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HOW CAN FOREST-DERIVED METHANE COMPLEMENT BIOGAS FROM ANAEROBIC DIGESTION IN THE SWEDISH TRANSPORT SECTOR?

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

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

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

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EXECUTIVE SUMMARY

Forest-derived methane may contribute significantly to a vehicle fleet independent of fossil fuels by 2030. At present, there is sufficient technical knowledge about energy conversion methods and several Swedish actors have investigated and prepared investments in production facilities, but the technology is not commercially mature yet and it needs support during a development period. Investments in the technology have become less favorable because of the drop in the oil price in 2014. In addition, the predictability of the policy instruments supporting production and use of renewable energy are perceived as low by investors. This report emphasize that these factors combined are major reasons why potential investments are postponed.

We have conducted a literature study and an interview study with three industry actors to answer the question "*How can forest derived methane complement biogas from anaerobic digestion in the Swedish transport sector?"* Interviews were mostly conducted in situ and in co-operation with the f3 project "Examining systemic constraints and drivers for production of forest-derived transport biofuels" (f3 2014-002370). The literature study included the recent development of renewable transport fuels in Sweden, existing and proposed policy instruments, and possible technical pathways from forest biomass to transport fuels.

Sweden has accomplished a high share of renewables in the transport sector – 12 % based on energy content or 17 % when accounting in accordance with the EU Renewable Energy Sources Directive (RES). Thus, Sweden has the highest share of renewables in the transport sector among the member states and has with a good margin accomplished the EU-RES target of 10 % renewables by 2020. The use of electricity in plug-in electric vehicles is not included in these figures and the number of electric vehicles is increasing rapidly.

The most common biofuels in transport are biodiesel, ethanol, and biogas. Biodiesel increases rapidly, mainly through low blend-in, and is now the most common biofuel in the Swedish transport sector. The majority is HVO (Hydrotreated Vegetable Oils), but the share of FAME (Fatty Acid Methyl Esters) is still considerable. The use of ethanol peaked during 2008 and has been decreasing since then. Ethanol is distributed through both low and high blend-in (E5 and E85).

The use of upgraded biogas in the transport sector has increased continuously since its introduction 1996. Upgraded biogas is complemented by natural gas to meet the vehicle gas demand. A voluntary agreement among the distributors maintains a minimum biogas share that corresponds to 50 %. The biogas share is much higher today (74 % by volume, average Jan.-Aug. 2015) and some large end-users use pure upgraded biogas. Upgraded biogas is mainly distributed in compressed form through gas cylinders (79 %), but also through injection to the natural gas grid (21 %). Very little biogas is distributed in liquid form (LBG).

Studies of the practical production potential shows that the current vehicle gas demand could be met entirely with upgraded biogas. However, an increased demand will eventually require other production pathways based on other feedstocks. Gasification of forest biomass is one such pathway. One alternative is that an increased demand is met with natural gas, resulting in fossil lock-in effects. Another alternative is a stagnated vehicle gas market.

Production of upgraded biogas and use in the transport sector have been promoted in different ways, e.g., demand on handling of waste that will promote anaerobic digestion, investment support to production facilities, support to distribution infrastructure, environmental car premiums, and exemptions of energy and CO_2 taxes. The tax exemptions are only granted until the end of 2015 but the Swedish government has applied for permission to the European Commission for a tax exemption until the end of 2020. A biofuel may only be compensated to a certain level to comply with rules set by the European Commission. If the renewable alternative is cheaper because of tax exemptions or tax reductions it is considered as overcompensation and illegal state aid and the compensation has to be adjusted. This has in Sweden occurred for FAME, E5 and E85, but since the cost for biogas is almost twice that of natural gas, it is not likely that the tax exemptions for biogas will be considered as illegal state aid.

Among the suggested policy instruments in the FFF inquiry are the price premium model and the quota obligation. The government prepared for a quota obligation but it was later withdrawn because the European Commission considered it as illegal state aid when combined with Sweden´s current CO_2 tax. These changes decrease the predictability for potential investors. The actors that we have interviewed propose different policy instruments to promote production of transport fuels from forest biomass: the price premium model, a quota obligation, or a system inspired by the tradable green certificate system. However, more important than the type of policy instrument is that the support is substantial and predictable during the payback period of the investment.

