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WELL-TO-WHEEL COST FOR FOREST-BASED BIOFUELS

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 42404-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

The main performers of this project have been Karin Pettersson (RISE), Henrik Gåverud (Sweco) and Martin Görling (Sweco). In addition, Mårten Larsson (Lantmännen, former Sweco), Rickard Fornell (RISE), Peter Berglund Odhner (Länsstyrelsen Skåne, former Sweco) and Erik Zinn (Göteborg Energi) has contributed to the work in the project. A reference group has been connected to the project, consisting of Björn Fredriksson Möller (E.ON), Per Hanarp (Volvo) and Tomas Ekbom (Svebio).

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SUMMARY

The primary aim of this study was to estimate the total well-to-wheel (WtW) cost for forest-based value chains with different energy carriers (different biofuels and electricity) for use in different transport segments in road traffic and compare these with fossil alternatives in a Swedish context. The comparison, based on the cost for the end user, illustrates how different alternative value chains can compete with fossil-based value chains and under which conditions there is potential for profitable biofuel production. In order to achieve a broader comparison of the studied value chains, estimates of total energy efficiency and greenhouse gas (GHG) emissions from a WtW perspective were also included.

Three different transport segments were considered – a car, a distribution truck and a long-distance truck. Based on performance in earlier studies, four different biofuel concepts were chosen, all integrated into existing industry. These were:

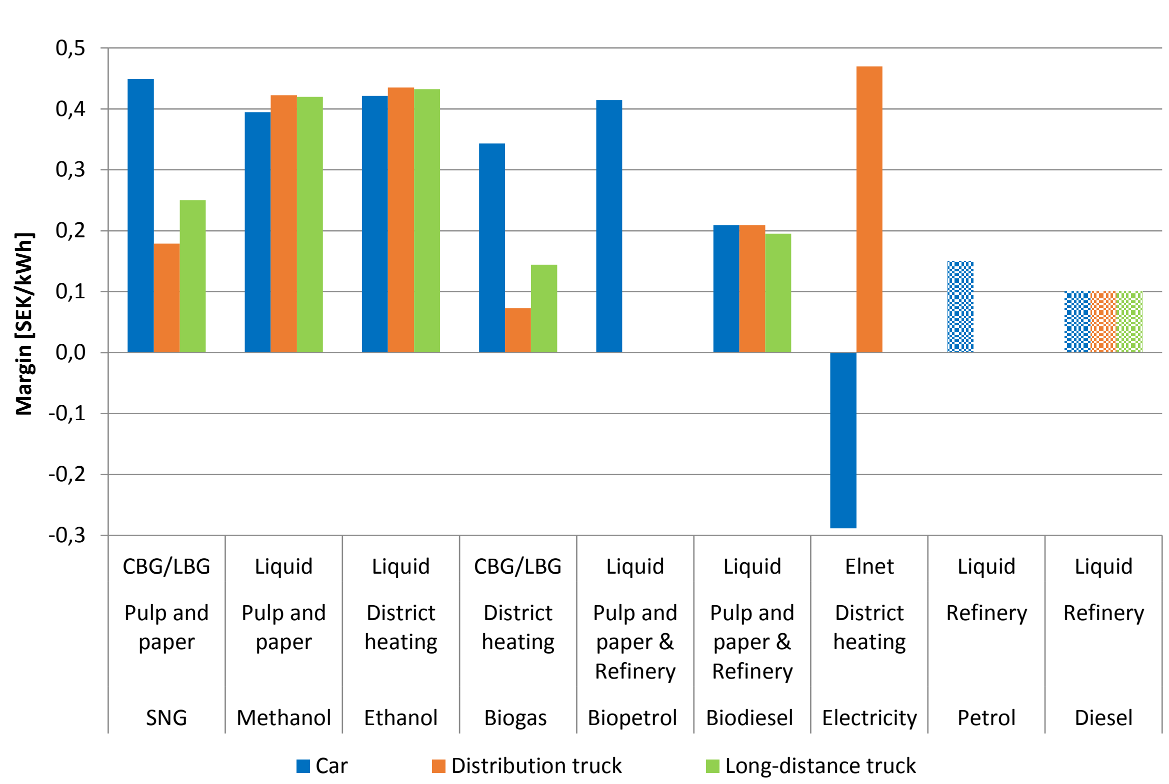
- SNG produced via gasification integrated with a pulp and paper mill.
- Methanol produced via gasification of black liquor integrated with a pulp and paper mill.
- Ethanol produced via hydrolysis and fermentation, with biogas as a by-product, integrated with a district heating system.
- Renewable diesel and petrol produced by first making a bio-oil from extracted lignin at a chemical pulp and paper mill and then upgrade the bio-oil at an oil refinery.

In addition, electricity from forest biomass was also included in the study and it was assumed to be produced in a combined heat and power (CHP) plant connected to a district heating system. Distribution was divided into three main distribution chains – one for liquid fuels, one for gas fuels (CBG or LBG) and one for electricity. In total, 14 different value chains were included in the analysis.

The cost efficiency calculations for the entire value chain – production, distribution and usage – resulted in the total cost for the end user, i.e. the total cost of ownership. The calculations contain the sum of all costs (and possible revenues), including the cost of capital. It was assumed that the technologies included in this study are commercially available and reliable in the considered time perspective, which is 2030. This means that the proposed technologies do not impose additional risk for investors and users, and that the end users' willingness to pay for renewable fuels and related vehicles are the same as for the traditional fossil alternatives.

The total cost was calculated both with and without policy instruments. It was assumed that the biofuels are used as high-blended fuels with tax exemption (current policy situation) and consequently not used as blend-in fuels. Current market prices for energy were used as input for the calculations. Efforts were focused on a sensitivity analysis to evaluate the potential impact of future price changes, as well as other relevant parameters, on the overall results. Margins for fuel producers and distributors were included for the fossil reference chain (current pump price), while it was not included for the biofuel chains. Instead an indicative margin was calculated by comparing the results of the total cost for the renewable alternatives with the total cost for the fossil reference cases. In cases with production of more than one biofuel, costs were shared on energy basis.

The results show that when policy instruments are excluded, none of the studied alternatives can compete with the fossil alternatives. However, for the truck segments, methanol and ethanol give close to the same total cost of ownership as for the fossil alternative. When including policy instruments, almost all alternatives show competitive costs compared to the fossil reference chains, with a significant potential margin for producers and distributors of biofuels. The margins for the studied value chains when policy instruments are included are shown in the figure below.



For the car segment all alternatives, except electricity, have a lower cost than fossil petrol and diesel when including policy instruments. The highest potential margin is shown by SNG followed by biopetrol, methanol and ethanol. The margins are rather substantial, considering that the calculated production costs amount to approximately 0.5-0.85 SEK/kWh and that the gross margin for fossil fuels, also included in the figure, have been estimated to 0.1-0.15 SEK/kWh by the Swedish Energy Agency.

The vehicle cost contributes with the largest share to the total WtW cost in all transport segments, especially for cars. The assumed annual driving distance have a large impact on the calculated cost per km. Electric vehicles benefits the most of longer annual driving distances, due to higher vehicle investment cost, but lower running costs. In this study the driving distance for cars was assumed to be around the average driving distance for a personal car in Sweden, i.e. 15 000 km/y. If the driving distance is changed to 20 000 km/y it will have a profound effect on the electric car's performance since it will then have the highest margin of all studied cases. For the other value chains, the driving distance, as well as other parameters related to the vehicle, only influence the margins to a small extent. The reason for this is that most parameters have similar influence on the biofuel vehicles as for the reference fossil vehicles.

For the truck segments, all alternatives have a lower cost when including policy instruments. The highest potential margins are obtained for electricity, methanol and ethanol for the distribution truck segment, and methanol and ethanol for the long-distance truck segment. The distribution truck and long-distance truck segments have a significantly higher yearly driving distance and higher energy usage per km resulting in fuel cost being a larger share than for the car segment. Consequently, the truck segments are more dependent on changes in production costs, fuel taxation and policies. However, the car segment is also significantly influenced by these types of changes.

Important parameters, that in general influence the results to a relatively large extent, include the biomass price, the crude oil price and for some cases the price of excess heat. However, most alternatives are still competitive, showing a significant potential margin, when these parameters are changed individually in an unfavourable direction.

The energy and CO_2 tax on fossil fuels are vital instruments to achieve a margin for producers and distributors of biofuels. Thus, the tax exemption on biofuels are the single most important policy instrument, adding a cost of around 0.7 SEK/kWh for petrol and almost 0.5 SEK/kWh for diesel. The taxes constitute about 25 % of the cost per km (2.0 SEK/km) for long-distance trucks. The corresponding figures for cars and distribution trucks are 12 % (0.31 SEK/km) and 20 % (1.3 SEK/km), respectively.

The electricity-based value chain has a significantly lower energy usage per km compared to the biofuel-based value chains (for cars approximately 0.16 kWh/km, compared to around 0.6-0.95 kWh/km). Out of the biofuel-based value chains, biopetrol and biodiesel have higher energy usage than the other biofuels, due to higher energy usage related to the production.

The WtW GHG emissions were calculated according to the Renewable Energy Directive (RED), thus including allocation of emissions based on the energy content of the products. All value chains lead to a significant reduction of GHG emissions compared to the fossil reference chains. For almost all cases, the reduction is significantly above 90 % (over 95 % for most value chains). The exceptions are biopetrol and biodiesel, using (fossil) hydrogen in the production process, where the reduction is just above 70 %. Emissions related to the production of vehicles were not included. For electric vehicles, emissions related to battery production is a non-negligible part of the total life cycle emissions.

In summary, all the studied value chains have potential to be profitable and contribute to significant reductions in GHG emissions. Looking at all transport segments, the value chains with methanol and ethanol show the highest average potential margin for producers and distributors. Generally, the results are relatively robust in relation to changes of different parameters. However, for some value chains there are crucial factors that influence the result to a very large extent: the main example is the electricity-based value chain, where the car's yearly driving distance is crucial for profitability and competitiveness. In this study, electricity is assumed to be produced from forest biomass. If electricity from the electricity grid had been considered instead, both the well-to-gate costs and emissions would increase. The well-to-gate costs would be approximately 50 % higher. However, this change would not affect the overall results to any great extent, as the well-to-gate cost of electricity has a relatively small impact on the total well-to-wheel cost for the electricity-based value chains, regardless of transport segment.

SAMMANFATTNING

Det primära syftet med denna studie var att uppskatta den totala kostnaden från källa-till-hjul (*well-to-wheel*, WtW) för skogsbaserade värdekedjor med olika energibärare (både olika biodrivmedel och el) för användning i olika transportsegment i vägtrafiken och jämföra dessa med fossila alternativ i en svensk kontext. Jämförelsen, baserad på kostnaden för slutanvändaren, illustrerar hur olika alternativa värdekedjor kan konkurrera med fossilbränslebaserade värdekedjor och under vilka förutsättningar det finns potential för lönsam biodrivmedelsproduktion. För att uppnå en bredare jämförelse mellan de studerade värdekedjorna inkluderades också uppskattningar av total energieffektivitet samt växthusgasutsläpp från ett WtW-perspektiv.

Tre olika transportsegment inkluderas i studien - en personbil, en distributionslastbil och en fjärrlastbil med släp. Fyra olika biodrivmedelskoncept, utvalda baserat på prestanda i tidigare studier, alla integrerade i befintlig industri, inkluderades:

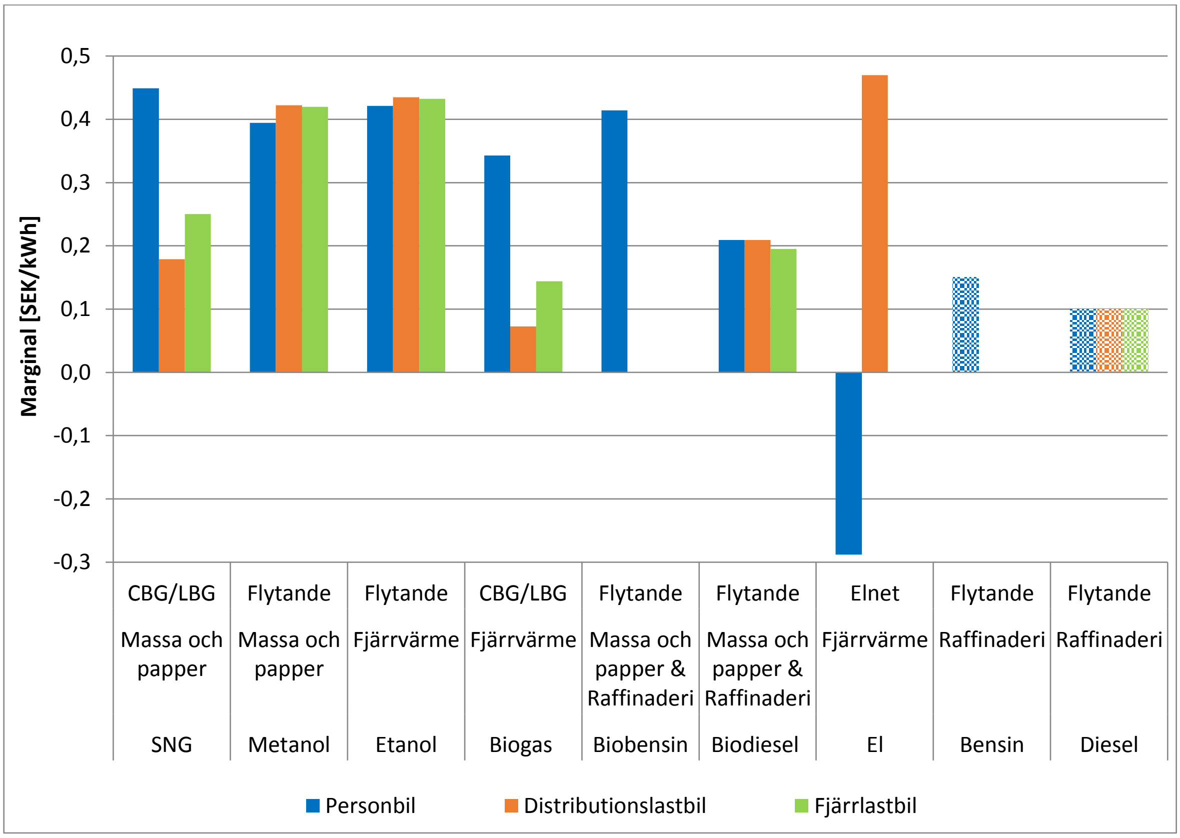
- SNG producerad via förgasning integrerad med ett massa- och pappersbruk.
- Metanol framställd via förgasning av svartlut, integrerad med ett massa- och pappersbruk.
- Etanol framställd genom hydrolys och fermentering, med biogas som biprodukt, integrerad med ett fjärrvärmesystem.
- Förnybar diesel och bensin producerad genom att först framställa en bioolja från extraherad lignin vid ett kemisk massa- och pappersbruk. Biooljan uppgraderas sedan vid ett oljeraffinaderi.

Dessutom inkluderades el från skogsbiomassa i studien. Denna el antogs vara producerad i en kraftvärmeanläggning ansluten till ett fjärrvärmesystem. Distributionen delades in i tre huvudsakliga distributionskedjor - en för flytande bränslen, en för gasbränslen (CBG eller LBG) och en för el. Totalt inkluderades 14 olika värdekedjor i analysen.

Beräkningarna av kostnadseffektiviteten för hela värdekedjan - produktion, distribution och användning - resulterade i den totala kostnaden för slutanvändaren, det vill säga den totala ägandekostnaden. Beräkningarna innehåller summan av alla kostnader (och eventuella intäkter), inklusive kapitalkostnader. Det antogs att de tekniker som ingår i denna studie är kommersiellt tillgängliga och tillförlitliga i det studerade tidsperspektivet, vilket är 2030. Det innebär att de föreslagna teknikerna inte medför ytterligare risk för investerare och användare och att slutanvändarnas betalningsvilja för förnybara drivmedel och relaterade fordon är desamma som för de traditionella fossila alternativen.

Den totala kostnaden beräknades både med och utan styrmedel. Det antogs att biodrivmedlen används som höginblandade drivmedel med skattebefrielse (nuvarande styrmedelssituationen) och följaktligen inte för låginblandning. Nuvarande marknadspriser för olika energibärare användes i beräkningarna. En känslighetsanalys genomfördes för att utvärdera den potentiella effekten av framtida prisförändringar, liksom andra relevanta parametrars påverkan, på de övergripande resultaten. Marginaler för drivmedelsproducenter och distributörer ingår i de fossila referenskedjorna som baseras på det nuvarande pumppriset, medan det inte ingår i biodrivmedelsvärdekedjorna. I stället beräknades en indikativ marginal genom att jämföra den totala kostnaden för de förnybara alternativen med den totala kostnaden för de fossila referenserna. I fall med produktion av mer än ett biodrivmedel delades kostnaderna på energibasis.

Resultaten visar att när politiska styrmedel inte inkluderas, kan inget av de studerade biobaserade alternativen konkurrera med de fossila alternativen. Men för lastbilssegmenten ger metanol och etanol nästan samma totala ägandekostnad som för det fossila alternativet. När styrmedel inkluderas visar nästan alla alternativ konkurrenskraftiga kostnader jämfört med de fossila referenskedjorna, med en betydande potentiell marginal för producenter och distributörer av biodrivmedel. Marginalerna för de studerade värdekedjorna när styrmedel ingår visas i nedanstående figur.



För personbilssegmentet visar alla alternativ, förutom el, på en lägre kostnad än referenskedjorna när styrmedel inkluderas. De högsta marginalerna uppvisas av SNG, följt av etanol, biobensin och metanol. Marginalerna är ganska stora, med tanke på att de beräknade produktionskostnaderna uppgår till cirka 0,5-0,85 SEK/kWh och att bruttomarginalen för fossila bränslen, som också ingår i figuren, har uppskattats till 0,1-0,15 SEK/kWh av Energimyndigheten.

Fordonskostnaden utgör den största andelen av den totala WtW-kostnaden i alla transportsegment, särskilt för personbilar. Den antagna årliga körsträckan har stor inverkan på den beräknade kostnaden per km. Elfordon gynnas mest av längre årlig körsträcka på grund av högre fordonsinvesteringskostnader, men lägre driftskostnader. Basantagandet i denna studie var en årlig körsträcka på 1 500 mil för personbilar. Denna körsträcka är något längre än den genomsnittliga körsträckan för en personbil i Sverige. Om körsträckan ändras till 2000 mil/år ändras resultatet för elbilen radikalt och får den högsta marginalen av alla studerade fall. För de andra värdekedjorna påverkar körsträckan, liksom andra parametrar relaterade till fordonet, marginalen i relativt liten utsträckning. Orsaken till detta är att de flesta parametrar har liknande kostnadsmässig påverkan på alla fordon, oavsett om de som är avsedda för biodrivmedel eller för fossila drivmedel.

För lastbilssegmenten har alla studerade värdekedjor en lägre kostnad än den fossila referenskedjan när politiska styrmedel beaktas. De högsta marginalerna uppvisas av el, metanol och etanol för distributionslastbilssegmentet, och av metanol och etanol för fjärrlastbilssegmentet. För lastbilssegmenten, med en betydligt längre årlig körsträcka och högre energianvändning per km, utgör bränslekostnaden en större andel än för bilsegmentet. Därmed påverkas dessa segment mer av förändringar i produktionskostnader och drivmedelsbeskattning. Dock ska det betonas att även personbilssegmentet påverkas betydligt av dessa typer av förändringar.

Viktiga parametrar som generellt påverkar resultaten i relativt stor utsträckning inkluderar biomassapriset, råoljepriset och i vissa fall priset på överskottsvärme. De flesta alternativen är emellertid fortfarande konkurrenskraftiga och visar en signifikant potentiell marginal när dessa parametrar ändras individuellt i en ogynnsam riktning.

Energi- och CO_2-skatten på fossila drivmedel är centrala styrmedel för att uppnå marginal för producenter och distributörer av biodrivmedel. Skattebefrielsen för biodrivmedel är det enskilt viktigaste styrmedlet, vilket ger en kostnad på ungefär 0,7 SEK/kWh för bensin och nästan 0,5 SEK/kWh för diesel. Skatterna utgör ca 25 % av kostnaden per km (2,0 SEK/km) för fjärrlastbilar. Motsvarande siffra för personbilar och distributionslastbilar är 12 % (0,31 SEK/km) respektive 20 % (1,3 SEK/km).

De elbaserade värdekedjorna har en betydligt lägre energianvändning per km jämfört med de biodrivmedelsbaserade värdekedjorna (för personbilar ungefär 0,16 kWh/km, jämfört med ungefär 0,6-0,95 kWh/km). Av de biodrivmedelsbaserade värdekedjorna har biobensin och biodiesel högre energianvändning än de andra biodrivmedlen, detta till följd av högre energianvändning i samband med produktionen.

De totala utsläppen av växthusgaser beräknades enligt Förnybarhetsdirektivet, vilket innebär att utsläppsfördelningen baseras på produkternas energiinnehåll. Alla studerade värdekedjor leder till en betydande minskning av växthusgasutsläppen jämfört med de fossila referenskedjorna. För nästan alla fall är minskningen betydligt större än 90 % (över 95 % för de flesta värdekedjorna). Undantagen är biobensin och biodiesel, som använder (fossil) vätgas i produktionsprocessen, för vilka reduktionen är precis över 70 %. Utsläpp relaterade till framställan av fordon är inte inkluderade. För elfordon utgör utsläpp vid framställan av batteriet en icke försumbar andel av de totala livscykelutsläppen.

Sammanfattningsvis visar alla studerade värdekedjor på potentiell lönsamhet och möjlighet att bidra till betydande minskningar av växthusgasutsläppen. Sett till alla transportsegment, visar värdekedjorna med metanol och etanol på den högsta genomsnittliga potentiella marginalen för producenter och distributörer. Generellt är resultaten relativt robusta i förhållande till förändringar av olika parametrar. För vissa värdekedjor finns det emellertid kritiska faktorer som påverkar resultatet i stor utsträckning. Det viktigaste exemplet är den elbaserade värdekedjan, där bilens årliga körsträcka är helt avgörande för dess konkurrenskraft. I den här studien har el producerad från skogsbiomassa studerats. Om elektricitet från elnätet istället hade beaktats skulle både källa-till-grind (*well-to-gate*)-kostnaderna och -utsläppen öka. Kostnaden från källa-till-grind skulle bli cirka 50 % högre. Denna förändring påverkar emellertid inte den totala WtW-kostnaden i särskilt i stor utsträckning, eftersom kostnaden för el har en relativt liten inverkan på den totala kostnaden för de elbaserade värdekedjorna, oavsett transportsegment.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

In Sweden, the parliament has decided that the vehicle fleet should be fossil independent by 2030 (SOU, 2013). In connection with the decision on the climate policy framework 2017, the parliament decided that greenhouse gas emissions (GHG) from domestic transport should decrease by at least 70 percent by 2030 compared to 2010 (Trafikutskottet, 2017). This transformation requires significant efforts in several areas of action: planning and developing attractive and accessible cities that reduce demand for transport and increase transport efficiency, infrastructure measures and change of traffic, more efficient vehicles and more energy-efficient vehicle usage and a switch to electricity and biofuels (SOU, 2013). In 2017, the government presented the so-called Fuel change (*Bränslebytet*), a package of new policy instruments aimed at reducing the transport sector's emissions and over time increasing the use of biofuels (Trafikutskottet, 2017).

Biofuels can be produced through many different production chains depending on the use of raw materials, the conversion process and which biofuel should be produced. The demand for biofuels produced from lignocellulosic feedstock is projected to increase significantly in the future, as part of reaching the targets for renewable energy in the transport sector, especially in forest-rich countries, like Sweden (SOU, 2013). Using forest-based raw materials for biofuel production is a priority in Sweden due to good greenhouse gas performance and often relatively large local assets. Several different technologies for biofuels based on lignocellulosic feedstock are under development. The two main production routes are ethanol produced via fermentation and gasification, which is followed by synthesis into, for example, methanol, dimethyl ether (DME), synthetic natural gas (SNG) or Fischer-Tropsch (FT) fuels. In addition to these fuels, which are mainly aimed for use as high-blend or pure biofuels, several tracks for hydrocarbon-based fuels produced from lignocellulosic feedstock are under development. These fuels are, at least in the short-term perspective, mainly aimed to be used as drop-in fuels. The fuel and vehicle sectors are tear-resistant in many ways, not least due to high investment costs. The vehicles and infrastructure that we choose today will be used for a long time. This is the reason why drop-in fuels have been pinpointed as a short-term priority. However, in a more long-term perspective, these fuels can also be used as high-blend or pure biofuels.

To estimate the total energy, climate as well as cost efficiency of a motor fuel, the entire value chain from well-to-wheel (WtW) needs to be considered. Factors such as cost and collection area for the raw material, efficiency, investment cost and opportunity for integration of the biofuel production process, distribution system for the biofuel and the cost and efficiency of the vehicle, all influence the total cost of a value chain and thereby the cost per km for the final vehicle user. By comparing the total cost for different bio-based value chains with the cost for the fossil-based value chains, it is possible to see if and under what conditions biofuels are competitive. When estimating the energy efficiency and GHG emissions of a value chain, it is natural to have a WtW perspective. However, there are relatively few previous studies that study the total *cost* from WtW.

1.2 AIM OF STUDY

The primary aim of this study is to estimate the total WtW cost for forest-based value chains with different energy carriers (both different biofuels and electricity) for use in different transport segments in road traffic and compare these with fossil alternatives in a Swedish context. The comparison, based on the cost for the end user, illustrates how alternative value chains can compete with today's fossil-based value chains and under what conditions there is potential for profitable biofuel production. The impact of various possible policy instruments is included in the analysis.

An important part of the study is to identify and highlight how important parameters affect the results. This includes changes in energy prices and policy instruments, but also other parameters such as size and capital cost of the biofuel production plant, vehicle residual value and yearly driving distance. In order to achieve a broader comparison of the value chains, estimations of total energy efficiency and GHG emissions from a WtW perspective are also included.

The studied value chains are chosen based on different criteria including performance in previous evaluations. The time perspective is 2030. The studied value chains should therefore be technical and commercially relevant in that time perspective. It is assumed that the biofuels studied are used as high-blended or pure fuels.

1.3 RELATED WORK

There are several studies that in different ways evaluates costs for biofuel- and electricity-based value chains. Common delimitations are to estimate the cost in a well-to-gate, well-to-tank or tank-to-wheel perspective, but there are considerably fewer studies looking at costs for the entire value chain from well-to-wheel. Further, when narrowing it down to a Swedish context and biofuels based on forest raw material, the number further decrease considerably.

The most closely related study to the present study published in recent years, is the so-called Metdriv study (Börjesson et al., 2016) where the energy, GHG and cost performance of existing and potential, new, methane-based vehicle systems solutions was analysed and described from a WtW perspective. The study included different value chains, including gasification-based fuel production based on forest biomass, but focus only on methane (SNG) as vehicle fuel. The overall conclusion of the study regarding costs was that for renewable methane vehicle fuel systems, the WtW costs will be comparable or slightly higher, compared to fossil-based vehicle fuel systems, based on current market prices of fossil fuels.

Several WtW studies publications have been conducted within the framework of the EU Joint Research Centre (JRC), the Institute for Energy and Transport (IET). The latest report was published in 2014 (Edwards et al., 2014). This report focusses mainly on energy efficiency and GHG emissions, while cost estimations have only been made for part of the chain (e.g. vehicle costs). Another related study by Elgowainy et al. (2013) have compared the cost of ownership and WtW GHG emissions for light-duty vehicles. That study includes not only several fuels and production pathways but also different combination of drivetrains (ICE, hybrid, battery electric, fuel cell).

