The role of methane and hydrogen in a fossil-free Swedish transport sector

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This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that constitute the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Research Theme Technology and Social Change at Linköping University, the Division of Energy and Environment at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm. Associated research groups are the Division of Environmental Systems Analysis at Chalmers University of Technology in Göteborg as well as the Division of Electric Power Systems at the Royal Institute of Technology in Stockholm.

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ABSTRACT

Drastic reductions of greenhouse gas emissions are required to limit the severe risks associated with a changing climate. One measure is to disrupt the fossil-fuel dependency in the transport sector, but it appears difficult and costly in comparison to other measures.

Vehicles and fuels are available, but no single alternative can replace petrol and diesel in all parts of the transport system. None of them are ideal regarding all of the following aspects: vehicle performance, fuel production potential, sustainability, infrastructure, technology development and economy. Instead, several fuels are needed.

In this thesis, the aim is to investigate the role of methane and hydrogen in a fossil-free vehicle fleet in Sweden, and compare them with other fuels in terms of well-to-wheel energy efficiency and economy. Processes for producing methane from biomass, waste streams from pulp mills and electricity are studied with techno-economic methods. Furthermore, well-to-wheel studies and scenarios are used to investigate the fuel chains and the interaction with the energy and transport systems.

Effects of policy instruments on the development of biogas in the Swedish transport sector are also analysed and policy instruments are suggested to increase the use of methane and to introduce hydrogen and fuel cell electric vehicles. The results reveal that tax exemptions and investment support have been and will continue to be important policy instruments, but that effective policy instruments are needed to develop fuelling infrastructure and to support alternative vehicles.

Electricity will be an important transport fuel for several reasons; the electric powertrain enables high energy efficiency and electricity can be produced from various renewable energy sources. Nevertheless, other fuels will be needed as complements to electricity. The results reveal that methane and hydrogen and associated vehicles may be necessary to reach a fossil-free vehicle fleet in Sweden. These fuels have several advantages:

- The function of the vehicles resembles conventional vehicles but with lower local and global emissions.
- Methane is a well proven as a transport fuel and hydrogen infrastructure and FCEVs, are commercial or close to commercialisation.
- They enable high well-to-wheel energy efficiency.
- They can be produced from renewable electricity and act as energy storage.

Keywords: renewable transport fuels, biogas, methane, hydrogen, electrofuels, pyrolysis, well to wheel, transport policy, energy policy
SAMMANFATTNING

Utsläppen av växthusgaser innebär en risk för drastiska förändringar av människans förutsättningar att leva på jorden. Att ersätta fossila bränslen med förnybar energi är eniktig åtgärd i arbetet för att minska utsläppen. Det har dock visat sig relativt svårt och dyrt att genomföra i transportsektorn.

Olika drivmedel och fordon har föreslagits, men det är svårt att välja ett specifikt alternativ som kan ersätta bensin och diesel fullt ut i hela transportsystemet. Troligtvis för att inget alternativ är uppenbart överlägset de andra i en sammanvägning av aspekter som fordonets egenskaper, produktionspotential, hållbarhet, distributionsmöjligheter och ekonomi. Därför behövs flera drivmedel och fordonstyper för att uppnå en fossilberoende fordonstol. 

Syftet med avhandlingen är att utreda vilken roll metan och vätska kan spela i ett fossilberoende vägtransportsystem i Sverige, utifrån jämförelser med varandra och med andra drivmedel med avseende på ekonomi och energieffektivitet. Processer för att producera metan från biomassa, elektricitet samt avfallsströmmar från massabruk har studerats utifrån ett teknoekonominiskt perspektiv. Det kompletterats med scenariostudier och studier av bränslekedjan från energikälla till fordon.

Vidare har styrmedel för biogas i transportsektorn analyserats i syfte att föreslå strategier för att introducera mer biogas och även vätska och bränslecelfordon. Resultaten visar att styrmedel som skattebefrielse och investeringsstöd har varit viktiga och kommer vara viktiga även för vätska, men att ytterligare stöd behövs till infrastruktur och fordon.

Elektricitet kommer vara ett viktigt bränsle i transportsektorn då elfordon är energieffektiva och elektricitet kan produceras från en rad fornybara energikällor. Men andra drivmedel behövs som komplement till elfordon. Resultaten visar att metan och vätska kan behövas för att uppnå fossilberoende fordonstoflotta i Sverige. Dessa drivmedel har flera fördelar:

- Fordonen för dessa bränslen kan användas på samma sätt som konventionella fordon men har lägre lokala och globala utsläpp.
- Metan används redan som transportbränsle, och infrastruktur och fordon för vätska är nära en kommersiell fas.
- De möjliggör hög energieffektivitet i bränslekedjorna.
- De kan produceras från förnybar elektricitet och fungera som energilager.
LIST OF PAPERS


Related journal publication not appended:

VII. Olsson L, Hjalmarsson L, Wikström M, Larsson M. 2015. Bridging the implementation gap: Combining backcasting and policy analysis to study renewable energy in urban road transport. Transport Policy 37, 72-82.

My contribution to appended papers

I am the main author of Papers II-VI. Papers I and II were written together with my colleague Martin Görling. I was responsible for the Aspen Simulations and Görling for the heat integration. Paper III was written together with Mikael Jansson, who was responsible for the investment calculations.

Per Alvfors supervised Papers I-VI, Stefan Grönkvist Papers II-VI, Mats Westermark Papers I and II and Cecilia Wallmark Paper V.
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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BEV</td>
<td>Battery electric vehicle</td>
</tr>
<tr>
<td>CBG</td>
<td>Compressed biogas</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical oxygen demand</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl ether</td>
</tr>
<tr>
<td>FAME</td>
<td>Fatty acid methyl ester</td>
</tr>
<tr>
<td>FCEV</td>
<td>Fuel cell electric vehicle</td>
</tr>
<tr>
<td>FT-diesel</td>
<td>Fisher-Tropsch diesel</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher heating value</td>
</tr>
<tr>
<td>HVO</td>
<td>Hydrogenated vegetable oil</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal combustion engine vehicle</td>
</tr>
<tr>
<td>LBG</td>
<td>Liquid biogas</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
</tr>
<tr>
<td>PEME</td>
<td>Polymer electrolyte membrane electrolysis</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>SOE</td>
<td>Solid oxide electrolysis</td>
</tr>
<tr>
<td>TCO</td>
<td>Total cost of ownership</td>
</tr>
<tr>
<td>WtW</td>
<td>Well-to-wheel</td>
</tr>
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<td>WWT</td>
<td>Wastewater treatment</td>
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</table>
INTRODUCTION

Drastic reductions of greenhouse gas emissions in the next few decades are essential to reduce the risks associated with global warming and climate change. The Intergovernmental Panel on Climate Change [IPCC 2014] explains the severe situation:

“Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.”

”Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.”

A transition is needed throughout the whole of society, but this work focuses on a specific area: the possibilities to reduce emissions from the road transport sector by replacing fossil fuels with sustainable fuels based on renewable energy.

1.1 Challenges in the road transport sector

Several problems are associated with the current road transport system. In urban areas, local environmental problems related to traffic are obvious to many people, these problems include polluted air, congestion, noise, and accidents. There still seems to be relatively little awareness of the risks related to global climate effects caused by extensive use of fossil fuels in this sector.

The transport sector contributes significantly to global emissions of greenhouse gases, and it is also a sector that seems more difficult and costly to transform compared to the energy utility, industrial and residential sectors. It is debatable whether measures in the transport sector should be given priority over less costly and perhaps more urgent measures, for example in the energy utility sector. In the future, the energy utility and transport sectors will likely become more integrated and utilize the same energy sources, and in such a case, it is necessary to transform both sectors. Furthermore, it is necessary to initiate the transition in all sectors, especially those where emission reductions seem most difficult to achieve, such as the transport sector. In Sweden, there is already a high share of renewable energy in the energy utility sector, and therefore it seems motivated to address the problems in the transport sector.
In the EU 2020 targets for climate change and energy sustainability, there is a goal that each Member State shall introduce 10% renewable energy in the transport sector [EU 2009a]. But according to the EU 2030 goals for energy and climate, transport does not seem to be a prioritized area, as it is not included. Sweden, on the other hand, has proclaimed an impressive vision of a fossil-free vehicle fleet in 2030, which has been defined as a fleet of vehicles that mainly can be fuelled with electricity or biofuels [Swedish Ministry of Enterprise, Energy and Communications 2013]. However, few substantial changes have been made in policies for alternative fuels and vehicles that would allow achievement of this goal within the coming 15 years. As this time period is comparable to the lifetime of a passenger vehicle, major changes would be needed immediately to even approach this vision.

Reduced transport demand and shifting from road transport with motor vehicles to other means of transport are commonly mentioned as some of the most important measures for a more sustainable transport sector. In order to accomplish this, adequately designed national policies are necessary. However, because road transport of passengers and goods is a crucial part of the economy, it may be difficult to introduce policies that aim to reduce road transport. For the same reason, it is difficult to introduce policies that may threaten the consumption of other goods or services. In the longer term, it is also difficult to reduce the total transport demand when the world’s population and economies are growing. In addition, in the foreseeable future there will still be a demand for transport services that require road transport vehicles in different forms. If the global and local environmental impacts from road transport vehicles are to be reduced, it is necessary to switch to fuels based on renewable energy and to more efficient vehicles that cause less local pollution.

Today’s transport sector is based on oil, and the cost competitiveness of renewable transport is benchmarked in relation to the oil price. A higher oil price is commonly mentioned as a possibility for introducing more renewable fuels, and the oil price is a crucial parameter when making projections for development in the energy and transport sectors. In 2014, after several years with an average price of crude oil around USD 100 per barrel, there was a drastic drop down to a level around USD 50 per barrel, and it is currently continuing down towards USD 40 [oil-price.net 2015]. This drastically changes the prerequisites for introducing alternative fuels on the market. Therefore, the unexpected price reductions for oil rendered projections based on previous higher oil prices obsolete.

So far, Sweden has been relatively progressive in the development of biofuels, and introduced bioethanol, biodiesel and biogas in volumes that already surpass the EU 2020 goals. Nevertheless, the transformation to a fossil-fuel independent vehicle fleet has still barely begun.
Biodiesel and bioethanol are mainly sold as low-blend (5-10%) and biogas is commonly sold in a medium-blend form (above 50%). In a fossil-free vehicle fleet, all vehicles must be adapted to operate on high-blend or pure biofuels and/or electricity. This will not be achieved by increasing the use of low-blend biofuels in conventional vehicles. Moreover, sustainability issues remain for the first-generation biofuels based on sugar, starch and vegetable oils, raising doubts as to whether they can contribute to a sustainable transport fleet in the long term.

The possibilities are still uncertain for renewable fuels and alternative powertrains to fully substitute fossil fuels in the transport sector with regard to user demand and economy. Energy gases, such as methane and hydrogen, may have a significant role in a more sustainable transport fleet, as they can be produced from a range of renewable energy sources with high energy-conversion efficiency. Furthermore, methane-fuelled vehicles produce less local emissions compared to conventional vehicles, and hydrogen-fuelled fuel cell electric vehicles (FCEVs) are energy efficient and have no local emissions from the powertrain. However, the physical properties of energy gases differ significantly from those of conventional fossil fuels and require changes in fuelling infrastructure and vehicles. Therefore, an effective system of policy instruments is needed to introduce such fuels, if they are deemed to be able to contribute to an energy-efficient and sustainable transport sector.

1.2 Biofuel production

Numerous pathways are available for using renewable energy sources in the transport sector, and while many of them are described in Figure 1, the diagram does not include every possible pathway. The fuel pathways that are used on a commercial scale today are the first-generation biofuels, which are commonly defined as transport fuels produced from starch, sugar or vegetable oils. However, in one production pathway commonly defined as first generation – anaerobic digestion of organic waste – more complex molecules than those previously mentioned may be degraded.

Sugar and starch can be fermented to create ethanol, and organic waste can be treated with anaerobic digestion from which biogas (methane) is produced. Both these processes are examples of biological conversion pathways. Hydrogenated vegetable oils (HVO) and fatty acid methyl esters (FAME) are liquid fuels sharing many similarities with fossil diesel, and both of them can be denoted as biodiesel. However, while the properties of HVO are very similar to those of diesel and HVO can be used in high blends without adaptation of the engine, only lower blends of FAME can be used in conventional diesel engines. In Sweden, both are commonly used as drop-in fuels mixed with fossil diesel. Ethanol is commonly used as drop-in fuel in fossil petrol, but it has also been introduced as a high-blend fuel (85%) in Sweden.
Figure 1. Overview of fuel chains from renewable energy sources for use in different types of vehicles (based to some extent on Magnusson [2012]). Pathways that are used today are shown with black solid lines and pathways not yet used on a commercial scale are shown in grey, and the dashed lines represent the pathways that are studied in this thesis. FAME – fatty acid methyl ester, FT – Fischer-Tropsch, HVO – hydrogenated vegetable oils, DME - dimethyl ether.
Upgraded biogas is identical to natural gas and these two are commonly sold as a mixture; in Sweden, the share of biogas in this fuel type is usually between 50 and 100%. The term biogas is commonly related to methane produced via anaerobic digestion, and it can refer either to raw biogas, which is a mixture of methane and carbon dioxide, or to upgraded biogas (above 95% methane content). The upgraded biogas is commonly denoted biomethane, which can also be used as a more general term for methane produced via other production pathways. In this thesis, biogas mainly refers to upgraded biogas produced via anaerobic digestion and biomethane to methane produced via gasification or pyrolysis.

The fuel pathways based on lignocellulosic biomass are commonly classified as second-generation and the most frequently mentioned pathways are gasification followed by different synthesis processes and ethanol produced from cellulosic biomass. These processes have been under development for a long time and at least gasification is close to commercialization, but the technology has yet to be proven in large-scale commercial applications over prolonged periods of time.

Gasification means heating of e.g. biomass in an environment with limited access to oxygen, which leads to decomposition into an energy-rich gas called syngas that contains hydrogen, methane, carbon monoxide and carbon dioxide. The syngas is further treated, for example to shift the equilibrium towards hydrogen or methane, if this is the desired product, or to produce liquid fuels such as methanol or Fisher-Tropsch liquids that can be further refined into diesel and petrol. Pyrolysis can also be included in the category of second-generation biofuels. This process is similar to gasification, but takes place at a lower temperature, which means that the decomposition of the biomass is less extensive. Second-generation biofuel production opens up a significantly larger feedstock base than that of first-generation biofuels, because the process can use biomass from the forest and fast-growing energy crops as well as waste from forestry and agriculture. Moreover, these pathways enable production of a wider range of fuels, and some of them may be more easily integrated in the current transport system than first-generation biofuels.

Fuels that do not match the two previous definitions and are further away from commercialisation can be classified as third-generation biofuels. This becomes a broad category including electrofuels or fuels produced with engineered algae or other microorganisms. The term electrofuels normally refers to the use of electricity for splitting water and carbon dioxide into a syngas that is used to synthesise different transport fuels.

Many of the suggested renewable fuels are designated for the conventional internal combustion engine vehicle (ICEV), but electric vehicles fuelled by electricity or hydrogen can enable significantly higher end-use energy efficiency.
Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) can be directly fuelled by electricity, and PHEVs also have a combustion engine fuelled by a liquid fuel. Fuel cell electric vehicles (FCEVs) are fuelled by hydrogen that is converted into electricity in a fuel cell for use in an electric motor.

End-use efficiency of electric vehicles is significantly higher than that for conventional vehicles; this increases the possibilities to achieve high energy efficiency in the whole fuel chain, from renewable energy source to use in the vehicle. This will be explored further in this thesis. Furthermore, electricity and hydrogen can be produced from a range of energy sources.

1.3 Renewable transport fuels in Sweden

Due to periods of relatively strong policy instruments for introducing biofuels as well as infrastructure and vehicles, biofuels have a relatively firm foothold in Sweden. In 2013, biofuels’ share of the energy end use in the Swedish road transport sector was close to 11%, based on the energy content. Using the accounting methods in the EU Directive on the promotion of renewable energy sources [EU 2009a], Sweden had 16.7% renewable energy in the transport sector in 2013 [Eurostat 2015]. Hence, Sweden has already more than fulfilled the EU 2020 goal of 10% renewable energy in the transport sector. Sweden is the only country that has already reached this target and the average share for the whole EU28 region is 5.4% [Eurostat 2015].

In Sweden, high-blend ethanol and biogas have been introduced, but it is still the low-blend fuels, biodiesel and bioethanol that comprise the bulk of renewable fuels. In 2014, 86% of the biodiesel and 52% of the bioethanol were sold as low-blend [SCB 2015a]. It should be noted, however, that in an international context Sweden are among the countries that have achieved a relatively high use of high-blend ethanol.

The use of biodiesel has increased dramatically during recent years and the use of biogas is increasing slowly but steadily. In contrast to this, the use of ethanol is showing a declining trend. During the three last years, as shown in Figure 2, the volumes of both low-blend and high-blend biodiesel increased while all types of use of ethanol are decreasing [SCB 2015a]. The main contributor to the dramatic increase in biodiesel volumes is HVO, which increased more than ten times from 2011 to 2013 [SEA 2015] and now constitutes more than half of Swedish biodiesel volumes. HVO is mainly produced from slaughter waste, tall oil, and palm oil [SEA 2015]. Contrary to what might be expected, only a small fraction of the feedstock for the biofuels used in Sweden is of domestic origin [SEA 2015].
The use of electricity in the Swedish road transport sector is still very limited; in 2014, there were about 2000 BEVs and about 5000 PHEVs in use [SCB 2015b]. These numbers refer to passenger vehicles, but there are also 833 light trucks and a few buses classified as BEVs.

![Graph showing biofuels production worldwide from 1995 to 2013](image)

**Figure 2:** The amount of biofuels (TWh/y) (black lines) used in the Swedish transport sector are shown on the left axis, and the total share (shaded grey field) of biofuels in energy end-use in the domestic road transport sector on the right axis [SEA 2015].