There is a large potential in forest biomass for transport fuel production in Sweden. Different pathways, which result in different transport fuels, compete not only for the feedstock and the end-users, but also for financing, research & development funds, and the policy makers' attention. This study suggests that:

- In order to attract investments in forest-derived methane, the vehicle gas market must continue to increase. Increased policy support directed at the demand may be needed. This is because the gasification technology is sensitive to economies of scale and the size of the facilities that have been considered are equivalent to the entire market for upgraded biogas. To invest in such a facility implies too large a risk given the size of the current demand and the uncertainties of the future market.

- If methane should be able to play an increasingly important role in a future transportation sector, the gasification technology needs policy support during a development period.

- The predictability of policy support is perceived as low. The predictability is more important than the specific type of policy instrument to attract investments. The interviewees in this report suggest the following policy instruments for the support of forest-derived methane: the price premium model, a quota obligation, or a system inspired by the tradable green certificate system.

- The current low oil price decreases the likelihood for investments. Policy instruments that compensate for the oil price risk are needed, e.g. the price premium model.

- Swedish industry actors can realize the potential in forest biomass through production of transport fuels if beneficial conditions are given. Such a development does not only contribute to a vehicle fleet independent of fossil fuels but also to regional development.

SAMMANFATTNING

Metan från skogsråvara kan ge ett betydande bidrag till en fossiloberoende fordonsflotta år 2030. Teknisk kunskap finns och flera svenska aktörer har utrett och förberett investeringar i produktionsanläggningar men teknologin är ännu inte kommersiellt mogen och behöver stöd under en utvecklingsperiod. Investeringsmöjligheterna försämras av att oljepriset föll mycket kraftigt under 2014 och har sedan dess legat kvar på en historiskt sett låg nivå. De politiska styrmedel som ska stödja förnyelsebar energiproduktion och -användning uppfattas dessutom som oförutsägbara. Dessa faktorer samverkar och bidrar till att potentiella investerare avvaktar med beslut.

För att svara på frågan *hur metan från skogsråvara kan komplettera biogas från anaerobrötning i fordonssektorn* så har vi utfört en litteraturstudie samt en enkät- och intervjustudie med tre relevanta industriaktörer. Intervjuerna utfördes huvudsakligen på plats och i samarbete med f3 projektet ”Analys av systembarriärer för produktion av skogsbaserade drivmedel” (f3 2014-002370). Litteratur- och statistikstudien behandlade utvecklingen av förnyelsebara transportmedel, befintliga och föreslagna styrmedel, samt möjliga tekniska produktionsvägar från skogsråvara till drivmedel.

Sverige har uppnått en hög andel förnybara drivmedel i transportsektorn – 12 % baserat på energiinnehåll eller 17 % enligt EUs beräkningsregler i Förnybarhetsdirektivet (RES). Sverige har därmed högst andel förnybara drivmedel bland medlemsländerna i EU och har med råge uppfyllt EU RES målet om 10 % förnybara bränslen i transportsektorn till år 2020. Elanvändning från laddfordon – elbilar och laddhybrider – räknas inte med i dessa siffror och antalet ladd fordon växer mycket snabbt.

Bland biodrivmedlen är biodiesel, etanol och biogas de mest utvecklade alternativen. Biodiesel ökar snabbt, främst genom låginblandning, och är idag det vanligaste biodrivmedlet i Sverige. Merparten är HVO (Hydrotreated Vegetable Oils), men även FAME (Fatty Acid Methyl Esters) förekommer. Etanolanvändningen hade sin topp under 2008 och har minskat sedan dess. Etanol används både i hög- och låginblandning, E85 respektive E5.

Användning av uppgraderad biogas i transportsektorn har ökat stadigt sedan introduktionen 1996. För att möta efterfrågan på fordonsgas kompletteras den uppgraderade biogasen med naturgas. En frivillig överenskommelse bland distributörerna upprätthåller en lägsta andel biogas i fordonsgas som motsvarar 50 %. I dagsläget är andelen biogas mycket högre, över 70 % räknat på volym. Användning av 100 % uppgraderad biogas förekommer också, t.ex. i Stockholms lokaltrafik. Uppgraderad biogas distribueras främst i komprimerad form med hjälp av gascylindrar (79 %), genom så kallad flakning, men även genom inmatning på naturgasnätet (21 %). Mycket litet biogas distribueras i flytande form, s.k. LBG.