Argonne National Laboratory (2016) has published an analysis of the costs of different powertrains in USA today and in the future (2025-2030). The analysis is based on the underlying assumptions that all studied fuels and vehicles are produced in large volumes, and no taxes or policy instruments are included in the study. The results show that battery-powered electric vehicles (BEV) still have a higher cost of ownership in the period 2025-2030, 36 and 52 % higher than the cost for a conventional petrol vehicle for an electric vehicle with a range of 144 and 336 km respectively. All alternative powertrains in the study are relatively expensive compared to conventional fossil fuelled vehicles. However, the plug-in electric hybrid or electric hybrid combined with liquid biofuel have low costs compared to the other alternative powertrains. Furthermore, the study shows that the vehicle cost is a large part of the total cost of ownership (60-90 %).

In a study by the Roland Berger consultants (2016), the most cost-effective measures for reducing greenhouse gases from the long-distance trucks in the EU until 2030 was evaluated. Advanced biofuels used as drop-in fuels in fossil diesel was evaluated as the most cost-effective option. According to the study, the most important alternative powertrain in 2030 is liquefied natural gas (LNG) engines. It is likely that a large part of the fuel for the LNG trucks is of fossil origin, and the cost competitiveness of the powertrain is significantly lower if only liquefied biogas (LBG) is used.

The ICCT (2016) analysed the current and future technology costs of electric vehicles and presented the incremental cost compared to an internal combustion engine vehicle from 2030. For 2015, the incremental cost was about 60 000 SEK and 175 000 SEK for a BEV with a range of 100 miles and 300 miles respectively. However, in 2030 the incremental cost is estimated to close to zero for the BEV with a shorter range and about 40 000 SEK for the longer range. These results indicate that the total cost of ownership for a BEV can become comparable to that for a conventional vehicle sometime between 2020 and 2030.

Börjesson Hagberg et al. (2016) studies the whole of Sweden's energy system and its development towards reducing carbon dioxide emissions, with particular focus on the role of biofuels and integrated biofuel production. The type of energy system modelling carried out in Hagberg et al. includes a range of possible options for satisfying the transport needs in Sweden and taking into account all steps from well-to-wheel. However, it is not possible (or the purpose) in this type of study to illustrate the effect of different parameters in the value chains (which is a focus in this study), and simplifications must also be implemented (for example, a certain cost per installed plant capacity regardless of the capacity of the plant).

1.4 OUTLINE OF REPORT

Chapter 2 includes a description of the methodology for the figures of merits included in this study, i.e. cost efficiency (Section 2.1), energy efficiency (Section 2.2) and GHG emissions (Section 2.3), together with general assumptions that are applicable to all studied cases or part of the value chain.

Chapter 3 presents the selection criteria for the studied value chains. Section 3.1 motivates the selection of production pathways (selected biofuel/energy carrier and production technology). Section 3.2 shortly presents all studied cases including specification of raw material, energy carrier, production technology, integration of production into existing industry, distribution and usage of biofuels (transport segment). Sections 3.3-3.6 include a more detailed description of the studied value chains and related assumptions following the value chain from well-to-wheel. Section 3.7 presents the main assumptions related to the fossil reference chains.

Chapter 4 presents and discusses the results concerning cost efficiency (Section 4.1), energy efficiency (Section 4.2) and GHG emissions (Section 4.3) for the studied cases. The results for cost efficiency are presented per transport segment. Furthermore, for each transport segment, the economic results are presented in three sections: excluding policy instrument, including policy instruments and a sensitivity analysis. Finally, the conclusions are presented in Chapter 5.

2 METHODOLOGY AND GENERAL ASSUMPTIONS

This chapter includes a description of the methodology for figures of merits included in this study, i.e. cost efficiency, energy efficiency and GHG emissions, together with general assumptions that are applicable to all studied cases or part of the value chain. More detailed descriptions and assumptions related to specific cases or part of the value chain can be found in Chapter 3.

A future optimistic approach has been used when conducting this study. A general assumption was that the production technologies included in this study are commercially available and reliable. Further, there is an established market for all fuels, including adapted vehicles. For the economic evaluation, it was assumed that the proposed technologies don't impose additional risk for investors and users. In summary, the end users' willingness to pay for renewable fuels and related vehicles are the same as the traditional fossil alternatives (e.g. no risk premium).

2.1 COST EFFICIENCY

The cost efficiency calculations for the entire value chain – production, distribution and usage – result in total cost for the end user, i.e. the total cost of ownership. All results are presented in SEK per km and costs and prices are expressed in 2017-year price level (excluding VAT). For the production of biofuels, all capital expenditures and operating expenditures are considered given the assumptions presented in Chapter 3. These calculations contain the sum of all costs, including the cost of capital, but there are no economic margin (profit) included in the production stage of the value chain. This means that the expected market gate price, *ceteris paribus*, will be higher than the results of these calculations, i.e. the cost levels can be considered as the minimum acceptable price for the producers. The results are compared with fossil fuel market prices, i.e. prices that include margins for producers and distributors. When the alternative fuels are not competitive to fossil fuels in a situation without production margin, the actual production will have an even harder competitive situation in reality. The results can, thus, be interpreted as when the renewable fuels have higher costs than the fossil alternatives, the circumstances must be changed to make the renewable alternative competitive. On the other hand, when the results indicate that the renewable fuel has a lower total cost than the fossil alternative, it has to be considered that there is no economic margin included for the renewable fuel in the production stage. Thus, the difference between the total cost for fossil alternatives and the renewable fuels constitutes the potential economic margin for a producer of renewable fuels under given conditions (investment cost, biomass prices, taxes etc.).

For distribution a combination of costs and market prices have been used in the calculations depending on which distribution alternative that is most efficient. When e.g. a ship transportation is used from a refinery, it is assumed that the shipping service is bought from a shipping company (i.e. market prices including margin in that separate stage). But when it comes to e.g. the filling station, the capital expenditures and operating expenditures, i.e. costs, are considered. In Chapter 3 the studied value chains are described in detail.

Market prices for vehicle and related operation and maintenance (taxes, insurances, service, tires etc.) have been used to calculate the vehicle related costs. Three transport segments have been used in this study – a car, a distribution truck and a long-distance truck. See Chapter 3 for detailed specifications regarding the vehicles and related costs.

All relevant combinations of fuels and vehicles are calculated both with and without policy instruments. Furthermore, a sensitive analysis has been made for relevant parameters in the value chain (see Chapter 4).

All calculations are made for pure fuels (containing 100 % renewable fuels), i.e. not blended fuels. In practise this refers to high-blended biofuels but to have the results for e.g. ED95, it must be considered that the fuel also has a small fossil component. Also in the production stage there are in some cases an integrated production of several fuels, e.g. biogas is a by-product when producing ethanol (see Chapter 3 for further details on production integration). In cases with production of more than one biofuel, costs have been shared on energy basis.

The discount rate for plant investments and vehicles is 6 %, while expected economic lifetime and (residual value) is specified for each type of investment. The sensitivity analysis includes changes in capital recovery factors (CRFs) as a proxy for changes in cost of capital, discount rate and/or economic lifetime.

2.1.1 Energy prices

Current market price levels for energy are used as input for the calculations. The prices used are summarised in Table 1. Energy prices have historically fluctuated significantly, and is not only dependent on supply and demand, but also e.g. political decisions. Furthermore, supply and demand are also affected by both long term and short-term external factors e.g. the weather and the economic business cycle. Since these fluctuations are impossible to foresee with good precision, efforts have instead been focused on the sensitivity analysis (presented in Chapter 4) to evaluate the potential impact of future price changes on the overall results.

The production of biofuels in this study is assumed to be based on forest biomass (see further Section 3.3), either forest residues and/or industrial by-products in the form of bark or lignin. The price of forest residues listed in Table 1 does not include transportation costs. The transportation cost function for forest residues are presented in Section 3.3.

The electricity price is an estimated spot market price, i.e. a price excluding taxes and distribution. The price is used in the production and distribution parts of the value chain. In the production stage the price represents both the revenue for sold electricity and the cost level for bought electricity. In the distribution stage, electricity is used in the fuel filling stations. The LBG process uses relatively much electricity. When consuming electricity for industrial use, the distribution cost is low in relation to consuming electricity for non-industrial use (100 SEK/MWh for industrial use and 360 SEK/MWh for non-industrial use). The industrial distribution tariff is used in the production stage and also in the LBG liquefaction process. The non-industrial distribution tariff is used in the distribution stages (i.e. the fuel filling stations and also for charging electrical vehicles). Furthermore, the tax is also differentiated between industrial and non-industrial use. The ordinary electricity tax is 331 SEK/MWh (2018). The reduced electricity tax for industrial use is much lower, 5 SEK/MWh. Renewable electricity produced as a by-product in the biofuel production plants was assumed to be entitled to electricity certificates.

Table 1. Energy prices (SEK/MWh).

Commodity	SEK/MWh	Data from
Forest residues[a]	144	Wetterlund et al. (2017)
Bark	96	Wetterlund et al. (2017)
Electricity[b]	400 [c]	Nord Pool Spot (2019)
Electricity distr. – industrial use[d]	100	Swedish Energy Markets Inspectorate (2018)[e]
Electricity distr. – other use[f]	360	Statistics Sweden (2018), Swedish Energy Markets Inspectorate (2018) [g]
Electricity tax – industrial use	5	The Swedish Tax Agency (2018a)
Electricity tax – other use	331	The Swedish Tax Agency (2018a)
Electricity certificates	150[h]	Svensk Kraftmäkling (2019)
Natural gas[i]	335	Furusjö et al. (2017)
Hydrogen[j]	402	Furusjö et al. (2017)
Crude oil	399[k]	SPBI (2018)

[a] Excluding transportation costs.
[b] Estimated spot price excluding distribution, i.e. both the cost for bought electricity and the revenue for sold electricity.
[c] Estimation from sport prices the last two years. In 2017 the average spot price for electricity in Sweden was about 300 SEK/MWh and in 2018 the corresponding price was about 450 SEK/MWh.
[d] Concerns biofuel production plants and LBG liquefaction plants.
[e] Average cost for a 20 MW plant (140 GWh/y) is about 90 SEK/MWh. The actual cost is influenced by the load profile. Sweco has also calculated the cost of 100 SEK/MWh in similar projects based on the pricelist of Vattenfall, one of the largest electricity distribution companies in Sweden (no official reference available).
[f] All non-industrial users (fuel filling stations, vehicle charging etc.).
[g] According to Statistics Sweden, the cost is 360 SEK/MWh for large households. Average cost for 100 A-customers is, according to Swedish Energy Markets Inspectorate, 355 SEK/MWh.
[h] Average monthly market price in 2018 was 154 SEK/certificate.
[I] Average Swedish price in 2016 for industrial customers. Including distribution costs and taxes.
[j] Calculated as 3.564 times the price of natural gas from steam-methane reforming, on a mass basis Furusjö et al. (2017).
[k] Corresponds to 75 USD/barrel, which was the approximate level of the crude oil price during 2018.

Hydrogen is required to upgrade bio-oil to renewable diesel and petrol (see Section 3.4.4). This case also influences the need for hydrogen at the refinery. The crude oil price is used to calculate the fossil diesel and petrol price (see Section 3.7).

2.1.2 Policy instruments for road transport

As mentioned, results will be presented excluding and including policy instruments. Results excluding policy instruments represent the total costs for production and distribution of the fuels and also costs related to the vehicle (capital cost, tires, insurance etc.). Excluding policy instruments means that external effects such as environmental impact are not taken into account. In the case including policy instruments, the actual taxes, subsidies and other government interventions are considered. Given that all instruments were developed in order to include external effects[1] in the market prices and given that all estimations of these external effects were perfect, then the case including policy instruments would have been a case including also the socio-economic cost in the well-to-wheel chain. Although taxes and subsidies might be designed with the intention to "punish bads" and "further goods", other factors such as political positions and government incomes and expendi-

[1] An external effect, or an externality, is a positive or negative effect of producing, distributing or use a good or a service and that is not included in the market price of the actual good or service. Externalities can be e.g. noise, smell, view or emissions but also side effects in other markets (e.g. a local airport might benefit local business through increased accessibility).

tures also affect tax and subsidy levels, criteria, exceptions etc. And even if the intention was to internalize the external effects in the market prices, the uncertainty is of great importance regarding the total external impact of producing, distribute and use of a certain fuel. Consequently, it is a great simplification to state that including actual policy instruments represent the market prices including also the socio-economic and the environmental cost for each fuel. Although the case including policy instruments reflects the actual situation for the market players. In relation to the case without policy instruments, it also gives an illustration of how the current policies direct both producers, distributors and users of fuels.

Sweden has a goal to reduce the emissions from domestic transport by 70 % by 2030 compared to 2010. Several policy instruments have been introduced to reach this goal. This section briefly describes the policy instruments with relevance to this study.

Taxes on fuels

There are two systems for taxation of biofuels depending if they are sold as high-blended or blend-in fuels. Since 2018 there is a reduction quota system in place for biofuels that are blended in fossil petrol and diesel. High-blended fuels (e.g. E85, ED95) are not included in the reduction quota system but receives tax exemptions or tax reductions (see Table 2). In this study, it is assumed that the biofuels are used as high-blended fuels with tax exemption and consequently not used as blend-in fuels.

Table 2. Taxes on transport fuels 2018 (The Swedish Tax Agency, 2018a).

Fuel	Energy tax	CO_2 tax [SEK/Litre]	Total [SEK/Litre]	Total [SEK/kWh]
Petrol	3.87 SEK/litre	2.57	6.44	0.71
Diesel	2.34 SEK/litre	2.19	4.53	0.46
HVO, Biogas, E85, ED95, Methanol	0	0	0	0
Electricity	0.331 SEK/kWh	-	-	0.331

Investment support – Infrastructure and trucks

Klimatklivet, “the climate step”, is a policy instrument which grants funds to “climate smart” measures that reduce local CO_2 emissions. During 2015-2020 4 billion SEK (of governmental budget) is allocated to Klimatklivet. So far almost 2 billion SEK have been granted to projects within Klimatklivet. A wide range of measures can receive support such as transports, biogas, district heating, infrastructure and communication actions. (Swedish Environmental Protection Agency, 2018)

In this study it is assumed that the following investments could get 50 % support from Klimatklivet:

- Biogas refuelling station
- LBG liquefaction plant and refuelling station
- Charging infrastructure
- Trucks adopted for alternative fuels (50 % of the additional cost compared to corresponding diesel truck)

These assumptions are based on the type of project that previously have been grated funding from Klimatklivet. Historically it has been possible to receive funding for refuelling station investments under certain conditions, e.g. small-scale distribution of biodiesel. In this study it is assumed that commercial-scale refuelling stations for liquid biofuels can be built at the same cost as for fossil fuels, and hence not qualify for additional investment support.

Bonus-malus system for new cars

New low emission cars qualify for a bonus at purchase, while new vehicles with high emissions are taxed extra (malus) the first three years. The highest bonus is 48 000 SEK excl. VAT (60 000 SEK incl. VAT) for fully electric cars. Gas cars receives a purchase bonus of 8 000 SEK excl. VAT. (10 000 SEK incl. VAT). Malus are payed for vehicles emitting above 95 g CO_2/km in mixed driving. Vehicles emitting between 95 and 140 g CO_2/km is charged additional annually 66 SEK per g CO_2/km in extra vehicle tax during the first three years (malus). The malus increases to 86 SEK per g CO_2/km for emissions above 140 g CO_2/km. (The Swedish Transport Agency, 2018). Ethanol and methanol cars are not affected of the bonus-malus system, i.e. they are neither eligible for bonus nor taxed extra (malus).

Road and vehicle tax for heavy vehicles

The amount of vehicle tax payed for heavy vehicles are depending on weight and fuel. The vehicle tax for the distribution truck and the long-distance truck amounts to 2 799 SEK/y and 9 491 SEK/y, respectively. Trucks, in both segments, that uses another fuel than diesel pays a reduced vehicle tax, 984 SEK per year. (The Swedish Tax Agency, 2018b)

Road taxed is calculated based on axles and engine emission standards. The tax amounts to 7 194 SEK for distribution trucks (max 3 axles, Euro 2 or better) and 11 991 SEK for long-distance trucks (> 4 axles, Euro 2 or better) (The Swedish Tax Agency, 2018c).

2.2 ENERGY EFFICIENCY

The energy efficiency was calculated by estimating the total energy use from well-to-wheel. The results are presented as kWh energy used per km, divided into different energy carriers related to production (biomass, electricity, diesel, heat and hydrogen) and distribution (electricity and diesel). For the production concepts including more than one biofuel, allocation of energy usage has been done based on energy content, as for the economic calculations.

No conversion of the energy carriers to the same basis (such as electricity equivalents) were considered. Using mixed sources of energy carriers in efficiency calculations could contribute to a tendency to overestimate the “quality” of certain energy carriers, especially when the level of exergy in the different flows (such as biomass, electricity and heat) is so diverse (Tunå et al., 2012). This should be borne in mind when looking at the results.

2.3 GHG EMISSIONS

The calculation of the total GHG emissions used the same system boundary as for the other figures of merits, i.e. well-to-wheel. The results are presented as CO_{2eq} per km.

The calculations were made according to the Renewable Energy Directive (RED) and thus do not include system expansion. Instead allocation was used, based on the energy content of the products. Consequently, the use of by-products was not included in the analysis. Figure 1 illustrates the GHG calculation methodology used in this study, i.e. according to RED in comparison to using system expansion as is suggested by the ISO standard (ISO, 2006).

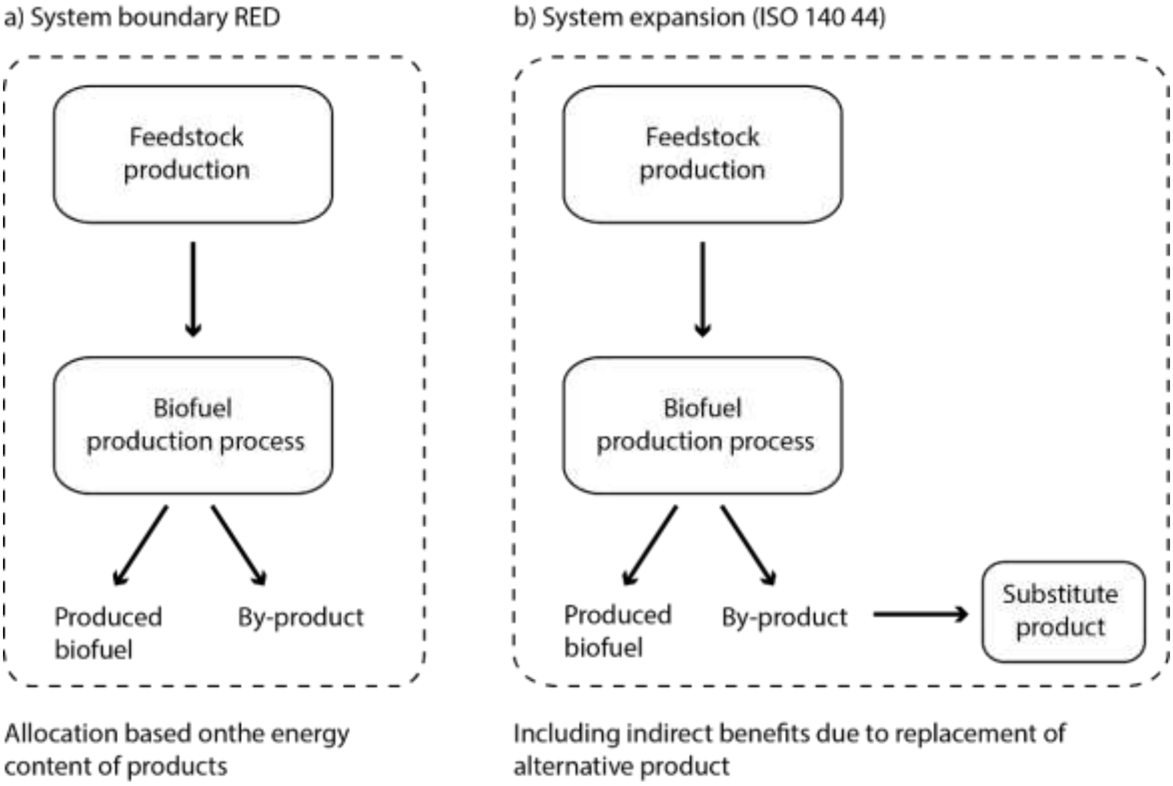


Figure 1. GHG calculation methodology according to a) the Renewable Energy Directive (RED) (used in this study) and b) the ISO standard (Börjesson et al., 2013).

The reason for this choice of method is primarily that important policy instruments and goals, both on national and EU level, are based on greenhouse gas calculation according to the Renewable Energy Directive. However, previous studies show that the differences between calculations with and without system expansion are small for most fuel value chains (Börjesson et al., 2013, Börjesson et al., 2016, Furusjö and Lundgren, 2017). However, there are exceptions to this. The Renewables Energy Directive's method for calculating GHG emissions do not allow for consideration of any use of excess heat. Thus, even if considerable amounts of excess heat from a biofuel process is used in an industrial process or a district heating system, no emissions could be allocated to this heat. This is reasonable if the excess heat is unavoidable. As discussed by Pettersson and Harvey (2015), many industrial processes have excess process heat, even if they are very energy efficient. The excess heat that cannot be avoided and that cannot contribute to decreased primary energy usage at the process plant, can be called unavoidable excess heat. The emissions associated with this excess heat are thus zero.

Table 3 shows the GHG emission factors used in the calculations of WtW GHG emissions. According to RED, the Nordic electricity mix is considered for emissions associated with electricity. The emissions for the electricity-based value chain in this study is not influenced by the emissions factor for the Nordic grid, instead it is assumed that the electricity used as a “biofuel” for transport is produced from forest biomass in a CHP plant (see Section 3.4.5).

Table 3. GHG emission factors (kg $CO_{2\text{-}eq}$/MWh).

	kg $CO_{2\text{-}eq}$/MWh	Data from
Diesel	342	EU (2015)
Electricity	126	Martinsson et al. (2012)
Heavy fuel oil	308	Anheden et al. (2017)
Hydrogen	270	Anheden et al. (2017)
Natural gas	248	Gode et al. (2011)
Petrol	335	EU (2015)

For the value chains including methane, methane slips have been considered. For SNG and biogas production the methane slips used were 7.2×10^{-6} kg $CO_{2\text{-}eq}$/MWh (Ahlström et al., 2017) and 5.4 kg $CO_{2\text{-}eq}$/MWh (Börjesson et al., 2016) respectively. The methane slip related to incomplete combustion of methane in the engines was set to 0.63 kg $CO_{2\text{-}eq}$/MWh (Ahlström et al., 2017).

Emissions associated with the manufacture of vehicles/vehicle components and infrastructure are not included in the analysis. This is a common delineation in well-to-wheel analyses. In this context, it can be emphasized that for electric vehicles, emissions related to battery production is a non-negligible part of the total life cycle emissions (see e.g. Nordelöf et al., 2016).

3 STUDIED VALUE CHAINS – DESCRIPTION AND ASSUMPTIONS

The studied value chain concepts were selected based on a number of selection criteria:

1. Performance in earlier studies comparing different alternative fuels.
2. The concept should be technically and commercially relevant for 2030.
3. Data access. Data should be available from previous studies.
4. The data used should mirror the potential of what can be achieved in the future regarding for example biomass-to-biofuel yield, effective internal/external integration for increased energy efficiency of the biofuel process, investment costs for biofuel production and energy usage and investment cost for vehicles.

Section 3.1 motivates the choice of production pathways (selected biofuel/energy carrier and production technology). Section 3.2 shortly presents all studied cases including specification of raw material, energy carrier, production technology, integration of production in existing industry, distribution and usage of biofuels (transport segment). Sections 3.3-3.6 include a more detailed description of the studied value chains and related assumptions following the value chain from well-to-wheel. Section 3.7 presents the main assumptions related to the fossil reference chains.

The selection of production pathways (selected biofuel/energy carrier and production pathway) are mainly based on the first selection criteria, the results from earlier comparisons of alternative transportation fuels (Section 3.1). Selection criteria 2-4 are mainly used in the choice of specific technologies/data (Sections 3.3-3.6 and Appendix A).

3.1 CHOICE OF PRODUCTION PATHWAYS

Mainly based on the results from earlier comparisons of alternative transportation fuels, the following energy carriers and production pathways were selected:

- SNG produced via gasification
- Methanol produced via gasification
- Ethanol produced via hydrolysis and fermentation (with biogas as a by-product)
- Renewable diesel and petrol (refinery products from bio-oil)
- Electricity from a CHP plant

Several comparisons of lignocellulosic-based value chains with different biofuels indicate high energy and cost efficiency as well as large potential to reduce fossil GHG for bio-based synthetic natural gas (SNG)[2] (Ekbom et al., 2012; Börjesson et al., 2013; Hannula, 2015; Isaksson, 2015; Pettersson et al., 2015; Börjesson Hagberg et al., 2016; Holmgren et al., 2016). This is primarily due to the high yield (biomass-to-SNG) and total energy system efficiency that can be achieved in integrated gasification-based SNG production.

Börjesson Hagberg et al. (2016) studies the whole of Sweden's energy system and its development towards reducing carbon dioxide emissions, with particular focus on the role of biofuels and integrated biofuel production. The result concerning biofuel value chains has provided a basis for the selection that has been made in this study. The results of forest-based fuels in the transport sector

[2] Hereafter, SNG is used to denote renewable SNG.

are dominated by methanol (produced via black liquor gasification) and SNG (produced via gasification of solid biomass), but also a significant amount of forest-based ethanol is present in the solutions.

The BeWhere Sweden model has been developed in previous projects to study cost efficient localisation of biofuel production (Wetterlund et al., 2013; Wetterlund et al., 2013; Pettersson et al., 2015; Wetterlund et al., 2017). Also here the results are dominated by methanol and SNG from the same production pathways as in Börjesson Hagberg et al. The BeWhere model consider costs from well-to-tank, while the model used by Börjesson Hagberg et al. takes into account all steps from well-to-wheel. To study well-to-wheel costs, which is the main purpose of this study, could naturally mean that results concerning the most cost-efficient options could differ compared to if evaluations from well-to-gate or well-to-tank are made.

As mentioned in the introduction, hydrocarbon-based fuels produced from lignocellulosic feedstock have been pinpointed as a short-term priority due to the ability to blend with fossil fuels and use directly in existing vehicles. In these tracks a bio-oil is first produced. The bio-oil can replace fossil oil and be upgraded in existing refineries. Few previous studies have compared tracks for hydrocarbon-based fuels with e.g. gasification-based tracks for production of SNG or methanol. The reason for this is the poor access to data for the hydrocarbon-based tracks due to generally low technical maturity. As one of the few studies including comparisons of these tracks with gasification-based tracks, Furusjö et al. (2017), point out it is paradox that short-term priority is being given to technologies with the lowest maturity and corresponding high technical uncertainty. Furusjö et al. compared the studied tracks from a number of different aspects including profitability, energy efficiency and GHG emissions. The comparison of profitability is made from well-to-gate and shows that there are tracks for production of hydrocarbon-based fuels that can compete with the gasification-based tracks.

The electrification of the road transport sector is steadily increasing. One option for using an increased outtake of forest biomass for transport, except producing biofuels, is to produce electricity and use in battery-powered electric vehicles.

More detailed descriptions and motivations to specific technology choices can be found in Sections 3.4.1-3.4.5 and Appendix A.

3.2 STUDIED CASES

Table 4 presents the studied cases including specification of raw material, energy carrier, production technology, integration of production in existing industry, distribution and usage of biofuels (transport segment). Acronyms can be found on page 65. Sections 3.3-3.6 include a more detailed description of the studied value chains and related assumptions following the value chain from well-to-wheel. Section 3.4, describing the different biofuel concepts is supplemented with Appendix A that for example includes motivations to the choice of technology and host industry in each case.

Table 4. Studied cases.