### 1.3.1 International outlook

Biofuel production worldwide has increased significantly since 2000, but in main production countries there has been a trend of declining production volumes during recent years, see Figures 3 and 4. The production is concentrated to Europe, the USA, Brazil and China. As biofuel production in North and South America is so clearly concentrated USA and Brazil, respectively, statistics are presented only for these countries and not for their corresponding regions. In Asia and Oceania combined and Europe, the production volumes are slightly more spread out among different countries, and statistics are therefore presented per region.
Ethanol is the main biofuel in terms of production volumes, and in 2012, ethanol production was about three times higher than biodiesel production (based on energy content) [IEA 2015a]. USA has by far the highest production of ethanol followed by Brazil, and these two countries dominate world ethanol production, as seen in Figure 3.
The production volumes in the regions of Asia and Oceania combined and Europe are relatively modest in comparison. Germany and France are the main producers of ethanol in Europe, although production does exist in many other European countries. In Asia and Oceania, ethanol is mainly produced in China.

Europe is the leader in biodiesel production and Germany and France are also here the main producers. In Asia and Oceania, the main producers are China, Indonesia and Thailand.

1.4 *A Swedish road transport sector fuelled by renewable energy*

In accordance with the visions of a fossil-free Swedish transport fleet by 2030 and no net greenhouse gas emissions in Sweden by 2050, fossil fuels will be phased out from the Swedish transport sector relatively fast and replaced by fuels produced from renewable energy sources [Swedish Ministry of Enterprise, Energy and Communications 2013].

In 2008, the Swedish Government proclaimed a vision of a so-called fossil-fuel-independent vehicle fleet by 2030. The definition of this vision and the available measures to reach it were analysed in an official inquiry by the appointed Swedish commission on fossil-free road transport [Swedish Ministry of Enterprise, Energy and Communications 2013]. The fossil-fuel-independent fleet was defined in the following way: a road transport fleet with vehicles mainly fuelled by biofuels or electricity.

Higher taxes on fossil fuels and continued tax exemptions for some renewable fuels were suggested as general policy instruments, and a fuel mandate was also suggested to stimulate the production of biofuels. Furthermore, a bonus-malus system was suggested for reducing the emissions from light-duty vehicles, where vehicles fuelled by petrol or diesel are taxed over their lifetime, and the funds are used to grant clean-car bonuses to vehicles with low emissions. The suggested systems of policy instruments for light-duty vehicles are in many ways similar to the current system, but with clean-car bonuses and higher taxes.

In 2015, biomass converted to liquid biofuels has been the main renewable energy source in the transport sector, but to reach the goal, it may be necessary to bring about more drastic changes in transport than merely introducing low-blend and high-blend biofuels for fuelling conventional combustion engine vehicles. Moreover, when working towards this goal, a range of other policy goals connected to vehicles and fuels must be considered, such as waste management, local emissions, noise pollution, congestion of roads in urban areas, and safety in traffic.
Many things must be taken into account as Sweden strives to create a more sustainable transport sector, and the main function of the transport system must not be forgotten: to provide sufficient mobility at an acceptable cost. However, in this section, it is discussed if it is even possible to cover the energy demand in a Swedish road transport sector without fossil fuels, considering the technologies at hand.

In a report from the Swedish commission on fossil-free road transport, the potential for replacing fossil fuels is estimated in scenarios for the years 2030 and 2050; see Table 1 [Swedish Ministry of Enterprise, Energy and Communications 2013]. In a scenario for 2050, where the full potential of each measure is realized, the vehicle fleet is completely fossil free and renewable fuels are even exported. The measures with the highest potential for reducing the use of fossil fuels are those that reduce the energy demand in the transport sector.

Assuming that the full potential for reduced energy end-use can be reached in 2020, 20 TWh of biofuels are needed every year to cover 65% of the energy demand in the transport sector. The commission for fossil-free road transport proposes an example of how this could be achieved, using 3 TWh ethanol, 4-5 TWh biodiesel (HVO and FAME) and 12-13 TWh of biogas and DME. The biogas production is assumed to include about 4 TWh from anaerobic digestion and the rest would come from large gasification facilities. This exemplification is based on the possibilities to transform the vehicle fleet, i.e. to introduce vehicles that can use high-blend or pure fuels based on renewable energy. The limitations in domestic production potential or imports are not the basis for the division into fuel categories.

It should be noted that transport work performed by the electric motor is more efficient compared to that of biofuels in a combustion engine, and that the share of transport work in the scenario for 2050 (Table 1) covered by electricity is significantly greater than the 45% of energy end-use suggests. In the scenario mentioned here, the share of transport work fuelled by electricity is 60%, 100% and 25% for the sectors of passenger cars, city buses and long-distance trucks, respectively. Furthermore, it should be noted that hydrogen-fuelled FCEVs are included in the electricity category. According to these scenarios, it seems theoretically possible to cover the energy demand in a fossil-free Swedish transport sector – given a drastic transformation of the current transport sector.
Table 1. The potential contribution of various measures to achieving a fossil-free vehicle fleet. Energy-efficiency measures are in relation to the situation in 2010, while the other measures to reduce energy use are in relation to the reference scenarios of 2030 and 2050. [Swedish Ministry of Enterprise, Energy and Communications 2013]. The categories addressed in this thesis are shaded in grey.

<table>
<thead>
<tr>
<th>Type of measure</th>
<th>2030</th>
<th>2050</th>
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<tbody>
<tr>
<td>Increased traffic in the reference scenario</td>
<td>15%</td>
<td>32%</td>
</tr>
<tr>
<td>Reduced demand for transport and increased transport efficiency.</td>
<td>9-20%</td>
<td>15-33%</td>
</tr>
<tr>
<td>Transfer to other means of transport (cargo) and increased use of public transport.</td>
<td>1-3%</td>
<td>2-4%</td>
</tr>
<tr>
<td>More energy-efficient vehicles, including hybridization.</td>
<td>34-42%</td>
<td>45-49%</td>
</tr>
<tr>
<td>More energy-efficient vehicles, via electric vehicles and plug in hybrids.</td>
<td>4-8%</td>
<td>13-20%</td>
</tr>
<tr>
<td>Energy efficient use of vehicles</td>
<td>8-15%</td>
<td>10-15%</td>
</tr>
<tr>
<td><strong>Reduced energy use compared to 2010</strong></td>
<td>39-60%</td>
<td>53-70%</td>
</tr>
<tr>
<td>Electricity - share of the energy use</td>
<td>3-14%</td>
<td>19-45%</td>
</tr>
<tr>
<td>Biofuels - share of the energy use</td>
<td>32-65%</td>
<td>55-55%</td>
</tr>
<tr>
<td>Fossil fuels - share of the energy use</td>
<td>65-21%</td>
<td>26-0%</td>
</tr>
<tr>
<td><strong>Reduced use of fossil fuels compared to 2010</strong></td>
<td>58-91%</td>
<td>87-100%</td>
</tr>
</tbody>
</table>

In Sweden in 2014, renewable transport fuels were mainly food-crop based ethanol and biodiesel that are sold in low-blend formulations, together with biogas from anaerobic digestion of waste [SEA 2015; SCB 2015a]. According to the long-term scenarios for the Swedish energy system, developed by the Swedish Energy Agency [SEA 2014a], no major changes in this development are expected until 2030.

In the reference scenario for 2030, which takes into account the effects of already decided policy instruments, the energy demand is reduced by 12% due to more energy-efficient light-duty vehicles, and the share of renewable fuels is 19% [SEA 2014a]. The majority of the renewable fuels are low-blend biofuels of which hydrogenated vegetable oils (HVO) constitute the main part, and the amount of electricity in road transport vehicles is negligible. Hence, the main part of the renewable energy in the transport sector comprises low-blend liquid fuels produced from biomass, while biogas and electricity constitute only a small part of the energy use. The transport fleet in this projection is very dependent on fossil fuels.
Significant volumes of renewable fuels are needed to cover the energy demand in the road transport sector. There are limitations, however, in the technical and economic production potential for all biofuels. Technical potential refers to the availability of biomass or land for growing biomass and the conversion efficiencies in the fuel chain, while economic potential refers to what can be produced at a cost level comparable to that of conventional fuels. Furthermore, extensive biofuel production may cause problems with sustainability, and these problems are the subjects of widespread debate considering competition with food production and reduced biological diversity. A large-scale introduction of biomass in the transport sector depends on the development of so-called second-generation fuels, which are defined as fuels produced from lignocellulosic biomass, such as liquid or gaseous fuels produced by gasification of biomass.

Hansson and Grahn [2013] evaluated the possibilities for domestic biofuel production capacity in Sweden, and in the scenarios for 2030, they estimated it to be between 13 and 26 TWh per year, which includes the biofuel types we currently use in Sweden and fuels produced via gasification of biomass. The commission on fossil-free road transport estimated a biofuel production potential of annually 25-30 TWh in 2030 [Swedish Ministry of Enterprise, Energy and Communications 2013]. These production potentials can be compared to the 79.4 TWh of fuel used in the Swedish domestic road transport sector in 2013 [SEA 2015].

Renewable electricity is another option for covering the energy demand in the road transport sector. Electricity can be used efficiently in BEVs, for producing hydrogen for FCEVs, or in plug-in hybrid vehicles (PHEVs) combined with, for example, biofuels or hydrogen as the back-up fuel. Electricity can also be used to produce synthetic hydrocarbon fuels similar to the fossil fuels used today. One clear advantage with using electricity for propulsion is the absence of local emissions from the powertrain. Moreover, all energy sources can be converted into electricity and hydrogen and there is no need for multiple parallel distribution infrastructures and vehicle types. However, it would be a significant leap from the current use of combustion engines and liquid and gaseous fuels to the use of electric vehicles; new infrastructures are needed, new user patterns have to be accepted and established, and new business models for transport fuels and vehicles must be implemented.

The current limitations in battery technology limit vehicle range, and pure electric propulsion is most suitable for lighter vehicles. Vehicle manufacturers have shown that it is possible to extend the range, but still it is expensive and questionable from a resource efficiency perspective, as smaller electric passenger cars with shorter range ability can be constructed with less material and are more energy efficient. Hence, a change in the use of vehicles and possibly also in the ownership and business models for vehicles may be necessary, if battery electric vehicles are to be introduced at a large scale.
For heavier vehicles and buses, full electrification is more difficult unless advanced charging solutions are used, such as electrified roadways. But for these vehicles as well as for passenger vehicles, plug-in hybrid solutions are possible. FCEVs can directly substitute current light-duty vehicles and buses in many ways, but the vehicle technology and fuelling infrastructure are still in an early market phase.

There are also other possible renewable energy sources beside food crops, lignocellulosic biomass and renewable electricity; numerous production pathways for transport fuels are under development. Production of transport fuels from heat, sunlight, algae and bacteria is underway, but mainly on a laboratory scale, and commercial large-scale applications are expected only in the long term.

What we do not know is how these technologies should be best applied to provide the needed transport services in a sustainable, resource-efficient way and at a reasonable cost. As this thesis is focused on energy and transport systems, both energy and resource efficiency and the availability of renewable energy sources are central for the discussion.

1.5 **Aim and scope**

The overall aim of this thesis is to study and analyse the integration of methane and hydrogen produced from renewable energy sources in Swedish energy and road transport systems. These fuels are studied in a system perspective that includes production processes, distribution and use in vehicles, to analyse the energy efficiency and demand for primary energy. Furthermore, policy instruments for introducing alternative fuels and vehicles are studied. The focus is the Swedish energy and transport system and its expected development until 2030. The following research questions are explored:

- How can methane and hydrogen be produced from renewable energy sources or waste in a resource-efficient way?
- What role will these fuels play in energy and transport systems?
- Which policy instruments have been important in the introduction of biogas in the Swedish transport sector?
- Which policy instruments should be used to continue the introduction of biogas and to introduce advanced fuels like hydrogen and FCEVs?
The issues were studied with a multidisciplinary approach and on different system levels in the included papers. Three different areas were investigated:

i. Energy efficiency and costs for production processes for renewable methane were studied as well as possibilities for integration with industrial processes. These studies resulted in Papers I-III.

ii. Energy efficiency in the whole fuel chain from energy source to use in different vehicles was studied, together with the costs. This is presented in Papers IV-V.

iii. Finally, policy instruments directed at production and use of renewable transport fuels were studied, and the results are presented in Paper VI.

1.6 Outline

Chapter 2 describes the theoretical background of interdisciplinary system studies and the methods that were used.

Chapter 3 gives an overview of the technical systems for methane and hydrogen that are studied in this thesis as well as related technologies. Furthermore, the applicability of the production processes is discussed. This chapter also presents the energy efficiency in the entire system, from “well to wheel”, and also the production potential for different fuels.

Chapter 4 presents reflections on the use of policy instruments for renewable fuels and also discusses how these can be applied.

It should be noted that in chapter 3 and 4, background, results, and to some extent discussion are gathered around each study object and not divided into separate chapters. The results from the appended papers are mainly found in sections 3.1.1, 3.1.3, 3.5, 4.1.3 and 4.5.

Chapter 5 presents the overall results of this thesis and discusses how the technical, economic, and policy aspects of this thesis can be useful for bringing about the transformation to a fossil-free Sweden, and, finally, Chapter 6 summarises the conclusions.
2 METHODOLOGY

The integration of renewable energy in the transport sector depends on several factors, such as technical capabilities, economy, behaviour, and policy. Altogether, these form a complex system that can be described and analysed from many different perspectives. Therefore, a systems approach is needed to analyse the system and understand how it interacts with its surroundings. Churchman [1968] defines a system as several interacting components that are separated from their surroundings by a system boundary. The imagined delimitation does not prevent interaction across the system boundary, and such interaction is a crucial part of the analysis of the system.

In this thesis, transport fuels are studied within three different system boundaries: the fuel production process; the whole fuel chain from production to use; and the entire road transport system in Sweden. The work focuses in the interaction with the surrounding energy system and society in particular, and methods from various disciplines are used in the analysis.

A technical perspective can give an indication of some of the boundary conditions in the system – such as resource efficiency and fuel production potential – but when studying the transformation and development of a technical system, this approach falls short. Here, a socio-technical perspective can be helpful; it is based on the view that technology is not meaningful without a context and that technical and social systems are closely intertwined without a clear boundary Hughes [1986].

Taking inspiration from these theories and perspectives, a multidisciplinary approach is applied in this thesis to study the role of methane and hydrogen in the transport sector.

2.1 Methods

2.1.1 Process modelling and simulation

Process simulation software was used to study synthesis of methane from pyrolysis gases. Aspen Plus® (v7.2) is a chemical process optimization software package that performs steady-state simulations. It was used to calculate the energy and material conversion steps in methane production from pyrolysis gases. This information was then used to estimate the possibilities for heat integration in the overall energy balance for two cases: fast pyrolysis of biomass and fuel production integrated with charcoal production. In the simulation software, the conditions are ideal and chemical equilibria are fully reached.
2.1.2 Well-to-wheel studies

Well-to-wheel (WtW) studies are commonly used for estimating the energy use and greenhouse gas emissions for a fuel chain from feedstock to use of the fuel in vehicles. It is a relatively structured method for system studies of transport fuels that enables comparisons based on these two indicators. WtW studies are similar to life cycle analysis (LCA), but they are not standardized in the same way and they are less comprehensive [ISO 2006; JEC 2014; Maclean and Lave 2003]. WtW studies focus on the fuel chain from energy source to use in vehicles, whereas LCA also includes the life cycle of facilities and vehicles, and sometimes other aspects [Torchio and Santarelli 2010; Zamel and Li 2006].

The WtW system is commonly divided in two parts: well-to-tank and tank-to-wheel, where the latter part concerns the energy efficiency of and direct emissions from the vehicle.

In this thesis, the WtW perspective is used to study fuel pathways from renewable energy sources to the use of the fuels in different types of vehicles. The purpose is to compare the energy efficiency in the whole system, to discuss how transport can be efficiently supplied by renewable energy; therefore, emissions and climate impact were not included.

2.1.3 Investment calculations

Investment calculations, also referred to as capital budgeting, were done in the study on biogas production in pulp mills. The following standard methods for evaluating investments were used: the annuity method, the payback method and the discounted payback method.

2.1.4 Scenario studies

Scenario studies were used to evaluate the possibilities for different technologies and fuels to contribute to the transformation of energy and transport systems. In general, scenario studies can be used for evaluating possible pathways, and also for assessing the future and formulating policies, preferably in combination with other methods.

Accurate predictions of the development of complex systems are impossible; scenarios do not predict the future, but they can give insight into possible pathways. A scenario can be explained as a description of a future state or the development process towards a future state [Börjesson et al. 2006]. Börjesson et al. divided scenarios into three categories: predictive, explorative and normative. Predictive scenarios aim to estimate the future development while normative scenarios address how to reach a specific target.
The explorative scenario is meant to answer the question *what can happen?*, and this type of scenario is used in this thesis to examine the implications of using hydrogen-fuelled FCEVs in the road transport sector in Sweden.

As for LCA or WtW studies, the results from scenario studies can only be interpreted and used in combination with the purpose of, and assumptions used in, the scenarios. When used in this way, scenarios can provide valuable input to assessments of future pathways.

2.1.5 Studies of the use of policy instruments

Policy instruments can be evaluated on the basis of several indicators: effectiveness, efficiency, legitimacy, accountability, legal certainty, and fairness [Mees et al. 2014]. In this thesis, the focus is mainly on effectiveness and to some extent on efficiency. These two terms refer to the field of economics, and describe the fulfilment of the intended policy goal as effectiveness and use of resources in an optimal way as efficiency [Mees et al. 2014].

The effectiveness of policy instruments has been evaluated both quantitatively and qualitatively. To some extent, the development is evaluated quantitatively with statistics of the development and timing of policy instruments. However, a purely quantitative analysis of such a complex process is not possible (or at least not meaningful). Therefore, the effectiveness of the policy instruments is also analysed in a more qualitative way, based on available knowledge about effects of policy instruments.
3 FUEL CHAINS FOR METHANE AND HYDROGEN

This section presents the results from the studies on production of renewable methane and the energy efficiency in the whole fuel chain from well-to-wheel, as well as related background on gasification, hydrogen production, infrastructure and vehicles.

3.1 Four production pathways for renewable methane

Renewable methane is currently used in the Swedish transport sector. The production is mainly based on biological treatment of societal waste such as sewage sludge or food waste. This process is called anaerobic digestion. However, the technical production potential for this pathway is limited, even if crops are grown to expand the feedstock base. To produce large amounts of renewable methane for the transport sector and perhaps also the stationary sector, it is necessary to find other routes of production. In this thesis, production routes from lignocellulosic biomass and electricity are explored. The energy source and/or initial process steps differ between these two routes, but the final fuel synthesis, called methanation, and cleaning steps are the same.