Studier av den praktiska produktionspotentialen visar att dagens efterfrågan på fordonsgas kan mötas med 100 % biogas. Fortsätter efterfrågan av fordonsgas att växa så måste nya produktionsvägar av metan tillkomma för att undvika fossila inlåsningseffekter. En sådan produktionsväg är förgasning av skogsbiomassa.

Produktion av uppgraderad biogas och användning i transportsektorn har vuxit med hjälp av politiska styrmedel, t.ex., investeringsstöd till produktion, miljömål som främjar också insamling och rötning av matavfall, stöd till distributionsinfrastruktur, miljöbilspremien som senare ersattes

av ett undantag från fordonskatten, samt undantag från koldioxid- eller energiskatt. Befrielsen från energi- och koldioxidskatt är dock endast garanterad till årsskiftet 2015/16 men regeringen har ansökt till den Europeiska kommissionen om statsstödsgodkännande för skattebefrielse av biogas t.o.m. 2020. Ett biodrivmedel får endast kompenseras upp till en viss nivå enligt Europeiska kommissionens regelverk. Om det förnyelsebara alternativet är billigare än det fossil p.g.a. skattelättnader så betraktas detta som överkompensation och illegalt statsstöd. Detta har också konstaterats för FAME, E5 och E85. Men eftersom kostnaden för uppgraderad biogas är nästan dubbelt så hög som för naturgasen så är det inte troligt att skattebefrielsen anses vara illegalt statsstöd.

I utredningen Fossilfrihet på väg föreslås bl.a. prispremiemodellen och kvotplikt. Den senare ansågs i kombination med nuvarande koldioxidskatt på fossila bränslen vara illegalt statsstöd av Europeiska kommissionen och fick därför dras tillbaka. Dessa tvära kast ökar osäkerheten hos potentiella investerare. De aktörer som vi intervjuat föreslår olika styrmedel för att främja produktion av produktion av drivmedel från skogsråvara: prispremiemodellen, kvotplikt eller ett system inspirerat av de gröna elcertifikaten. Viktigare än den specifika utformningen av styrmedel är dock förutsägbarhet under investeringens återbetalningsperiod.

I Sverige finns en stor råvarupotential för skogsbiomassa som kan användas till drivmedelsproduktion. Olika produktionsvägar som resulterar i olika bränslen – metan, metanol, DME m.fl. – konkurrerar inte bara om råvaran och slutanvändarna utan även om finansiering, forsknings- & utvecklingsstöd samt beslutsfattarnas uppmärksamhet. Denna studie pekar på att:

- För att göra det attraktivt att investera i produktion av metan från skogsråvara så måste fordonsgasmarknaden fortsatt främjas. En ökad efterfrågan är nödvändig för att bereda väg för metan från skogsråvara. Förgasningsteknologin har tydliga skalekonomiska fördelar. Storleken på de anläggningar som har övervägts motsvarar hela den svenska marknaden för uppgraderad biogas. Att investera i en anläggning av den storleken innebär en alltför stor risk givet storleken på dagens marknad samt osäkerheten kring dess framtida utveckling.

- Om metan ska spela en viktig roll i ett framtida transportsystem så måste förgasningsteknologin stödjas under en utvecklingsperiod eftersom den ännu inte är kommersiellt mogen.

- Förutsägbarheten för styrmedel uppfattas som låg vilket påverkar investerare negativt. Förutsägbarhet är viktigare än den exakta utformningen av styrmedlen. De industriella aktörerna har föreslagit styrmedel för att främja en storskalig produktion av drivmedel från skogsråvara i Sverige: prispremiemodellen, kvotplikt eller ett system inspirerat av de gröna elcertifikaten.

- Det nuvarande låga oljepriset försämrar förutsättningarna för investeringar. Styrmedel som kompenserar för oljeprisrisken, t.ex. prispremiemodellen, kan därför behövas.