Raw material	Energy carrier - production technology	Integration	Distribution	Usage
SNG produced via gasification				
FR, bark	SNG – BMG	PoP	CBG	Car
FR, bark	SNG – BMG	PoP	CBG	Truck distr
FR, bark	SNG – BMG	PoP	LBG	Truck long
Methanol produced via gasification				
BL (FR)	MeOH – BLG	PoP	Liquid	Car
BL (FR)	MeOH – BLG	PoP	Liquid	Truck distr
BL (FR)	MeOH – BLG	PoP	Liquid	Truck long
Ethanol produced via hydrolysis and fermentation (with biogas as a by-product)				
FR	EtOH (+Biogas) – HF	DH	Liquid	Car
FR	EtOH (+Biogas) – HF	DH	Liquid	Truck distr
FR	EtOH (+Biogas) – HF	DH	Liquid	Truck long
FR	Biogas (+EtOH)	DH	CBG	Car
FR	Biogas (+EtOH)	DH	CBG	Truck distr
FR	Biogas (+EtOH)	DH	LBG	Truck long
Renewable diesel and petrol (refinery products from bio-oil)				
LI (FR)	Diesel (+Petrol) – HTL	PoP & Ref	Liquid	Car
LI (FR)	Petrol (+Diesel) – HTL	PoP & Ref	Liquid	Car
LI (FR)	Diesel (+ Petrol) – HTL	PoP & Ref	Liquid	Truck distr
LI (FR)	Diesel (+ Petrol) – HTL	PoP & Ref	Liquid	Truck long
Electricity from a CHP plant				
FR	El – CHP	DH	Grid	Car
FR	El – CHP	DH	Grid	Truck distr
Fossil reference chains				
Oil	Diesel – conventional	Ref	Liquid	Car
Oil	Petrol – conventional	Ref	Liquid	Car
Oil	Diesel – conventional	Ref	Liquid	Truck distr
Oil	Diesel – conventional	Ref	Liquid	Truck long

SNG produced via gasification is produced integrated with a pulp and paper mill from forest residues and bark (see Section 3.4.1). Methanol is produced via gasification of black liquor (indirectly using forest residues to keep the energy balance) naturally integrated with a chemical pulp and paper mill (see Section 3.4.2). Ethanol is produced via hydrolysis and fermentation, with biogas as a by-product, integrated with a district heating system (see Section 3.4.3). When presenting the final results, ethanol and biogas are presented separately for transparency reasons. Allocation of costs, energy and emissions has been done based on energy content, as described in Chapter 2. The same goes for renewable diesel and petrol. Renewable diesel and petrol are produced by first producing a bio-oil from extracted lignin at a chemical pulp and paper mill. The bio-oil is then upgraded to diesel and petrol at an oil refinery (see Section 3.4.4). Electricity is produced in a CHP plant connected to a district heating system (see Section 3.4.5).

Distribution is divided into three main distribution chains – one for liquid fuels, one for gas fuels and one for electricity. There are, however, some differences also within the liquid and gas distribution chains between the different fuels (see Section 3.5 for further details).

Three different transport segments are considered – a car, a distribution truck and a long-distance truck. The car is a medium sized car that can be used for private or business. The distribution truck is a 16-18 ton truck mainly used for local/regional distribution services. The long-distance truck is a 40-60 ton truck used for domestic and international transportation of goods.

For the car segment all cases, except renewable diesel and electricity, are compared with the fossil petrol reference chain. For both the truck segments, the reference chain constitutes of the fossil diesel value chain.

As been mentioned, this study focuses on biofuels for usage as high-blended fuels with tax exemption, and consequently not used as blend-in fuels. In the short-term perspective some cases, especially the renewable petrol and diesel cases, will be used as blend-in fuels. This could also partly be the case for ethanol (and methanol). However, there are no technical reasons for not using these fuels in high-blend or pure applications, which makes this a relevant comparison in the medium- or long-term perspective.

3.3 FOREST BIOMASS

Wetterlund et al. (2017) presented forest biomass potentials for the year 2030. They were mainly based on the so-called forest impact assessments (*skogliga konsekvensanalyser*, SKA) that the Swedish Forest Agency (*Skogsstyrelsen*) has carried out in collaboration with SLU (Claesson et al., 2015). In the forest impact assessments, a number of scenarios were calculated that give the magnitude of the potential harvesting and a future forest permit given a number of conditions. Two of the scenarios presented were: Today's forestry (*Dagens skogsbruk*) and Double nature conservation areas (*Dubbla naturvårdsarealer*). The scenario Today's forestry describes the development assuming the current focus and level of ambition in forest management and observed felling behaviour. In the scenario Double nature conservation areas, the development of the forest is simulated given that the areas reserved for reserves, voluntary provisions and consideration areas during harvesting are doubled.

There is good potential to increase the outtake from the forest, for example to use for the production of biofuels. This mainly applies to the extraction of forest residues in the form of GROT (*grenar och toppar*, branches and tops), but also stumps. The withdrawal of GROT could roughly be tripled (to about 30 TWh/y) compared to what is taken out and used today, even in more restrictive scenarios (Claesson et al., 2015). As far as stumps are concerned, previous potential assessments have indicated similar levels as for GROT, but in recent years considerably more restrictive assessments have been made of what is a sustainable extraction of stumps. According to de Jong et al. (2017), such a level is around 4.5 TWh/y (today less than 1 TWh is used annually). Forest biomass consists not only of biomass directly from the forest but also of industrial by-products. There are opportunities to increase the utilization of low-value by-products in the form of bark and sawdust from the sawmill and pulp and paper industry, which today is not fully utilized, especially not during the summer. In addition, there is a none negligible potential in the use of waste wood.

Furthermore, abandoned arable land could be used for biomass production, for example by growing fast-growing deciduous trees for energy purposes. The potential for this has been estimated at about 2.3 TWh/y (Olofsson and Börjesson, 2016). Overall, the potential for increased use of forest biomass amounts to approximately 35-45 TWh/y year 2030. In this study it has been assumed that the potential lies at the lower end of the intervals, i.e. 35 TWh/y. In addition, some competition for the available raw material has been taken into account (25 % has been assumed to be used for other purposes, for example to substitute fossil raw materials and fuels in the petrochemical and iron and steel industries). Table 5 presents data regarding forest biomass outtake and transportation.

Table 5. Data for forest biomass outtake and transportation.

			Data based on
Increased outtake of forest biomass	TWh/y	35	Wetterlund et al. (2017)
Availability for biofuel production (average)	MWh/km²/y	58[a]	
Fuel needed for outtake of forest biomass	kWh/MWh	3	Eliasson and Johannesson (2014)
Transportation cost	SEK/MWh	10.6 + 0.34d	Wetterlund et al. (2017)
Fuel needed for transportation of forest biomass	kWh/MWh,km	0.05	Network for Transport and Environment (NTM) (2010)

[a] The availability around pulp mills is assumed to be 20 % higher than average.

From the assumed availability of forest biomass for biofuel production (MWh/km^2/y), presented in Table 5, and the need for biomass from the forest in the different cases, the uptake area needed and the average transportation distance was calculated using a factor of 1.4 to account for non-straight roads. The transportation was assumed to be performed by truck.

3.4 INTEGRATED BIOFUEL PRODUCTION

Because the potential for increased sustainable biomass outtake is limited, it is important to use the resource efficiently. Previous studies have shown the advantages of co-located, integrated biofuel production over stand-alone plants in terms of total energy and cost efficiency (Johansson et al., 2013, Ljungstedt et al., 2013, Andersson et al., 2014).

In Sweden, the pulp and paper industry is a major industry that accounts for a large share of potential sites for the co-location of biorefineries, such as biofuel plants. There are several reasons why the pulp and paper industry are especially interesting for the co-location of biorefineries. These include available biomass resources on-site, closeness to additional biomass resources, long-term experience and well-developed infrastructure for handling large volumes of biomass, and access to heat sinks and/or heat sources (Pettersson and Harvey, 2013). Possible disadvantages of co-location with the pulping industry could be long distances to and lack of knowledge about the products and their markets e.g. motor fuels.

Oil refineries are today mainly based on fossil feedstocks and are exploring options to integrate renewable feedstock into their operations. There are a number of advantages resulting from co-locating biorefineries at oil refinery sites. In addition to general integration advantages such as making use of existing infrastructure, these industries can often use biorefinery products such as bio-oil as feedstocks in their production processes. Furthermore, there are often substantial opportunities for heat integration with the biorefinery processes, and these industries have experience and know-how concerning the (final) products and their market. Possible disadvantages could be long transport distances and lack of experience of handling large biomass resources.

For biorefineries with large amounts of low temperature excess heat, the possibility for integration with a district heating system could be crucial in order to reach profitability. A disadvantage compared to integration with an industrial process, is that the heat demand in a district heating system varies significantly over the year. In many district heating systems it is very difficult to compete with existing base load technologies including waste CHP and existing deliveries of industrial excess heat. There could in these situations still be opportunities for (more) industrial excess heat in the systems, but only for a part of the year (e.g. 5000 h/y).

Integration with existing industry or district heating systems (here called host industries) have been considered for all studied biofuel production process. The integration includes heat integration with surplus heat from the biofuel production process being utilised to meet heat demands in the host industry, utilisation of industrial by-products (bark and lignin) as feedstock for biofuel production and utilisation of bio-oil in an existing refinery. Motives for choice of host industry and a description of the integration can be found in the section for the respective technology case (Sections 3.4.1-3.4.4) and Appendix A.

Table 6 presents the energy balances for the considered biofuel production concepts. The yearly operating time was set to 8000 h/y.

Table 6. Energy balances for the considered biofuel production concepts, based on one unit of fuel input to the biofuel production.

Biofuel - production technology - host industry	Biofuel 1	Biofuel 2	Steam/heat	Electricity prod.	Electricity use	H_2 use	Data based on
SNG-BMG-PoP	0.70	-	0.14	0.08	0.07	-	Wetterlund et al. (2017)
MeOH-BLG-PoP	0.54	-	0.20[a]	-	0.11	-	Wetterlund et al. (2017)
EtOH/BG-HF-DH	0.42	0.14	0.22	0.11	0.04	-	Wetterlund et al. (2017)
Diesel/Petrol-HTL-PoP/Ref	0.38	0.08	0.10[b]	0.01	0.02	0.15	Anheden et al. (2017), Furusjö et al. (2017)
El-CHP-DH	0.31	-	0.76	-	-	-	Nohlgren et al. (2014)

[a] Including purge gas used for steam generation.
[b] Including fuel gas used for steam generation.

It was assumed that the potential host industries are facing major energy investments, where they have the choice between investing in either conventional energy technology, or biofuel production plants that can fulfil the same utility services and in addition produce biofuels. With this approach, new biofuel production plants are only burdened with the incremental biofuel plant costs compared to alternative investments in conventional technology, which allows for an estimation of the potential role of existing industrial infrastructure in mitigating future biofuel production costs. However, this puts high requirement on technology availability. An alternative approach is to only consider the variable cost for the alternative technologies, which was done in a sensitivity analysis (see Section 4). Table 7 presents efficiencies for the alternative heat production technologies (CHP plants) in the considered host industries. For further descriptions, see Sections 3.4.1-3.4.4.

Table 7. Efficiencies for alternative heat production technologies.

Host industry	η_{el}	η_{heat}	Data based on
PoP	0.20	0.70	Wetterlund et al. (2017)
DH	0.31	0.76	Nohlgren et al. (2014)
Ref	0.20	0.70	

The pulp and paper mill considered is a generic integrated pulp and paper mill based on data of real mills from previous studies. The main data required to perform the calculation required in this study include flow of black liquor (430 MW) and falling bark (86 MW, all used in a bark boiler on site). For further discussion regarding the choice of mills and its consequences, the reader is referred to Appendix A.

Table 8 presents the investment cost functions used. Capital costs have been calculated through the annuity method using an economic lifetime of 15 years and an interest rate according to Section 2.1 (resulting in a CRF of 0.1/y). Annual operation and maintenance (O&M) costs were set to 4 % of the investment cost in all cases (this value is used in many previous studies, e.g. Furusjö et al., 2017). For the EtOH/BG-HF plant, an additional annual cost for chemicals and enzymes was added, corresponding to 2.3 % of the investment cost (Wetterlund et al., 2017). For the Diesel/Petrol-HTL additional costs for catalysts and chemicals was set to 200 SEK/$MWh_{biofuel}$/y (Anheden et al., 2017, Furusjö et al., 2017).

Table 8. Investment cost functions. C is the capacity in MW. All investment costs were recalculated to a 2017 monetary value using the Chemical Engineering's Plant Cost Index (CEPCI).

Biofuel production technologies	Inv. cost function a · C^b ($MSEK_{2017}$)			Data based on
	a	b	C (MW)	
SNG-BMG	62	0,7	Input wood fuel	Wetterlund et al. (2017)
MeOH-BLG	199	0.5	Input black liquor	Wetterlund et al. (2017)
EtOH/BG-HF	45	0.7	Input wood fuel	Wetterlund et al. (2017)
LI-HTL	52	0.7	Input lignin oil	Anheden et al. (2017), Furusjö et al. (2017)
HDO	5.3	0.6	Input bio-oil	Anheden et al. (2017), Furusjö et al. (2017)
Recovery boiler	25	0.7	Input black liquor	Wetterlund et al. (2017)
Steam boiler (wood fuel)	23	0.7	Input wood fuel	Wetterlund et al. (2017)
Steam cycle	22	0.7	Produced electricity	Wetterlund et al. (2017)
Biomass handling system	2.0	0.7	Input wood fuel	Wetterlund et al. (2017)
Biogas upgrading	2.6	1.0	Input raw biogas	Wetterlund et al. (2017)
Integrated drying	19	0.7	Drying capacity	Wetterlund et al. (2017)

Several studies have shown the advantage of large production plants due to economy of scale. For example Wetterlund et al. (2017) shows the advantages of large production plants, where the lower specific investment cost for the production plant is larger compared to the increased transportation costs for raw material due to larger required uptake area. However, there are aspects including available size of heat sinks that could make a somewhat smaller plant size more profitable compared to making it bigger (see e.g. Ahlström et al., 2017). Furthermore, even if the specific investment cost becomes lower, the absolute investment cost increases. The large capital investment required for e.g. large-scale gasification is a major obstacle to investors (Wetterlund et al., 2017). Therefore, there is an increasing interest in looking at smaller plants, e.g. in the case of black liquor gasification to establish commercial facilities. In this study we have chosen a plant size of 430 MW input wood fuel, as in Holmgren (2015). Optimal size could differ depending on several parameters, for example the specific technology. In this study, a sensitivity analysis is performed where the plant size is reduced to half, to see the effect on the results of considering a smaller plant size.

In the coming sections (3.4.1-3.4.4), the different biofuel concept including integration with host industry is shortly described. In addition, factors that limiting for the technical potential are discussed. Previous studies regarding integrated biofuel production, motives of choice of technology and host industry together with technical maturity (TRL level) and development of the technology can for each biofuel concept be found in Appendix A. The TRL level is similar for all the studied biofuel concepts, except the concept producing renewable diesel and petrol. A lower technical maturity does not only mean higher technical insecurity. In addition, the uncertainty concerning mass and energy balances for the concept as well as investment coast increases.

3.4.1 SNG produced via gasification

In this study data for the SNG concept was taken from Wetterlund et al. (2017), who in turn based it on data from Holmgren (2015). The SNG concept used is based on indirect dual fluidised bed gasification. The biomass is dried from 50 % MC to 20 % MC using an air dryer before entering the indirect gasifier. The produced gas is cleaned before the adiabatic methanation process. MEA technology is used for the CO_2 separation. For a more detailed description of the SNG concept, see Holmgren (2015). The energy balance for the SNG concept can be found in Table 6, presented above. Figure 2 presents a schematic overview of the SNG plant integrated with a chemical pulp and paper mill.

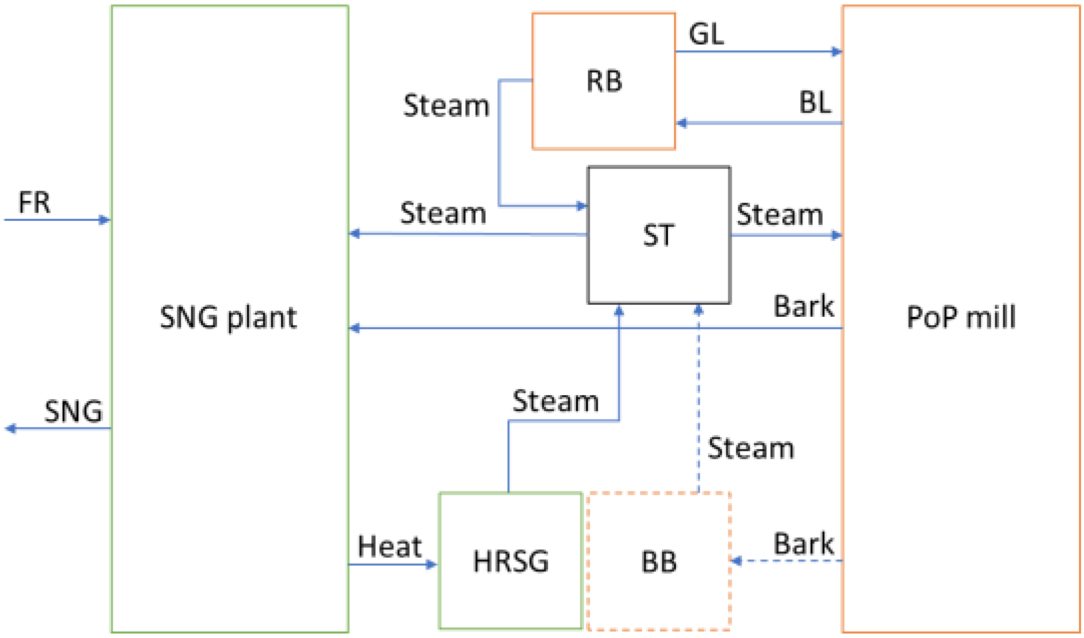


Figure 2. SNG plant integrated with a chemical pulp and paper mill.

There are significant amounts of high temperature heat from the process, enabling integration of a heat recovery steam generator (HRSG) connected to a steam turbine producing electricity, steam for internal process heat demands as well as steam for heat demands at the pulp and paper mill.

When modelling the integration of the SNG plant, it was assumed that the steam surplus from the SNG plant would cover the mill’s steam deficit (here defined as the extra steam needed in addition to the steam from the recovery boiler), thereby replacing the bark boiler that would otherwise be required. The bark boiler (alternative heat production technology) is shown with a dashed line in Figure 2. Falling bark from the mill was considered available for usage in the SNG plant. Excess low temperature heat at the mill was assumed to be used for biomass drying prior to gasification.

The potential for the value chain with SNG produced integrated with a chemical pulp and paper mill are limited by the total available heat sinks at these types of mills (total steam deficit). Even if there are many pulp and paper mills in Sweden, the energy efficiency is steadily increasing, making the steam deficit at integrated chemical pulp and paper mills smaller. However, there are other opportunities for integration of the SNG concept that could achieve close to the same total efficiencies as integration with a chemical pulp and paper mill (see Wetterlund et al., 2017). These include integration with mechanical pulp and paper mills, sawmills and district heating systems. If all possible heat sinks are considered, the potential will instead be limited by the availability of forest biomass.

3.4.2 Methanol produced via black liquor gasification

Data for the methanol concept was based on data from Wetterlund et al. (2017), who in turn based it on data from Andersson et al. (2016). The methanol process considered here is based on high-temperature entrained-flow gasification of black liquor. Black liquor gasification is currently being developed as an alternative technology to the recovery boiler for energy and chemical recovery at chemical pulp mills. The black liquor is gasified in a high-temperature entrained flow gasifier. The product gas in then cleaned and conditioned before the final catalytic synthesis of methanol. For a more detailed description of the methanol concept, see Andersson et al. (2016). The energy balance for the methanol concept can be found in Table 6, presented above. Figure 3 presents a schematic overview of the methanol plant naturally integrated with a chemical pulp and paper mill.

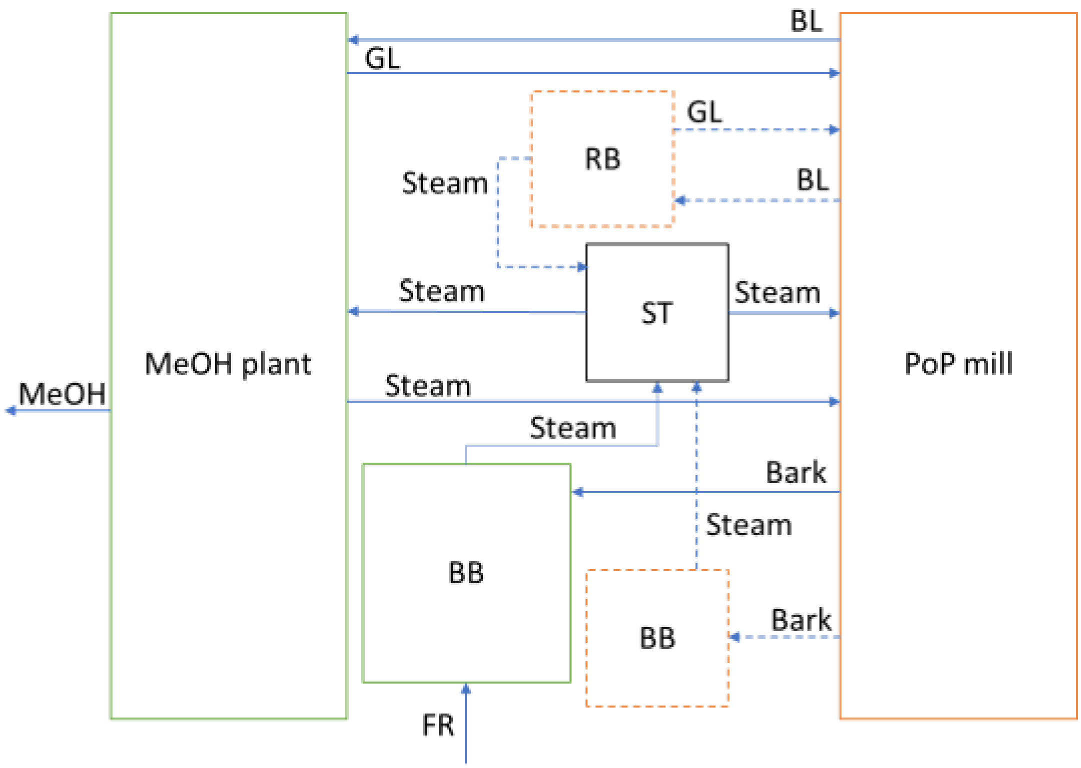


Figure 3. Methanol plant integrated with a chemical pulp and paper mill.

There are significant amounts of excess steam from the black liquor gasification-based methanol plant that are considered for use in the mill processes. However, the steam production is significantly lower than for the reference operation (no biofuel production) with a recovery boiler. Consequently, more wood fuel must be fired in the bark boiler when the recovery boiler is replaced with a black liquor gasification plant. This is indicated in Figure 3 by a greater bark boiler than for the reference operation.

The potential for the value chain with methanol produced via black liquor gasification are limited by the availability of black liquor which in turn is dependent on the amount of chemical pulp produced. However, in the more short-term perspective, the potential is rather limited by the availability of vehicles for methanol (see Section 3.6). Methanol can also be produced via gasification of solid biomass. Then, the availability of heat sinks and/or solid forest biomass (not black liquor) will be the limiting factor, as discussed for the SNG value chain.

3.4.3 Ethanol produced via hydrolysis and fermentation (with biogas as a by-product)

Data for the ethanol concept was taken from Wetterlund et al. (2017), who in turn based it mainly on data from Joelsson et al. (2015). The ethanol concept used starts with a steam pre-treatment step, followed by simultaneous hydrolysis and fermentation and anaerobic digestion, for production of ethanol and biogas. For a more detailed description of the ethanol concept, see Joelsson et al. (2015). The energy balance for the ethanol concept can be found in Table 6, presented above. Figure 4 presents a schematic overview of the ethanol plant, producing biogas as a by-product, integrated with a district heating system.

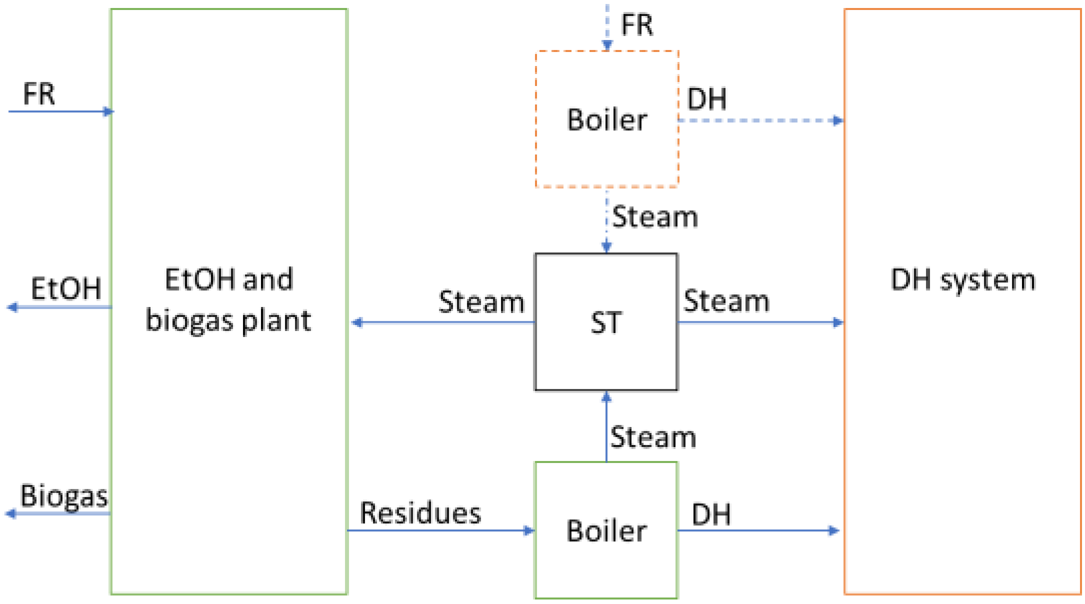


Figure 4. Ethanol plant integrated with a district heating system.

Residues from the process are used in a boiler to generate high-pressure steam, expanding through a steam turbine to generate electricity, steam for internal process heat demands as well as steam for district heating production. In addition, district heating is produced through flue gas condensation. It was assumed that the alternative heat production technology for district heating is a biomass-based CHP plant (with efficiencies according to Table 7).

The potential for the value chain with ethanol and biogas produced integrated with a district heating system is limited by the availability of suitable heat sinks in district heating systems. However, as for the SNG case, other integration opportunities exist. The ethanol plant could be integrated with industrial plants such as pulp and paper mills or sawmills, with somewhat lower total efficiencies, but still comparable to the energy balance for the concept integrated with a district heating system considered in this study (see Wetterlund et al., 2017).

3.4.4 Renewable diesel and petrol (refinery products from bio-oil)

Data for the concept producing renewable diesel and petrol from bio-oil was based on Anheden et al. (2017) and Furusjö et al. (2017). The concept starts with membrane-based separation of lignin at a chemical (kraft) pulp and paper mill. The lignin is then depolymerised (by a hydro thermal liquefaction (HTL) process) to produce a bio-oil. The bio-oil is then transported to a refinery, where a hydrodeoxygenation (HDO)-based upgrading to diesel and petrol takes place. For a more detailed description of the concept, see Anheden et al. (2017). The energy balance for the concept can be found in Table 6, presented above. Figure 5 presents a schematic overview of the production of renewable diesel and petrol integrated with a refinery and the foregoing lignin oil production by separation and depolymerisation of lignin at a chemical pulp and paper mill.