Gasification converts biomass into a mixture of gaseous components called syngas, which can be further synthesized into methane. Pyrolysis is similar to gasification but produces gaseous, liquid and solid products, and this thesis explores the possibility to produce methane from the gaseous and liquid products. A syngas similar to that from gasification can be produced by decomposition of water and/or carbon dioxide by electrolysis. This route is a possibility for using electricity as an energy source for producing methane, commonly referred to as power to gas.

In the first part of this chapter, anaerobic digestion and the possibility to integrate the process in a pulp mill are explored (paper III). This is followed by a general description of methane production via gasification to give a background to the study on possibilities to produce methane via pyrolysis of biomass. Two possibilities are explored: fast pyrolysis and integration with charcoal production (Papers I and II). Finally, methane production via electrolysis of water is described.
3.1.1 Biogas production via anaerobic digestion

This section gives an introduction to biogas production via anaerobic digestion and the production potential in Sweden for this method. It also presents the results from Paper III from a case study on anaerobic digestion in pulp mills (Section 3.1.1.1).

The conversion processes in anaerobic digestion is divided in several steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and each step involves a specific consortium of microorganisms. As this is a biological process, it is sensitive to process conditions such as pH, temperature, alkalinity, concentration of volatile fatty acids, and availability of nutrition and toxic components [Chen et al. 2008; Yadvika et al. 2004]. If these parameters are outside the intervals suitable for the microorganisms, it can lead to reduced methane production and even complete process failure. Such conditions are called inhibition. However, in some cases and given time, the microorganisms can adapt to different process conditions; this is a crucial feature for enabling new applications and feedstock. The feedstock usually undergoes a pre-treatment process to make it more available to the microorganisms.

In Sweden, anaerobic digestion has long been used for handling sludge from wastewater treatment or other organic waste. The feedstock is degraded under anaerobic conditions in a series of complex reactions performed by different consortia of microorganisms. The biogas system has several environmental and societal benefits: organic waste is converted to a renewable transport fuel, valuable nutrition can be recycled, and greenhouse gas emissions from untreated waste at landfills are avoided. This means that greenhouse gas emissions are avoided as fossil transport fuels and fossil-based fertilizers are replaced.

A relatively large fraction of the feedstock is converted to methane and carbon dioxide, and this mixture is denoted biogas. The biogas consists of 45-85% methane and 15-45% carbon dioxide as well as some trace components. This energy-rich gas can be directly combusted or upgraded to a high methane content (>95%), and is thus fully sufficient for use as a transport fuel or for injection into a natural gas grid. The gas is upgraded by removal of carbon dioxide, water and impurities like sulphur-containing components, and the upgrading processes are further described by Persson [2003] and Ryckeboes et al. [2011]. The upgraded gas is denoted biomethane or biogas. In Sweden, a mixture of biogas and natural gas is sold as fuel for vehicles, here denoted as vehicle gas (a direct translation of the Swedish term), but methane for vehicles is also referred to as compressed natural gas (CNG) or compressed biogas (CBG).
During 2013, 1.7 TWh of biogas were produced in the following biogas production facilities in Sweden: wastewater treatment plants (40%), co-digestion plants (34%), landfills (14%), industrial waste treatment plants (7%), and farm-scale biogas plants (5%) [SEA 2014b]. Co-digestion plants treat multiple types of substrate, but mainly municipal solid waste. Of the total production of raw biogas, 54% is upgraded, 31% is used for heating, and 3% is used for electricity production. The use of biogas differs significantly between Sweden and the rest of Europe. Combined heat and power is the main use for biogas all over Europe. In the EU in 2013, biogas production reached 156 TWh, of which Germany accounted for half and Italy and the UK also had significant shares [EurObserv’ER 2014]. Hence, in total numbers, the Swedish biogas production appears relatively small, but Sweden is one of the leading countries in the development of biogas for transport.

There is a large potential for increasing biogas production in Sweden, but it is still limited in comparison to the energy use in the Swedish road transport sector. The most comprehensive study of the Swedish biogas production potential from waste, by Linné et al. [2008], estimated a total potential of 15.2 TWh per year, but with realistic limitations, the potential is estimated to be 8.4 TWh. “Limitations” refer to the economic limitations to realizing the biogas potential, and are based on the economic conditions at the time of the study. The major share of this potential, 70%, is connected to agricultural waste, such as manure and crop residues, and the rest is industrial waste streams and societal waste streams such as sewage sludge and food waste. So far the possibility to use agricultural waste has been limited and it is uncertain how much of this potential can be available for production of biogas. Energy crops have also been considered for biogas production, and assuming that 10% of the arable land in Sweden were to be used for energy crops for biogas, the annual production potential has been estimated to be 7 TWh [Linné och Jönsson 2004].

Lönnqvist et al. [2013] reviewed documents regarding the resource potential for biogas production from residues and energy crops, as a way of assessing a realistic potential. They found that around 2020, the potential that could be available amounts to about 8.86 TWh per year, but that uncertainties remain with respect to the possible use of energy crops, for which the potential was estimated to about 3.09 TWh per year.

Another study by Dahlgren et al. [2013] focused on the total realizable biogas potential in Sweden 2030 from a market perspective, and this study is based on other studies on production potential, such as the study by Linné et al. [2008]. In the study by Dahlgren et al., the potential for Sweden in 2030 was estimated in three different scenarios with the following intervals for minimum and maximum biogas production (TWh/y): 1.2-2.5, 4.9-7.7, and 5.3-9.6.
For the highest interval of biogas production, it is assumed that economic growth is good, that fossil fuel prices are high, that policy instruments are in favour of biogas production, and that 10% of arable land is available for energy crops [Dahlgren et al. 2013]. In the scenario with the lowest interval, the economic conditions are less favourable, and profitability is limited for other biogas facilities than those for codigestion and sewage sludge.

According to the potential study by Linné et al., about 170 GWh biogas per year can be produced from substrates available in the pulp and paper industry. In comparison, Magnusson [2012] estimated a technical potential for biogas production in Swedish pulp and paper mills to be about 1 TWh per year. About 20% of the potential was allocated to bleached Kraft pulp mills and 15% to unbleached Kraft pulp mills. More technical trials and economic evaluation are needed, but Paper III reveals that it may be possible to use at least part of the potential in bleached Kraft pulp mills, as described in the following section.

3.1.1.1 Anaerobic digestion in pulp and paper mills
As mentioned, anaerobic digestion was initially a method for waste treatment, but it also evolved into a method for producing a renewable transport fuel. There is a potential for applying this concept in pulp and paper mills in the same way. It is already used in some mills, but in Sweden the application in bleached Kraft pulp mills is limited at present.

Figure 5 A typical pulp mill with streams considered for anaerobic digestion.
The pulp and paper industry constitutes a significant part of Swedish industry. Chemical pulp is the most common production pathway for pulp in Sweden; about 70% of the produced pulp is chemical pulp, and the main chemical pulping method is called Kraft pulping. There are waste streams from different parts of the pulp and paper process and extensive wastewater treatment (WWT) is needed to reduce the amount of organic and toxic components. The pulp mill is not described in any detail here, but some principal steps and the origins of different waste streams are illustrated in Figure 5.

In addition to the possibility for recycling energy from the waste streams, other potential benefits of applying anaerobic digestion in pulp mills have been identified: reduced secondary sludge volumes, reduced electricity demand for the activated sludge treatment, reduced use of chemicals, and reduced space needed for the WWT equipment [Rintala and Puhakka 1994; IVL 2012]. These benefits can potentially reduce the costs of WWT, while the biogas can be sold or can replace other fuels in internal processes.

The basis for the study was a simulation model for a typical Nordic Kraft pulp mill, with a production of 1000 air-dry tonnes bleached pulp per day. The conventional WWT is based mainly on aerobic activated sludge treatment where microorganisms degrade organic and toxic components. This process requires additional nutrients and aeration through stirring. The conventional WWT is the process in Figure 6, excluding the external tank reactor.

![Figure 6: A typical wastewater treatment facility with an added external tank reactor for anaerobic digestion of sludge streams.](image)

Two options for treatment of waste streams from Kraft pulp mills were investigated; one of them was integrated in the wastewater treatment process (Case 1) while the other was external treatment of sludge from the wastewater treatment process (Case 2). In Case 1, a high-rate anaerobic reactor is integrated in the WWT prior to the activated sludge process; see figure 6.
Evaporator condensates and alkaline streams from the bleach plant are treated in the anaerobic reactor while the other streams are by-passed directly to the activated sludge process. The streams that pass through the anaerobic reactor are also passed through the activated sludge process for further reduction of COD and toxic components. In Case 2, the primary and secondary sludge from the original WWT is treated in an external stirred tank reactor with a retention time of about 20 days; see Figure 6. The Kraft evaporator condensate is also treated in the external reactor.

This study shows that there is a potential to produce about 27 MWh of biogas per year in both cases, which corresponds to 6700 Nm$^3$ of biogas or 7600 litres of diesel. However, the potential benefits mentioned in the beginning of this section are not fully applicable to Case 2, and in Case 1 those potential benefits were smaller than expected.

The main practical problem with the implementation of anaerobic digestion in pulp mills is the robustness of the process, which currently is lower than that for activated sludge treatment. The robustness is mainly an issue for the integration of a high-rate reactor, because a failure in this reactor would affect the treatment capacity, while failure in an external reactor is less severe. It should also be noted that anaerobic treatment of the waste streams studied here seems technically feasible based on experiments, but the principle also has yet to be proven in large-scale continuous trials.

The simulations did not include any detailed simulation of the processes within the anaerobic digestion reactor, but rather simplified models to estimate energy and mass flows. Regardless of the level of detail in a model, it is still merely a representation of the actual process and there is a risk of obtaining inaccurate results. As the models calculate ideal conditions and the processes modelled in this thesis are simplified compared to the actual processes, the main risk would be to overestimate the energy and conversion efficiencies. In both these cases, the models have been used for estimating processes that are not currently available. Hence, it has not been possible to validate the models with actual data. The handling of such uncertainties has been discussed further in the papers.

3.1.2 Methane production via gasification

Gasification of biomass is one of the main pathways for the so-called second-generation biofuels and other chemicals based on lignocellulosic biomass, including for example wood and straw biomass. This technology is also an opportunity for efficient electricity production from biomass; it enables efficient energy conversion of many types of feedstock, such as waste from forestry, agriculture and society. The technology shows great promise but several challenges remain with respect to the handling of particulates, hydrocarbons and alkali metals in the syngas [Yang and Chen 2015].
It is crucial, therefore, to develop gas-cleaning technologies that can enable long-term continuous operation of the process [Neubauer 2013]. There are also economic risks: a relatively large scale is needed for economic viability, and the process needs continuous supply of certain types of biomass with uncertain future costs [Neubauer 2013].

In the gasifier, biomass is heated to high temperatures with limited availability of oxygen, which leads to decomposition into gaseous components; the energy-rich product gas is called syngas. It consists mainly of hydrogen, carbon monoxide, carbon dioxide and methane. Some other components, such as longer hydrocarbons and impurities, are also present. The gas composition depends on the feedstock as well as the process type and operation.

In the case of electricity production, syngas is normally combusted in a gas turbine and the heat in the exhaust gas is used to produce steam for a conventional steam turbine. This process is called an integrated gasification combined cycle and has the potential for high overall energy conversion efficiency.

However, in this thesis, the main focus is on fuels for the transport sector, and syngas can be used to produce a range of such fuels: hydrogen, methane, methanol, methane, dimethyl ether, or Fisher-Tropsch fuels that are similar to diesel or gasoline. After the gasifier, the syngas goes through steps for cooling and cleaning, and possibly also steps for reforming, H₂/CO₂-shift and carbon dioxide removal. The reforming decomposes the larger molecules into smaller molecules and the shift changes the ratio between carbon monoxide and hydrogen. These two components are the most abundant energy-rich components in synthesis gas and they are the building blocks in subsequent synthesis reactions to produce transport fuels. The overall potential conversion efficiency from biomass to different transport fuels varies and the following values have been reported by Zhang [2010]: methane: 65%, dimethyl ether: 60%, methanol: 55%, and Fischer-Tropsch diesel: 35-45%. Van der Meijden et al. [2010] reported efficiencies of 54-67% for different types of gasifiers in methane production, while Neubauer [2013] reported that 60% cold gas efficiency for biomass to methane is frequently mentioned in the literature.

The production pathway for methane is called methanation, which includes the reactions between hydrogen and carbon monoxide or carbon dioxide into methane and water. The reaction rate is enhanced at high pressure and in the presence of a catalyst. The reaction is exothermic and cooling is needed to maintain a suitable temperature in the process, because the conversion yield decreases above 300 °C [Molino and Braccio 2015].
To achieve maximum conversion efficiency, the ratio between carbon monoxide and hydrogen is important. This can be adjusted through the so-called water gas shift reaction, which can take place in a reactor before methanation or simultaneously in the methanation reactor. Finally, water and carbon dioxide are separated from the methane.

Considering the plans for large-scale demonstration plants for fuel production from syngas, methane (which often is called synthetic natural gas in this context) seems to be the main option [Neubauer 2013]. The high production efficiency and the existing market for methane are likely strong reasons for choosing methane over the other fuels. In Sweden, there are also plans for methanol production. The production capacity for the planned methanol production facilities in Sweden adds up to 3.7 TWh per year, while the corresponding number for methane produced by gasification is 3.2 TWh per year [Hansson and Grahn 2013]. The first large-scale demonstration facility for production of methane via this pathway is called GoBiGas and is located in Göteborg, Sweden. It was in operation at the end of 2014 and is expected to produce about 180 GWh per year [Göteborg Energi 2015].

Dahlgren et al. [2013] evaluated the attainable methane production potential in Sweden in 2030, and concluded that given favourable economic conditions, the production potential of methane produced via gasification of biomass is 6-12 TWh per year. However, it should be noted that the favourable economic conditions include factors such as good economic growth, high fossil fuel prices, and favourable policy instruments. Otherwise, according to the other scenarios, the production costs will be too high in comparison to the market prices for vehicle gas, and the attainable potential would be between 0-4.2 TWh per year [Dahlgren et al. 2013]. Hansson and Grahn also constructed scenarios for the domestic biofuel production potential in 2030 and estimated it to be 13-26 TWh per year, of which about 30-40% of the fuels were based on gasification. Of the fuels from gasification, biomethane constituted about half, and the rest comprised methanol and DME. In comparison to the scenarios by Dahlgren et al. [2013], this scenario study focused more on currently planned facilities, and less on the economic prerequisites for them, though in one of the scenarios a ten-year delay of the plans was assumed due to poor economic prerequisites.

3.1.3 Methane production via pyrolysis of biomass

This section provides background on pyrolysis processes and presents the results from Papers I and II. Pyrolysis is a way to refine biomass into a product with higher energy content, but also for extracting valuable chemical components. Three components are formed in the pyrolysis reaction: pyrolysis gas, bio-oil (pyrolysis oil), and char. Charcoal production is a traditional way of refining biomass, while bio-oil production is a more recent way of refining biomass.
Pyrolysis is a thermo-chemical treatment of biomass that may provide a pathway for producing transport fuels. It is similar to gasification and is a part of the total gasification reaction. In this thesis, the pyrolysis gas and bio-oil in gaseous phase are together referred to as pyrolysis vapour.

Bio-oil is the condensable fraction of the product gas from the pyrolysis reactor. It consists of hundreds of types of molecules and the composition varies with feedstock and process conditions. The molecules are based on carbon, hydrogen and oxygen and they vary in size and shape. After condensation of the bio-oil a gas remains, referred to here as pyrolysis gas, which contains mainly carbon dioxide, carbon monoxide, water, methane and ethylene (Paper II).

The ratio between the products from the pyrolysis process depends on feedstock as well as process setup and operation, but the most significant difference is the residence time. Fast pyrolysis with a short residence time gives the highest share of bio-oil, while slow pyrolysis (carbonization) gives a higher share of charcoal; see Table 2.

<table>
<thead>
<tr>
<th>Process</th>
<th>Conditions</th>
<th>Yield [weight basis, %]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature [°C]</td>
<td>Residence time</td>
</tr>
<tr>
<td>Fast</td>
<td>~500</td>
<td>~1s</td>
</tr>
<tr>
<td>Intermediate</td>
<td>~500</td>
<td>~10-30s</td>
</tr>
<tr>
<td>Slow – torrefaction</td>
<td>~290</td>
<td>~30 min</td>
</tr>
<tr>
<td>Slow – carbonization</td>
<td>~400</td>
<td>hrs to days</td>
</tr>
<tr>
<td>Gasification</td>
<td>~800-1000</td>
<td>5</td>
</tr>
</tbody>
</table>

In processes focusing especially on bio-oil or charcoal, the by-products are usually combusted to provide process heat. In bio-oil production, char and pyrolysis gases are combusted, while in charcoal production, bio-oil and pyrolysis gas are combusted.

Today, charcoal is mainly used in developing countries for cooking purposes. It was previously used in the steel industry, though it was replaced by coal for economic reasons [Emrich 1985]. Charcoal has been suggested as a soil amendment because it may act as a fertiliser and improve the structure of the soil while also acting as a carbon sink [Lehmann et al. 2006].
There is also an interest for using bio-coal in large-scale heat and power production, for instance in coal-fired power plants [Wang et al. 2014], and in the steel industry [Feliciano-Bruzual 2014].

Bio-oil has been suggested for a range of energy applications, such as combustion, or as a fuel for diesel engines or gas turbines. However, as the properties of bio-oil are far from ideal compared to the conventional fossil fuels, and can vary as well, it has been difficult to introduce this fuel on the market. Large-scale tests have shown nevertheless that bio-oil can replace heavy fuel oil in district heating, but that standardisation of the quality and properties of bio-oil is needed to ensure reliable and efficient combustion [Lehto et al. 2014]. A more extensive description of fast pyrolysis can be found in the reviews by Bridgwater [2012], Ringer et al. [2006], Bridgwater and Peacocke [2004], and Butler et al. [2011]. Facilities for production of fuel for combustion or transport via fast pyrolysis are available and more are planned or under construction [Lehto et al. 2014]. Furthermore, Meier et al. [2013] provide an overview of the development of fast pyrolysis in IEA member countries.

There are several possibilities for upgrading pyrolysis products into fuels and chemicals, and a range of such products can be produced in the same facility. Production of transport fuels via pyrolysis has been suggested in the literature: hydrogen, Fisher-Tropsch diesel, petrol and methanol [Sarkar and Kumar 2010; Iojoiu et al. 2007; Heracleous 2011; Wang et al. 1997; Czernik et al. 2007; Jones et al. 2009; Ng and Sadhukhan 2011]. In this thesis, methane production via pyrolysis is explored.

