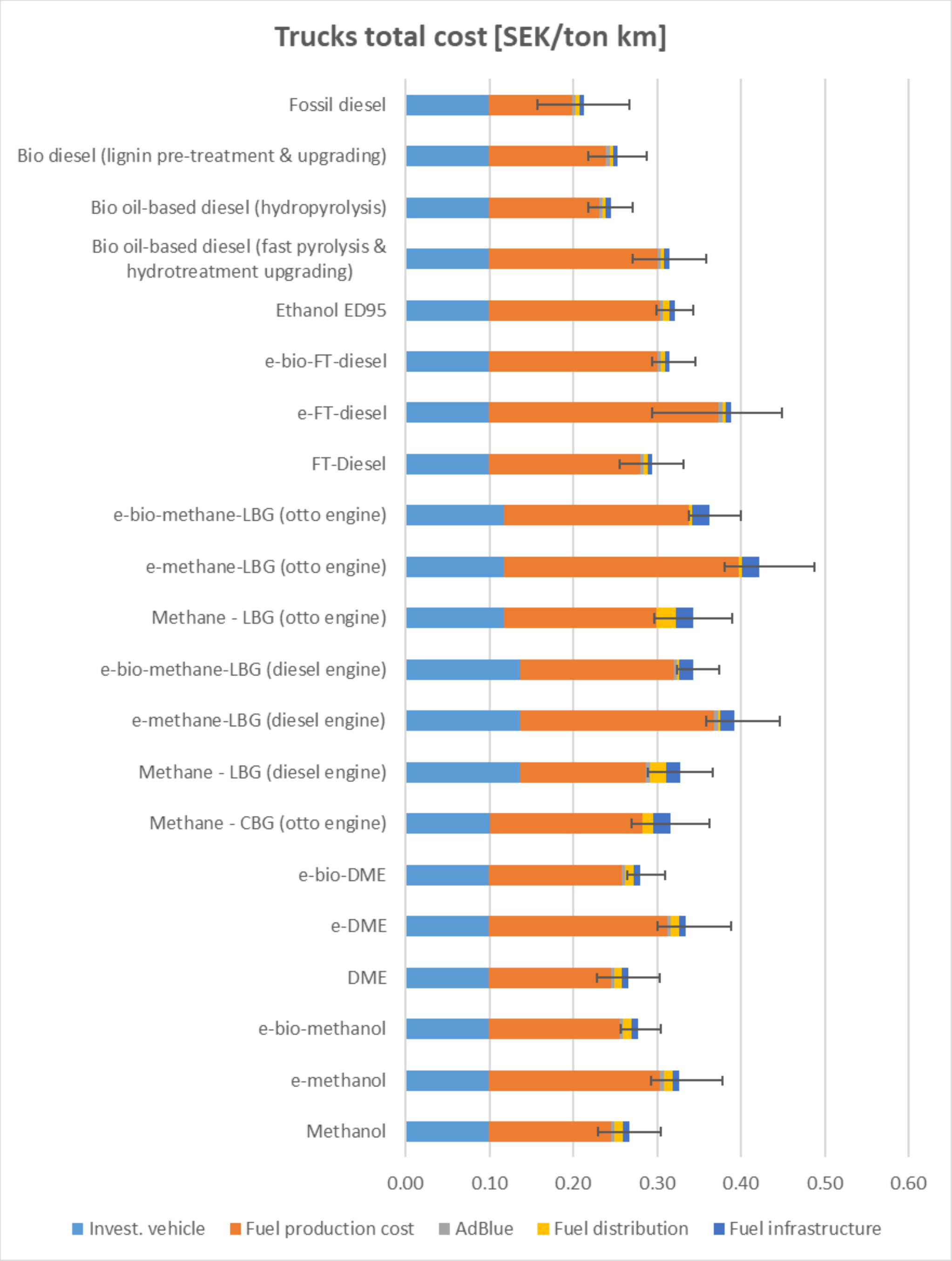

Figure A 1. The total cost per studied forest biomass-based fuel pathway in comparison to the corresponding cost for the studied electrofuels and bio-electrofuels pathways (including total fuel related cost and vehicle cost) for trucks. The bio-electrofuels are marked with the prefix “e-bio” in the figures.