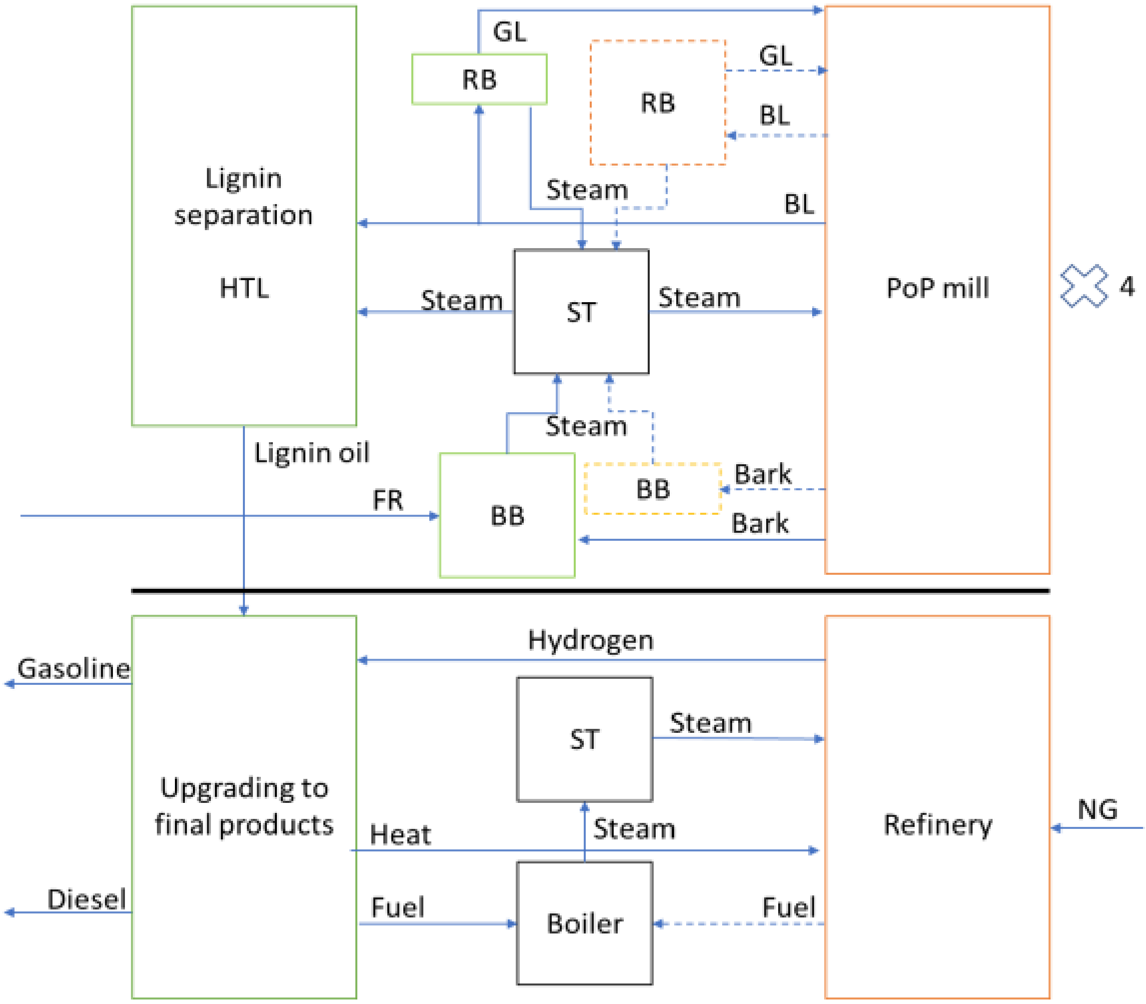


Figure 5. Production of renewable diesel and petrol integrated with a refinery. The lignin oil is produced by separation and depolymerisation of lignin at a chemical pulp and paper mill.

Since lignin is separated from the black liquor, its energy content naturally decreases. Consequently, less steam is produced by the recovery boiler when lignin separation is implemented. In addition, the depolymerisation process requires steam. In this study it was assumed that this is compensated by increasing the steam production in the bark boiler with purchased forest residues.

There is a limit to how much lignin that is possible to remove (without influencing the combustion in the recovery boiler). To be able to reach the same plant size as the other cases (430 MW input fuel), lignin from four mills are used.

The produced bio-oil is assumed to be transported by ship to a refinery for final upgrading[3]. The final upgrading to diesel and petrol requires hydrogen. It was assumed to be produced at the refinery from natural gas in a conventional way (steam reforming process). The upgrading of the lignin oil generates excess heat and fuel, which was assumed to be used at the refinery, thereby reducing the need for other fuels used for heating purposes at the refinery. In accordance with Johansson (2013), it was assumed to (on the margin) influence the need for natural gas.

The potential for the value chain with diesel and petrol produced from bio-oil is limited by the availability of lignin (that can be extracted), which in turn is turn is dependent on the amount of chemical pulp produced. As for the case of methanol produced via black liquor, there are tracks for production of renewable diesel and petrol that are based on solid biomass instead. The potential is then limited by the availability of solid forest biomass (or other factors connected to integration) instead of lignin.

3.4.5 Electricity from a CHP plant

Renewable electricity from forest biomass for use in electric vehicles was assumed to be produced in a CHP plant connected to a district heating system. The energy balance for the concept can be found in Table 6, presented above, and was based on Nohlgren et al. (2014). This case is naturally different compared to the other cases producing biofuels for usage in transport together with other products such as heat and electricity that is not intended to be used for transport purposes. Heat in the other cases is priced by its alternative costs, which are based on alternative heat production in CHP plants (see Table 7). This approach is naturally difficult to use in this case since the same technology is considered as for the alternative heat production in the other cases. For this case it was therefore assumed that allocation was made based on the energy content of the products (electricity and heat)[4].

The considered plant size is, as discussed above, set to 430 MW biomass input. This is a very large plant for a CHP plant in a district heating system. However, to use the same biomass plant input in all cases, this was not changed for this plant only. The operating time is also set to the same as the other plants, 8000 h/y. This is also questionable for this type of plant. In several district heating systems, operating times for biomass CHP of around 4500-5000 h/y would be more realistic. The excess heat would then be placed over the base load capacity, such as waste CHP and existing deliveries of industrial excess heat. In the sensitivity analysis, presented in Section 4, both a reduction of the plant size and a combination of reduction of plant size and lower yearly operating time is performed. For this value chain the potential is limited by, as for the case of ethanol, available heat sinks in district heating systems.

3.5 DISTRIBUTION OF BIOFUELS

Distribution costs for fuels vary with several factors and can significantly differ between different types of fuels, especially between liquid and gaseous fuels. Previous estimates of distribution costs indicate around 0.07 SEK/kWh for diesel, 0.05-0.31 SEK/kWh for methanol and 0.24-

[3] Transportation cost: 20.5 (SEK/MWh) + 0.01 (SEK/MWh/km) d (km); transportation distance: 500 km; Heavy fuel oil needed for transportation: 0.009 kWh/MWh/km. (Anheden et al., 2017)
[4] When allocating based on the energy content of the products, an adjustment was made for the heat production. Heat produced by flue gas condensation was not included, thereby lowering n_{heat} from 0.76 to 0.59.

1.1 SEK/kWh for methane (Becker et al., 2011; Mignard et al., 2003 and Ogden et al., 1999). In addition to taking part of data from existing studies we have also been in contact with a number of branch organisations and companies supplying distribution services in different parts of the distribution chain and asked them about volumes, prices, energy usage etc. This has been done since there are relatively large uncertainty regarding particularly distribution prices – through contacting relevant market players, and thus performing a comparison to the real market, the uncertainty in the adopted numbers should be lower than if just numbers from existing studies had been used.

3.5.1 Renewable petrol and diesel

There are no fundamental cost-related differences between distribution of fossil and renewable petrol and diesel. Since these fuels are produced in refineries, the distribution chain covers everything from transporting the fuels from the refinery to when the fuels are sold to the final consumer.

In Sweden almost all refinery capacity is located on the west coast (in Gothenburg and in Lysekil). Almost all refined fuels are transported by containerships to depots located in about 20 cities along the coasts.[5] Since a substantial part of the fuels are transported to Stockholm and other large cities on the east coast (e.g. Södertälje and Norrköping), this shipping distance is assumed as standard in the calculations.[6] The total cost for shipping fuels from the refineries to the Stockholm area varies depending on the circumstances on the shipping market the actual day. Since shipping prices are set in USD, variations on the foreign exchange market also affects the price in SEK. According to relevant market players, both oil companies (buyers of shipping services) and a shipping company (seller of shipping services), a rough estimation of the average price for the actual shipping service is about 0.1-0.2 SEK/litre. In this study we assume the shipping price from the refinery to the depot to be 0.15 SEK/litre.

From the depots the fuel is then transported to the fuelling stations by truck. There is a huge variation regarding the distance of this transportation. According to information from oil companies and haulage companies a rough estimation of an average trip for a truck from the depot to 2-4 fuelling stations and then back to the depot is around 200 kilometres. Furthermore, this distance is used in the calculations in this study. According to a number of oil companies this implies a distribution cost for transporting the fuel from the depot to the fuelling station of approximately 0.1 SEK/litre.[7]

The final step in the distribution chain, investing in and operate a fuelling station, constitutes the largest distribution cost. There is a huge cost variation depending on e.g. standard, size and distributed volume for the station but also depending on local conditions. In this study we have estimated the investment cost for the fuelling station for all liquid fuels to be 6 MSEK for a station with a distributed volume of 3 million litres annually. The depreciation time for the fuelling station is set to 15 years. The cost for operation of maintenance of this unmanned station is estimated to be about 300,000 SEK per year or 0.1 SEK per distributed litre.

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[5] There are two depots located in inland cities – in Jönköping and Västerås. The Jönköping depot is provided by train and the Västerås depot is provided by containerships on Mälaren lake.
[6] Parts of the volumes are transported a shorter distance to cities in south Sweden (e.g. to Malmö, Helsingborg and Karlshamn) while some part is shipped a much longer distance to depots in the north (Sundsvall, Umeå, Piteå and Luleå).
[7] The cost varies between the different companies, the distance and also between other circumstances (e.g. volume per filling station). In populated areas close to a depot the cost for distributing the fuel to a filling station can go down to about 0.05 SEK/liter while the cost in rural areas can be as high as over 0.3 SEK/liter.

3.5.2 *Ethanol and methanol*

Ethanol and methanol are distributed from the production plant directly to the fuelling stations, i.e. there is no need for transportation to a refinery and then further on to depots. The transportation cost from the production unit to the fuelling stations is assumed to be 50 % higher per kWh for ethanol and methanol relative the transportation of (renewable and fossil) petrol and diesel from the depots to the fuelling stations due to lower energy content. For ethanol and methanol, we assume an average distance of 200 km (round trip) to the fuelling station. For a larger production plant a longer distance might be necessary to reach a sufficient market. In this study, however, we assume that the establishment of a larger production plant is a consequence of a higher demand for the actual fuel and thus we use the same distribution distance for all production sizes. In reality, however, it might be necessary to increase the distribution distance when increasing the size of the production plant. Furthermore, the cost for distributing ethanol and methanol to the fuelling stations are estimated to be 0.15 SEK/litre.

Since the conditions for fuelling stations are the same for all liquid fuels, the assumptions and costs regarding the final step in the distribution chain presented in Section 3.5.1 is valid also for ethanol and methanol, i.e. totally 0.1 SEK/litre. However, the cost per kWh is higher for ethanol and methanol since these fuels have a lower energy density than petrol and diesel.

3.5.3 *CBG*

There are two main options for transporting gaseous fuels, pipeline or as compress gas in swap bodies, where the latter is the most common procedure in Sweden for biogas. Unlike other countries, the Swedish natural gas grid only covers the most southerly part and the west coast of Sweden which limits the location where grid distribution is a viable option without additional investments in infrastructure. Thus, road transport of swap bodies is deemed to be the major alternative in Sweden for a foreseeable future. The distribution cost has been estimated for both options and the conclusions is that the costs are comparable.

The cost estimation for truck distribution of swap bodies are based on an average distribution distance of 200 km (round trip). The amount of energy per truck load substantial lower due to lower energy density in the compressed gas, and the additional weight of bottles for the compressed gas. As for methanol and ethanol we assume that the establishment of a larger production plant is a consequence of a higher demand for the actual fuel and thus we use the same distribution distance for all production sizes. But in reality it might be necessary to increase the distribution distance when increasing the size of the production plant.

The investment cost for a CBG filling station is estimated to 7.5 MSEK[8] which is depreciated over 15 years, and the operation and maintenance costs are estimated to 500 000 SEK/y. The annual distributed volume is assumed to be the same for all fuels, 30 GWh/y.

3.5.4 *LBG*

Biogas can be liquified to increase the energy density and thereby facilitate distribution and handling. A liquefaction plant is needed to convert the gas into a liquid by cooling to -125-140˚C at 4-10 bar, reducing the volume by 1/600 compared to uncompressed gas and about 1/3 compared to

[8] Based on Klimatklivet's funding statistics regardning new CBG and LNG refueling stations.

CBG. This process is commercially available in large scale and commonly used to facilitate shipping of natural gas over great distance. LBG for road transports will primarily be used for heavy trucks since lighter transport can be made with compressed biogas despite the lower energy density.

The cost estimation for a liquefaction plant in the scales relevant for this study (0.5-2.4 TWh/y) have been difficult since it is significant bigger than plants built for biogas (50 GWh/y) and at the same time not directly comparable with large facilities (50-200 TWh/y). The specific investment is assumed to be $1000 per tonne of annual (TPA) production capacity which is in the higher end of large-scale project facility (Songhurst, 2014) but about 40 % lower specific investment cost than the small scale LBG built in Sweden[9]. The electricity consumption for liquefaction is 0.5 kWh/kg (Wärtsilä, 2016) and the cost for operations and maintains is estimated to 3 % per year of the initial investment (excluding cost of electricity). A 20 years depreciation period have been assumed for the liquefaction plant.

The cost for road transport of LNG is calculated using the same assumptions as for other liquid fuels, with account taken for the lower energy content per shipment. The investment cost for a LNG dispenser amounts to 11.3 MSEK[8], 15 years lifespan, and the annual sale to 30 GWh. Transportation costs have been based on truck distribution with a 200 km round trip distance.

3.5.5 Electricity

Electricity is distributed in the conventional electricity grid from the CHP plant to the final consumer. The distribution tariffs include both transmission and distribution and relevant authority fees etc. The relevant average distribution tariff in Sweden is about 0.36 SEK/kWh (Statistics Sweden, 2018; Swedish Energy Markets Inspectorate, 2018) including both fixed cost, energy cost and cost for peak load.

Additionally, the actual electricity installation may need to be adjusted in order to enable vehicle loading. The assumed costs for these installations are 14 400 SEK for cars and 0.5 million SEK for a depot for trucks (Emobility.se, 2018). The depreciation time for these units is set to 15 years and the cost for operation and maintenance are assumed to be 5 % of the installation cost including charging losses.

It has been assumed that one charger is installed per truck to make sure that the productivity of the truck is not affected, which could be the case if the infrastructure is shared. Further, the private car is assumed to only use home charging.

3.6 USAGE OF BIOFUELS FOR ROAD TRANSPORTATION

Total annual vehicle costs (excl. fuel) has been calculated for relevant cases for cars, distribution trucks and long-distance trucks. These costs include:

- Purchasing cost (annual capital cost)
- Costs for operation and maintenance (service, repair, insurance, tires, other materials, vehicle inspection)

[9] Air Liquide, 2018, personal communication.

- Taxes, fees and subsidies (vehicle taxes and vehicle purchasing bonus)

Capital costs have been calculated through the annuity method. The present value of the residual value for each year has been calculated and then subtracted from the annual capital cost. The economic lifetime and the residual value are different for the different vehicles and are specified below.

3.6.1 Car

The annual driving distance for the car is set to 15 000 km in the base case. The average annual driving distance for a car is about 12 000 km in Sweden. Thus, the base case distance is a bit above the average driving distance. The car is assumed to be used for a period of 10 years and the economic residual value after the period is set to 20 % of the initial vehicle price.

Volkswagen Golf is available with engines relevant for almost all fuels analysed in this study – petrol, diesel, SNG/biogas, ethanol and electricity. Regarding methanol it is assumed that the usage conditions are the same as for ethanol, although it is highly uncertain whether methanol cars will be introduced on the market.

The official standard market prices, fuel consumption, assumed costs for operation and maintenance etc. for the different Golf models are presented in the Table 9.

Table 9. Costs and fuel consumption for cars (Volkswagen, 2018; Bilsvar, 2018).

Fuel	Unit	Diesel	Petrol	SNG/Biogas (CNG/CBG)	Ethanol/ Methanol	Electricity
Model		Golf TDI115 DSG7	Golf TSI110 DSG	Golf 1,4 TGI 110 Blue Motion DSG	Golf 1,4 TSI 125	e-Golf
Price (excl. VAT)	SEK	195 520	174 320	196 320	177 520	323 120
Costs for operation and maintenance (excl. taxes)[a]	SEK	15 600	13 600	13 600	14 600	12 600
Vehicle tax[b]	SEK	2 161	680	360	415	360
Purchase bonus/subsidy (excl. VAT)	SEK	-	-	8 000	-	48 000
Fuel consumption	fuel/10 km	0.39 l	0.48 l	0.35 kg	0,71 l	1.3 kWh
Energy use	kWh/10 km	3.8	4.4	4.6	4.7	1.3

[a] Includes service, repair, insurance, tires, other materials etc.
[b] Refers to the average vehicle tax for 10 years including malus tax for petrol and diesel vehicles the first 3 years.

3.6.2 Long-distance truck and distribution truck

The annual driving distance is set to 50 000 km for the distribution truck and to 200 000 km for the long-distance truck. The distribution truck is assumed to be used for 10 years and the economic residual value after the period is set to 20 % of the initial vehicle price. The corresponding values for the long-distance truck is 6 years and 30 % residual value.

Currently, the diesel engine is the main option for long-distance trucks for distribution or long-distance transport. The powertrain has been developed and cost optimized over a long period and is produced in large numbers. There are other options such as powertrains for ethanol (ED95) or compressed or liquefied biogas (CBG/LBG), but they have been developed more recently and are produced in smaller volumes. The production costs and retail prices for them are therefore higher than for a diesel trucks. However, until 2030 there is a potential for larger production volumes and lower production costs.

ED95 is used in modified diesel engines. Trucks with these types of engines could theoretically be produced at similar costs as conventional diesel engines. However, today vehicles for CBG or LBG have a higher price than diesel vehicles. This will probably be the case also in 2030. The higher production costs can to some extent be explained by the fact that compressed or liquefied gas requires a slightly different technology than liquid fuels. In this report, it is assumed that LBG is used in a dual-fuel engine.

According to a report published by the IEA, a CBG truck would cost 33-50 % more than a diesel truck in 2015 and about 35 % more in 2030 (IEA, 2016). The additional cost for an LBG truck is estimated to 47-50 % more than for a diesel truck in 2015 and 40-50 % more in 2030, according to the same IEA report. Furthermore, the cost for an electric truck is estimated to be 180 % higher than for a diesel truck in 2015 and 100 % higher in 2030.

This can be compared with an estimation from the consultant firm Roland Berger of a price difference of 30 000 EUR between the LBG truck and the diesel truck, which also could correspond to about 30 % higher costs (Roland Berger, 2016). Another study, MetDriv, also estimated the price for an LBG truck to up to 30 % more than for the diesel truck, while the price for the CBG truck could be 10 % (or more) more than for the diesel truck (Börjesson et al., 2016).

In this study, it is assumed that a distribution truck for CNG costs 30 % more than the corresponding diesel truck and that a long-distance truck for LNG costs 30 % more than the corresponding diesel truck. A power train for ethanol (ED95) is assumed to be equal with diesel. As shown above, all these proportions assume improved technical and market conditions (larger volumes demanded and produced) relative todays situation.

Regarding fully electric distribution trucks, there are few relevant cost estimates in the literature. The future costs are uncertain and depend heavily on the development of battery costs. For a simplified cost estimate of the cost of the electric truck, it is here assumed that the cost increase compared to a diesel truck is the cost of the battery pack. A range of 200 km and a consumption of 1.25 kWh electricity per km would result in a battery pack of around 250 kWh. Cost estimates for that is given in Table 10.

Table 10. Estimated cost of the battery pack in a fully electric distribution truck (IEA, 2016).

	Unit	Current price	Target 2030
Battery cost	[SEK/kWh]	3150	900
Battery size	[kWh]	250	250
Total cost	[SEK]	800 000	225 000

The current price for batteries has been used since it is possible to get investment support for electric trucks at today's cost. It is unlikely that electric trucks would be subsides if the price target for 2030 is reached.

In the literature the higher service cost for CBG and LBG has been estimated to 14 % and 15-20 % respectively. In this study, it is assumed that the service cost continues to decrease and that it is around 10 % higher than for diesel trucks in 2030.

Table 11 and Table 12 summarize the base assumptions and data regarding trucks.

Table 11. Costs and fuel consumption for distribution trucks.

Fuel	Unit	Diesel	Gas (CNG/CBG)	ED 95	Electricity
Price MSEK (excl. VAT)	MSEK	1.2	1.55	1.2	2
Costs for operation and maintenance (excl. taxes)[a]	SEK	79 000	83 400	79 000	74 800
Vehicle & Road tax	SEK	10 000	8 200	8 200	8 200
Purchase subsidy (excl. VAT)[b]	SEK	-	175 000	-	400 000
Fuel consumption	fuel/10 km	3 l	2.6 kg	4.8 l	12.5 kWh
Energy use	kWh/10 km	29.4	34.4	29.4	12.5

[a] Includes service, repair, insurance, tires, other materials etc.
[b] Subsidy through the subsidy programme Klimatklivet; 50 % of the additional cost compared to a diesel truck.

Table 12. Cost and fuel consumption for long-distance trucks.

Fuel	Unit	Diesel	LBG/LNG	ED 95
Price (excl. VAT)	**MSEK**	3.5	4.55	3.5
Costs for operation & maintenance (excl. taxes)[a]	SEK	323 300	339 300	323 300
Vehicle & Road tax	SEK	21 482	12 975	12 975
Purchase subsidy (excl. VAT)	SEK		525 000	
Fuel consumption	litre/10 km	4.5	3.4 kg	7.2
Energy use	kWh/10 km	44	44	44

[a] Includes service, repair, insurance, tires, other materials etc.
[b] 50% subsidy of the additional cost compared to a diesel truck.

3.7 FOSSIL REFERENCE VALUE CHAINS

Regarding the fossil reference value chains, petrol and diesel, the total cost per km has been calculated by estimating the pump price and then add the cost for usage of the fuels. The pump price (excl. taxes) was estimated based on correlation between the pump price and the oil price (Axelsson and Pettersson, 2014). The oil price used is presented in Table 1 (Section 2.1.1). The vehicle-related costs are presented in Section 3.6. Thus, the fossil reference value chains include economic margins also in the production (and distribution) stage. This implies that when the alternative fuels are not competitive to fossil fuels in the calculations in this study, the actual production will have an even harder competitive situation in reality. The results in this study can, thus, be interpreted as when the renewable fuels have higher costs than the fossil alternatives, the circumstances must be changed to make the renewable alternative competitive. On the other hand, when the results indicate that the renewable fuel has a lower total cost than the fossil alternative, it has to be considered that there is no economic margin included for the renewable fuel in the production stage.

4 RESULTS AND DISCUSSION

This chapter presents and discusses the results concerning cost efficiency (Section 4.1), energy efficiency (Section 4.2) and GHG emissions (Section 4.3) for the studied cases. The results for cost efficiency are presented per transport segment. Furthermore, for each transport segment, the economic results are presented in three sections: excluding policy instrument, including policy instruments and a sensitivity analysis.

4.1 COST EFFICIENCY

This section presents the total cost per km for the studied cases presented in Table 4. In addition, potential margins for producers (and distributors) of biofuels are presented. The total cost consists of the production, distribution and vehicle cost. For a presentation of these costs separately, and what they consist of, the reader is referred to Appendix B (production cost), Appendix C (distribution cost) and Appendix D (vehicle cost). In addition, Appendix B includes the resulting total net input and output of different energy carriers, as well as the net investment cost, compared to the alternative investment for the host industries, for the considered production plants.

As mentioned in Section 2.1, margins for producers and distributors are included for the fossil reference chain (current pump price), while it is not included for the biofuel chains.

4.1.1 Car segment

Excluding policy instruments

Figure 6 presents the total cost for the car segment, excluding policy instruments such as taxes and subsidies. The dominating cost for the car segment is the vehicle cost. The main part of the vehicle cost is depreciation of the vehicle. For all cars except the electric car, the depreciation constitutes about 60 % of the total cost of ownership. For the electric car the corresponding value is 75 %, due to higher purchase price. Almost all cars (taxi cars excepted) are parked most of the time. Even if the annual driving distance (15 000 km) is assumed to be above average, it is a relatively short distance to allocate the annual depreciation cost. It can also be noted that the distribution cost accounts for a minor share of the total cost in all car cases.

The fuel production cost, per km, is roughly the same for all biofuels and this level is also in parity to the corresponding cost level for petrol and diesel. This implicates that given that the distribution and vehicle costs not were higher for renewable fuels, the biofuels could be competitive from a strictly economic perspective also without policy interventions. However, distribution and usage of ethanol, methanol and biomethane are more expensive than for petrol and diesel and thus the total usage cost from well-to-wheel is higher for the renewable fuels. Regarding biopetrol and biodiesel, that for natural reasons have the same distribution and usage cost as the fossil alternatives, the production cost is more than 20 % higher than for fossil diesel and petrol.

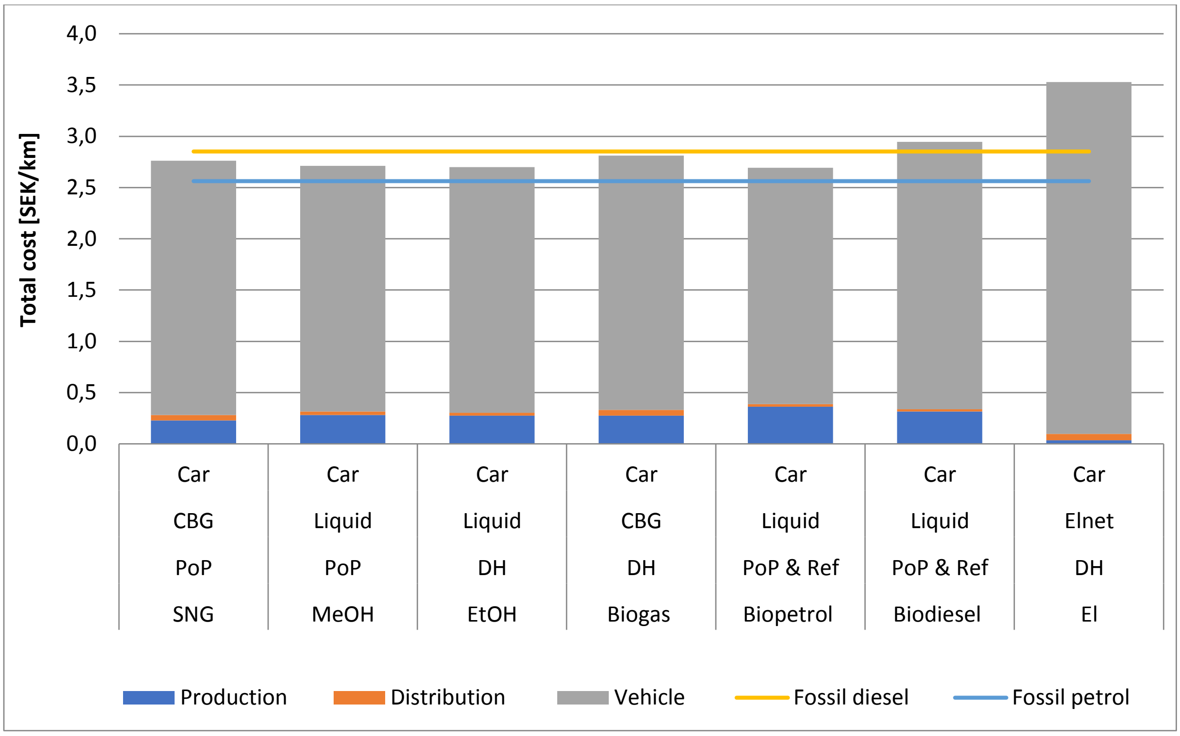

Figure 6. Total cost for the car segment, excluding policy instruments.