For methane production processes via pyrolysis of biomass, gasification becomes the main alternative for comparison. The difference between pyrolysis and gasification is that gasification takes place at a higher temperature; the disintegration of biomass is more complete and the resulting syngas more homogeneous. Furthermore, in gasification, air or oxygen is added and the material is partially oxidized, while pyrolysis takes place in absence of oxygen.

In methane production via gasification, there is a loss of chemical energy when the hydrocarbon chains are completely decomposed into hydrogen and carbon monoxide before they are used to synthesize methane. In the pyrolysis pathway, there is a possibility to produce methane via direct cleavage of hydrocarbon chains, thus avoiding losses in chemical energy. Moreover, because the pyrolysis pathway takes place at a lower temperature, the risk of ash melting is removed, and alkali metals remain in the char. This protects the downstream equipment, and enables use of annual crops and other difficult fuels that can contain relatively high levels of alkali metals. Thus, pyrolysis has some inherent advantages when compared to gasification.
3.1.3.1 Processes for methane production via pyrolysis

Two pathways for methane production via pyrolysis of biomass were explored in Papers I and II. The first option is a fast pyrolysis route, commonly used for bio-oil production. In our case, both the pyrolysis gas and bio-oil are upgraded to biomethane while the charcoal is sold. The second option is a possible integration of methane production in an industrial charcoal production facility, which can enable high overall energy conversion efficiency. In the charcoal production process, both pyrolysis gas and bio-oil are commonly combusted for process heat, but in this case they are converted to methane, and the process heat is covered with additional biomass.

It should be noted that the bio-oil is in a gaseous phase throughout the production processes, i.e. it is not condensed, as it would be if the desired product was bio-oil. The fuel synthesis from pyrolysis vapour to methane is similar in both processes but the surrounding system is different, and heat integration between the different process steps is crucial to reach high overall efficiency in both cases. The principal layout of the two systems and the system boundaries are shown in Figure 7.

![Diagram](https://via.placeholder.com/150)

Figure 7: System delimitations in the two studies of methane production via pyrolysis.

The fast pyrolysis route starts with drying and grinding of the biomass before the fast pyrolysis reactor, which is a bubbling fluidized bed with external heating and vapour circulation. The bed is fluidized with the recirculated vapour. After the pyrolysis, the char particles are removed by cyclonic separation and the gas is further cleaned from particles via a centrifuge or filter bed. The pyrolysis vapour then goes through sulphur cleaning in an iron oxide bed and is then ready for fuel synthesis.
In the case of charcoal (Paper II), the evaluation does not directly involve the pyrolysis process itself, but only the heat integration with it. The possibility to upgrade pyrolysis gases to methane instead of combusting them for heat to the charcoal process is evaluated. The heat demand is replaced by adding a boiler for combustion of additional biomass. These two adjustments are evaluated as a separate system (Figure 7), and the purpose of this delimitation is to independently evaluate the possibility of introducing methane synthesis in charcoal production processes as a retrofit to available production facilities or as part of the design of new facilities. The cleaning steps and fuel synthesis are the same as in the fast pyrolysis route. However, in this case, the added biomass for heating the charcoal process is accounted as the imagined feedstock for methane production in the energy efficiency evaluation.

3.1.3.2 Fuel synthesis
Fuel synthesis refers to the process for conversion of pyrolysis gases into methane and the final upgrading to remove carbon dioxide, water and impurities so that the product can be used as a transport fuel. Fuel synthesis consists of four principal steps: pre-reformer, water gas shift, methanation, and upgrading, as shown in Figure 8. In this process the water-gas shift takes place in the same reactor as the methanation, but these two steps can also be separated in different reactors. The fuel synthesis was modelled in Aspen Plus to estimate the energy and material balance of the fuel synthesis, as part of the evaluation of the overall energy efficiency of the two pathways.

![Figure 8: Process flowsheet for fuel synthesis of methane from pyrolysis vapour.](image)

The purpose of the pre-reformer is to decompose longer hydrocarbons into a mixture of methane, carbon monoxide, hydrogen and carbon dioxide. In comparison to complete reforming or the gasification reaction, the idea is also to avoid complete decomposition of the methane into a mixture consisting mainly of carbon monoxide, hydrogen, and carbon dioxide.
The pre-reforming takes place at 500°C and at normal pressure in an adiabatic fixed-bed reactor filled with a nickel-based catalyst, which to some extent is based on Hornung et al. [2009]. The continuous operation of the pre-reformer is a crucial and currently uncertain step in fuel synthesis, and the whole concept depends very much on further development of this step. Deactivation of the catalyst will be a major challenge in the development of this process, and experimental work is needed to explore this challenge further. Without a doubt, effective operation of the cleaning steps before the pre-reformer will be crucial for the durability of the catalyst.

In the next process step, methanation and water-gas shift reactions take place simultaneously. The water-gas shift reaction increases the share of hydrogen, as carbon monoxide reacts with water to become hydrogen and carbon dioxide. Thus the ratio between hydrogen and carbon monoxide is adjusted to a level that is favourable for a high conversion yield for methane. In methanation reactions, hydrogen is reacted with carbon monoxide or carbon dioxide to form methane and water. The reactions take place over a nickel-based catalyst and the equilibrium for methane formation is favoured by low temperatures and high pressures [Kopyscinski et al. 2010]. Here, this process is assumed to take place at 300°C and 10 bar.

Finally, carbon dioxide is removed in a water scrubber and water is removed by condensation to achieve a high methane content in the product gas. Techniques for carbon dioxide removal are described further by Persson [2003] and Ryckebosch et al. [2011].

3.1.3.3 Results
In the two pyrolysis pathways and the gasification pathway, the main inputs are biomass and electricity and the outputs are biomethane, bio-char and heat. However, the share of the products varies, and to enable comparison, all the inputs have been normalised to biomass and all the outputs to biomethane. The electricity input was converted to biomass with an electrical efficiency of 33% (LHV), and the biochar output was converted to biomass with a conversion efficiency of 85% and deducted from the input biomass. Hence, if 1 MW char was produced, then 1.17 MW of biomass is deducted from the input. This approach implies that charcoal is assumed to be a desired product, as is the case in commercial charcoal production. Moreover, it was assumed that the excess high-temperature heat (>300°C) in the fast pyrolysis pathway is used for internal electricity production with a conversion efficiency of 33%, which was deducted from the electricity input. This is also the case with the gasification processes to which the pyrolysis processes are compared in Table 3. It shows that the pyrolysis pathways have the potential to achieve similar or even slightly higher conversion efficiency than methane production via gasification.
Comparison with the other transport fuels produced via pyrolysis proved difficult, as they included a range of inputs that could not be easily compared with those in the pyrolysis pathways studied here.

The conditions in the simulation of the fuel synthesis are ideal and chemical equilibriums are fully reached, so there is a risk of overestimating the conversion efficiency of the fuel production process. Moreover, it is difficult to validate the results; actual detailed data for the simulated process was not available since it was an exploratory pre-study. However, the results were still relevant for initial estimates of the mass and energy balance of the studied processes.

The approach of allocating biomass to the char product and studying the co-production of biomethane and charcoal is based on the assumption that there is an application and market for this product. However, at least in Sweden, this prerequisite is currently uncertain and must be evaluated in more detail.

<table>
<thead>
<tr>
<th>Energy balance</th>
<th>Fast pyrolysis</th>
<th>Slow pyrolysis</th>
<th>O₂ gasifier</th>
<th>Indirect gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Electricity</td>
<td>-5.1</td>
<td>-8.7</td>
<td>-2.7</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

| Output         | Biomethane     | 69.7           | 92.9        | 66.3             | 67                |
|                | Biochar        | 18.5           | 10.2        | 5                |

Normalised energy balance

<table>
<thead>
<tr>
<th>Input</th>
<th>Biomass</th>
<th>93.8</th>
<th>126.5</th>
<th>96.2</th>
<th>97.1</th>
</tr>
</thead>
</table>

| Output         | Biomethane     | 69.7           | 92.9        | 66.3             | 67                |
|                | Efficiency     | 0.74           | 0.73        | 0.69             | 0.69              |

*a Adapted from Mozaffarian and Zwart [2003]*

Both pathways for methane production show a great potential for high energy efficiency in comparison and with methane produced via gasification. In a more general perspective, these studies show that pyrolysis can be the basis for the production of a range of fuels and chemicals.
However, it should be noted that these are pre-studies that evaluate the potential of the processes and that more detailed design and development work is required to make a more detailed assessment of technical and economic feasibility.

The potential for producing biomethane via the fast pyrolysis route can be similar to that mentioned for gasification. In Sweden, there is currently a limited potential for co-production of biochar and biomethane, because the market for biochar is limited. However, if new applications and markets for biochar can be found, this can be an interesting option.

3.1.4 Synthetic methane from electricity and carbon dioxide

Electricity can be used in BEVs or to produce hydrogen for use in FCEVs, but also as feedstock for producing transport fuels similar to the conventional fuels. The production of such fuels is based on the dissociation of water and/or carbon dioxide into an energy-rich syngas. The processes for dissociation are the same as those described for hydrogen production and the following fuel synthesis processes are the same as those described in Section 3.1.2 for syngas from gasification. As in the gasification case, the syngas can be used to produce a range of potential transport fuels: methane, methanol, dimethyl ether and Fischer-Tropsch liquids similar to gasoline and diesel. An overview of these production pathways can be found in publications by Nikoleris and Nilsson [2013] and Graves et al. [2000].

The electrofuel pathway opens up a possibility to supply the current transport sector with renewable transport fuels and also to store electricity as a synthetic fuel. With limitations in the biofuel production potential and a relatively slow introduction of electric vehicles, fuels from electricity have the potential to increase the availability of renewable fuels. Currently it may not seem feasible to produce such fuels, as there still is a high share of fossil fuels in the energy sector, and the same fuels – but with fossil origin – are combusted to produce electricity. However, given a limitation in the availability of fossil transport fuels or a strong focus on reducing the use of them, electrofuels may be one option. Besides these prerequisites, this option can be used for storing electricity in an energy system with a high share of intermittent energy production. A high share of renewable electricity in the power system will require strategies for managing loads and storing energy, and synthetic fuel is one technical solution for this. During production peaks, surplus electricity can be purchased at a low price and converted to renewable fuel.

The feedstock for producing electrofuels comprises water, electricity and carbon dioxide. There are several methods for dissociating water and carbon dioxide. In Paper IV, electrolysis of water or co-electrolysis of water and carbon dioxide is considered. The methods for electrolysis are described further in Section 3.2.
In the case of water electrolysis, hydrogen is produced and then combined with carbon dioxide, and in the co-electrolysis case, a syngas containing hydrogen, carbon monoxide and carbon dioxide is produced. These two syngas mixtures can then be converted to methane in the methanation process described for the gasification and pyrolysis cases.

The other methods for dissociation of water and/or carbon dioxide are also described in Section 3.2 on hydrogen production: thermolysis, thermochemical methods or photoelectrolysis [Graves et al. 2000]. The dissociation methods for water have been studied more extensively than those for carbon dioxide, but there is a potential for developing both [Graves et al. 2000]. Furthermore, as mentioned in Section 3.2, production pathways that use electricity are available today or are relatively close to commercialisation, but production methods based on heat have the potential for enabling efficient production at low cost.

There are two main possibilities for collecting carbon dioxide for fuel production: capturing it from industrial waste streams, for example in combustion of fossil fuels, or from the air. From a technical and economic point of view, it would be more favourable to obtain it from industrial streams with a high carbon dioxide concentration than from air. The latter option is more expensive and requires more energy [Graves et al. 2000]. Carbon capture and storage has been put forward as a possibility to reduce the carbon dioxide emissions from fossil fuel combustion to the atmosphere, but if it is used for fuel production it can instead be called carbon capture and use.

However, in the case of industrial streams, the location of the production process is decided by the availability of suitable industries. Biofuel production processes such as anaerobic digestion or gasification may be suitable for integration for several reasons: they are already producing transport fuel and they have streams with high concentrations of carbon dioxide. The integration in biofuel production has been studied, for example by Mohseni et al. [2012].

In theory, the technical potential for producing fuels from electricity is large and can cover the energy demand in the transport sector. The access to carbon dioxide may be one limitation in the technical production potential. The economic production potential for electrfuels is determined by the electricity price and the cost for electrolyser, which is a large part of the production costs, and the price of fossil fuels. A large-scale application requires significantly higher fossil fuel prices and relatively low electricity prices.
3.2 **Hydrogen production**

This section gives an overview of production of hydrogen and also describes possibilities for integrating hydrogen in biofuel production. Hydrogen can be produced from several fossil and renewable energy sources. It is commonly produced from fossil fuels and a small amount (4%) is produced via electrolysis of water. About 38% is produced via steam reforming of natural gas, 30% as a fraction from the petroleum refining process and 18% via gasification of coal [IEA 2015b]. The principle for reforming and gasification is basically a decomposition of the feedstock into smaller gaseous components by using heat, high pressure and catalysts. Hydrogen is one of the components in the product gas and the reaction equilibrium can be pushed towards a high share of hydrogen, which can be separated from the other components during the subsequent cleaning steps.

Numerous production pathways based on renewable energy sources are under development and even if most are far from commercialization, a few are already commercially mature, such as electrolysis and gasification of biomass; see Table 4. Steam reforming of methane produced from renewable energy sources, for example biogas produced from anaerobic digestion is also an available production pathway. The production methods can be classified into several broad categories based on the principles of the production, such as water splitting with heat or electricity, gasification of biomass, and biological hydrogen production. The principles for gasification of biomass are described further in Section 3.1.2. The biological hydrogen production pathways are not addressed in more detail in this thesis, but there are methods based on photosynthesis in algae, biological degradation of different feedstock or a combination of the two.

Electrolysis is a central technology in the production of the renewable transport fuels that are studied here, both for hydrogen production and for production of other synthetic fuels from electricity. In the electrolysis reaction, water is decomposed into hydrogen and oxygen. Alkaline and polymer electrolyte membrane electrolysis (PEME) are commercially mature technologies [Millet and Grigoriev 2013], although PEME reached this stage only recently. It is believed that solid oxide electrolyzers (SOE) will be commercialised in the medium term [Holladay et al. 2009]. The PEM electrolysis and SOE electrolysis have the potential for higher electrical efficiencies compared to alkaline electrolyzers; see Table 5. SOE is run at high temperature and the high efficiency shown in Table 5 is based on a situation where high-temperature heat is available from another process and not included in the energy balance [Holladay et al. 2009]. Moreover, PEME has the advantage of stop-and-go cycling, which is not possible with the other two technologies. Some of the features of the technologies mentioned for electrolysis are compared in Table 5. Methods for splitting water with photonic energy or heat are under development and such methods include photolysis, photoelectrochemical splitting and thermochemical water splitting.
Dincer and Acar [2015] compared different hydrogen production technologies and showed that the methods based on photonic energy have a potential for low greenhouse gas emissions. All in all, they found thermochemical cycles to be a promising alternative due to potential for both low emissions and cost-effective production.

The technical potential for supplying the transport sector with hydrogen is relatively large, as a diversity of renewable energy sources can be converted to hydrogen and as FCEVs are energy efficient. However, as for other alternative fuels and technologies, the production potential for renewable hydrogen is limited with respect to the current production costs [Hughes and Agnolucci 2012]. The possibility to cover hydrogen demand in a future Swedish transport sector with domestic renewable energy sources is elaborated upon in Paper V.

Table 4. Hydrogen production technologies based on renewable energy. Modified from Holladay et al. [2009]. The efficiencies for different types of electrolysis are shown in Table 5 together with more detailed data for this technology.

<table>
<thead>
<tr>
<th>Production technology</th>
<th>Feedstock</th>
<th>Efficiency</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass gasification</td>
<td>Biomass</td>
<td>35-50%</td>
<td>Commercial</td>
</tr>
<tr>
<td>Alkaline electrolysis</td>
<td>H₂O + electricity</td>
<td>-</td>
<td>Commercial</td>
</tr>
<tr>
<td>PEM electrolysis</td>
<td>H₂O + electricity</td>
<td>-</td>
<td>Commercial*</td>
</tr>
<tr>
<td>Solid oxide electrolysis</td>
<td>H₂O + electricity + heat</td>
<td>-</td>
<td>Medium term</td>
</tr>
<tr>
<td>Photolysis</td>
<td>Sunlight + H₂O</td>
<td>0.5%</td>
<td>Long term</td>
</tr>
<tr>
<td>Dark fermentation</td>
<td>Biomass</td>
<td>60-80%</td>
<td>Long term</td>
</tr>
<tr>
<td>Photo fermentation</td>
<td>Biomass + sunlight</td>
<td>0.1%</td>
<td>Long term</td>
</tr>
<tr>
<td>Microbial electrolysis cells</td>
<td>Biomass + electricity</td>
<td>78%</td>
<td>Long term</td>
</tr>
<tr>
<td>Thermochemical water splitting</td>
<td>H₂O + heat</td>
<td>NA</td>
<td>Long term</td>
</tr>
<tr>
<td>Photocatalytic water splitting</td>
<td>Sunlight + H₂O</td>
<td>12.4%</td>
<td>Long term</td>
</tr>
</tbody>
</table>

*Adjusted from near term in Holladay et al. to commercial according to Millet and Grigoriev [2013]. It should be noted that the efficiencies are dependent on the specific system boundaries for each process and that the different energy sources used as feedstock may not be directly comparable.

Table 5 Comparison of electrolysers [Millet and Grigoriev 2013], conversion efficiencies from electricity to hydrogen (HHV).

<table>
<thead>
<tr>
<th></th>
<th>Alkaline</th>
<th>PEM</th>
<th>Solid oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range (°C)</td>
<td>Ambient/120</td>
<td>Ambient/90</td>
<td>800/1000</td>
</tr>
<tr>
<td>Efficiency at</td>
<td>60-80%</td>
<td>80%</td>
<td>100%</td>
</tr>
<tr>
<td>i(A/cm²)/U_cell(V)/T(°C)</td>
<td>0.2-0.5/2.0/80</td>
<td>1.0/1.8/90</td>
<td>3.6/1.48/950</td>
</tr>
<tr>
<td>Durability (h)</td>
<td>100,000</td>
<td>10,000-50,000</td>
<td>500-2000</td>
</tr>
</tbody>
</table>
3.2.1 Hydrogen in biofuel production

Hydrogen is already used in biofuel production. As mentioned in Section 1.3, the production and use of HVO – hydrogenated vegetable and animal oils – have increased significantly in recent years. In hydrogenation, also denoted hydrotreatment, the oils are treated with hydrogen under the influence of a catalyst to remove oxygen and other components to improve the quality of the fuel. Hydrotreatment of pyrolysis oil, for example, is also under development, to enable upgrading to transport fuels.