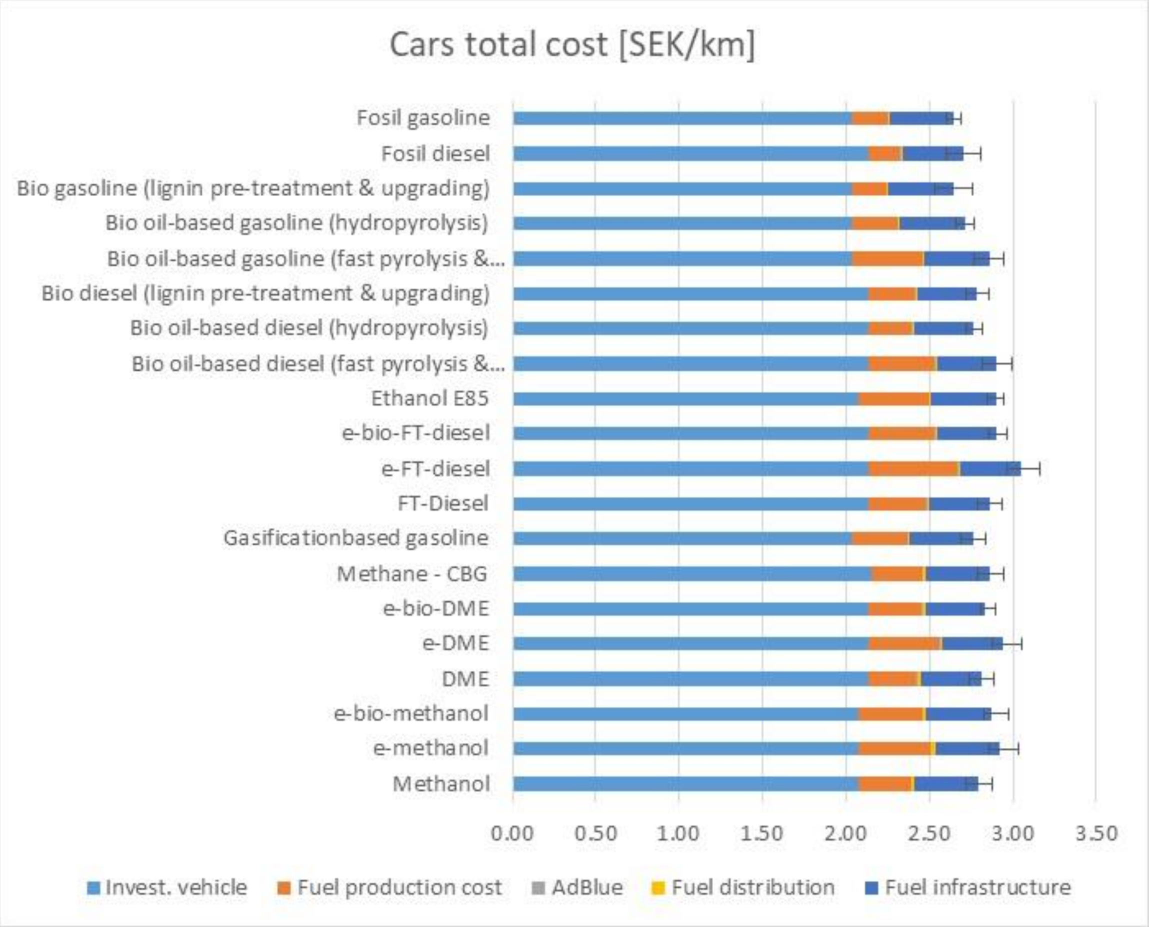

Figure A 2. The total cost per studied forest biomass-based fuel pathway in comparison to the corresponding cost for the studied electrofuels and bio-electrofuels pathways (including total fuel related cost and vehicle cost) for cars. The bio-electrofuels are marked with the prefix "e-bio" in the figures.

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