The cost of producing electricity is considerably lower than for the biofuels (see Appendix B) due to the combined heat and power concept used in this study. Further, the electric drivetrain is also about three times more energy efficient than conventional internal combustion engines (see Table 9). However, the electrical car has a 65-85 % higher purchase cost than the other alternatives. An annual driving distance of 15 000 km is not enough to compensate for the larger depreciation cost per km. However, as will be shown in the sensitivity analysis below, an increased driving distance will have huge impact on the competitiveness of the electric car.

To summarize, the total cost per km is in parity, but not competitive, with the fossil reference for all cases except for the electricity case that stand out due to higher vehicle purchase price. Keep in mind that margins for producers and distributes are included for the fossil reference chains, but not for the biofuel chains. Thus, to be competitive, the total cost for a biofuel (including electricity) case must be a bit lower than the total cost for the corresponding fossil reference chain. As mentioned in Chapter 2, for the car segment all cases, except renewable diesel and electricity, are compared to the fossil petrol value chain.

Including policy instruments

Figure 7 presents the total cost for the car segment, including policy instruments. The taxes on fossil fuels, making them more expensive, contributes significantly to the competitiveness for all biofuels. Within the bonus-malus system, only vehicles dedicated to alternative fuels receives benefits. Practically, this means that primarily electric cars but to some degree also gas cars are subsidised in the system. Cars that use biofuels that can be used in conventional engines (e.g. ethanol cars that also can use petrol as a fuel) are not given a bonus in the bonus-malus system. These cars are not malus taxed, but they are still liable for the ordinary vehicle tax. All biofuels are deemed to be competitive with policy instruments, including significant margins for producers and distributors.

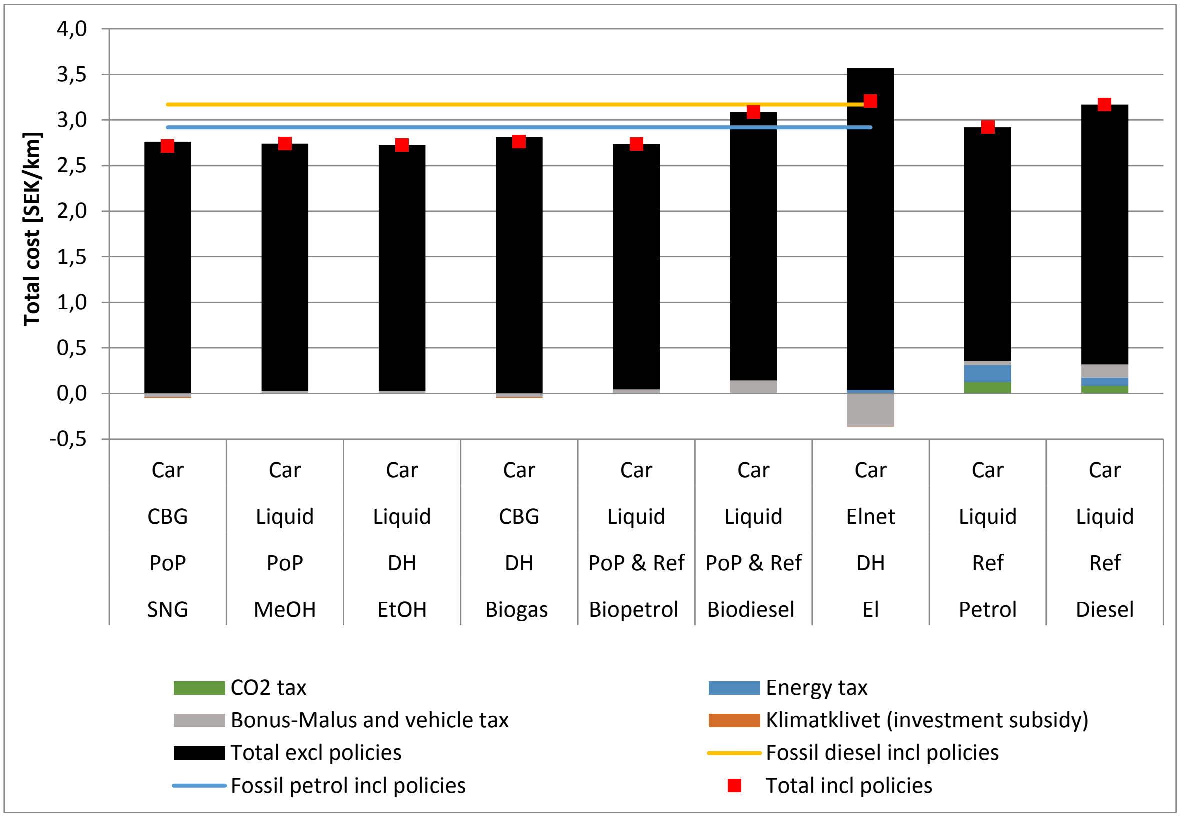

Figure 7. Total cost for the car segment, including policy instruments.

The electricity-based value chain has the highest cost both with and without policy instrument, despite receiving the larges subsidies (mainly purchase subsidy for the electric vehicle). This means that the current policies give the largest subsidy to promote the fuel that has the highest well-to-wheel cost of all renewable fuels given a driving distance in parity with the average driving distance for Swedish cars.

At the same time the renewable fuels that has the lowest well-to-wheel cost without policy instruments included (with the driving distance close to average as assumed here) – biopetrol, ethanol and methanol – are all taxed rather than subsidized. This is since these cars are not exempted from vehicle tax. Primarily the renewable diesel, but also the renewable petrol, is also punished in the bonus-malus-system since the vehicles and the engines are the same independently whether the diesel/petrol is fossil or renewable. Since the fossil alternatives are taxed also on the fuel side, and not only on the vehicle side, the competitiveness of the renewable alternatives is, despite the vehicle tax and the malus, better when policy instruments are included.

As mentioned, no margin for biofuel producers and distributors are included in the calculations of the total cost. Instead an indicative margin has been calculated by comparing the results of the total cost for the renewable alternatives with the total cost for the fossil reference cases. The indicative margin is presented in Figure 8. The margin is between approximately 0.20-0.45 SEK/kWh (corresponding to approximately 0.10-0.20 SEK/km, which can be seen in Figure 7) for the biofuel cases. For electricity, the margin is negative, as could also be seen from Figure 7. Since some of the fuels are produced in the same plant, it is highly relevant to look at the plant margin in these cases. For the ethanol and biogas plant the margin is 0.40 SEK/kWh (mostly influenced by the margin for ethanol, since about three times more ethanol than biogas is produced, see Table 6). For the plant producing renewable diesel and petrol, the margin is 0.25 SEK/kWh (the margin is significantly more influenced by the margin for diesel, since nearly five times as much diesel as petrol are produced, see Table 6).

The estimated margins are rather substantial taking into account that the calculated production costs for the biofuel cases amount to approximately 0.5-0.85 SEK/kWh (see Appendix B) and that the gross margin for fossil fuels have been estimated to 0.1-0.15 SEK/kWh by the Swedish Energy Agency (Swedish Energy Agency, 2017).

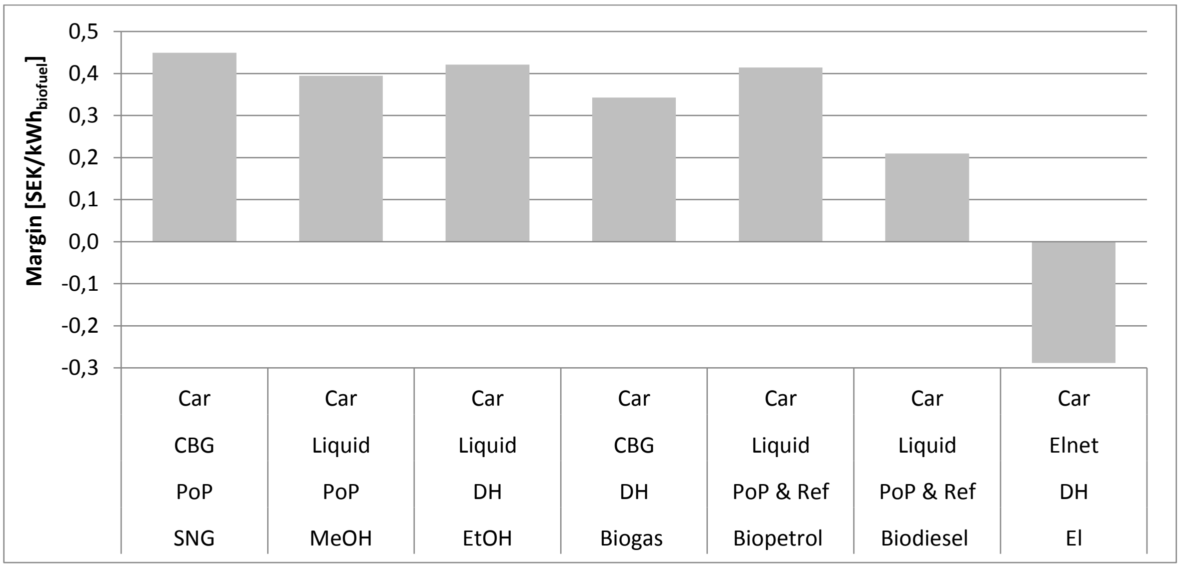

Figure 8. Margin for producers and distributors based on the total cost difference compared to the fossil reference chains for the car segment.

The margins can also be related to the fuel taxes on fossil fuels, i.e. the energy tax and the CO_2 tax. The energy tax is 0.43 SEK/kWh for petrol and 0.24 SEK/kWh for diesel. The CO_2 tax is 0.28 SEK/kWh for petrol and 0.22 SEK/kWh for diesel. Thus, the total fuel tax is around 0.7 SEK/ kWh for petrol and almost 0.5 SEK/kWh for diesel (corresponding to 0.31 and 0.23 SEK/km). These numbers are in parity with the presented margins.

There are several parameters that are uncertain that could impact the results. In the next section, a sensitivity analysis is presented where the influence of changing chosen parameters are shown.

Sensitivity analysis

The sensitivity analysis is an important part both to check how the assumptions influence the overall results, but also to ensure that the results are robust. The parameters included in the sensitivity analysis are listed in Table 13.

A change of the capital recovery factor could also represent a change of the investment cost, or a combination of these. The doubled price of forest biomass is in line with future projections for the Swedish market (Andersson, 2010).

A sensitivity analysis where a number of parameters was combined, has been included. These parameters include higher energy prices (biomass, electricity, crude oil), higher CRF and that the heat price is based only on the variable costs (for the alternative heat production technology). Thus, all these changes, except the higher crude oil price and the higher electricity price for some cases, disfavours the biofuel cases.

Table 13. Parameters included in the sensitivity analysis for the car segment.

	New value/Base value
Related to production of biofuels	
Size biofuel production plant -50 %	215/430 MW biomass input
Biomass price +100 %	289/144 SEK/MWh (FR)
Natural gas and Hydrogen price +50 %	503/335 and 603/402 SEK/MWh
CRF +25 %	0.13/0.10
CRF -25 %	0.08/0.10
Heat price based only variable costs	Varies between different biofuel cases
Size production plant -50%, Yearly operating time 5000 h/y (only for electricity case)	215/430 MW biomass input, 5000/8000 h/y
Related to production and distribution of biofuels	
Electricity price + 50 %	600/400 SEK/MWh
Electricity price – 50 %	200/400 SEK/MWh
Related to vehicle usage	
Vehicle 25% residual value	25/20 %
Vehicle 15% residual value	15/20 %
Yearly driving distance 10000 km/y	10000/15000
Yearly driving distance 20000 km/y	20000/15000
Yearly driving distance 30000 km/y	30000/15000
No residual value battery	Same residual value as the reference car
Yearly driving distance 30000 km/y, 10 % residual value	30000/15000, 10/20 %
Related to fossil reference chains	
Crude oil price 50 USD/barrel	50/75 USD/barrel
Crude oil price 100 USD/barrel	100/75 USD/barrel
Combination	
Biomass price +100 %, CRF +25 %, Heat price based only variable costs, Electricity price +50 %, Crude oil price 100 USD/barrel	289/144 SEK/MWh, 0.13/0.10, varies between different biofuel cases, 600/400 SEK/MWh, 100/75 USD/barrel

Figure 9 (all cases except the electricity case) and Figure 10 (electricity case) presents the results of the sensitivity analysis for the car segment. The analysis has been performed for all listed parameters. However, only those affecting the margin more than 0.1 SEK/kWh (for one or more of the cases) is presented.

The biomass price generally has the largest impact on the fuel productions cost, e.g. a 100 % increase in the biomass cost would make the margin for renewable diesel production negative. A decrease in crude oil price to 50 USD/barrel would naturally reduce the margin in all cases, but it will remain positive for all fuels.

To base the heat price that the biofuel plant receives for excess heat deliveries to the host plants only on variable costs (instead of also including alternative investment cost as has been done in the base case) do not influence the margin to a great extent for most cases. However, for the MeOH case the influence is greater, leading to a reduction of the margin with more than 50 % (see Figure 9). The reason for this is that the alternative investment cost is very large for this case, as it includes the entire boiler and steam turbine system, including a recovery boiler.

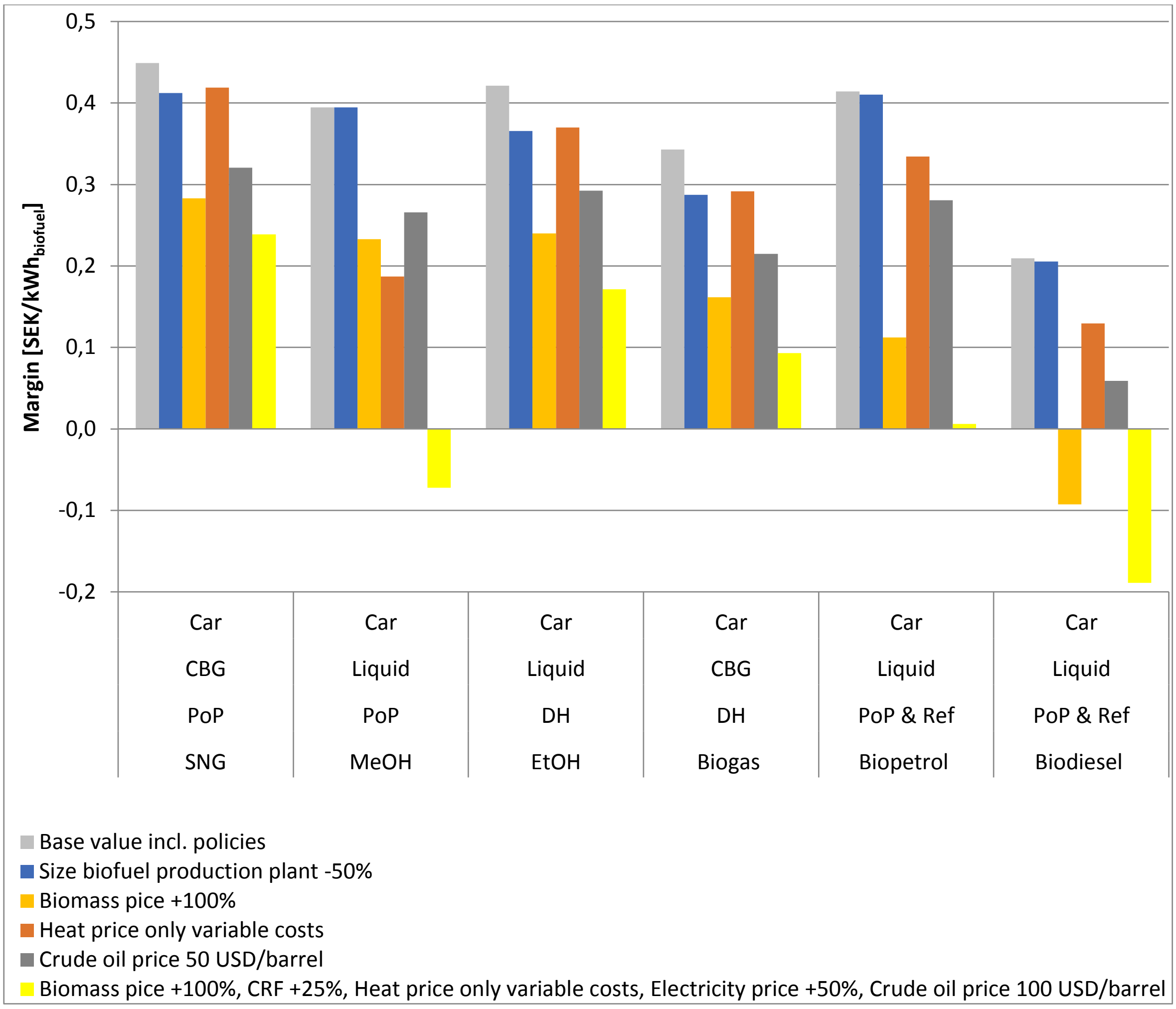

Figure 9. Sensitivity analysis, showing the influence on the margin for producers and distributors, for the car segment (excluding the electricity case).

An increase of the natural gas and hydrogen price (not included in Figure 9) has a very small influence on the results. The reason for this is that the increased cost for hydrogen is compensated by an increased revenue for sold heat (the heat price is partly based on the natural gas price, see Section 3.4.4).

For the sensitivity analysis where a number of parameters are combined, most cases still has a positive margin, even if it is significantly lower than when the base assumptions are used. In some cases, it is still relatively high (SNG, EtOH). However, for the MeOH and biodiesel cases, the margin is negative under these conditions. The MeOH case is, as discussed, greatly influenced by the pricing of excess heat, which has the largest influence on this case out of the changed parameters in the combined sensitivity analysis. This highlight that finding window of opportunity for investments, where the mill is going to invest in new energy technology, is really a critical factor the MeOH case in this study, based on black liquor gasification. In addition, the MeOH case is also more negatively influenced by the increase in electricity price than the other cases. Diesel with the lowest margin from the beginning, also has a negative margin under these conditions. For example, as mentioned above, this case is greatly influenced by a higher biomass price. This is due to the relatively high biomass usage per kWh biofuel in this case (see Table 6).

The analysis also included different inputs of annual driving distance. The results showed minor changes in margin for all fuels except for electricity. This result is expected since the vehicle costs for biofuels and the fossil fuels are in the same range, while electric vehicles that have considerably higher investment cost but lower running cost. Further, diesel cars with higher fuel efficiency but higher fixed cost also benefits from a longer driving distance.

Figure 10 presents the results of the sensitivity analysis for the electricity-based value chain. These results are presented separately to emphasize the parameters most important for electric vehicles.

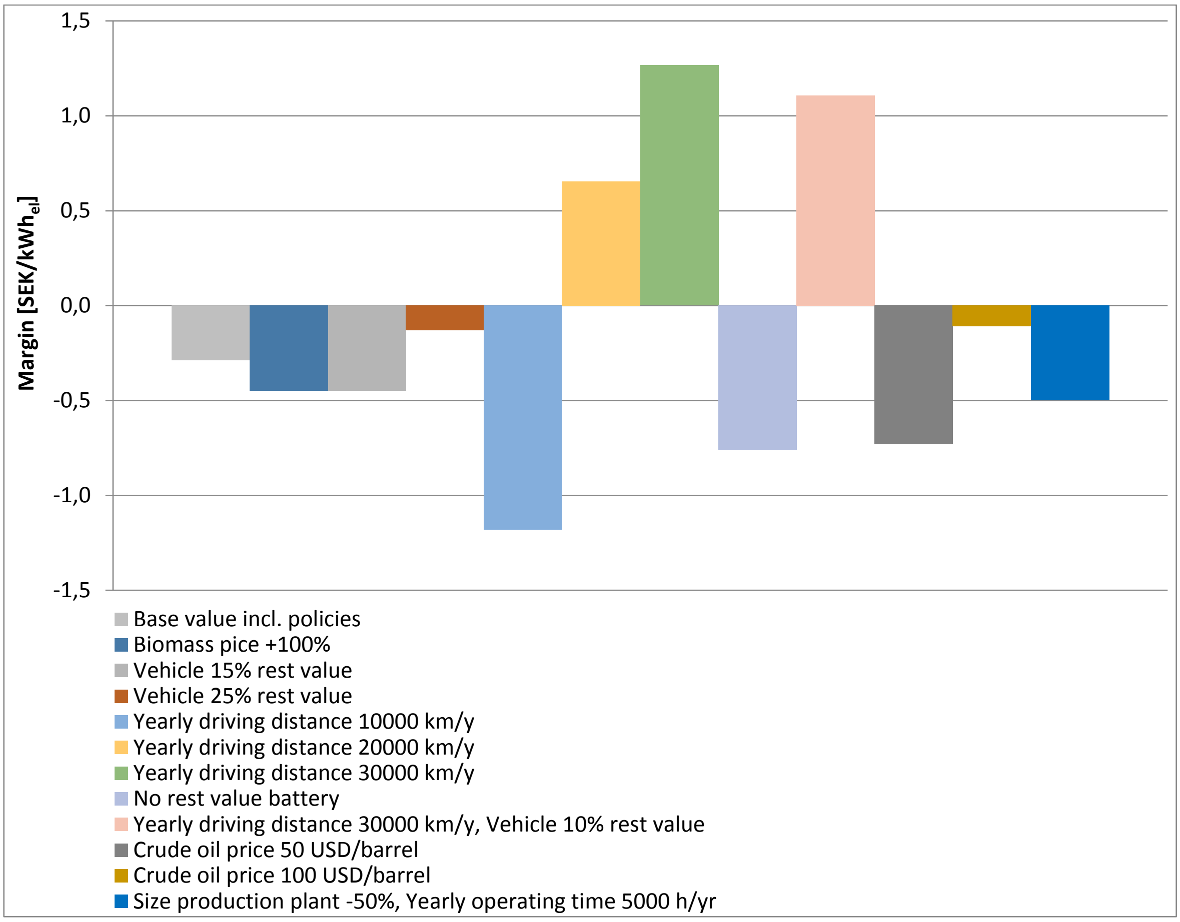

Figure 10. Sensitivity analysis for the electricity case (car segment).

As mentioned previously the driving distance has very large influence due to low operating costs and high cost for depreciation of the vehicle. When changing the yearly driving distance from 15000 to 20000 km/y, the electricity case will have a significantly positive margin, in contrast to the negative margin in the base case. The uncertainty regarding battery lifespan is tested calculating the cost if the battery had no value at the end of the 10-year period. In this case the residual value for the electric car was assumed to be equal to the residual value for the petrol car. This parameter, together with the other parameters presented in Figure 10, all significantly influence the potential margin for the electricity case. Other parameters include change in crude oil price, reduced size and operating time of the production plant, change in vehicle residual value and increased biomass price.

4.1.2 Distribution truck segment

Excluding policy instruments

The results regarding total cost for the distribution truck segment, excluding policy instruments, are presented in Figure 11. Fossil diesel has been used as the reference, since petrol is rarely used for distribution trucks.

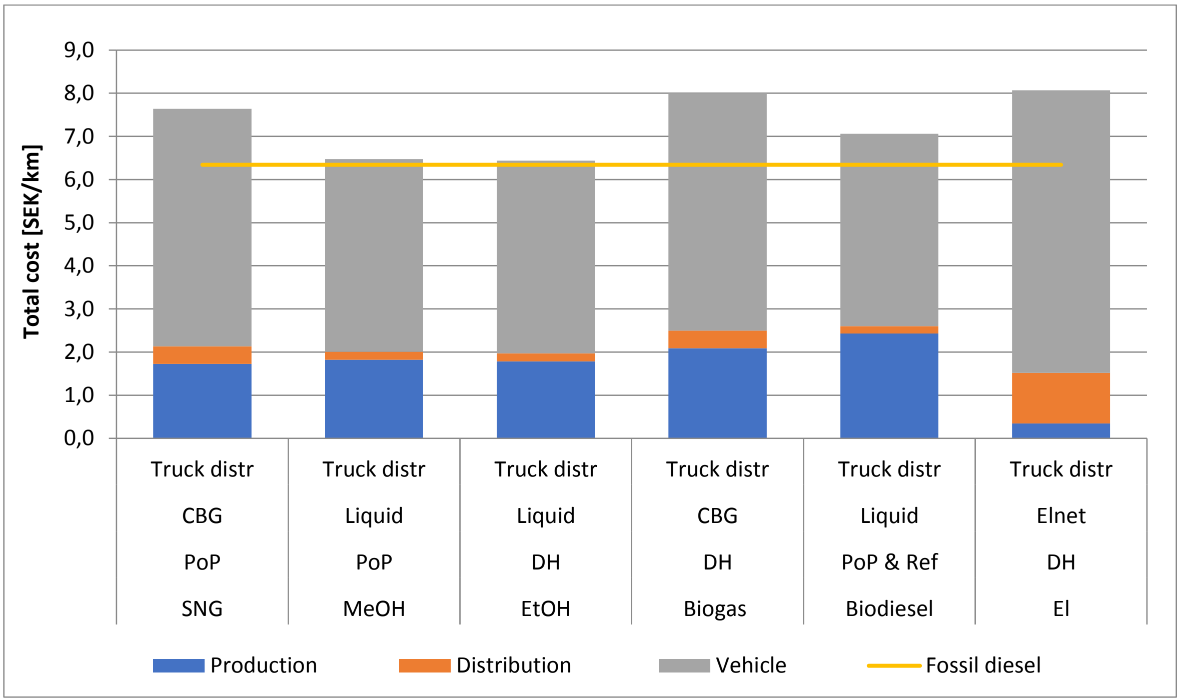

Figure 11. Total cost for the distribution truck segment, excluding policy instruments.

The vehicle costs are less dominant in this segment compared to personal cars since the trucks travels a longer distance each year and hence variable costs constitutes a larger share of the total cost. However, the higher vehicle costs for CBG and electricity is still a vital factor for making the liquid fuels more cost competitive (see Section 3.6.2). The fact that the energy efficiency is deemed to be lower for CBG is also affecting the results.

Without policy instruments, methanol and ethanol have the lowest total cost in this segment. The cost for these value chains are deemed to be in line with the fossil alternative even without policies. While, electricity, CBG and renewable diesel could not compete with the fossil alternative without policy instruments.

As for the car segment, the fuel production cost, per km, is roughly the same for all biofuels but considerably lower for electricity. However, a difference can be seen between renewable diesel and the other biofuels for this segment (the renewable diesel case has a higher production cost per kWh than the other biofuel cases, see Appendix B). The distribution cost constitutes a greater part of the total cost than for the car segment, but still a significantly smaller part than the production cost. The exception is the electricity case. The distribution cost for electricity includes both grid fees and costs related to install and operate the charging infrastructure for depot charging of the truck. It should also be noted that the distribution cost for electricity includes margin for the network owner, unlike the distribution for the other fuels where the no margin for the distributor is included.

Including policy instruments

The total cost for the distribution truck segment, including the effects of policy instruments, is shown in Figure 12. The results indicate that all biofuels (including electricity) are competitive when policy instruments are considered. The major component for making the alternative fuels a viable option is the cost increase for the reference case when adding the current taxes on fossil diesel.

Electric and gas fuels distribution trucks benefits from investment support for vehicles and infrastructure. The mentioned fuels would not be competitive without these additional investment support. Further, compared to other biofuels energy tax is paid for electricity used for road transports.