Furthermore, hydrogen can be added as feedstock in a range of biofuel production processes, such as fuel production via gasification and pyrolysis, and it can be used to produce synthetic hydrocarbons, as explained in Section 3.1.4. Hydrogen can be added at different stages of biofuel processes, for instance in the syngas before fuel synthesis.

3.3 Infrastructure for methane and hydrogen

Infrastructure is a major challenge in the introduction of any alternative fuel, when this fuel requires a separate infrastructure parallel to that for conventional fuels. A large part of biofuels are delivered in the same or similar infrastructure as conventional fuels. A large introduction of infrastructure for an alternative liquid fuel, such as methanol, would be challenging, but the introduction of a new infrastructure for gaseous fuels would be even more challenging, especially for hydrogen with even lower volumetric energy density than methane.

Infrastructure for energy gases differs from that for liquid fuels. At normal temperature and pressure, the volumetric energy densities for these gases are low. Compression to relatively high pressures or liquefaction is required to increase the energy density enough to enable transport by lorry or to store enough fuel in the fuel tank. In the fuel tank in the vehicle, methane is usually compressed to about 200 bar and hydrogen to 350 or 750 bar. As an example of the low volumetric energy density of methane, one litre of petrol is equivalent to 4 litres of compressed biogas (200 bar) or 1.7 litres of liquefied biogas.

The compression or liquefaction processes are energy-demanding and also require more expensive equipment than processes for liquid fuels. Energy gases can be transported in pipelines in an energy-efficient way, but pipelines are expensive and require significantly large volumes of gas before the investment is feasible. The choice of transport depends on the volumes of fuel, the transport distance and the possible synergies with available infrastructure.
For example, biogas can be co-distributed in the natural gas grid. In general, in terms of cost effectiveness, compressed gas by lorry is suitable for small volumes and short distances, and liquefied gas is appropriate for larger volumes and longer distances, while investments in pipelines require very large volumes [Benjaminsson and Nilsson 2009]. Benjaminsson and Nilsson describe the infrastructure for methane, but the same principle applies to hydrogen.

In the case of hydrogen, it is also possible to produce this fuel at the filling station, which is called on-site production. Methane or electricity can be transported to the filling station in the available energy infrastructure and converted to hydrogen on-site. This can save energy and reduce investments in a distribution infrastructure for hydrogen. Nevertheless, the specific production costs may increase as the scale of each production process is relatively small compared to that of a centralised production facility.

Overall, the distribution of these energy gases is significantly more costly than that for conventional fuels, with respect to construction of new infrastructure. It should also be noted that investments in infrastructure for conventional fuels have been done over a long period of time and that there is a good availability of such infrastructure. To reach a similar availability for methane and hydrogen would be very costly from the perspective of the whole distribution system. Vehicle owners are used to good availability of filling stations in Sweden and abroad. It is therefore a challenge to reach an acceptable availability of infrastructure for renewable fuels. There is a chicken–or-egg barrier: the users expect sufficient infrastructure before buying an alternative vehicle, and a significant market and demand is needed to motivate investments in infrastructure. In Sweden, there are about 2700 conventional filling stations and this number was even higher a few decades ago. According to studies on infrastructure for alternative fuels, the number of filling stations for alternative fuel must correspond to about 5-20% of currently available conventional filling stations before the corresponding numbers of alternative vehicles can reach mass markets [Hughes and Agnolucci 2012; Steenberghen and López 2008].

3.3.1 Methane infrastructure

In Sweden, some regions offer relatively good availability of methane filling stations – mainly urban regions in the south part of Sweden. At the end of 2014, there were 156 public filling stations in Sweden, see Figure 9. This corresponds to about 5% of the number of conventional stations. A mixture of natural gas and biogas is commonly sold at filling stations, and biogas is also co-distributed in natural gas pipelines. Only a small part of Sweden is covered by natural gas pipelines, and the only transmission grid is on the southwest coast of Sweden.
Figure 9 Public filling stations for methane in Sweden [Swedish Gas Association 2015a].
3.3.2 Influence of an available natural gas grid

Increased use of natural gas and construction of related infrastructure for this has been suggested as a pathway or bridge to increased use of biogas [Swedish Gas Association 2010]. In Paper VI, an attempt is made to quantify the influence of the natural gas grid on the development of upgraded biogas by comparing a region with an available gas grid (the southwest region of Sweden) with a region without an extensive natural gas grid (the region of Mälardalen) (Figures 10 and 11). The study was based on data on the locations of the natural gas grid and on statistics for geographical data on the development of upgrading capacity for biogas. The developments in the two regions are compared over time.

The development in the region of Mälardalen shows that it is possible to achieve production and utilisation of biogas without access to a natural gas grid. Furthermore, it shows that a large part of the upgrading capacity has been built without connection to the gas grid, including facilities relatively close to the gas grid (same municipality). Hence, from the collected data presented in Paper VI, it may be deduced that a natural-gas network not has been a prerequisite for development of biogas in the transport sector. Therefore, extended use of natural gas cannot be motivated to any extent by an alleged positive influence on the development of biogas.
3.3.3 Hydrogen infrastructure

Hydrogen infrastructure is currently limited but is available to some extent in the USA, Germany, Japan, and South Korea. In 2013, there were 224 hydrogen filling stations in operation, and the majority of these stations are concentrated to specific regions in North America, Europe, and South East Asia [Alazemi and Andrews 2015]. Alazemi and Andrews [2015] give a more detailed description of the state of hydrogen infrastructure worldwide.

In Sweden, there are now hydrogen filling stations in Malmö, Stockholm and Göteborg. Many countries close to Sweden have plans to significantly expand infrastructure for hydrogen, for example Norway, Denmark and Germany.

Several European countries including Sweden are participating in the project HIT TEN T that aim to provide hydrogen infrastructure for transport along corridors the trans-European transport network. The pre-requisites for introducing hydrogen in the Swedish transport sector is described in the report by Wallmark et al. [2014].

3.4 Vehicles fuelled by methane or hydrogen

Methane-fuelled vehicles have been used for a relatively long time while FCEVs have become available recently (but in an early market introduction phase). Both these powertrains can provide performance similar to that of conventional vehicles, and they can also be applied in most types of vehicles.
Methane can be used in the conventional Otto engine, but the fuel tank needs to be adapted to gas. It can also be used in a dual-fuel engine, where methane is mixed with diesel and combusted in the diesel engine. The diesel is necessary for enabling ignition in a compression ignition engine. The Otto engine is suitable for cars, light transport vehicles, and buses, while the dual-fuel engine is more suitable for heavy long-distance lorries. For such lorries, liquid biogas is a way to enable storage of sufficient amounts of fuel. In 2014, the methane powertrain was used mainly in cars, light trucks and buses but also in heavy trucks; see Figure 12.

![Figure 12. Number of vehicles in Sweden fuelled by methane [Transport Analysis 2015]. P+M refer to cars that can be fuelled with petrol or methane, while M refers to cars dedicated to methane.](image)

Hydrogen can be used in FCEVs that enable high energy efficiency, and water as the only local emissions. In the FCEV, the fuel cell converts hydrogen and oxygen to electricity. The electricity is then used in an electric engine that propels the vehicle. A small battery is also used to control the fuel cell and to manage the power supply to the engine. In comparison to using a battery as the only energy storage, compressed hydrogen enables storage of more energy and thus a longer driving range. The fuel cell electric powertrain is suitable for many different types of vehicles, but currently, the limitations in energy storage and also the power density in the fuel cells limit use to lighter vehicles rather than heavy long-distance lorries.
FCEVs have been tested in demonstration projects for some time and recently the first vehicles manufactured in series were released on the market: Hyundai ix35 and Toyota Mirai. The handling and performance of the vehicle is similar to that of a conventional vehicle. The range is 500-594 km and the refuelling time is three minutes [Hyundai 2015; Toyota 2015]. In Sweden, the ix35 is sold for SEK 629 000 (excl. VAT) [Hyundai 2015], while the price for the Mirai has been stated to be USD 56 934 (SEK 486 000) (without specifying the market) [Kim 2015]. The production numbers are still modest and the possibility to purchase these vehicles is still limited. Three Hyundai ix35 FCEVs are currently used in Sweden. As these are the two first fuel-cell car models manufactured in series and they are made in only small volumes, there is a possibility to significantly reduce the prices with development of the vehicle and manufacturing processes as well as with economies of scale. The availability of FCEVs is low, as they are manufactured in small volumes. However, most of the large car manufacturers plan to release FCEV models in the near future.

3.5 Energy efficiency

Fuels are commonly compared on a well-to-wheel basis regarding energy/resource efficiency and emissions. In this thesis (Papers IV and V), comparisons on the use of available renewable energy sources were performed. A compilation of well-to-wheel energy efficiency for light-duty vehicles in Europe has been done by [JEC 2014]. In Papers IV and V, data from literature has been compiled to form intervals for the energy efficiency in the different steps, see Figure 13. These papers compare the use of the following renewable energy sources in different vehicle types: electricity, methane (biogas from anaerobic digestion) and biomass (lignocellulosic). The vehicles are: a hydrogen-fuelled FCEV, methane-fuelled combustion engine vehicle, and a battery electric vehicle. Paper IV compares different options for using electricity in vehicles: in a battery electric vehicle, for producing hydrogen for a FCEV or for producing synthetic hydrocarbons for a combustion engine vehicle.

Three main energy sources for renewable energy are available today that can complement the use of first-generation biofuels that are based on food crops: biogas from anaerobic digestion, biomass-based second-generation biofuels, and fuels based on electricity. The technology to convert these energy sources into transport fuels is available or will likely be mature in the short term. Biogas from anaerobic digestion is considered an energy source here since it is produced mainly from waste treatment and it is considered the first tradable form of energy. Furthermore, in many cases anaerobic digestion is the most feasible option for treating waste and recycling the energy in it.
Figure 13. Energy efficiency in the fuel chains (LHV). The data is a compilation of the data used in presented in Papers IV and V, and assumptions and references can be found in those papers.
Biogas is assumed to be used for hydrogen production via steam reforming, or for electricity production in a combined cycle involving a gas turbine and a steam cycle. These are both relatively energy-efficient options. When biomass is the feedstock, gasification and further synthesis into hydrogen or methane are assumed. This production pathway for methane has similar conversion efficiencies as pyrolysis, see Section 3.1.3.3. Hence, the results also apply to the pyrolysis pathways studied in this thesis. Conversion of biomass into electricity is assumed to be through combustion in a combined heat and power plant, as this is the main conversion pathway in use in Sweden today. However, there are conversion pathways with higher conversion efficiency from biomass to electricity such as condensing powerplants or the integrated gasification combined cycle, which would enable a slightly higher overall energy efficiency for the pathway. Nevertheless, combined heat and power has a higher overall energy efficiency than condensing power when the heat is accounted for and is therefore the preferable option if there is a heat demand. If renewable electricity is the energy source, it is assumed that it is converted to the different synthetic fuels described in Paper IV.

The average losses in the Swedish electricity grid are used to estimate the distribution losses for electricity, and for distribution of methane and hydrogen, compressed gas on trailers is assumed (around 100 km one way).

The results from Paper V reveal that, for all energy sources included in the comparison, the most energy efficient pathway is likely to produce electricity and use in BEVs, and the second most efficient pathway is to produce hydrogen for FCEVs, see Figure 14. The reason being the high-energy efficiency in these two powertrains, which compensates for losses in the production and distribution steps (see Figure 13). The hydrocarbon fuels can be produced and distributed with relatively high efficiencies, but the conventional combustion engine has limited energy efficiency. For electricity, BEVs are naturally significantly more efficient than the other options, and the overall efficiency for synthetic hydrocarbon fuels from electricity is low. Nevertheless, it may be relevant to produce such fuels for the reasons elaborated upon in Section 3.1.4.

With methane as energy source, BEVs and FCEVs are likely to be more efficient options than using the methane directly in a combustion engine, see Figure 14. Therefore it may be relevant to convert these fuels to such energy carriers in the long term. However, currently, it seems more reasonable to use renewable methane directly in the transport sector and produce electricity and hydrogen from other energy sources. The reason for this is that those energy carriers can be efficiently produced from a range of energy sources while there is a limited potential for producing renewable fuels like methane. For biomass as energy source, the difference between the powertrains is smaller, but FCEVs and BEVs are still the most efficient options. Only methane is included here because the production
process for it has a higher conversion efficiency than other hydrocarbons from biomass, at least the route via gasification [Zhang 2010]. Furthermore, methane can potentially be distributed with low energy losses and used in a combustion engine at a relatively high energy efficiency for this powertrain.

Figure 14. Well-to-wheel energy efficiency for using electricity (E), methane (M) and biomass (B) to produce different transport fuels for use in three different powertrains.

Based on the well-to-wheel studies in Papers IV and V, and the prerequisite that only renewable energy should be used in the transport sector, both BEVs and FCEVs should be put into service where possible. Furthermore, liquid and gaseous biofuels as well as synthetic fuels from electricity should preferably be used in sectors such as heavy and/or long-distance traffic where the electric powertrains are currently unsuitable.

The level of detail in WtW studies varies, but the studies are commonly based on simplifications, assumptions and case-specific data, and thus the results must be used with caution. The overall results for energy use and emissions cannot be taken outside the context of the study, and presented separately from the assumptions and purpose of the study. Moreover, quantitative results from different studies cannot be directly compared, as data and assumptions can vary greatly between the studies. However, if the same trends occur in many different studies with different assumptions, or of the differences in energy efficiency are very large for two studied chains, then there is a clear indication that a fuel pathway may be a good option from an energy and resource perspective.
4 POLICY INSTRUMENTS DIRECTED AT RENEWABLE TRANSPORT FUELS

This section describes the economics of renewable transport fuels and the policy instruments that are directed towards these fuels. A general background is given for costs for alternative fuels and vehicles, financial and administrative policy instruments and policy instruments available in the EU and Sweden. Results from Papers III and IV on costs for methane produced from electricity or pulp-mill waste streams are presented in Section 4.1.3, and the effects of policy instruments directed at biogas in the Swedish transport sector are presented in Section 4.5 (Paper VI). Implications for continued support to biogas and other types of renewable methane are discussed, as well as policy instruments for introducing hydrogen and FCEVs.

A central part of the analysis of policy instruments for biogas was based on prior evaluations of the use of policy instruments for the transport sector, in both scientific literature and state-initiated evaluations. In the evaluation of biogas (Paper VI), the analysis of effectiveness is mainly based on the actual development of the use of biogas in the transport sector in relation to available policy instruments at different times. Furthermore, general experiences of the effectiveness of different types of policy instruments are taken into account. The efficiency is not evaluated in Paper VI, but this aspect is included in the cases where the efficiency has been evaluated in other studies.

4.1 Economics of renewable transport fuels

The ICEV fuelled by petrol or diesel is currently the common reference for properties, convenience and costs, and all alternatives are judged in relation to it. One must keep in mind that the current level of costs for owning a conventional car are related to the fact that it is a product for a global mass market, where the technology and infrastructure has been developed and financed over a long period of time. Furthermore, the fact that it is fuelled by cheap fossil energy plays a crucial role; it is one of the main barriers for introducing alternative fuels and vehicles in the transport sector.

The total additional costs for using different renewable transport fuels vary significantly, as they are in different stages of development and their properties require different types of infrastructure and vehicles.
For the first-generation liquid biofuels, the higher production cost and especially the feedstock cost are the main additional costs compared to fossil-fuel vehicles, because these biofuels can be integrated as low-blends in the current infrastructure and vehicles. When used as high-blend renewable fuels, they require construction of new infrastructure and adapted vehicles, but these technologies are still close to the current transport regimes in terms of function and costs. However, as a transport fuel biogas requires new and more expensive infrastructure and adapted vehicles, even if the vehicles are still modified combustion-engine vehicles. For hydrogen, the fuelling infrastructure and vehicles are even more costly than for methane.

4.1.1 Total cost of ownership
The total cost of ownership (TCO) describes the lifetime costs for a vehicle. It includes the initial fixed cost of purchasing a vehicle and variable costs, such as fuel cost, tyres, insurance, maintenance etc. The main costs are the vehicle purchase cost followed by the fuel cost over the vehicle’s lifetime. In the case of alternatively fuelled vehicles, it is challenging to reduce both the vehicle cost/price and the costs for production and distribution of fuel down to the same level as for conventional fuels and vehicles.

It is difficult to exactly predict the TCO, but it can be estimated using assumptions. Such estimates are useful for comparing the investment alternatives for vehicle fleets in organisations. Moreover, this method is used in research on the transport system to evaluate the costs for alternative vehicles/powertrains under development and compare them with costs for conventional vehicles. Even though economy is important for private vehicle buyers [Hu and Green 2011], it is unusual for them to calculate a comprehensive TCO for each vehicle alternative and there are also other influential factors in addition to costs. Nevertheless, a TCO comparable to that of a conventional vehicle is an important indicator to enable an introduction on mass markets, even if private buyers do not evaluate the TCO in detail.

TCO is definitely more important when choosing vehicles in companies and other organizations, because all investments must be carefully analysed. Many alternative fuels and vehicles are first introduced in such organizations, which has been the case for biogas vehicles, due to green procurement policies and certainly also due to specific policy instruments such as the reductions in fringe benefit tax (Paper VI). In Sweden, companies register most of the new methane vehicles and they are used as taxis, leasing cars, company cars and vehicles for municipalities, county boards and companies owned by the municipality [Kågesson and Johnsson 2012]. Hence, this is an important niche for biogas vehicles, and it is therefore important that they have a feasible TCO. The introduction in this niche may also affect private car owners, as company cars are transferred to private ownership relatively quickly [Kågesson 2013]
According to the results in Paper VI, the TCO for methane-fuelled cars is slightly higher than for comparable cars with diesel engines. Despite the lower price (per energy unit) for biogas compared to diesel (see Section 4.1.2), the total fuel cost is still higher for a methane-fuelled car due to lower engine efficiency.