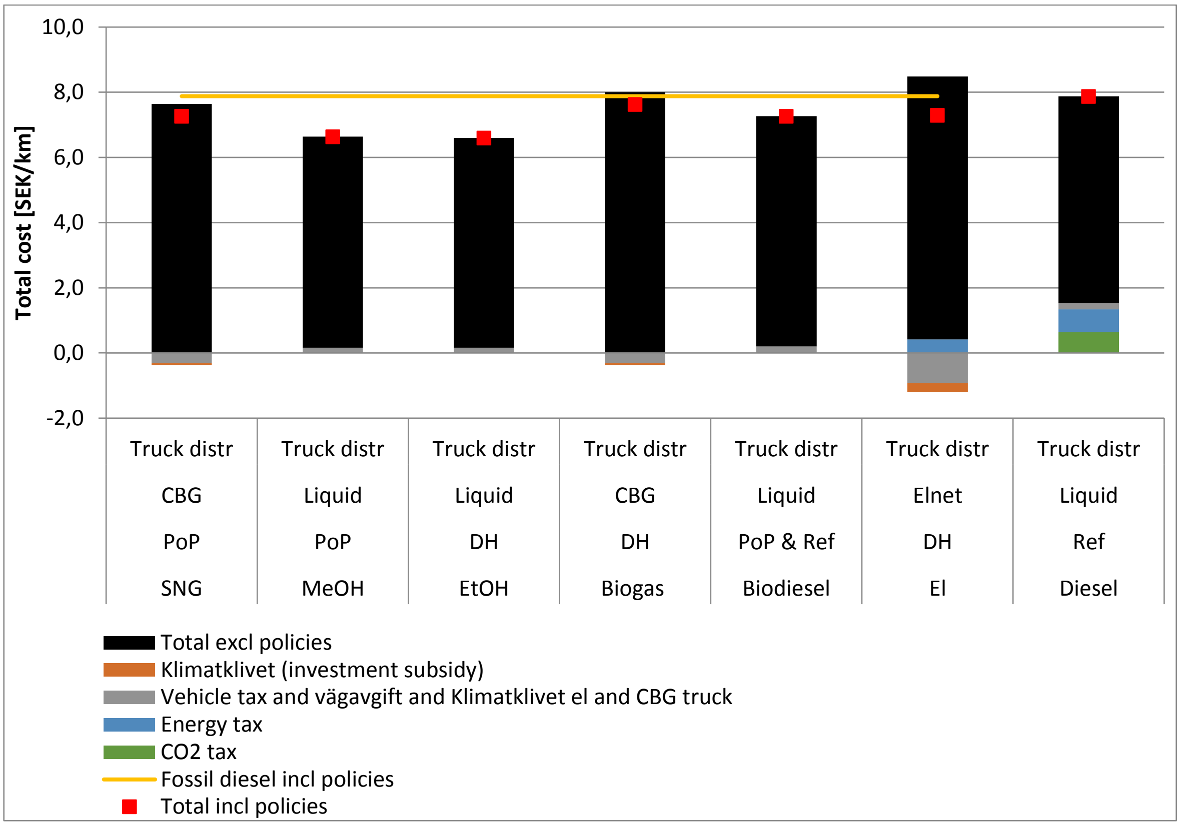

Figure 12. Total cost for the distribution truck segment, including policy instruments.

Figure 13 presents the margin (SEK/kWh$_{biofuel}$) for producers and distributors based on the total cost difference compared to the fossil reference chain for the distribution truck segment. Electricity receives the highest margin. This could be somewhat misleading since there is a large difference in energy usage per km compared to the other fuel alternatives. If these are compared on another basis, e.g. SEK/km as in Figure 12, it would give a somewhat other picture. The results indicate a viable margin for electricity, all the liquid fuels and SNG (approximately 0.2-0.5 SEK/kWh, corresponding to 0.6-1.3 SEK/km), while biogas operates on a rather slim margin. As mentioned earlier, the gross margin for the fossil reference chain have been estimated to about 0.1 SEK/kWh for diesel (Swedish Energy Agency, 2017).

The margins can also be related to the fuel taxes on fossil fuels, as discussed for the car segment. The total fuel tax is almost 0.5 SEK/kWh for diesel (corresponding to 1.3 SEK/km). As for the car segment, these numbers are in parity with the presented margins.

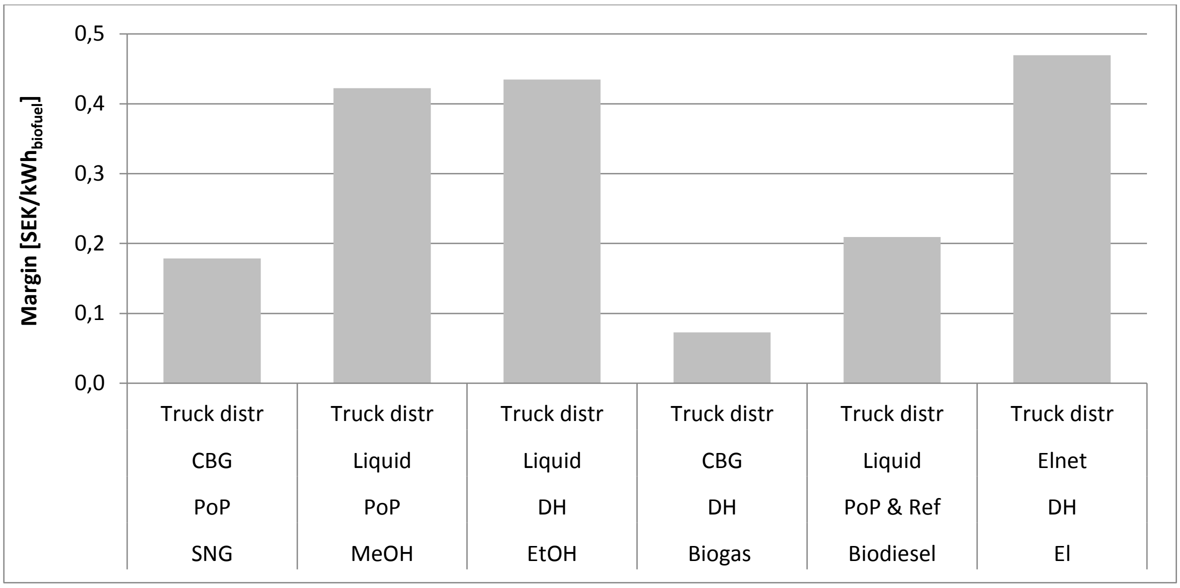

Figure 13. Margin for producers and distributors based on the total cost difference compared to the fossil reference chain for the distribution truck segment.

Sensitivity analysis

For the distribution truck segment, mostly the same parameters as for the car segment have been included in the sensitivity analysis (see Table 13). The difference is that the driving distances have not been investigated. The distance used (50 000 km/y) is based on an average distance travelled for a truck used every day. Thus, it not realistic to assume a higher value especially not for the electric truck that needs downtime for charging.

Figure 14 presents the result of the sensitivity analysis for the distribution truck segment. As for the car segment, only the parameters affecting the margin more than 0.1 SEK/kWh (for one or more of the cases) is presented. The increased biomass price, together with lowered oil price, have the largest impact on the results. A 100 % increase in the biomass cost would eliminate the margin for SNG production, while the margin for biogas and renewable diesel is significantly negative. However, for MeOH, EtOH and electricity there is still a significant margin (approximately between 0.25-0.3 SEK/kWh). The margin for all fuels except biogas remains positive even if the crude oil price decreases to 50 USD/barrel. However, the margin for SNG and renewable diesel is small under these conditions.

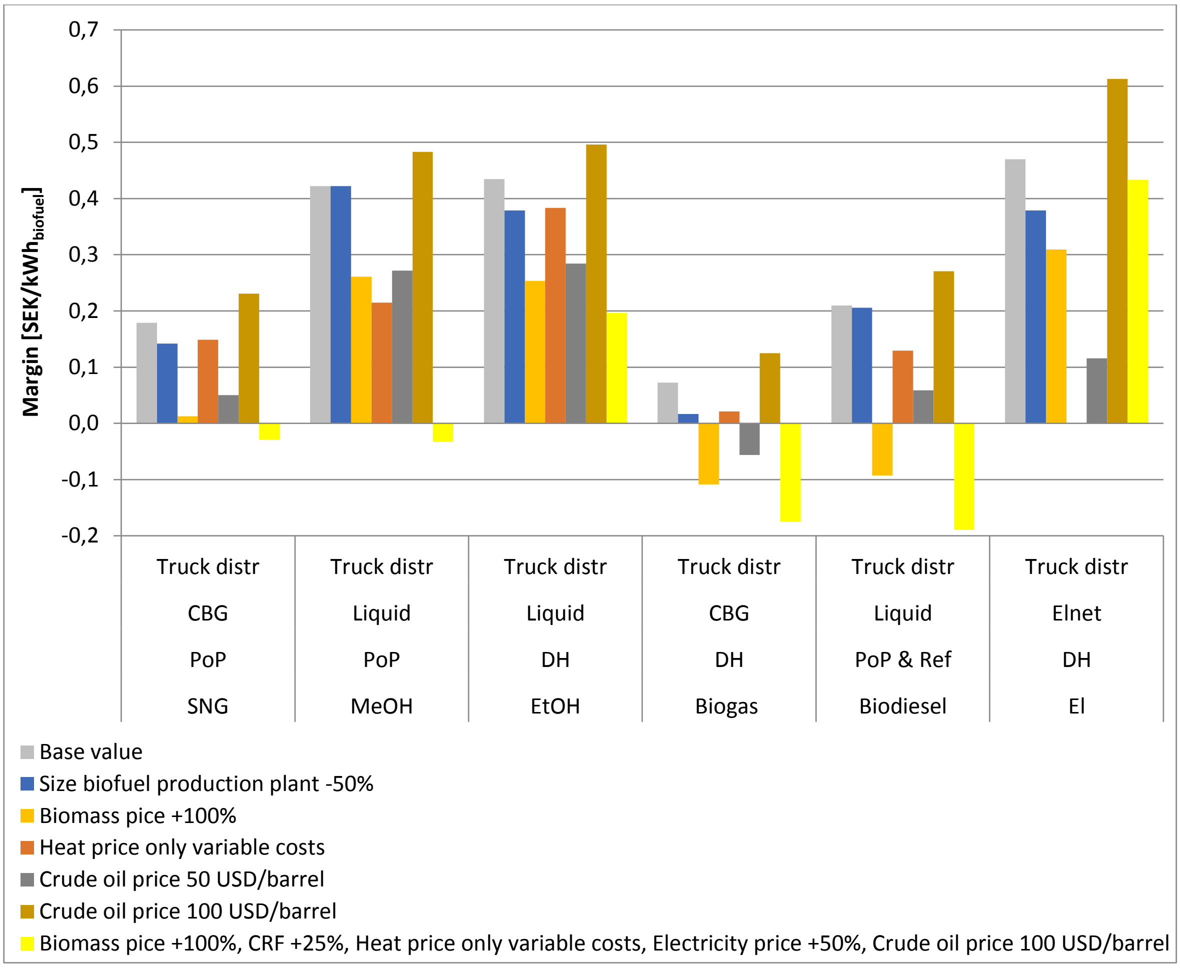

Figure 14. Sensitivity analysis, showing the influence on the margin for producers and distributors, for the distribution truck segment.

For the sensitivity analysis where a number of parameters are combined (Figure 14, in yellow), most cases do not have a positive margin. The MeOH and biodiesel cases have negative margins for the same reasons as discussed above for the car segment. For this segment, also the gas cases (SNG and biogas) have negative margins due to the somewhat lower efficiency for the CBG distribution truck relative to the other vehicles in the distribution truck segment. This difference in engine efficiency is more significant in the distribution truck segment than in the car segment where a petrol car is used as reference. The electricity case is almost not influenced by this sensitivity analysis. The increased cost for biomass is for this case compensated by the increased crude oil price, increasing the cost for the fossil reference chain (the electricity case is not influenced by the change of the electricity and heat prices). The EtOH case still have a quite significant margin despite the rather large changes in energy prices. However, considering that EtOH is produced together biogas, one can see that the average margin per kWh for these fuels are only slightly positive. The margin for the production concept is, however, somewhat higher (0.1 SEK/kWh), since approximately three times as much ethanol as biogas are produced (see Table 6).

4.1.3 Long-distance truck

Excluding policy instruments

Figure 15 presents the total cost for the long-distance truck excluding policy instruments. The results for the long-distance truck segment is in high degree the same as for the distribution truck segment. However, the vehicle cost share is lower than for the distribution truck segment (and of course much lower than for the car segment). The fundamental idea with a long-distance truck is, as with e.g. a taxi, that it should be used as much time as possible. Consequently, the driving distance is much higher than for a distribution truck, 200 000 km per year.

The results indicate that none of the renewable options are economically viable without policy instruments. Methanol and ethanol are showing the best results, almost reaching the same cost as the fossil reference.

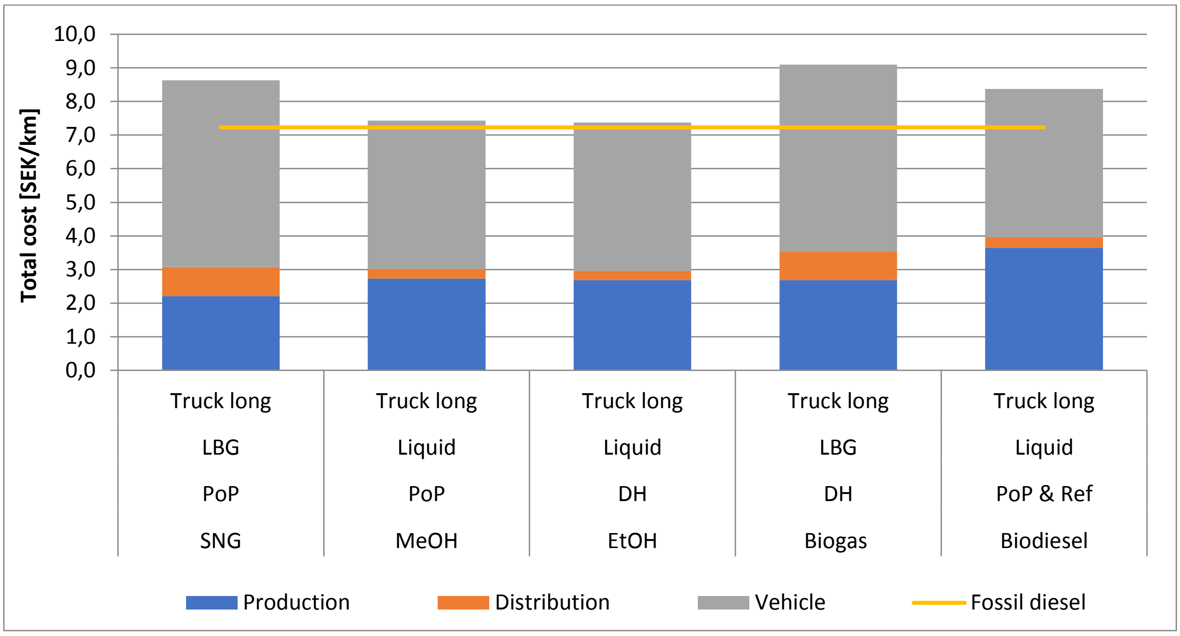

Figure 15. Total cost for the long-distance truck segment, excluding policy instruments.

Including policy instruments

Figure 16 presents the total cost for the long-distance truck including policy instruments. As can be seen, all biofuels are deemed to be competitive with fossil diesel when taking into account the policy instruments. The most important policy is the taxation of fossil diesel which adds about 2 SEK/km (0.46 SEK/kWh) for the reference case. LBG benefits somewhat from investment subsidies for vehicles and liquefaction plant, but also from lower vehicle tax. The gas trucks performed somewhat better for this segment compared with the distribution truck segment, since a higher engine efficiency was used for liquefied gas (the same energy efficiency as for diesel was assumed).

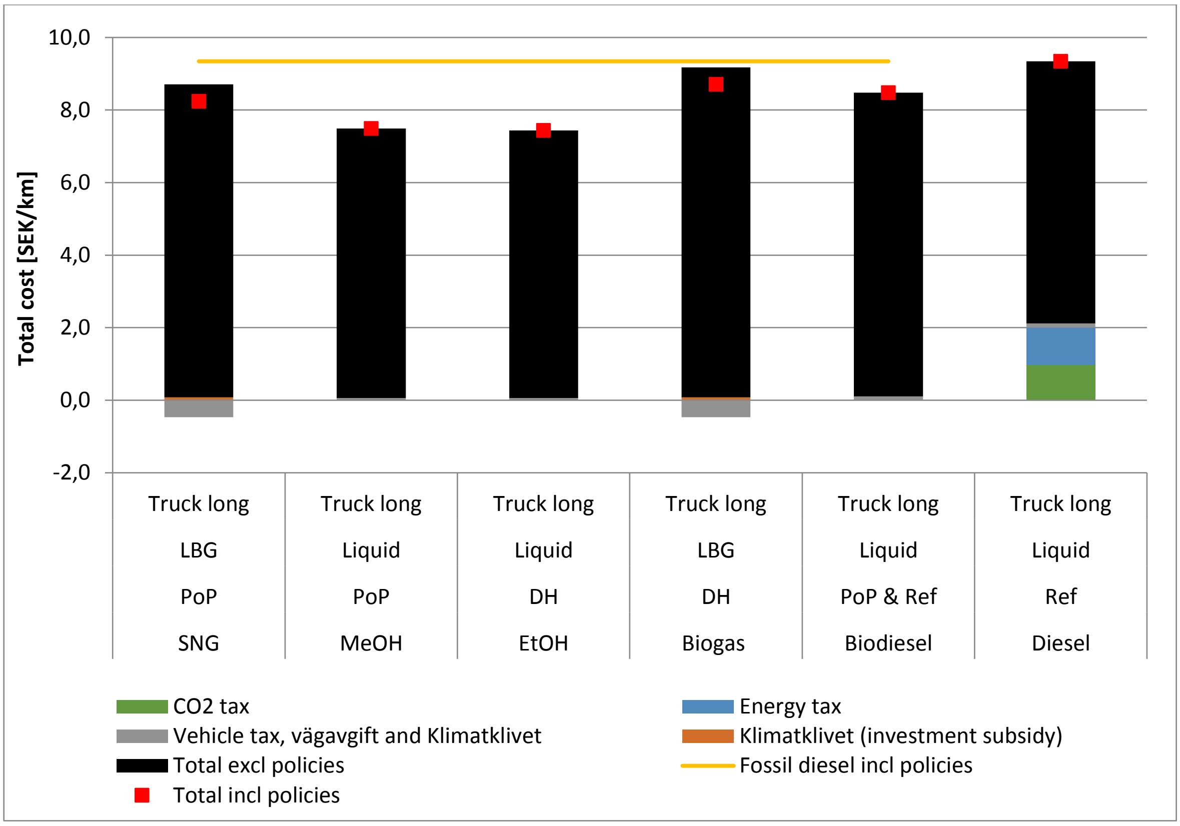

Figure 16. Total cost for long-distance trucks, including policy instruments.

Figure 17 presents the margin (SEK/kWh$_{biofuel}$) for producers and distributors based on the total cost difference compared to the fossil reference chain for the long-distance truck segment. The total cost for all biofuel cases enable a significant margin (approximately between 0.15-0.45 SEK/kWh as can be seen in Figure 17, corresponding to 0.65-1.9 SEK/km as can be seen in Figure 16). All alternative fuels show a potential higher margin than for fossil diesel (0.1 SEK/kWh).

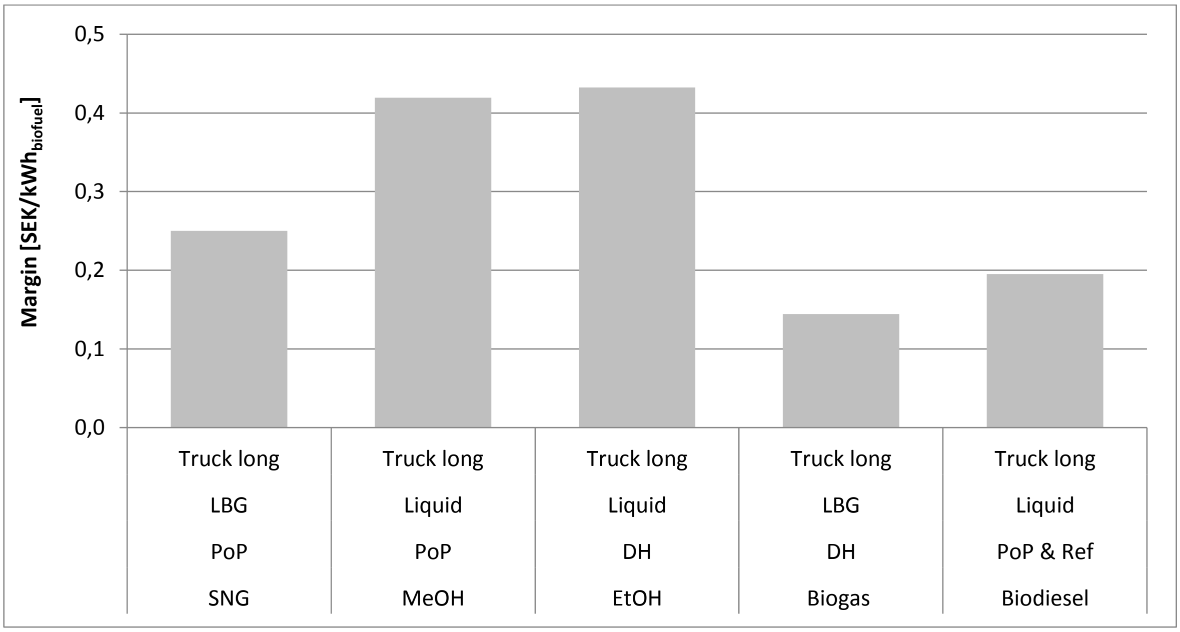

Figure 17. Margin for producers and distributors based on the total cost difference compared to the fossil reference chain for the long-distance truck segment.

Also for this segment, the total fuel tax of almost 0.5 SEK/kWh for diesel (corresponding to 2.0 SEK/km) are in parity with the presented margins for the best performing fuels.

Sensitivity analysis

The same parameters as for the car segment have been included in the sensitivity analysis for the long-distance truck segment, with the exemption of the driving distance (see Table 13). Further, the base value for vehicle residual value after 6 years is 30 %. Consequently, the values used in the sensitivity analysis are different compared to the car segment (25 % and 35 % have been used). Figure 18 presents the result of the sensitivity analysis for the distribution truck segment. As for the other segments, only the parameters affecting the margin more than 0.1 SEK/kWh (for one or more of the cases) is presented.

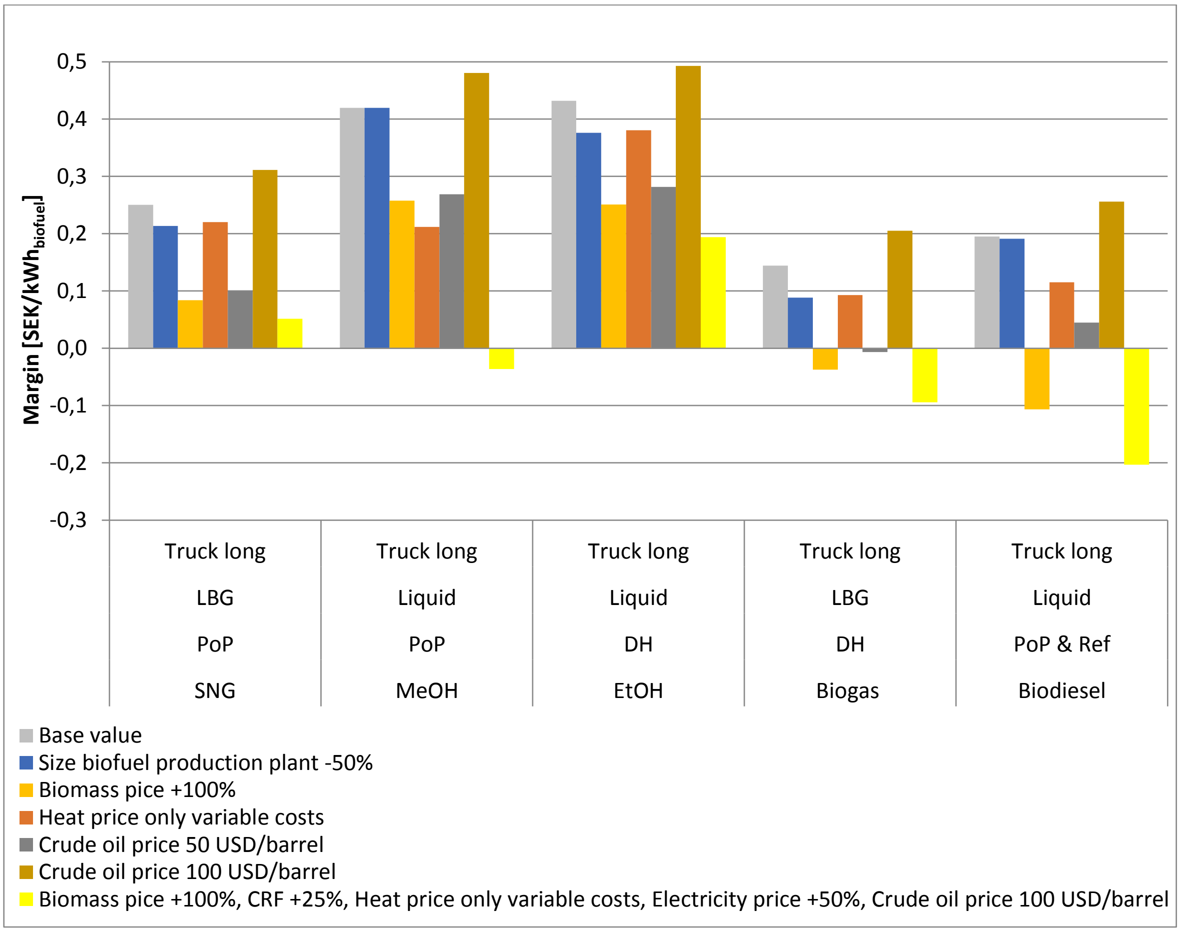

Figure 18. Sensitivity analysis, showing the influence on the margin for producers and distributors, for the long-distance truck segment.

In the long-distance truck segment, the fuel cost constitutes a greater share of the total cost compared to the other investigated segments. Since the fuel cost is more significant, changes in fuel related costs gives an even greater impact than for the other segments. For example, a 100 % increase of the biomass price would mean a negative margin for both biogas and renewable diesel. However, as for the distribution truck segment, MeOH and EtOH still have a significant margin when increasing the biomass price (around 0.25 SEK/kWh). The margin for all fuels except biogas remains positive even if the crude oil price decreases to 50 USD/barrel.

For the sensitivity analysis where a number of parameters are combined, most cases do not have a positive margin. The main difference compared to the results for the distribution truck segment is that in addition to the EtOH case, who still have a quite significant margin, also the SNG case have a small margin.

Changes in vehicle residual value only hade minor impact on the margin since the vehicle costs are rather similar for all trucks, including the reference truck.

4.2 ENERGY EFFICIENCY

Figure 19 presents the energy usage for the car segment. One can see three groups with similar energy usage: SNG, MeOH, EtOH and biogas (around 0.6 kWh/km), biopetrol and biodiesel (approximately 0.85-0.95 kWh/km) and finally electricity (approximately 0.16 kWh/km). The total energy usage is mainly influenced by different energy carriers related to the production, including biomass, electricity, heat and hydrogen, and the vehicle energy usage. Energy usage related to biomass and biofuel distribution only constitutes a minor share of the total energy usage. The energy usage per kWh biofuel/el is similar within the three groups (1.2-1.5 for the first group, 2.2 for the second group and 1.1 for electricity). The difference between the first two groups and electricity increases per km, due to the much higher energy efficiency of the electric drivetrain compared to the internal combustion engines used for the other fuels, as previously pointed out.

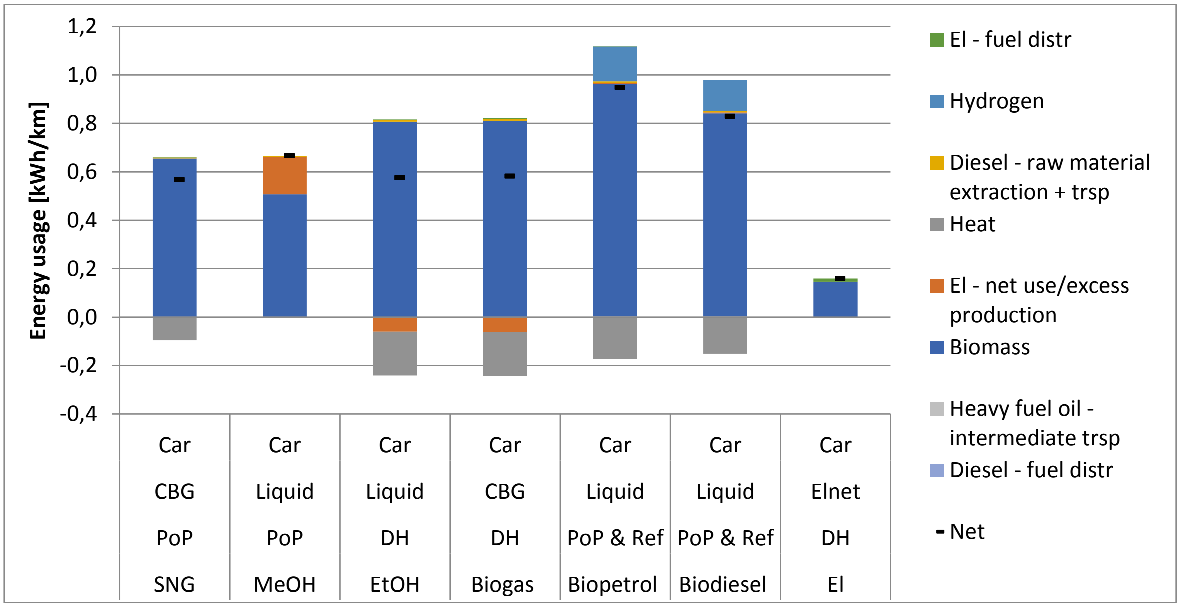

Figure 19. Energy usage for the car segment.

As mentioned in Section 2.2, using mixed sources of energy carriers in efficiency calculations could contribute to a tendency to overestimate the "quality" of certain energy carriers. For MeOH, for example, a rather large share of the energy usage constitutes of electricity, while for the other biofuels the use of biomass is, to different degrees, higher. If converting these energy carriers to e.g. electricity equivalents, the value of the biomass would be less than half of the value for electricity (see e.g. (Andersson et al., 2013)). On the other hand, several of the cases, including EtOH, biogas, biopetrol and biodiesel has significant amounts of excess heat contributing to a decrease of the net energy usage. If considering electricity equivalents, the value of excess heat could be as low as 10 % of the value of electricity.

In the calculation of energy efficiency, the consequences of using the excess heat at the host plants have not been included (in the economic calculations, the price for heat has been estimated considering the alternative heat production cost). The exception is the MeOH case. The reason for this is that the MeOH case is unavoidably integrated with a chemical pulp and paper mill, and it was therefore deemed appropriate to also include the unavoidable consequences of this integration. For other cases the integration is more flexible. EtOH, for example, could be integrated with a pulp and paper mill, or other industry, instead of a district heating system (the energy balance could then be somewhat different due to a different temperature level of the heat needed).

Figure 20 presents the energy usage for the distribution truck segment. The results are similar to the results for the car segment (one can also here see three different groups). The difference is the order of magnitude of the energy usage due to much higher vehicle energy usage per km. The total energy usage is about 6-9 times higher than for usage in personal cars. There is also a small difference in mutual order between EtOH and SNG/biogas, where the efficiency for the CBG distribution truck is somewhat lower relative to the other vehicles in the distribution truck segment as previously been discussed (this is not the case in the car segment).

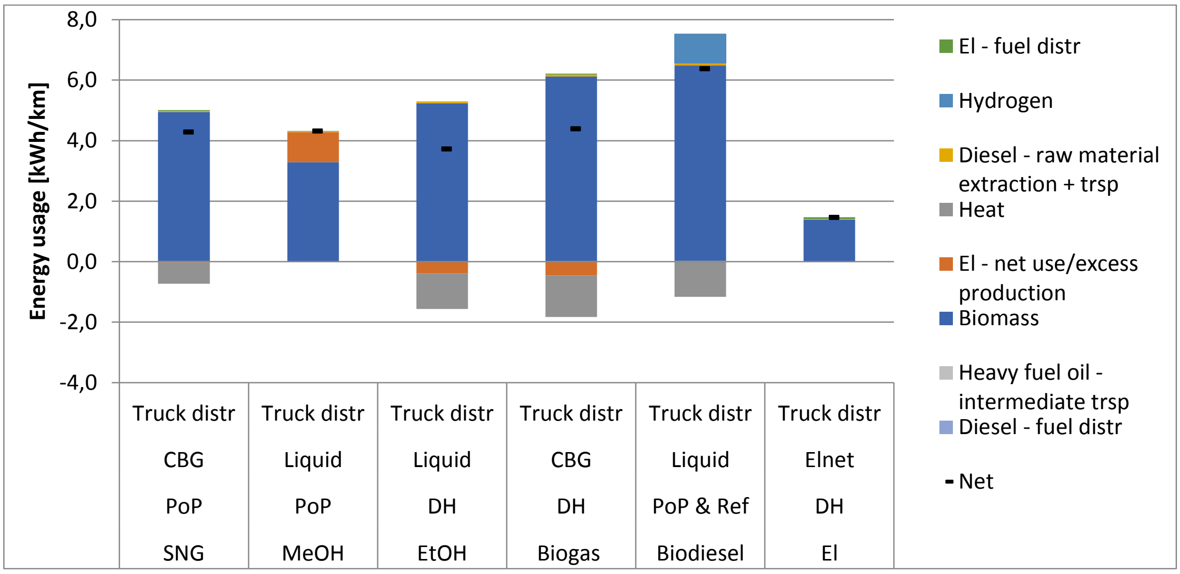

Figure 20. Energy usage for the distribution truck segment.

Figure 21 presents the energy usage for the long-distance truck segment. The results are similar to the results for the distribution truck segment. However, the energy usage is higher due to higher vehicle energy usage per km compared to the distribution truck segment (and much higher compared to the car segment). The mutual order between EtOH and SNG/biogas is here similar to the results for the car segment.

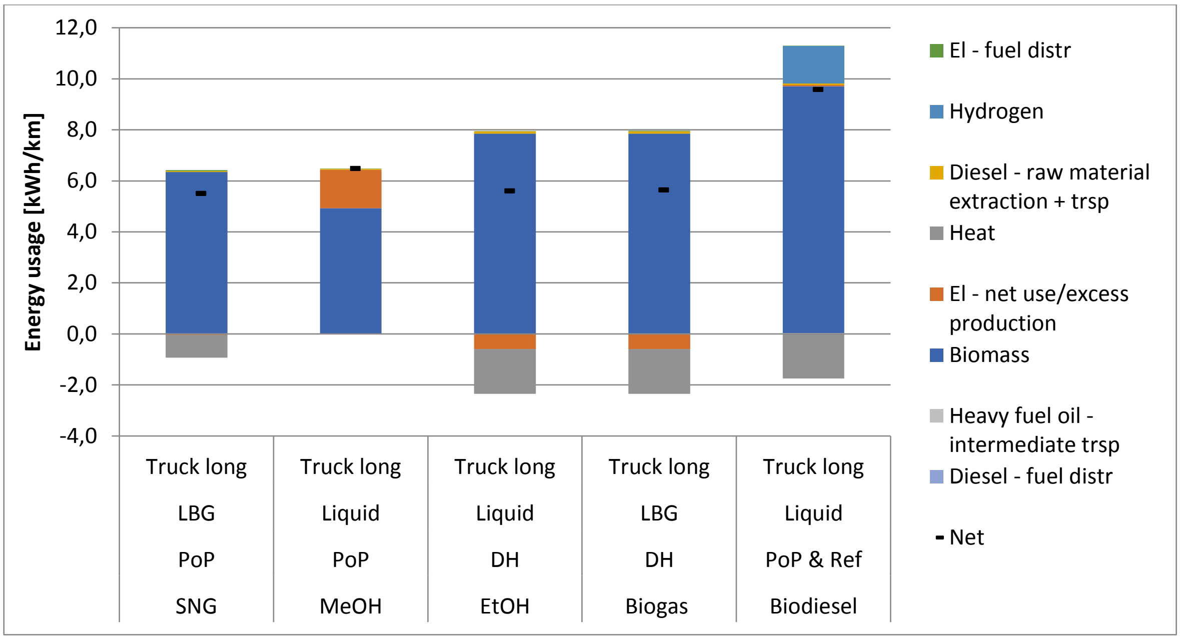

Figure 21. Energy usage for the long-distance truck segment.

4.3 GHG EMISSIONS

Figure 22 presents the results regarding total GHG emissions for the car segment. The values for the fossil reference chains are also included in the figure. The results are very similar for the other segments (and therefore not shown here), except concerning the absolute levels of emissions per km. The emissions for a certain value chain in the car segment are about 10 % of the emissions for the same value chain in the long-distance truck segment, due to very different vehicle energy usage per km.

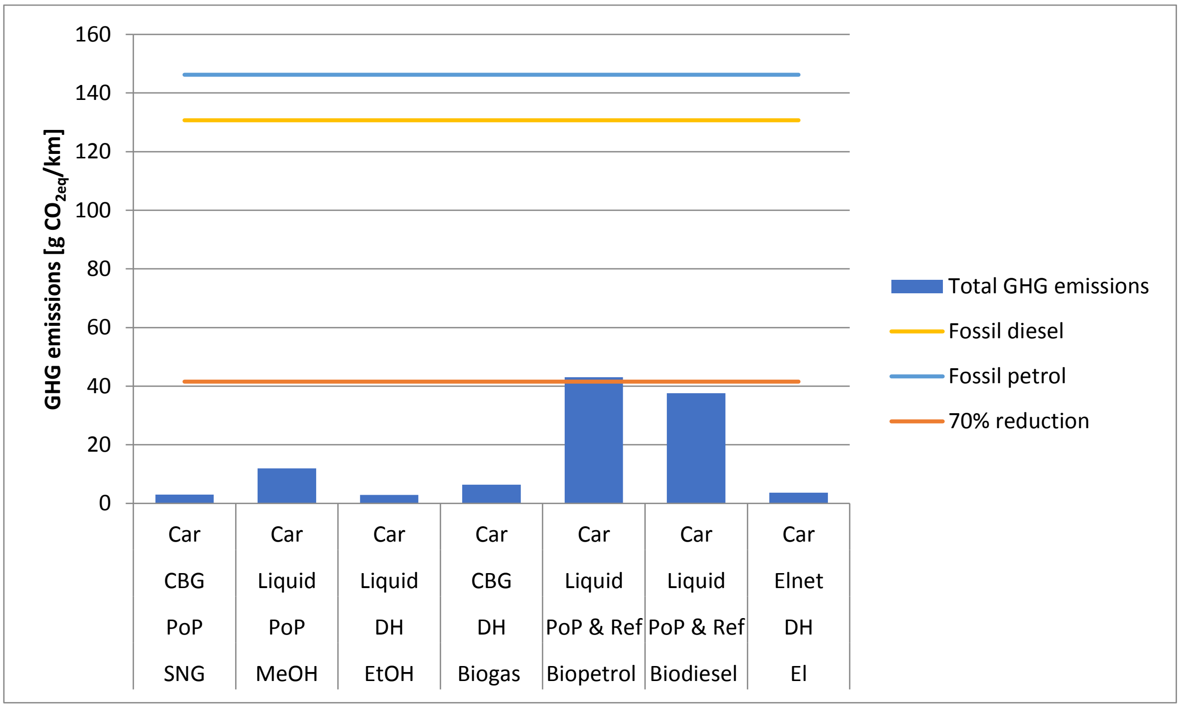

Figure 22. GHG emissions for the car segment.

Looking at Figure 22 one can see two groups with similar GHG emissions: SNG, EtOH and electricity with extremely low emissions and biopetrol and biodiesel with significantly higher emissions than the other studied value chains. Biogas and MeOH have somewhat higher emissions than the value chains with the lowest emissions (however, still very low emissions). The reason for the significantly higher emissions for the biodiesel and biopetrol value chains is the usage of (fossil) hydrogen when upgrading the bio-oil to motor fuels. Today, refineries often produce hydrogen by steam reforming of fossil hydrogen. This has been assumed to be the case in this study. However, another option not commercially applied today, but that could be an option in the future, is to produce hydrogen from electrolysis of water. If this were considered, with emissions for electricity according to the Nordic electricity mix used in this study, the emissions associated with hydrogen would be about 60 % of the emissions for hydrogen used in this study (Anheden et al., 2017). The emissions for hydrogen production constitute about 90 % of the total emissions for biopetrol and biodiesel. If hydrogen from electrolysis of water would be considered, the emissions associated with these value chains would decrease with more than 35 %. Still, the emissions associated with these value chains would be significantly higher than most of the other value chains. However, with decreasing grid electricity emissions in the future, the emissions would naturally be even lower.

The reason for the somewhat higher emissions for MeOH, is the relatively high net usage of electricity associated with the production (the GHG calculations are based on the energy flows presented in Table 6, since no consideration of usage of excess heat in the host plants is considered within the RED methodology used here). For biogas the somewhat higher emissions are due to the methane slip during biogas upgrading.

All value chains lead to a significant reduction of GHG emissions compared to the fossil reference chains. For the first group (SNG, EtOH and electricity), the reduction is 97-98 %, for biogas it is 95-96% (dependent on transport segment), for MeOH it is 92 % and for biopetrol and biodiesel the reduction is 70-71 %. The level of 70% reduction is indicated in Figure 22 (average reduction compared to diesel and petrol). With different hydrogen production considered, as discussed above, also the reduction for biopetrol and biodiesel could be significantly higher than 70 %. As pointed out in Section 2.3, emissions associated with the manufacture of vehicles and vehicle components and infrastructure are not included in the analysis. In this context, it can be emphasized that for electric vehicles, emissions related to battery production is a non-negligible part of the total life cycle emissions.

4.4 FURTHER DISCUSSION

All fuel production processes covered in this study are based on integration with other industries, the pulp and paper industry, district heating systems and/or oil refinery industry. These combinations are deemed to be cost and energy efficient but there are prerequisites that need to be met, e.g. available amount of black liquor and demand for district heating. To assign the excess heat a value corresponding to the total cost of alternative heat production, including capital costs, puts high requirements on technology availability. To only base the value of excess heat on the variable cost of heat production, does not put the same requirement on technology availability. Furthermore, it puts the back-up responsibility outside the economic system boundary of the biofuel plant.

The sensitivity analysis indicates that changes in the cost of production can have significant impact for the margin. The main reason for this is that these changes influence the value chains rather differently, while e.g. a change in driving distance impose almost the same change in all cases including the reference cases. However, since market prices for energy are correlated it is rather unlikely that the future prices on energy will diverge. Thus, if the cost of biomass would increase 100 % it would also affect (or be affected) by a higher crude oil price or changes in taxation. In this study, different parameters were varied independently. When comparing future systems, like the ones considered here, the analysis can be further improved by considering different consistent energy market scenarios considering the relationships between different parameters (see e.g. (Axelsson and Harvey, 2010, Harvey et al., 2018).

Current taxes and policies have been used even if the future for the tax exemption for high-blended biofuels and the investment subsidies through Klimatklivet are highly uncertain. As mentioned in Section 2.1.2, there are different systems for high-blended (tax exemption) and low blended (quota) fuels. As discussed in Section 3.2, some cases will be used as blend-in fuels in the short-term perspective, especially the renewable petrol and diesel cases. However, there is no technical reasons for not using these fuels in high-blend or pure applications, which makes this a relevant comparison in the medium- or long-term perspective. Hence, tax exemption was assumed to be able to make a more fair and transparent assessment since it can be based on market prices and the current tax legislation. Further, the reduction quota system will be used until 2030, although reduction targets for coming years have not been presented which makes it difficult to estimate a premium for GHG emission reduction.

The bonus-malus-system for cars primarily subsidies electric cars (to some extent also gas cars). For the driving distance assumed in this study, which is close to the average driving distance for cars in Sweden, electric cars have the highest WtW cost. This means that the bonus-malus system favours the fuel/technique that in most cases is most expensive and not competitive compared to the fossil alternatives even with this relatively large subsidy (about 0.4 SEK/km in the base case). From a strict cost-efficiency perspective a larger competitive advantage would have been obtained if a corresponding subsidy was given to the other renewable alternatives, i.e. subsidising more competitive techniques than electric cars with the same amount would probably have had a larger effect. However, such subsidies could have been problematic/questionable from a legal perspective.

The vehicles in the car segment are represented by VW Golf. The facts that VW Golf is a rather small car with low fuel consumption could have significant impact on the results. For example, gas vehicles would perform better in a comparison where the fuel consumption is higher, since gas is the least expensive fuel but impose a somewhat higher vehicle investment. With a small/medium car the difference in consumption per kilometre is small between petrol and diesel. Calculations for a larger car model would probably make diesel (both renewable and fossil) more competitive than (renewable and fossil) petrol since the diesel engine is more efficient than the petrol engine. The corresponding calculations using a larger car model would probably have had the effect that the renewable fuels would have diesel as the main reference fossil fuel instead of petrol, which is the case in the calculations for the VW Golf in this study. The advantage with VW Golf is that figures regarding cost and fuel consumption were available for all fuels except methanol (and for methanol the ethanol engine can be seen as a highly relevant illustration regarding the cost levels).

An optimistic approach regarding the future has been applied in this study, as the production technologies, vehicles and a fuel markets are assumed to be available. This approach can be questionable for some of the alternatives, for example methanol cars that to our best knowledge is not a priority for any of the vehicle manufactures. The results for the margins available for producers and distributors are based on the prerequisites that the market prices are in parity with fossil alternatives. This is currently not the case for biogas that has a lower market price than petrol and diesel, while biodiesel is sold at a premium compared to fossil alternatives.

In terms of cost, biopetrol and biodiesel generally do well or very well in relation to the other value chains. However, the situation is a bit different when it comes to energy efficiency and GHG emissions. Although energy use is much higher for all biofuels included relative to electricity, there is also a significant difference between biopetrol and biodiesel and the other biofuel value chains. This difference is due to a higher use of energy in the production of biopetrol and biodiesel. When it comes to GHG emissions, there is also a significant difference and the reduction potential is lower for biopetrol and biodiesel than for the other studied alternatives (although using a different methodology could change this result). Alternative production methods for hydrogen, associated with lower GHG emissions, are necessary in order for these fuel value chains to compete with the other alternatives studied here from a GHG emissions point of view. Furthermore, the technology considered for bio-oil production has by far the lowest technical maturity of the included concepts, which makes commercial operation in 2030 a challenge.

In summary, all the studied value chains have the opportunity to be profitable and contribute to significant reductions in GHG emissions. The value chains with methanol and ethanol show the highest average potential margin for producers and distributors, which is also very stable, looking at the different transport segments. Generally, the results are relatively robust in relation to changes of different parameters. However, for some value chains there are crucial factors that influence the result to a great extent. The clearest example is the electricity-based value chain, where the car's driving distance is absolutely crucial for profitability and competitiveness. In this study, electricity produced from forest biomass (in a CHP plant connected to a district heating system) has been studied. If electricity from the electricity grid had been considered instead, the results for well-to-gate costs, energy use and GHG emissions would been changed. However, the gate-to-wheel part would not been affected. Both the well-to-gate costs and the emissions would increase. The calculated production cost for electricity produced from forest biomass in this study is SEK 0.28 SEK/kWh, while the electricity price used is SEK 0.40/kWh. However, this change would not affect the overall results to a great extent, as the well-to-gate cost of electricity has a relatively small impact on the total well-to-wheel cost for the electricity-based value chains, regardless of transport segment.

5 CONCLUSIONS

In this study the total well-to-wheel cost for forest-based value chains with different energy carriers (SNG, methanol, ethanol, biogas, biodiesel, biopetrol, electricity) for use in different transport segments (car, distribution truck and long-distance truck) in road traffic has been estimated and compared with fossil alternatives in a Swedish context. The comparison, which is based on the cost of the end user, illustrates how different alternative value chains can compete with today's fossil-based value chains and under what conditions there is potential for profitable biofuel production. In order to achieve a broader comparison of the value chains, estimates of total energy efficiency and GHG emissions from a WtW perspective are also included. Based on the results, the following conclusions can be drawn:

- When policy instruments are excluded, none of the studied alternatives can compete with the fossil alternatives. However, for the truck segments, methanol and ethanol give close to the same total cost of ownership as for the fossil alternative.
- When including policy instruments, almost all alternatives show competitive costs compared to the fossil reference chains, with a significant potential margin for producers and distributors of biofuels (generally between 0.15-0.5 SEK/$kWh_{biofuel}$) given the base assumptions used in this study.
- For the car segment all alternatives, except electricity, have a lower cost than fossil petrol and diesel when including policy instruments. The highest potential margin is shown by SNG followed by biopetrol, methanol and ethanol.
- For the truck segments, all alternatives have a lower cost when including policy instruments. The highest potential margins are obtained for electricity, methanol and ethanol for the distribution truck segment, and methanol and ethanol for the long-distance truck segment.
- The vehicle cost contributes with the largest share to the total WtW cost in all transport segments, especially for cars. Thus, the assumed annual driving distance have a large impact on the calculated cost per km. Electric vehicles benefits the most of longer annual driving distance due to higher vehicle investment cost and lower running costs.
- For distribution truck and long-distance truck segments the fuel cost contributes with a higher share making these segments more dependent on changes in production costs, fuel taxation and policies. However, the car segment is also significantly influenced by these types of changes.
- Important parameters that in general influence the results to a relatively large extent include the biomass price, the crude oil price and for some cases the price of excess heat. However, most alternatives are still competitive, showing a significant potential margin, when these parameters are changed individually in an unfavourable direction for a specific alternative.
- The energy and CO_2 tax on fossil fuels are vital instruments to achieve a margin for producers and distributors of biofuels. Thus, the tax exemption on biofuels are the single most important policy instrument, adding cost of around 0.7 SEK/kWh for petrol and almost 0.5 SEK/kWh for diesel. The taxes constitute about 25 % of the cost per km (2.0 SEK/km) for

long-distance trucks. The corresponding numbers for cars and distribution trucks are 12 % (0.31 SEK/km) and 20 % (1.3 SEK/km), respectively.

- The electricity-based value chain has a significantly lower energy usage per km compared to the biofuel-based value chains (for cars 0.16 kWh/km, compared to around 0.6-0.95 kWh/km). Out of the biofuels, biopetrol and biodiesel have higher energy usage than the others, due to a more energy-intensive production.
- All value chains lead to a significant reduction of GHG emissions compared to the fossil reference chains. For almost all cases, the reduction is significantly above 90 % (over 95 % for most value chains). The exceptions are biopetrol and biodiesel, using (fossil) hydrogen in the production process, where the reduction is just above 70 %.

NOMENCLATURE

BB	Bark boiler
BEV	Battery-powered electric vehicles
BL	Black liquor
BLG	Black liquor gasification
BMG	Biomass gasification
CBG	Compressed biogas(/SNG)
CHP	Combined heat and power
DH	District heating
EtOH	Ethanol
FR	Forest residues
GL	Green liquor
HDO	Hydrodeoxygenation
HTL	Hydro thermal liquefaction
ICE	Internal combustion engines
LBG	Liquified biogas(/SNG)
LI	Lignin
LNG	Liquified natural gas
MeOH	Methanol
O&M	Operation and maintenance
TPA	Tonnes per annum
NG	Natural gas
PoP	Pulp and paper (mill)
RB	Recovery boiler
Ref	Refinery
SNG	(Renewable) Synthetic natural gas
ST	Steam turbine
WtW	Well-to-wheel

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APPENDIX A: INTEGRATED BIOFUEL PRODUCTION – PREVIOUS STUDIES AND MOTIVES FOR CHOSEN CONCEPTS AND INTEGRATION

SNG PRODUCED VIA GASIFICATION

Many previous studies have investigated integration possibilities for gasification-based bio-SNG production and evaluated the performance of the integrated concepts (e.g. Gassner and Maréchal, 2012; Heyne, 2013; Hannula, 2015; Holmgren, 2015; Isaksson, 2015; Mesfun et al., 2016; Ahlström et al., 2017).

In this study data for the SNG concept is taken from Wetterlund et al. (2017), who in turn based it on data from Holmgren (2015). The original process concept was developed and simulated by Heyne (2013). The concept used is based on indirect dual fluidised bed gasification. Holmgren (2015) motivates the choice of gasification technology based on previous studies: "Studies that have investigated which type of gasification technology is best suited for SNG production have reached different results. Gassner and Maréchal (2012) concluded from their study with a systematic process integration analysis that the technology that seems to be the most efficient individually is not necessarily the best technology from an overall plant perspective. Heyne et al. (2013) concluded that the key aspect for biomass gasification is the efficient heat integration and cogeneration of power rather than the choice of gasification technology. In terms of real projects for bio-SNG production; the technology choices also differs; In the Gobigas project (20 MWSNG demonstration plant in Gothenburg) an indirect atmospheric gasifier was chosen based on a pre-study conducted in 2006 (Gobigas, 2015); whereas in the full scale Bio2Gas project, a 200 MW SNG system planned by E.ON, the choice of technology is instead slightly pressurised oxygen-blown CFB gasification (Möller et al., 2013)."

While Holmgren (2015) only consider integration with a district heating system, Wetterlund et al. (2017) also include the possibility of integration with pulp and paper mills, sawmills as well as stand-alone operation. Based on the results in Wetterlund et al., integration with a chemical pulp and paper mill was chosen in this study.

Market chemical pulp mills often have a steam surplus, i.e. the steam from the recovery boiler is greater than the need for process steam. Thus, integration with biofuel plants with excess steam is of less interest. However, for integrated chemical pulp and paper mills, there is often a steam deficit that needs to be covered with an additional boiler using falling bark and if needed additional purchased wood fuel and/or other fuels. Here, it is assumed that the steam deficit of the considered mill is equal to steam surplus of the SNG plant of the considered size. Analysing statistics of the energy balances of the Swedish pulp and paper mills (SFIF, 2012) one can see that there are several mills with steam deficits in the same range as considered here.

In Sweden, the development of gasification technology for the production of SNG has mainly taken place in the Gobigas plant, which was started with the aim of producing SNG on a commercial scale in the future by thermal gasification of residues from forestry. As a first stage, a demonstration plant on a somewhat smaller scale has been run by Göteborg Energi. However, they have decided not to proceed with the next stage and are now looking for a new owner of the plant (Trafikutskottet, 2017).

The TRL level for the SNG concept used here was assumed to be similar to that for methanol concept (see next section).

METHANOL PRODUCED VIA BLACK LIQUOR GASIFICATION

Many previous studies have investigated integration possibilities for gasification-based methanol production (including black liquor gasification) and evaluated the performance of the integrated concepts (Ekbom et al., 2005; Pettersson, 2011; Holmgren, 2015; Isaksson, 2015; Andersson et al., 2016).

Data for the methanol concept is based on data from Wetterlund et al. (2017), who in turn based it on data from (Andersson et al., 2016). The methanol process considered here is based on high-temperature entrained-flow gasification of black liquor. In Wetterlund et al. (2017) who described the costs to reach certain levels of domestically produced biofuels in Sweden, under different scenarios and conditions, black liquor gasification-based methanol production is generally favoured over methanol production via solid biomass gasification.

The size of a black liquor gasification plant and the following upgrading of the syngas to methanol (or other fuels) is for each mill determined by the production of black liquor. In order to achieve larger plants, benefitting from economy of scale, co-gasification of black liquor and pyrolysis liquid has been suggested and investigated. However, Zetterholm et al. (2018) showed that pure black liquor gasification, without co-gasification of pyrolysis liquid, generally has a better economic performance (lower methanol production cost) than co-gasification of back liquor and pyrolysis liquid.