The TCO for hydrogen-fuelled FCEVs is expected to reach a similar level as that for conventional vehicles, around 2025 [Swedish Ministry of Enterprise, Energy and Communications 2013; Mckinsey 2010; Sun et al. 2010] or at least by 2030-2035 [Offer et al. 2010; Elgowainy et al. 2013].

4.1.2 Fuel prices in Sweden

As shown by fuel prices per energy unit at Swedish filling stations from 2005 to 2014, the highest price is paid for ethanol (E85) and petrol, followed by diesel and vehicle gas; see Figure 15. The prices for petrol and diesel without energy tax, carbon dioxide tax and VAT show that a significant part of the price consists of taxes and that exemptions from such taxes can provide a considerable support for alternative fuels. Full tax exemptions leave room for twice as high costs for production and distribution together with the profit margins. Moreover, it shows that by excluding taxes, the prices for diesel and petrol are the same, but that the tax is higher on petrol.

The high-blend biofuels – ethanol and biogas – contain fossil fuels; E85 contains around 15% petrol (more during the cold season) and biogas contains from zero to about 60% natural gas. Prices for these fuel blends excluding taxes have not been estimated. However, the biofuel component is fully exempted from energy and carbon dioxide taxes, while these taxes are paid for the fossil components. For vehicle gas, the natural gas component lowers the total fuel price, because natural gas is significantly cheaper than biogas and the tax on natural gas used for motor vehicles is relatively low (Paper VI).
Figure 15. Fuel prices in Sweden (yearly average) [SPBI 2015a]. Prices excluding energy and carbon dioxide tax and VAT are also shown for diesel and petrol. The prices are converted from litre to kWh according to the conversion factors available from SPBI [2015b] using the energy content for petrol with 5% ethanol, diesel with 5% biodiesel and ethanol with 15% petrol. The vehicle gas prices were derived from statistics from the Swedish Gas Association [2015b] given in per litre gasoline equivalent and were converted to kWh with the energy content for petrol from SPBI [2015b].

4.1.3 Costs for renewable methane

This section presents costs for methane produced in a Kraft pulp mill and for synthetic fuels produced from electricity. Investment calculations were done for the process setup of anaerobic digestion in a Kraft pulp mill to produce LBG or CBG, presented in Section 3.1.1.1 and Paper III.

In Paper III, the production cost for biogas is estimated to be between EUR 49 and 85 per MWh, which corresponds to between EUR 0.47 and 0.82 per litre of diesel equivalent (based on the annuity method with a depreciation time of 15 years and an interest rate of 6%). The higher cost is for LBG production (including a local filling station) and the lower cost is for CBG production (without a filling station). The diesel price in Figure 15 is for approximately one litre of diesel (which corresponds to 9.8 kWh), and the comparison with the diesel price reveals that the biogas production cost is relatively competitive.
Furthermore, the investment calculations (annuity method) show an annual profit of EUR 34-70 per MWh of biogas and a discounted payback period of 4.3-7.8 years, with the assumptions that the biogas can be sold in the transport sector and that the Swedish tax exemptions for biogas remain in place. The shortest payback period may be acceptable in the industry.

Synthetic fuels produced from electricity and carbon dioxide are described in Section 3.1.4 and Paper IV. The costs for production are compared in Figure 16. If the costs in the figure are compared to the fuel costs in Sweden without taxes (Figure 15), it is obvious that most of the cost estimates for synthetic fuels are considerably higher than those for the conventional alternatives. Nevertheless, assuming that synthetic fuels can be exempted from taxes, it may be possible to compete with conventional fuels, at least if the lowest estimates are accurate.

![Figure 16 Production costs for synthetic fuels from electricity.](chart)

- **a)** Input of 7500 t hydrogen (EUR 3 per kg) per year [Tremel et al. 2014].
- **b)** Electricity price: EUR 0.024-0.072 per kWh [Becker et al. 2011].
- **c)** Electricity price: EUR 0.016-0.112 per kWh, and capacity factor of 90 and 40 [Fu et al. 2010].
- **d)** Electricity price: EUR 0.016-0.024 and 0.032-0.04 per kWh, respectively [Graves et al. 2000].
- **e)** [Galindo et al. 2007]
- **f)** [Mignard et al. 2003]
- **g)** Demo-scale, 1.2 MW methanation reactor. Electricity price: EUR 0.047 per kWh [Mohseni et al. 2013].
- **h)** Fuel production based on a 180 MW solar or wind power park, respectively [Davis and Martín 2014].
- **i)** [Kelly 2014]
- **j)** [Hughes and Agnolucci 2012]
The distribution cost for the fuels increase with decreasing volumetric energy density in the fuel: diesel (EUR 0.007 per kWh [Becker et al. 2011]), methanol (EUR 0.005-0.031 per kWh [Mignard et al. 2003; Ogden et al. 1999]), methane (EUR 0.011-0.032 per kWh [Dahlgren et al. 2013]) and hydrogen (EUR 0.024-0.11 per kWh [Yang and Ogden 2007]).

The results from Paper IV reveal that in the short term in Sweden, methane may be closest to achieving feasible costs for production and distribution, because methane already is introduced in the transport sector and there are favourable policy instruments directed at methane as a transport fuel. However, in the longer term, hydrogen may be the most feasible alternative among synthetic fuels produced from electricity.

### 4.2 Policy instruments for alternative fuels and vehicles

Policies and measures for alternative fuels and vehicles can be classified in the following way according to Grönkvist et al. [2013]:

- **Administrative (command and control)**
  - Mandatory quotas, blending standards or fuel volumes
  - Mandatory infrastructure
  - Emission standards for fuels and vehicles
- **Financial (economic)**
  - Taxes
  - Subsidies
  - Public procurement
- **Support for research and development**
- **Information**

The classification of policy instruments differs slightly in the literature, but the categories financial/economic instruments and administrative/regulatory are commonly included, while the remainder of the policy instruments are classified in different ways [Browne et al. 2012; Borras and Edquist 2013]. They can be classified, for example, as soft instruments [Borras and Edquist 2013] or divided into procurement instruments, collaborative instruments and communication and diffusion instruments [Browne et al. 2012].

The main focus in this thesis in terms of policy instruments is on administrative and financial policy instruments. Therefore, policies for support to R&D and information are not addressed further in this section.
4.2.1 Administrative instruments

Administrative instruments can be used to force producers and distributors of vehicles and fuels to introduce renewable fuels and connected infrastructure, or to reduce the emissions from vehicles and fuels. Regulations of emissions from fuels and vehicles have been employed for a relatively long time, and have recently been adapted also to include greenhouse gas emissions. Furthermore, mandates can be used to force fuel suppliers to sell a certain volume or quota of renewable transport fuels, or to introduce infrastructure for alternative transport fuels. The volumes or quotas are commonly ramped up gradually to reach a specific target set for a few years ahead. The blending mandates can be set for each fuel separately, for example, specifying the minimum share of biodiesel in diesel, and/or set as a total share of all renewable fuels combined [Cansino et al. 2012].

Mandate systems create a predictable market, because the size of the market each year is defined. This can give more certainty in the longer term for investors than a financial incentive that may change or disappear with relatively short notice. However, there is also a problem of predicting a realistic market share for biofuels, because excessively high quotas may be too difficult and expensive to fulfil and excessively low quotas would mean that the biofuel potential not is utilized.

In mandate systems, fuel suppliers and eventually the end-users of transport fuels carry the costs for reducing the environmental impact from the transport sector. Fuel suppliers have to finance the extra costs with revenues from the fuels they sell. This can be perceived as more just, as opposed to using tax revenues for subsidising the introduction.

During the introduction of biofuels in the EU, renewable fuel mandates were used by many Member States. The mandates are designed in slightly different ways but were basically constructed so that a certain percentage of the sold fuel volumes was renewable. Wiesenthal et al. [2009] mention that it may be an efficient instrument for increasing the use of biofuels, but that the quota will be fulfilled by the lowest-cost biofuels, which may increase the share of import fuels and mainly support low-blend fuels. Thus, complementary policy instruments are needed to create incentives for innovation and to introduce high blend fuels, more advanced vehicle technologies, and infrastructure for these new options [Wiesenthal et al. 2009].

In Sweden, the act on the obligation to provide renewable fuels is legislation aiming to increase the availability of infrastructure for alternative fuels [Swedish Code of Statutes 2005]. According to this, it is mandatory for fuelling stations to provide a renewable fuel, if the sales volumes are above a specified limit. The legislation has led to increased availability of renewable fuels [Swedish Parliament 2009].
However, it was criticized for introducing only ethanol pumps, as this was the alternative with the lowest investment cost, and for increasing the costs for rural fuelling stations that already had a strained economy [Swedish Parliament 2009]. In the current situation of diminishing use of high-blend ethanol (see Section 1.3), the effects of this policy instrument may be even more questionable.

In California, a mandate for zero-emission vehicles (ZEV mandate), such as BEVs or FCEVs, was introduced in 1990 [Wesseling et al. 2014]. This made it mandatory for intermediate and large-volume vehicle manufacturers to sell a certain share of such vehicles. However, significant changes and delays in the mandate were made after critique from the industry, which argued that the vehicle technology development was slower than expected and that customer demand was insufficient. Based on experiences from the ZEV mandate, Wells Bedsworth and Taylor [2007] argue that it is better to support advanced vehicle technologies with economic incentives rather than technology-forcing regulations, while Wesseling et al. [2014] point out that demand-pull initiatives can be used to deal with the industry opposition to the mandate.

The lessons from using mandates to introduce alternative fuels and connected infrastructure and vehicles indicate that administrative/regulatory instruments are effective, but that they are difficult to design and implement, and that mandates may not be sufficient to overcome obstacles if the technology is not mature enough. The design must be based on predictions for development of technology and markets, and if such predictions fail, the system may lead to unnecessarily slow development or unrealistic and expensive obligations for the industry. Furthermore, such policy instruments commonly introduce low-cost technologies that are already available and must be complemented by other policy instruments that can create innovation and development of the sector. On the same theme, it may be problematic that these policy instruments favour a specific technology over other technologies.

4.2.2 Financial instruments

There are naturally financial barriers for introducing alternative fuels, as the current ICEVs and fuelling infrastructure have been developed over a long time and huge investments have already been made.

If the alternative fuels and vehicles differ significantly from the current transport regime, it may take a long time and large investments to reach comparable technology development, production volumes and fuelling infrastructure. Hence, financial instruments are needed to support the introduction of such technology. The support can be given as tax exemptions or incentives for fuels or vehicles, or as investment grants or loans to production facilities and infrastructure.
Moreover, alternative technologies can be supported by green public procurement or in public-private partnerships.

It is controversial to use public funds for introducing new technologies, either as direct support in the form of grants, subsidies or procurement, or as indirect support in the form of tax exemptions. In the competition with other policy areas such as health care, school or employment, this use is commonly not prioritized, especially in times of slow economic development. Hence, there are limits to the amount of public funds that can be dedicated to alternative fuels and vehicles, and the cost-effectiveness of the financial policy instruments has to be considered.

Grönkvist et al. [2013] argue that in general, variable support such as tax exemptions connected to output or input of the fuel production may be a more cost-effective policy instrument than investment grants, because such support generates similar effects for all actors in the market and it can also stimulate technical development. Furthermore, they suggest that recurring investment support programmes may influence investors to delay financially rational investments in anticipation of another investment programme, and thus can be counterproductive. However, the advantage of investment grants is that they can provide certainty for investors in long-term investments, whereas variable support may change during its lifespan or some may perceive a risk that it can change [ibid.]. Leach et al. [2011] investigated the cost-effectiveness of financial policy instruments for ethanol in North America, and suggested that a combination of investment grants and variable support would be more cost-effective than separate use of the instruments. Furthermore, they noted a combination of the two would reduce risks of overcompensation and also effectively reduce the perceived risks among investors.

Wiesenthal et al. [2009] concluded that investment support not was needed for first-generation biofuels when they were introduced in the EU, as the fixed costs for such production facilities were relatively small in relation to the feedstock costs – about 7% for biodiesel and 30% for bioethanol. However, they emphasized that investment support schemes may be needed for advanced renewable fuels with higher investment costs.

In the introduction of biofuels in the EU, partial or total tax incentives were effective policy instruments, especially in countries with high taxes on fossil fuels and where the incentive fully compensated for the higher costs of production and distribution of the alternative fuel [Cansino et al. 2012; Wiesenthal et al. 2009]. Furthermore, tax incentives can steer the biofuel market by adjusting the support level to different biofuels [Wiesenthal et al. 2009]. This is an important advantage in comparison to administrative/regulative instruments; based on past experiences, administrative/regulative instruments policy instruments seem to lack that ability.
In the same EU context, Wiesenthal et al. [2009] considered incentives for vehicles to be effective but only complementary to the incentives directed at the fuel. They also added that such incentives will be more important for alternative vehicles with significantly higher costs than conventional vehicles.

In many countries, large subsidies are used to introduce electric vehicles, but with varying effectiveness. Sierzchula et al. [2014] and Gass et al. [2014] both argue that in addition to vehicle subsidies, charging infrastructure is necessary to introduce electric vehicles. Norway has both these factors and a range of other policy instruments, and has achieved a remarkably rapid introduction of electric vehicles [Holtsmark and Skontoft 2014]. However, Holtsmark and Skontoft argue that the cost efficiency is low and that unwanted side effects occur, such as economic encouragement for households to buy a second car and a very low margin cost for driving that may encourage driving instead of cycling or using public transport.

Public procurement of alternative fuels and vehicles can be used to demonstrate the technology and create an early market. In Sweden, this policy instrument has been evaluated as a successful policy instrument that has not increased the life cycle cost of vehicle fleets [National Audit Office 2011].

4.3 EU policy for renewable fuels

EU policies affect energy use and carbon dioxide emissions in several ways. Directives regarding energy efficiency, reduction of greenhouse gas emissions, and introduction of infrastructure for alternative transport fuels set goals for the Member States to fulfil with national policy instruments of their choice. Furthermore, regulations for emissions for vehicles and fuels directly affect energy use and emissions, and the Energy Taxation Directive sets minimum levels for taxation of fuels. Most of the policy instruments in this section can be classified as administrative or regulatory, except the energy taxation directive, which is a financial instrument.

These policy instruments have the potential to be driving forces in transforming the transport sector, and to some extent they have already served as such. Changes are necessary to make them more effective and coherent, and such changes have also been proposed, but as the ambitions and agendas vary greatly among the Member States, it seems difficult to implement substantial changes. The changes referred to here are those in the Renewables Directive, Fuel Quality Directive and Energy Taxation Directive, which are described further below.
The Renewables Directive (2009/28/EG) [EU 2009a] sets goals for the share of renewable energy in 2020, and for the transport sector the goal is 10%. There are specific guidelines for calculating the share and it is not directly proportional to the amount of biofuels in the transport sector. For example, in Sweden in 2013, the share of biofuels was about 11% based on energy content, but 16.7% when calculated according to the Renewables Directive.

According to the guidelines, the amount of renewable energy includes energy use in the whole transport sector. This is then divided by the total energy use, but the “total” energy use includes only petrol, diesel, biofuel and electricity that are used in road or railway transport. Some fuels are calculated several times in the fulfilment of the directive with the purpose of encouraging the use of such fuels; fuels that are based on waste, residues, non-food cellulosic biomass or lignocellulosic biomass are counted 2 times and the amount of renewable electricity that is used in road transport vehicles is counted 2.5 times. In Sweden, biogas and HVO are mainly based on feedstock that fulfils the definition and are therefore counted twice.

The directive also specifies criteria with regard to sustainability, for instance that there is a 35% reduction of greenhouse gas emissions compared to corresponding fossil fuel emissions and that the fuels cannot be produced from feedstock grown on land with great value for local biodiversity or with high stocks of carbon in the soil or vegetation. In 2017, the demand for reduction of greenhouse gases will increase to 50%, and in 2018, the corresponding number will be 60% for facilities that are taken in operation after 1 January 2017.

The EU goals for 2030 regarding use of renewable energy sources and reduction of CO₂ emissions do not include specific goals for renewable energy in the transport sector [EC 2015a].

The Fuel Quality Directive (2009/30/EC) [EU 2009b] sets the limit for drop-in fuels and also obliges fuel suppliers to measure and reduce the life cycle greenhouse gas emissions for fuels. In petrol, 10% ethanol or 3% methanol is set as the upper limit, and in diesel, the upper limit is 7% FAME. The fuel suppliers are obliged to reduce greenhouse gas emissions by at least 6% per energy unit until 2020, counted from a baseline value for 2010.

Changes in the Renewables Directive and the Fuel Quality Directive were proposed in 2012 by the European Commission. In the proposal, the following changes were suggested: increased demands on reductions of greenhouse gas emissions, inclusion of emissions from direct and indirect land use, limited possibilities for first-generation biofuels to be counted in the fulfilment of the 2020 goals and limited economic support to such fuels [EC 2012].
The proposal is still not approved, but after the so-called second reading in the EU Parliament, the following measures were adopted: biofuels produced from grain and other starch crops, sugar crops, oil crops and energy crops shall comprise a maximum of 7% of the final consumption of energy in transport in 2020; and the Member States shall set national targets for advanced biofuels [EU 2015]. A suggested reference value for the latter target is that by 2020, advanced biofuels constitute at least 0.5% of the energy content in renewable energy sources used in the transport sector [EU 2015].

The Regulation to reduce the carbon dioxide emissions for new cars (333/2014) [EU 2014a] sets limits for the maximum average carbon dioxide emissions from new passenger cars and light trucks – a maximum which must be achieved by vehicle manufacturers. The target is that from 2020 onwards, new cars should emit on average 95 g CO₂/km.

However, the average emissions are measured in a standard driving cycle that for different reasons does not correspond actual driving conditions, and there can be a significant difference between measured fuel consumption and actual fuel consumption [Swedish Ministry of Enterprise, Energy and Communications 2013]. This is problematic, because the standardised measured fuel consumption is the basis for economic incentives. Furthermore, it means that projected overall emission reductions from the transport sector will be too optimistic when they are based on the standardised measured fuel consumption; in reality the actual reductions will be much smaller than expected.

The Energy Efficiency Directive (2012/27/EU) [EU 2012], with the target of 20% energy efficiency by 2020 compared with projected energy use, also affects the transport sector. The public sector is emphasised as a role model in fulfilling the target, which means that it may also have to increase the energy efficiency in its vehicle fleets. Furthermore, there is a requirement for introducing a mandate system for all energy distributors to increase the energy efficiency in end-use operations, or take other measures with the same effect.

The Energy Taxation Directive (2003/96/EG) [EU 2003] sets minimum tax levels for energy carriers, including transport fuels. This has potential to be an effective instrument for reaching policy goals in climate and energy. In 2011, the following changes to the energy taxation directive were proposed: a carbon dioxide tax and taxation of the energy content in the fuel instead of the volume [EC 2011]. The purpose of the changes is to adapt the energy taxation directive to be a more effective instrument for achieving policy goals regarding energy efficiency and climate.
The negotiations regarding the changes in the directive are still on-going and it is uncertain when they can be concluded, as the taxation of energy carriers is an important issue for Member States and as such, decisions regarding taxes in the EU require a unanimous decision among the Member States.

Standard limits for exhaust emissions from new vehicles have been applied for a long time in the EU. In 2012, carbon dioxide was included in the Euro emission standards, and in 2015, energy efficiency standards for passenger cars were included [Swedish Ministry of Enterprise, Energy and Communications 2013].

The Directive on Alternative Fuels Infrastructure (2014/94/EU) [EU 2014b] requires national policy frameworks for developing the market for alternative fuels, common technical specifications for connected infrastructure and facilitation of consumer information regarding alternative fuels. Furthermore, the coverage of different types of infrastructure for road transport fuels is specified:

- appropriate number of publicly accessible points for electricity in urban/suburban and other densely populated areas;
- appropriate number of points for CNG in urban/suburban and other densely populated areas by 2020, and along the TEN-T core network (important corridors in the development of a trans-European transport network) by 2025;
- appropriate number of points for LNG for heavy-duty vehicles along the TEN-T core network by 2025;
- and, finally, appropriate number of points for hydrogen in the Member States that choose to develop the use of this fuel by 2025.

The first proposal for the Directive on Alternative Fuels Infrastructure included more far-reaching requirements, for instance that hydrogen infrastructure was to be developed in all Member States. However, the requirements were lowered in the final directive and the phrasing in it seems to open up for each Member State to decide upon their own ambition level. Therefore, the directive is not likely to be a strong driving force in introducing alternative fuels, but merely points out that infrastructure is a key issue for alternative fuels.

The European Commission controls state aid in the EU to avoid unfair competition [EC 2015b]. The commission has the investigative and decision-making power in such issues, and state aid measures have to be approved before implementation. This has a significant influence on the possibilities for Sweden to apply policy instruments for introducing renewable fuels in the transport sector.
4.3.1 Possible effects of EU policy

The goal of 10% renewable energy in the transport sector by 2020 is relatively progressive compared to goals for other regions in the world. However, when it is fulfilled mainly by low-blend, first-generation biofuels, there is no real transition towards a transport sector without fossil fuels.

These problems are of course not unnoticed in the EU, and changes have been proposed to limit the amount of first-generation biofuels that can be counted in the fulfilment of the 2020 goal and to increase the use of advanced biofuels. Nevertheless, these changes seem to be too little, too late. More far-reaching changes in the Renewables Directive and the Fuel Quality Directive than those that will likely be implemented now could have been strong drivers for a more significant transition away from fossil-fuel dependency.

Furthermore, as there are no new goals specifically included for the transport sector in the 2030 goals, it seems that there will be limited efforts in the transport sector after the 2020 goal.

Several directives have the potential to be important policy instruments in the transition of the transport sector, particularly if the proposed changes are implemented. The proposed carbon dioxide tax in the Energy Taxation Directive would likely be an important driver for decarbonizing the transport sector and other sectors. In Sweden, there has been a carbon dioxide tax since 1990 and this has been an important and effective policy instrument for reducing carbon dioxide emissions, even though the effects in the transport sector and in relation to other policy instruments are uncertain [Ministry of Environment 2014].

In theory, the Directive on Alternative Fuels Infrastructure is a very important document for introducing alternative fuels, as it emphasizes the importance of providing infrastructure for such fuels and of having a plan for the introduction of alternative fuels. However, in practice, the specific demands for providing infrastructure are open for interpretation, and therefore it will be difficult to fully reach the intended effect of the directive. Nevertheless, it is an important visionary document that chooses a direction for the development of the transport sector.

The regulation to limit carbon dioxide emissions from new cars is an important tool for reducing the overall emissions in the transport sector, and this regulation has likely been important in the rapid emissions reductions in new cars that have been achieved in recent years [Swedish Ministry of Enterprise, Energy and Communications 2013]. This may not be a strong driver for completely removing fossil fuels, but mainly to reduce the energy use in and carbon dioxide emissions from conventional vehicles.
In summary, no strong drivers for a fossil-free road transport sector exist within the EU policy, and it also limits the possibilities to effectively use national policy instruments for this purpose, which is further discussed in section 4.4.1.

### 4.4 Policy instruments in Sweden

As seen in the introduction, Section 1.3, Sweden has introduced a range of alternative fuels and vehicles. This section describes the Swedish policy for introducing renewable transport fuels and connected infrastructure and vehicles. The long-term vision for Swedish climate policy is zero net emissions of greenhouse gases by 2050, and as a stepping-stone, a fossil fuel-independent vehicle fleet by 2030 [Swedish Ministry of Enterprise, Energy and Communications 2013].

Tax exemptions have been one of the most important policy instruments for renewable transport fuels in Sweden [National Audit Office 2011]. In Sweden, energy and carbon dioxide taxes are paid for transport fuels, but the carbon tax that was introduced in 1991 applies only to fossil fuels. Since 1995, it has been possible for the Swedish Government to grant short-term tax exemptions for renewable transport fuels, and the tax exemptions available in 2015 are shown in Table 6. According to the National Audit Office [2011] this policy instrument has been effective in terms of reaching climate policy targets, but not cost efficient in terms of reducing greenhouse gas emissions. This means that greenhouse gas emissions have been reduced – but at a high cost compared to other possible measures to reduce them.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Exemption form energy tax</th>
<th>Exemption from carbon dioxide tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVO</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Biogas</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>High-blend/pure bio fuels except FAME</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>FAME (high blend)</td>
<td>44%</td>
<td>100%</td>
</tr>
<tr>
<td>FAME (low blend)*</td>
<td>8%</td>
<td>100%</td>
</tr>
<tr>
<td>Ethanol (low blend)*</td>
<td>89%</td>
<td>100%</td>
</tr>
</tbody>
</table>

* These exemptions apply to only five volume per cent of the sold volumes of diesel or petrol.
The Local Investment Programme (LIP) (1998-2002) and the Climate Investment Programme (KLIMP) (2003-2008) gave investment grants to municipal and local actors for projects for reducing greenhouse gas emissions [Swedish Environmental Protection Agency 2009]. A significant portion of the grants, about one third, was directed at projects relating to biogas [Swedish Environmental Protection Agency 2011]. A new support scheme for local climate investments will be in place from September 2015, with 125 million for the 2015, and thereafter 600 million per year [Swedish Environmental Protection Agency 2015].

On the distribution side, the obligation to provide renewable transport fuel was established in 2006 and made it mandatory for fuel suppliers to provide at least one renewable transport fuel at a fuelling station. The law has significantly increased the share of fuelling stations that sell renewable transport fuels. However, mainly ethanol pumps have been installed because this technology has by far the lowest investment cost. Hence, this policy instrument is in practical terms not technology neutral, and it may have negative effects on development for other renewable transport fuels. In order to steer towards other alternatives than ethanol, investment support was granted to cover a part of the extra costs for other alternatives, mainly vehicle gas [Swedish Environmental Protection Agency 2012].

In Sweden, the policy framework for alternative vehicles includes an exemption from vehicle tax, reduced fringe-benefit tax, green public procurement and a “super-clean-car premium”. The vehicle tax consists of a fixed part and a variable part that is proportional to the carbon dioxide emissions of the vehicles. The carbon dioxide part applies to biofuels also, but the tax per unit of carbon dioxide is lower. For BEVs or PHEVs that use less than 37 kWh per 100km or cars that emit less than 95 g CO₂ per km (for petrol and diesel) or 150 g CO₂ per km (for ethanol or other gas than liquefied petroleum gas), there is a five-year exemption from the vehicle tax [Swedish Code of Statutes 2006]. The exemption from vehicle tax replaced the clean-car bonus of about EUR 1100 (SEK 10000) that was in place 2007-2009. A super clean-car bonus of about EUR 4300 (SEK 40 000) was instated in 2012, which is granted for cars that emit less than 50 g CO₂/km. Furthermore, alternatively fuelled vehicles have been introduced via green public procurement.

The fringe benefit tax is reduced down to the level of that for a conventional car for cars that can be fuelled by renewable fuel, and for vehicles that can be charged with electricity or fuelled by other gas than liquefied petroleum gas, it is reduced even below that [Swedish Code of Statutes 1999].

There are also local incentives for clean cars such as reduced or removed parking fees, and previously there was an exemption from the congestion fees in Stockholm for clean cars.
4.4.1 A new system of policy instruments in Sweden

The tax exemptions that support renewable fuels remain during 2015, but it is uncertain what kind of policy instruments that will be in place after that.

In 2013, legislation for a hybrid/mixed system with both fuel mandates and tax exemptions was approved by the Swedish Parliament, and because it was not approved by the EU Commission beforehand, it was left to the government to decide when the legislation should take effect [Swedish Code of Statutes 2013a,b]. The legislation included a mandatory blending of 9.5% of biofuels in diesel, of which 3.5% should be specially defined biofuels, and 4.8% biofuel in petrol, which was supposed to increase to 7% in May 2015. Furthermore, it included continued exemptions for energy and carbon dioxide taxes for high-blend fuels and exemption from carbon dioxide tax for low-blend fuels. The reasons for changing from a system based on tax exemptions to a mixed system were partly that the losses in tax revenues are increasing with increased shares of renewable fuels, and partly that EU legislation makes it problematic to continue the financial incentives for low-blend biofuels. In the EU legislation, overcompensation with tax exemptions is not allowed [EU 2003]. Overcompensation occurs when the economic support is higher than the additional costs that biofuels may bring compared with a similar fossil fuel.

However, the legislation was cancelled [SFS 2014:1368] because the system of policy instruments, specifically the tax exemptions for biofuels, did not get the required approval of state aid from the EU Commission. The Swedish tax on carbon dioxide that applies only to fossil fuels is considered state aid by the EU Commission and such state aid could not be combined with a quota system for fuel blending [Swedish Ministry of Enterprise, Energy and Communications 2014].

The current taxation of biofuels is only allowed by the European Commission until the end of 2015, and it is uncertain what possibilities there will be after that. A new system of policy instruments is under development, but it is still uncertain how biofuels will be supported in Sweden after 2015.

4.5 Effects of policy instruments for biogas

Ethanol and FAME have been introduced into the conventional transport system as low-blends in petrol and diesel, or as high-blend fuels in similar distribution infrastructures and vehicles as conventional fuels. Biogas differs from the liquid biofuels as it requires new infrastructure and adapted vehicles. This is also the case for high-blend ethanol and biodiesel, but the infrastructure for gaseous fuels is more costly. The introduction of biogas is an interesting case to draw conclusions from that can be useful when introducing fuels that differs even more from the current transport regime.
It is difficult to quantitatively analyse effects of policy instruments when several policy instruments are used and the combination of policy instruments vary over time. Moreover, there are several other factors that influence the development. Nevertheless, the financial policy instruments have significantly subsidised the production and use of biogas for transport, and must be seen as an important factor for this development. The importance of each specific policy instrument cannot be defined quantitatively but it can be analysed and discussed in a qualitative way.

The question is why Sweden, as one of few countries, has directed significant policy instruments and efforts to the introduction of biogas in the transport sector. As mentioned in Section 3.1.1, the biogas system has several environmental and societal benefits: organic waste is converted to renewable transport fuel, valuable nutrition can be recycled, and greenhouse gas emissions from untreated waste are avoided. Johnson and Silveira [2014] describes the benefits of anaerobic digestion as the quadruple win: waste disposal, reduction of local air pollutants, replacement of non-renewable imported fuels, and GHG reductions. Renewable fuels that provide solutions in a range of societal sectors are more likely to gain support and to be successfully introduced, as it can motivate different actors to work together [Johnson and Silveira 2014; Grönkvist et al. 2013].

Olsson and Fallde [2014] also acknowledge that biogas development in Sweden has been driven by concerns about the environment and waste management. Moreover, they suggest that increased biogas production can be achieved by addressing the plurality of the biogas system and applying local and sectorial measures, such as policies in waste management. Fallde and Eklund [2014] studied the biogas development in a Swedish city, and found that it was driven mainly by local actors, but also highly influenced by decisions at the national level.

The influence of national policy instruments is described and analysed in Paper VI. Sweden is one of the leading countries in the development of biogas use in the transport sector, to some extent due to a mix of policy instruments and because this fuel system brings benefits to several sectors of the society, as concluded in Paper VI. During certain periods, extensive support has been given through financial policy instruments directed at both the supply and demand sides of the fuel chain (see Figure 17). Despite this, there has been a lack of long-term commitment in many of the incentives, for example the exemptions from energy and carbon dioxide taxes. As for other biofuels, tax exemptions have been an important policy instrument, and much of the development of biogas production, fuelling stations and vehicles took place after the full exemption from energy and carbon dioxide tax was introduced in 2004 (Figure 17).
Figure 17 Statistics for production of raw and upgraded biogas [SEA 2014b] (uppermost diagram), filling stations for vehicles gas [Swedish Gas Association 2013] (middle diagram) and methane-fuelled vehicles [Transport Analysis 2015] (lowermost diagram) in Sweden, as well as related policy instruments (described further in Paper VI).
Based on experiences from the introduction of biofuels in the EU, tax exemptions are considered effective policy instruments, at least if they compensate for the additional costs of alternative fuels in comparison with fossil alternatives [Cansino et al. 2012; Wiesenthal et al. 2009].

On the production side, the combination of tax exemptions together with investment support seems to coincide with the fastest increase in production. Based on experiences of policy instruments directed at ethanol in North America, Leach et al. [2011] suggested that this combination can provide cost-effective support, as it reduces the perceived risks among investors. KLIMP gave significant investment grants to production facilities for biogas, but also to filling stations and vehicles [Swedish Environmental Protection Agency 2011].

The obligation to provide a renewable fuel at filling stations was not an important driver for providing infrastructure for biogas, as this option was significantly more costly compared to ethanol. Yet, the filling station support that was introduced to cover part of those extra costs may have been important for the development [Environmental Protection Agency 2012]. Significant numbers of the currently available filling stations were partially financed by this support, but the interest for and utilisation of the support was less than expected; less than half of the budgeted grants were distributed [Environmental Protection Agency 2012]. This can likely be explained by the structure of the grant as well as issues regarding the supply and demand of biogas and methane-fuelled vehicles [Environmental Protection Agency 2012], i.e. that there were uncertainties regarding possibilities to produce sufficient amounts of biogas and to create a market for it.

A large part of the biogas is used in cars and buses but the use in light and heavy trucks is also increasing (Figure 17). Methane-fuelled vehicles commonly have a petrol tank as back-up, but the number of dedicated methane vehicles is increasing.

Procurement – both public and private – has been important for all types of vehicles, due not only to mandatory green public procurement, but also to sustainability strategies in private companies (Paper VI). This has been supported by investment grants as well as reduced fringe-benefit tax. Sixty-one per cent of the biogas cars in Sweden are actually owned by a corporate body, which includes both public services and private companies, and this share was significantly higher in the introductory phase of biogas cars [Transport Analysis 2015].

Sales of biogas cars increased significantly around 2008, when the clean-car bonus and the exemption from congestion fees in Stockholm were in place (Figure 17). This suggests that such visible incentives may be effective for introducing alternative vehicles. However, many incentives for clean cars have also applied to efficient diesel cars, leading to increasing sales of such vehicles.
It is possible that efficient diesel vehicles that have been defined and incentivised as clean cars outcompete cars for high-blend biofuels, such as biogas, because the diesel vehicles can have a lower life cycle cost and enjoy high availability of the fuelling infrastructure (Paper VI).

The development of alternative fuels and vehicles in Sweden also depends on the surrounding region. Effects of EU policy instruments on the development of biogas in the transport sector have not specifically been analysed in this thesis, but the effects have probably been small. Waste-based fuels like biogas are counted twice in the fulfilment of the 2020 goal, but so far, biogas has not played a significant part in fulfilling the goal, except perhaps in Sweden and a few other countries. Nevertheless, infrastructure for methane is prioritised in the Directive on Alternative Fuels Infrastructure, which is an important statement that may strengthen the arguments for using more biogas in Sweden.

Considering the overall development for biogas in the transport sector, it is crucial that tax exemptions and some form of investment support remain to incentivise production of biogas. However, the focus cannot be only on increased production of biogas from anaerobic digestion, as both the technical and economic potentials for this are limited. A large-scale introduction of methane in the transport sector depends on the possibilities to introduce the other production pathways for methane. Policy instruments must be designed to support methane produced via gasification, via pyrolysis or from electricity. Significant investment support in combination with tax exemptions are needed to enable investments in large-scale production facilities with significantly higher investment costs than facilities for biogas production via anaerobic digestion. Moreover, it will be even more crucial to design support schemes that can guarantee long-term rules for the market.

Continued efforts to introduce both methane infrastructure for transport and methane vehicles are also needed to increase the acceptance for methane vehicles among private persons. It is necessary to develop the infrastructure with a clear strategy and support it with policy instruments. In some cases the development in this regard must be pushed ahead of the market development.

More visible and effective incentives for methane vehicles are needed to introduce them on a large scale. The current incentives for buying a methane vehicle – the five-year exemption from vehicle tax and the carbon dioxide tax – are spread over a long time period and they also apply to diesel and petrol vehicles. The effectiveness of them may therefore be reduced. The reduced fringe-benefit tax is effective, as can be seen by the share of biogas cars that are affected by it, but it applies only to company cars.
If the subsidies in all these policy instruments were collected to provide a clean-car bonus upon purchase of the vehicle, it is likely that this would be significantly more effective. Furthermore, it is important that the incentives can make methane–fuelled vehicles cost-competitive in relation to diesel vehicles, i.e. that there is a separation between policy instruments that are used to support vehicles for high-blend or pure renewable fuels and policy instruments used for conventional vehicles with low emissions. The emissions in conventional vehicles could for instance be reduced, by policy instruments such as carbon dioxide-differentiated vehicle tax and by administrative policy instruments, while vehicles for renewable fuels could be supported by a clean-car bonus.