Black liquor gasification is currently being developed as an alternative technology to the recovery boiler for energy and chemical recovery at chemical pulp mills. The black liquor gasification-based methanol plant is therefore unavoidable integrated with a chemical pulp (and paper) mill. In contrast to the SNG process, BLG benefit from integration with a mill having a steam surplus, as shown by e.g. Pettersson (2011). However, assuming a mill with a steam surplus used for condensing power production (which is relatively inefficient) as the reference is not a really fair comparison, overestimating the performance of the BLG concept. The reference mill operation case (i.e. without BLG) could also extract lignin and sell as fuel instead of producing condensing power. Then, the effect for BLG would be similar as if the technology would be integrated with a mill with a steam deficit. Therefore, in this study, the same generic mill has been used for this case as for the SNG case.

At the beginning of the 21st century, the company Chemrec built a pilot plant in Piteå for the production of methanol and DME through black liquor gasification (initially only the actual gasification step, later supplemented with upgrading and synthesis of fuel). The project was not commercialized in line with what the company had expected, and Chemrec chose not to continue to operate the plant. Luleå University of Technology took over the pilot plant to conduct research and to produce fuels. Due to a shortage of financiers, the plant is currently in moths. The Swedish Energy Agency believes that the plant is unique and could play an important role both in testing and verifying technology concerning synthesis gas processes on an industrial scale and for taking the technology to commercialization. (Trafikutskottet, 2017) Recently, funding was granted to utilize the facility in a project where the goal is to produce and test avalanche fuel based on black liquor in just a few years (SVT, 2018).

A technology maturity assessment was carried out by Furusjö et al. (2017) for different technologies under development, including the concept for black liquor gasification-based methanol production used in this study. Two different approaches were used:

- A weighted average approach, giving an estimate of the overall maturity of the chain of individual process technologies.
- A ”weakest link” approach, in which the main process step with the lowest maturity is used to represent the chain, since it can be considered the limiting factor with respect to development and application.

If a weighted average approach was used, BLG had a TRL level between 6 and 7 which corresponds to “Technology *demonstrated* in relevant environment (industrially relevant environment in the case of key enabling technologies)” on the TRL scale (see Furusjö et al., 2017). However, if the “weakest link” is considered, BLG had a somewhat lover TRL level, between 5 and 6, which corresponds to “Technology *validated* in relevant environment (industrially relevant environment in the case of key enabling technologies).

ETHANOL PRODUCED VIA HYDROLYSIS AND FERMENTATION (WITH BIOGAS AS A BY-PRODUCT)

Lignocellulosic ethanol production has been studied extensively the past decade, and there is a huge diversity in terms of how the process is designed. The most common approach for this type of biorefinery is to pre-treat the biomass in a first step, then to use enzymes for hydrolysing polysaccharides into monomeric sugars, and in an integrated procedure also ferment these sugars using micro-organisms such as yeast (also bacteria may be used, as suggested in Humbird, 2011).

The *pre-treatment* step can be designed in several different ways, and the selection of pre-treatment conditions will depend on different factors such as type of raw material used, the expected product portfolio (ethanol, biogas, hydrogen, district heat, biomass fuel etc.), the potential for integration and local markets for products, and the choice of microorganisms used in the bioreactors. As described by Galbe and Zacchi (2012), the pre-treatment step should be designed for:

- High recovery of all carbohydrates
- High digestibility of cellulose in enzymatic hydrolysis
- Low generation of degradation products from lignin and hemicellulose
- High solids concentration
- Low net energy demand
- Low capital and operating costs

For forest-based feedstocks it has been shown that softwood requires more severe conditions than hardwood, and that the pH-buffering effect of higher concentrations of bark in the feedstock also requires more severe conditions, if the bark is not pre-processed in some way in order to reduce buffering capacity.

The *bioreactor system* can also be designed in various ways, and as mentioned above can also utilize different types of microorganism. The prevalent design in a Swedish context is to use a simultaneous saccharification/hydrolysis and fermentation process (SSF) and with yeast as fermenting organism.

Processing of non-fermented biomass is a very important aspect of an ethanol production process since only part of the feedstock is fermented to ethanol. This type of biorefinery is a multi-product biorefinery, and sometimes it might not even be obvious that ethanol is the main product. The most common approach in techno-economic studies on lignocellulosic ethanol production in Sweden today is that residual streams from fermentation are separated into liquids and solids. The liquids including dissolved organic compounds are then assumed to be fed to an anaerobic digester to produce biogas, whilst the solids are sent to a boiler or are dried and pelletized to be sold as biofuels.

In 2015, a synthesis of research within the "Ethanol Programme", a research programme funded by the Swedish Energy Agency, was conducted by the main stakeholders in ethanol research in Sweden (universities, RISE and companies were involved). Within this synthesis project a number of reference process designs were developed by the stakeholders, based on the results from research within the programme. For woody biomass it was shown that SO_2-catalysed steam explosion pretreatment was the preferred method, especially if softwoods were seen as the main feedstock. Regarding the bioreactor system there were three alternatives suggested, and the main difference between these were if the yeast needed for fermentation was bought, cultivated on-site with molasses, or cultivated on-site with a mixture of molasses and liquids from the process itself. The downstream process included distillation and molecular sieves for upgrading the ethanol to product grade. The residual streams after distillation are separated in the suggested process and the liquid fraction is sent to a biogas plant and waste water treatment, whilst the solid lignin-rich part is utilized as fuel for steam and power production (either internally, or by drying and potentially pelletizing the lignin) (Petersson et al., 2015).

A biorefinery producing ethanol from lignocellulosic feedstocks will most likely have a demand for steam at elevated pressures for the pre-treatment of the raw material, for the distillation of the ethanol product, and also potentially for the drying of lignin. A well-integrated process will most likely not have excess heat at temperatures high enough for district heating purposes. The lignin-rich solids from the feedstock will however need to be taken care of. As mentioned, the suggested ways to do this in the reference process is to either include a boiler and turbine system in the plant (which is a necessity for a stand-alone plant), or to dry the lignin and possibly pelletize and sell as a product.

A number of integration studies have been conducted in Sweden on lignocellulosic ethanol production. For forest-based alternatives several studies were conducted in the Vinnova funded Forest Chemistry project, where a large number of stakeholders put their heads together in order to assess different paths for integrating the Swedish forest and chemical processing industries. Studies on integration at the Domsjö site in Örnsköldsvik (CHP integration), with the chemical cluster in Stenungsund (industrial integration), and finally with a pulp mill (fictive conversion of a pulp mill to ethanol production), where conducted within this project[10].

In the ethanol synthesis project from 2015, the import of steam from a CHP plant to the ethanol process, and export of lignin as biofuel from the ethanol plant to the CHP plant was assessed (no excess heat for district heating was assumed available from the ethanol process) (Petersson et al., 2015). A similar study was conducted by Olsson et al. (2011), where energy integration between different types of ethanol plants with the energy system in Borås were assessed.

[10] Forest Chemistry Project Sugar Platform, Report September 2014. Confidential.

Different process configurations based on the reference process, from synthesis of research within the “Ethanol Programme”, were designed and evaluated by Joelsson et al. (2015). In all cases, ethanol, biogas, carbon dioxide, electricity and heat were produced. Electricity and heat were generated, primarily by burning solid residues, to cover the need for heat and power in the plants. However, the surplus solids can either be used to generate more electricity and heat for district heating, or dried to produce pellets that can be sold. Another option was to produce both excess heat and pellets, depending on the market situation. Based on the results from Joelsson et al., Wetterlund et al. (2017) based a number of different options on the case from Joelsson et al. where only heat (not pellets) was produced. Integration with a district heating system, different pulp mills, a sawmill as well as stand-alone operation was considered by Wetterlund et al. In Joelsson et al. the produced biogas is not of transport fuel quality. However, Wetterlund et al. included upgrading of the produced biogas to transport fuel quality (Börjesson et al., 2016). Based on the results from Wetterlund et al., the option with integration with a district heating system from Wetterlund et al. were chosen for this study.

The heat surplus used for district heating is relatively large (96 MW considering the base size used in this study, i.e. 430 MW biomass input) for the EtOH case. The operating time was also set to the same as the other plants, 8000 h/y. As discussed in Section 3.4.5 for the electricity case, this is questionable for this type of plant. In several district heating systems, operating times for biomass CHP of around 4500-5000 h/y would be more realistic. The excess heat would then be placed over the base load capacity, such as waste CHP and existing deliveries of industrial excess heat. For the ethanol plant, no sensitivity analysis connected to the operating time was performed. However, the sensitivity analysis where the heat price is only based on variable cost (see Section 4.1), have a somewhat larger, but in the same size range, as the effect would be if the reduction in operating time would be considered. Furthermore, the ethanol plant could be integrated with industrial plants such as pulp and paper mills or sawmills, with somewhat lower total efficiencies, but still comparable to the energy balance for the concept integrated with a district heating system considered in this study (see Wetterlund et al., 2017).

The considered plant size is, as discussed above, set to 430 MW biomass input. This is a very large plant for a CHP plant in a district heating system. However, to use the same biomass plant input in all cases, this was not changed for this plant only. The operating time is also set to the same as the other plants, 8000 h/y. This is also questionable for this type of plant. In several district heating systems, operating times for biomass CHP of around 4500-5000 h/y would be more realistic. The excess heat would then be placed over the base load capacity, such as waste CHP and existing deliveries of industrial excess heat. In the sensitivity analysis, presented in Section 4, both a reduction of the plant size and a combination of reduction of plant size and lower yearly operating time is performed.

A central facility for the development of (among other things) biofuels in Sweden has for many years been the demonstration plant in Örnsköldsvik for the degradation of lignocellulosic material, for example wood or straw, to products that include, for example, ethanol. Sekab and RISE jointly run the plant called Biorefinery Demo Plant. The facility serves as an available resource for companies, universities and institutes where research and development work can be carried out (Trafikutskottet, 2017).

The TRL level for the ethanol concept considered in this study is assumed to be similar to the gasification-based concepts.

RENEWABLE DIESEL AND PETROL (REFINERY PRODUCTS FROM BIO-OIL)

As mentioned in Section 3.1, hydrocarbon-based fuels produced from lignocellulosic feedstock have been pinpointed as a short-term priority due to the ability to blend with fossil fuels and use directly in existing vehicles. In these tracks a bio-oil is first produced. The bio-oil can replace fossil oil and be upgraded in existing refineries. In contrast to the other studied biofuel concepts, relatively few previous studies have investigated integration possibilities and evaluated the performance from a system perspective for these type of value chains, especially based on other technologies than pyrolysis. The reason for this is the poor access to data for the hydrocarbon-based tracks due to generally low technical maturity. Some studies performed in recent years include Furusjö et al. (2017), Anheden et al. (2017) and de Jong et al. (2017).

Data for the concept producing renewable diesel and petrol from bio-oil was based on Anheden et al. (2017) and Furusjö et al. (2017), who in turn based it on data from SunCarbon[11]. The concept starts with membrane-based separation of lignin at a chemical (kraft) pulp and paper mill. The lignin is then depolymerised by a hydro thermal liquefaction (HTL) process to produce a bio-oil. Using a HTL process instead of a pyrolysis process for producing the bio-oil is for example motivated by de Jong et al. (2017) by the higher quality in terms of heating value, moisture content, oxygen content, and stability of the bio-oil from a HTL-based process than from a pyrolysis-based process. Looking at the results from Anheden et al. (2017), the concepts based on HTL generally has a significantly better economic performance than a concept for fast pyrolysis (not hydropyrolysis).

As for the black liquor gasification-based methanol plant, the production of bio-oil from lignin is naturally integrated with a chemical pulp (and paper) mill. Also for this case, the same generic mill has been used. The reason for this is the same as discussed for the methanol case above. The bio-oil is then transported to a refinery, where a hydrodeoxygenation (HDO)-based upgrading to diesel and petrol takes place. The replacement of fossil oil with bio-oil could lead to reduced production of fossil diesel/petrol. This has, however, not been considered in this study.

At ETC in Piteå (part of RISE) there is a pilot plant for upgrading biomaterials through so-called slurry hydrocracking. The intention is to convert biomass, for example lignin, into fuel. The facility should be an open and accessible research infrastructure where academia and industry can test different concepts before they are commercialized. Here, SunCarbon has run a project aimed at developing a value chain from black liquor lignin to aviation and vehicle fuels using the concept considered in this study.

As mentioned in the section about the gasification-based methanol production, a technology maturity assessment was carried out by Furusjö et al. (2017) for different technologies under development. This assessment included the concept for renewable diesel and petrol production from lignin via HTL used in this study. If a weighted average approach was used (see above), the TRL level for this concept is 4 which corresponds to “Technology validated in lab” on the TRL scale (see Furusjö et al., 2017). However, if the “weakest link” was considered, this concept has a somewhat lover TRL level, 3, which corresponds to “Experimental proof of concept”.

[11] Anheden et al. refer to SunCarbon (2016), SunCarbon Power point presentation 2016-09-28 and Furusjö et al. refer to Anheden et al. as well as SunCarbon (2017). Personal communication with Christian Hulteberg and Josefina Jernberg.

APPENDIX B – RESULTING ENERGY BALANCES, INVESTMENT COSTS AND TOTAL COSTS FOR PRODUCTION

Table B.1 presents the resulting total net input and output of different energy carriers, as well as the net investment cost, compared to the alternative investment for the host industries, for the considered production plants.

Table B.1. Resulting total net input and output of different energy carriers, as well as net investment cost, compared to the alternative investment for the host industries for the considered production plants.

		SNG-BMG-PoP	MeOH-BLG-PoP	EtOH/BG-HF-DH	Diesel/Petrol-HTL-PoP/Ref	El-CHP-DH[a]
Input						
Forest residues	MW	344	260	303	454	148
Electricity	MW	30	47	15	7	
Hydrogen	MW				68	
Output						
Biofuel 1	MW	299	232	182	171	133
Biofuel 2	MW			60	37	
Electricity[b]	MW	16	-32	12	-18	
Natural gas[c]	MW				116	
Investment cost	MSEK	4327	3027	3823	2901	787

[a] For this case allocation has been made based on the energy content of the products (electricity used for transportation and heat). The values shown are the values allocated to the "biofuel", i.e. the electricity.
[b] Negative values indicate that more heat is produced by the alternative heat production plant than by the biofuel plant.
[c] The natural gas that would otherwise be used for heat production at the refinery.

Figure B.1 shows the total (net) production cost (well-to-gate) for the considered production plants. The total production cost consists of the cost (and revenues) connected to plant capital, O&M, raw material (forest biomass), transportation of raw material, electricity, heat and hydrogen.

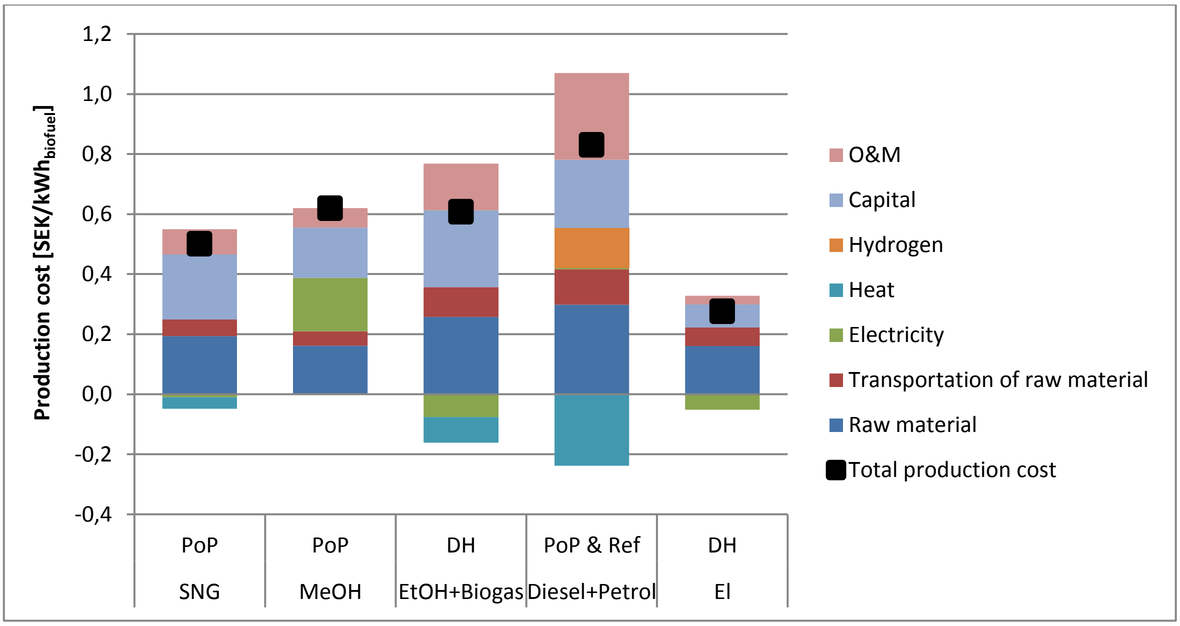

Figure B.1. Production cost (well-to-gate) for the considered production plants.

APPENDIX C – DISTRIBUTION COSTS

Figure C.1 shows the total distribution costs (gate-to-tank) for the considered distribution chains. The total distribution cost consists of the cost connected to distribution to refuelling station, refuelling station capital and O&M.

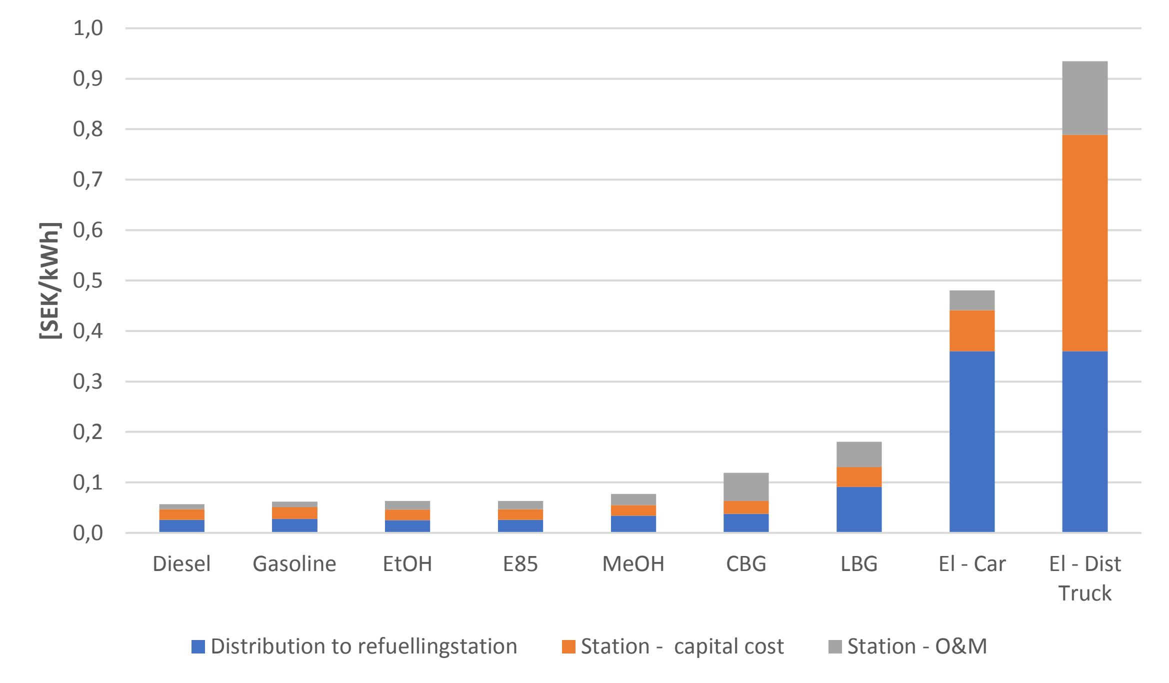

Figure C.1. Distribution costs (gate-to-tank) for the considered distribution chains.

APPENDIX D – VEHICLE COSTS

Figure D.1-D.3 shows the vehicles costs in the different transport segments. The total vehicle cost consists of the costs (and “revenues”) connected to annual depreciation (capital), O&M, taxes and Bonus Malus.

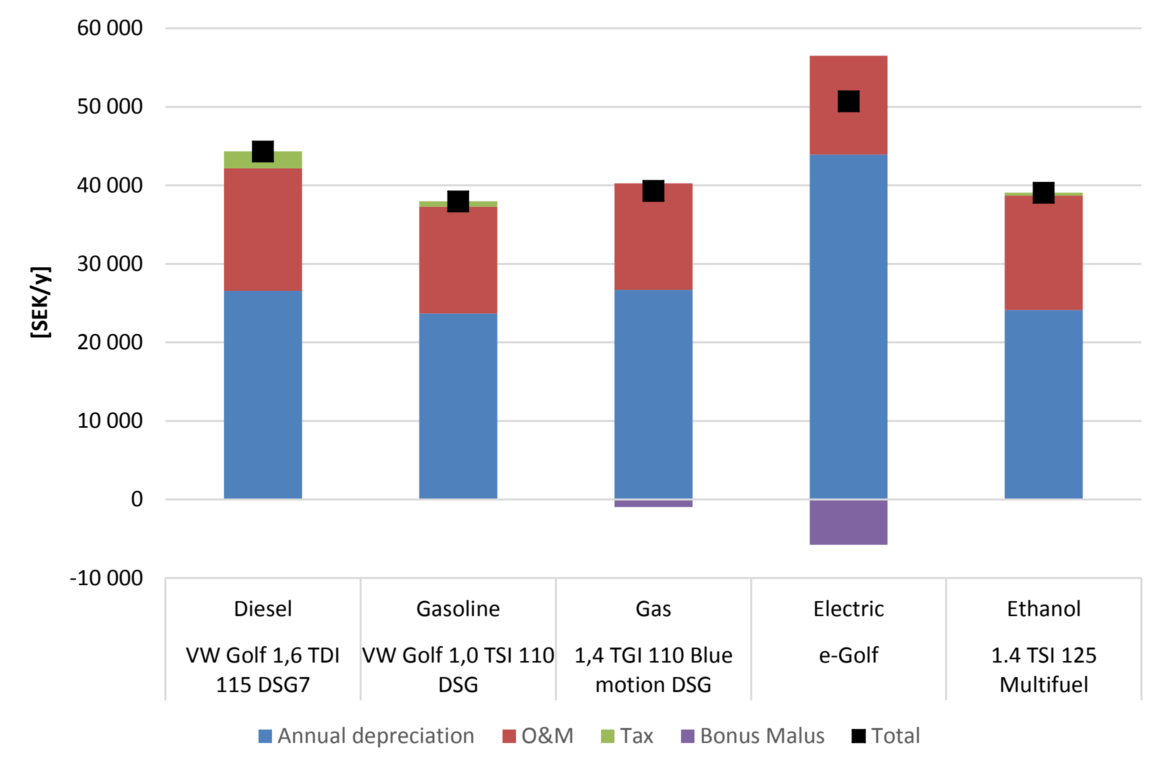

Figure D.1. Vehicle costs in the car segment.

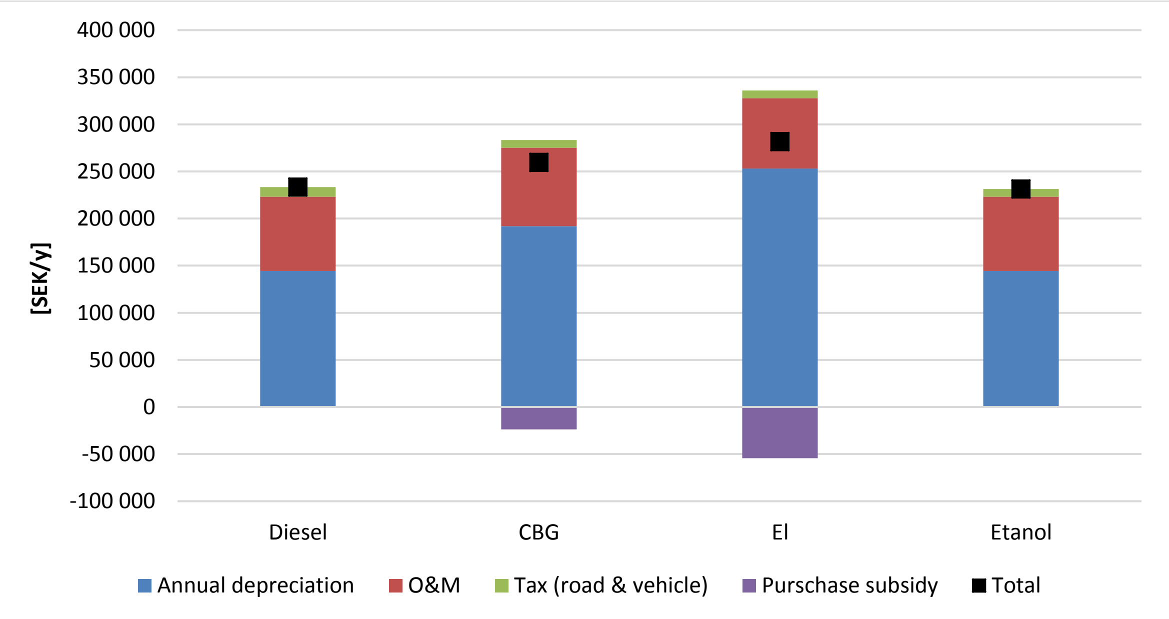

Figure D.2. Vehicle costs in the distribution truck segment.

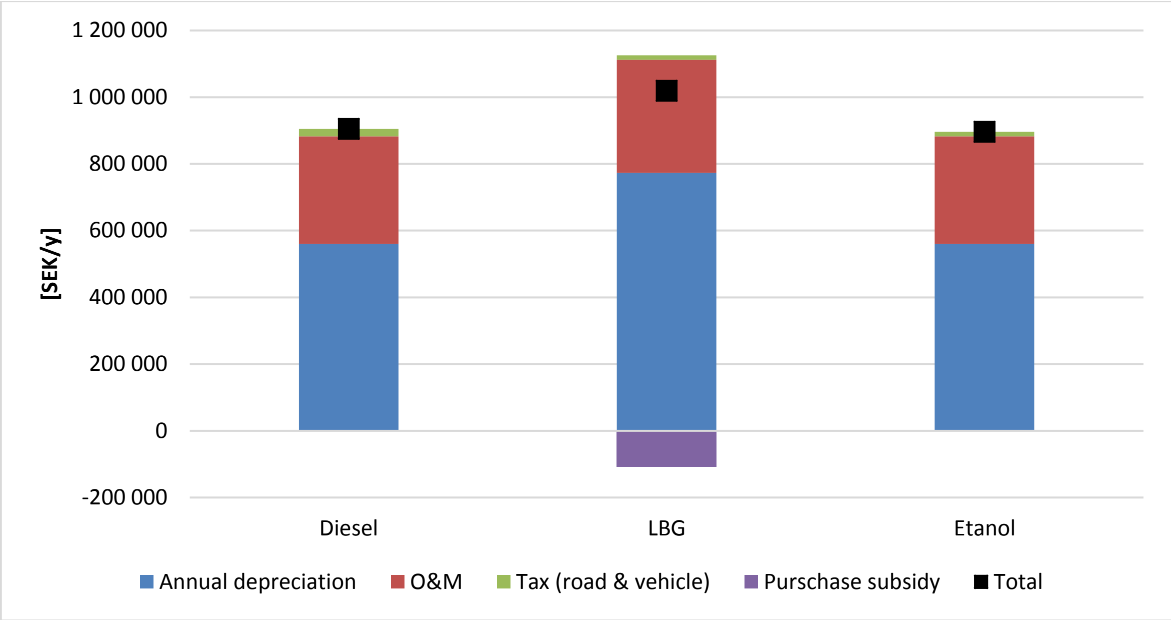

Figure D.3. Vehicle costs in the long-distance truck segment.