4.6 Policy instruments for hydrogen in the transport sector

In terms of energy efficiency and emissions, electric vehicles like BEVs and FCEVs are the preferable options in comparison to first and second-generation biofuels used in combustion engines. The main reasons are that BEVs and FCEVs have energy-efficient powertrains with zero local emissions, and that the WtW energy efficiency from renewable energy sources to use in these vehicles is high, as shown in Paper V.

These vehicles are therefore needed to reach the long-term targets for the transport sector; or, in the case of Sweden, these should be a part of the measures to fulfil the short-term vision of a fossil fuel-independent transport fleet 15 years from now. Despite this, it seems like these types of vehicles are not considered a significant part of fulfilling this vision, because few financial or other policy instruments are directed towards the introduction of such technologies. The reason for this may be that the support for biofuels has been relatively strong and that this has led to a high share of renewable energy in the Swedish transport sector, already overshooting the EU 2020 goal of 10%.

Hence, significant investments have already been made and results have been reached, which reduces the political ambition to continue the development. Furthermore, the vision of a fossil fuel-independent vehicle fleet may be perceived as unrealistic, and there are not any other more realistic targets to strive for.

The main barriers for introducing hydrogen in the transport sector are likely the chicken-and-egg problem for hydrogen infrastructure, and high costs for FCEVs and hydrogen produced from renewable energy sources [McDowall and Eames 2006]. These barriers are similar to those for methane but may be even more difficult to overcome for hydrogen. The maturity of the vehicle technology and associated costs were previously perceived as major barriers, but the vehicle concept has been proven in demo fleets and small-scale serial production. Furthermore, an acceptable TCO for FCEVs can be reached around 2025 [Swedish Ministry of
Enterprise, Energy and Communications 2013; Mckinsey 2010; Sun et al. 2010], given that there are markets around the world to enable increased production volumes and technology development.

Given the relatively strong support that has been needed to introduce biogas in a small part of the transport sector, the introduction of more advanced technologies like hydrogen-fuelled FCEVs will require a clear strategy and effective policy instruments. An introduction of hydrogen would likely resemble that for biogas and other renewable fuels. It seems reasonable to initially concentrate production and infrastructure to urban regions and introduce FCEVs in the same niches where methane vehicles have been introduced. Furthermore, the local and regional commitment that has driven biogas development is needed.

Several lessons may be learned from the introduction of biogas, and also other biofuels: the use of a combination of tax exemptions and investment support is an effective means for introducing a new fuel; long-term support to the whole system is needed. Particularly for hydrogen, sufficient support is needed for the infrastructure and vehicles. The infrastructure is more expensive than for other liquid or gaseous fuels, and FCEVs will be costly in the introduction phase. It is therefore necessary to find business models where public and private actors can share the costs, risks and benefits of introducing hydrogen infrastructure.

Tax exemptions and investment support could promote hydrogen production and infrastructure in the introduction. However, compared to the introduction of biogas, more of the support would need to be directed to the distribution infrastructure. Mandates for production and infrastructure may also be effective to provide a predictable introduction of hydrogen. This could also be combined with some type of economic support.

The measures suggested by the Swedish commission on fossil-free road transport – a significantly higher clean-car bonus and a tax exemption for hydrogen – would be effective policy instruments for introducing hydrogen-fuelled FCEVs [Swedish Ministry of Enterprise, Energy and Communications 2013; Wallmark et al. 2014]. It is uncertain whether such measures will be implemented. Nevertheless, even without significant support for vehicles, they can likely be introduced in public and private organisations as long as a basic infrastructure is provided. The possibility to replace conventional cars with a zero-emission vehicle fuelled by renewable energy can likely motivate a higher investment cost.
5 DISCUSSION

As emphasized in the introduction, this work is motivated by the necessity to reduce overall emissions of greenhouse gases. This affects all of society and a range of measures are needed to reach it. This thesis specifically addresses emission reductions in the road transport sector brought about by replacing fossil fuels with fuels produced from renewable energy sources. The focus is to analyse the possibilities for methane and hydrogen produced from renewable energy sources.

From an energy system perspective, we should aim to create systems that enable efficient use of available, renewable energy sources. Overall, the results reveal that methane can be produced from biomass and electricity in a resource-efficient way, in comparison with hydrocarbon energy carriers such as methanol and Fischer–Tropsch liquids. However, in a well-to-wheel perspective of renewable energy sources to use in a combustion engine or electric vehicle, use of electricity in BEVs and thereafter hydrogen in FCEVs is more energy efficient (Papers IV and V). The main reason being that the use of methane in a combustion engine vehicle provides significantly lower efficiency compared to an electric vehicle, BEV, or FCEV. Efficient use of renewable resources and the technical solutions discussed here will also coincide with other environmental goals, although energy efficiency has been the main focus in this thesis.

According to the report from the Swedish Commission on fossil-free road transport, there is a potential to reduce energy use in the road transport sector by 60% by 2030, for instance through more efficient vehicles and reduced transport demand [Swedish Ministry of Enterprise, Energy and Communications 2013]. Furthermore, there is a potential to cover 65% of the remaining energy demand with biofuels and 14% with electricity and hydrogen. In the scenario where the maximal potential for reduced energy use is fulfilled, 65% of the energy demand corresponds to 20 TWh biofuel per year.

According to an example in the report, the annual 20 TWh can be fulfilled with about 3 TWh from ethanol, 4-5 TWh from biodiesel (HVO and FAME) and 12-13 TWh of methane and DME [Swedish Ministry of Enterprise, Energy and Communications 2013]. This estimate is mainly related to the possibilities for a transition of the vehicle fleet and not to the fuel production potential.

Low-blend ethanol does not contribute to a fossil-free vehicle fleet to any extent, as it is based on the use of fossil fuels and the use of low-blend biofuels thereby diminishes as the use of fossil fuels is reduced.
Increased use of high-blend ethanol is according to the inquiry necessary to contribute to the goal of a fossil-free vehicle fleet. This requires continued introduction of vehicles for high-blend ethanol and that these are fuelled by ethanol and not petrol. During the last few years, the use of high-blend and low-blend ethanol has diminished in Sweden and the end-use is now around 2 TWh per year, as presented in Section 1.3. According to the Commission on fossil-free road transport, a broader market for ethanol vehicles, for example in the EU, is a prerequisite for introducing more ethanol vehicles in Sweden. There are also uncertainties regarding the development of second-generation ethanol produced from biomass. This would enable large-scale domestic ethanol production and reduce the emissions compared to first-generation ethanol.

Biodiesel is divided into HVO and FAME, and currently, both of these are mainly used as low-blend fuels. However, HVO can be used in high-blends in the current vehicle fleet, which is not the case for FAME. The previously mentioned 4-5 TWh per year of biodiesel have already been achieved through a drastic increase in the production and use of HVO, as shown in Section 1.3. Production and use of HVO has not been studied in this thesis. However, the extent to which domestic production and import of HVO can continue to increase seems uncertain, as there are limitations in the feedstock that is currently used. Tall oil and slaughter waste are limited resources and there are sustainability issues related to the use of palm oil.

Synthetic diesel can also be produced, for instance via pyrolysis, gasification, or from electricity, and thus can significantly expand the potential to supply the current vehicle fleet with fossil-free fuels. Still, these production pathways are less energy efficient than corresponding methane production pathways, at least compared to those via gasification of biomass or synthetic fuel production via electricity [Paper IV; Zhang et al. 2010].

Hence, there are several limitations and uncertainties regarding to what extent biodiesel and ethanol can cover a significant part of the energy demand in a fossil-free Swedish transport sector. Other alternatives are needed and the question is whether methane and hydrogen and hydrogen can be those alternatives.

Regarding the 12-13 TWh of methane and DME per year in 2030, it is likely that methane will be the main fuel of the two, as the introduction so far of DME has been limited. Methane would then be the main fuel in the whole transport sector and a significant increase in production capacity would be necessary. Even more methane would be needed if the energy demand in the transport sector is not significantly reduced and the electrification of the vehicle fleet is slower than assumed in the scenario.
Methane is already used on a large scale in transport sectors around the world, and in Sweden it has already been introduced with relatively good infrastructure coverage in several urban regions. Furthermore, if gasification of biomass is the basis for next-generation, large-scale fuel production, then methane is a suitable energy carrier, because it can be produced at a high efficiency.

The question is whether it is possible to produce such large amounts of methane by 2030. It is suggested that about 4 TWh per year will come from anaerobic digestion and the rest from gasification [Swedish Ministry of Enterprise, Energy and Communications 2013]. This is a significant increase, as the use of biogas in the Swedish transport sector currently approach 1 TWh/year.

Linné et al. [2008] carried out one of the most comprehensive studies on biogas production potential in Sweden, and Lönnqvist et al. [2013] completed a comprehensive review and analysis of the available studies on biogas potential in Sweden. Both studies conclude that there is a realisable biogas potential of 8-9 TWh of biogas per year. However, the extent to which it can be realised is uncertain.

Dahlgren et al. [2013] analysed the Swedish biogas potential in 2030 from a market-based perspective. Given the current prerequisites, regarding for instance low fossil-fuel prices, slow economic development and uncertainties regarding policy instruments, it seems that the scenario described in Dahlgren et al. [2013] for the lowest realisable production potential is the most likely. This projects a biogas production via anaerobic digestion of 1.2 to 2.5 TWh per year, and no production of methane via gasification. Nevertheless, it seems realistic to reach 4 TWh biogas per year in 2030 when considering the development in recent years and the presented estimates of the biogas potential, but not without a comprehensive system of policy instruments for biogas.

It is still uncertain whether second- and third-generation technologies for methane production can be used on a large scale and if they can be cost-competitive. Dahlgren et al. [2013] estimated that about 6-12 TWh of methane per year could be produced via gasification by 2030, given favourable economic conditions – but that less favourable conditions could result in 0-4.2 TWh per year. In Sweden in 2015, a demo-scale gasification facility is already in operation and expected to produce about 180 GWh methane per year, and there are also plans for two large-scale facilities annually producing 1 TWh and 1.6 TWh, respectively [Hansson and Grahn 2013]. The 4 TWh per year of biogas that can be produced via anaerobic digestion and the planned gasification facilities add up to about 6.8 TWh methane per year. A few more large-scale gasification facilities would be needed to reach the annual 12-13 TWh that were estimated in the scenario for a fossil-free vehicle fleet.
Besides gasification, several pathways for supplying the transport sector with renewable methane have been studied in this thesis. Methane can be produced via anaerobic digestion integrated in pulp mills, via fast or slow pyrolysis or from renewable electricity.

The results from the studies of methane production via pyrolysis in Papers I and II reveal that both routes – fast pyrolysis and integration in charcoal production – may be competitive from an energy conversion efficiency perspective, when compared to gasification. However, as these are pre-studies of the processes, further investigations are needed to determine the feasibility of these fuel production routes. The pyrolysis routes are similar to gasification in many ways and they would not significantly expand the production potential estimated for gasification. Nevertheless, these routes may be important for utilising the potential for methane produced from biomass, one reason being that it seems more suitable for small-scale facilities. The small scale enables application of the technology in regions with more limited demand for methane. Furthermore, pyrolysis may also be suitable for facilities that process low-grade biomass to different types of energy carriers and chemicals.

The results in Paper III for the techno-economic study on biogas production via anaerobic digestion of wastewater streams from bleached Kraft pulp mills show that there is a technical potential for producing biogas from these mills and that it may be a feasible investment. However, further studies are needed on demo-scale and large-scale implementation of such processes, to ensure successful operation. Magnusson et al. [2012] estimated that there was a technical production potential of about 1 TWh of methane from anaerobic digestion of waste streams in Swedish pulp and paper mills, and that 20% of that was in bleached Kraft pulp mills and 15% in unbleached Kraft pulp mills. The results in Paper III indicate that this potential may be possible to exploit also from an economic perspective. This route for methane production could make an important contribution to the current production of biogas via anaerobic digestion.

Methane can also be produced from electricity and carbon dioxide, and Paper V reveals that this pathway may become cost-competitive in comparison with biogas production in Sweden, at least under certain conditions. Moreover, the results in this paper indicate that methane production is cost-competitive compared to other synthetic transport fuels produced in a similar way, such as hydrogen, methanol, and Fischer-Tropsch liquids. This route can increase the use of renewable electricity in the transport sector and it can also act as an energy storage during production peaks in wind and solar power. However, hydrogen in FCEVs is the most energy-efficient pathway and, in the longer term, this alternative can be cost-competitive. If electricity were to be used to fuel a large part of the transport sector, as in the scenario for a fossil-free vehicle fleet, FCEVs are likely to be needed.
They can replace the functionality of many of the conventional vehicles in a way that other electric vehicles cannot.

Hydrogen infrastructure and hydrogen-fuelled FCEVs have been successfully demonstrated and may reach commercial maturity in 2025, if this technology track is pursued by enough countries. Furthermore, technologies are available for producing hydrogen from renewable energy sources such as biomass, renewable electricity and biomethane.

With the current prerequisites, both methane and hydrogen can play important roles in a fossil-free vehicle fleet and even be necessary to approach this vision. But without a clear strategy and effective policy instruments, the potential to use methane and hydrogen in the transport sector will not be utilised to any great extent. These fuels require new infrastructure and new vehicles. It is difficult to introduce all these parts of the system simultaneously while competing with the economy and convenience of the current, oil-based transport system.

Sweden has successfully increased production of biogas and its use in the transport sector. Several national policy instruments have supported the introduction. Incentives have been given both as tax exemptions and as direct investment support to vehicle owners, production facilities and infrastructure. The use of tax exemptions and investment support has been important in the introduction of biogas (Paper VI), but so have the shorter periods of direct support to all other parts of the fuel chain from production facilities to vehicles.

It may be necessary, however, to use more distinct strategies and policy instruments for infrastructure and vehicles, if methane is to be introduced on a large scale in the transport sector. Sufficient support for new production pathways for renewable methane is also required. The introduction of methane has already started and with the following measures, it can be continued by creating a broader acceptance for methane as a transport fuel: a clear statement from the government that methane will be an important fuel in the transport sector, a strategy for providing sufficient infrastructure, and effective incentives for vehicles that use methane.

Hydrogen infrastructure and FCEVs are costlier than infrastructure for biogas and ICEVs adapted to methane, and the introduction of hydrogen will require at least the same amount of dedication and support that has been available in the introduction of biogas. Effective policy instruments directed at hydrogen infrastructure will probably be at least as crucial as for biogas.
Overall, there is a need for general policy instruments that can remain in place over a longer period of time and steer towards a fossil-free vehicle fleet, for example a mandate system that set targets for pure or high-blend renewable fuels together with infrastructures for them; a system with financial policy instruments based on the emission reductions that each fuel achieves; or a certificate system. Furthermore, support must be directed to the vehicles that can be run on such fuels. This means that support will gradually be transferred from the first generation biofuels that are used as low-blend fuels to the technologies that can fully replace fossil fuels.

Beside such general policy instruments, it is also necessary to direct more specific policy instruments at fuels and technologies that can contribute to a more sustainable transport sector in the longer term. The Swedish Government have a strategy to focus on general policy instruments that are so-called technology neutral in the sense that they do not pick winning alternatives beforehand but the policy instruments create a market where alternative fuels can compete. This approach may be successful for lowering the current costs for emission reductions, but it will not be sufficient for a complete transformation of the transport sector.
6 CONCLUSIONS

It seems that, next to electricity, methane and hydrogen will be important energy carriers in a fossil-free vehicle fleet. Electrification of the vehicle fleet is a promising solution for the transport sector, but without major changes in infrastructure (such as extensive fast-charging solutions or electrified roadways), transport patterns or significant technology development, it appears difficult to cover the entire transport demand with electricity. Methane-fuelled ICEVs and hydrogen-fuelled FCEVs are therefore needed in a more sustainable fossil-free Swedish transport sector in addition to electrification of the vehicle fleet. The following reasons explain why they can be an important part of the transport sector:

- Vehicles fuelled by methane or hydrogen can substitute fossil-fuelled vehicles in terms of convenience, performance and range.
- The use of methane in the transport sector is well proven on a commercial scale, and the technology for using hydrogen, such as filling stations and FCEVs, is close to commercialisation.
- Hydrogen and methane have high well-to-wheel energy efficiency in relation to comparable liquid fuels, when the fuel is produced from biomass or electricity.
- Methane and hydrogen can be produced in significant amounts from domestic renewable energy sources.
- Biogas production via anaerobic digestion is a suitable way to achieve energy recovery from a range of societal waste streams and the production will fulfil several societal goals.
- Hydrogen-fuelled FCEVs have zero local emissions and methane have low local emissions compared to other hydrocarbon fuels.
- Both methane and hydrogen can increase the use of renewable electricity in the transport sector, and these energy carriers can also be used as energy storage.

6.1 Recommendations for further studies

Several of the fuels and technologies that are discussed in this thesis are close to commercialisation. Continued technical development is still important but more research is needed also on how to transform the current transport sector by creating systems of policy instruments that can support these technologies.
For the pyrolysis route for methane production and biogas production in bleached Kraft pulp mills, the technical concepts must be further developed and evaluated. The studies of the methanation route from pyrolysis gases is only a concept that needs to be proven and further developed in the lab, whereas the biogas production in a Kraft pulp mills is a proven concept that needs to be further evaluated in long-term, demo-scale tests and in mill-specific conditions.

Regarding the power to gas concept, some technical development is needed and also thorough evaluations of possible applications, for instance where energy storage is needed, where suitable carbon dioxide streams are available and how business models can be developed around the technology.

Hydrogen can be introduced in the Swedish transport sector, but more research is needed on energy- and cost-efficient macrosystems for producing and distributing this fuel. Furthermore, knowledge is needed on the effects of large-scale introduction of methane and hydrogen on the energy and transport systems, society, and environment.

Despite the fact that many of the technologies are mature, they are hindered by costs or lack of experience and/or acceptance. More knowledge is therefore required on how to create acceptance for new technologies and for policy instruments that aim to reduce the use of fossil fuels. Furthermore, knowledge is needed on effective systems of policy instruments that can support the introduction of such fuels and vehicles in a cost-efficient way. It is also necessary to find policy instruments that are acceptable among the public and that can be in place over a long period of time.
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