- Sverige har aktörer som kan förverkliga potentialen i skogsbiomassa genom tillverkning av drivmedel om gynnsamma förutsättningar ges. En sådan utveckling bidrar inte bara till en fossiloberoende fordonsflotta utan skapar även regional utveckling och arbetstillfällen.

ABBREVIATIONS

BL	Black liquor
BLG	Black liquor gasification
BTL	Biomass to liquid
DME	Dimethyl ether
DS	Dry substance
E5	Low blend-in ethanol and gasoline
E85	High blend-in ethanol and gasoline
ED95	High blend-in ethanol and diesel
EU	European Union
FAME	Fatty Acid Methyl Ester
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HVO	Hydrogenated Vegetable Oils
ILUC	Indirect land use changes
LBG	Liquefied biogas
LCA	Life Cycle Analysis
LHV	Lower heating value
LNG	Liquefied natural gas
M100	Pure methanol
M15	Low blend-in methanol and gasoline
MS	Member States
P&P	Pulp and paper
RES	European Union Renewable Energy Directive
SEA	Swedish Energy Agency
SNG	Synthetic natural gas
WGS	Water gas shift

TERMINOLOGY

ENGLISH	SWEDISH
Black liquor	Svartlut
Environmental car	Miljöbil
Fringe benefits	Förmånsvärde
Green liquor	Grönlut
Ley crops	Vallgröda
Pine	Tall
Recovery boiler	Sodapanna
Spruce	Gran
Vehicle tax	Fordonsskatt
Weak acids	Svagsyra

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1 INTRODUCTION

The use of upgraded biogas is growing quickly in the Swedish transport sector as a result of policy support: from 48 GWh in 2000 to 874 GWh in 2013. However, the total use of vehicle gas was 1 429 GWh in 2013, i.e. larger than the supply of upgraded biogas (Swedish Energy Agency, 2015a). Thus vehicle gas contains a mixture of upgraded biogas and natural gas to meet the demand. The biogas share was 74 %[1] during 2015 and the distribution companies have voluntarily agreed to maintain a minimum share of 50 % (Statistics Sweden 2015a; Strauch & Krassowski 2012). Natural gas is not only a complement to upgraded biogas; it also increases the economic attractiveness of vehicle gas. This is because its total costs including distribution generally are lower than the production and distribution costs of upgraded biogas (Sanches-Pereira et al. 2015). The natural gas share is thus a price regulator for vehicle gas.

The resources suitable for biogas production through anaerobic digestion are limited. Lönnqvist et al. (2013) have estimated the practical resource potential from residues and energy crops in Sweden to 8.9 TWh per year. Of this potential, 35 %, or 3.1 TWh per year, corresponds to energy crops, which can be expected to have larger production costs compared to biogas production based on residues. In addition, the cheapest and most accessible resources – i.e. sewage sludge and food waste – are to a large extent already utilized. Methane produced from other resources will be needed if the demand continues to increase. Methane can also be produced from forest-derived biomass by thermal conversion processes, such as gasification processes or – possibly – pyrolysis. The gasification process generates a syngas that can be treated in a methanation process to obtain the desired energy carrier.

The Swedish forest holds a significant resource potential for transport fuels (Staffas et al. 2013). It is also the feedstock for large industry branches in Sweden, e.g. pulp and paper, sawn wood products, and solid biofuels. The markets for these products are often global and the competition for forest biomass is increasing. Other potential products from forest biomass include textiles and bioplastics. The use of forest biomass in transport fuels production must thus compete with both incumbent industries and with other new products.

There are different and sometimes competing production pathways for biomass to biofuels. A variety of transport fuels can be produced from forest biomass: electricity, ethanol, dimethyl ether (DME), Fischer-Tropsch fuels, hydrogen, hydrogenated vegetable oils (HVO), methane, methanol, and synthetic gasoline. Some of these fuels need dedicated distribution infrastructure and vehicles, while others are compatible with the current systems, i.e. drop-in fuels. Methane produced by thermal conversion from forest-derived biomass is an example of a fuel, which is compatible with the existing distribution infrastructure in large parts of the more densely populated parts of Sweden, since it is interchangeable with vehicle gas. This pathway is not yet economically viable and significant research and development efforts are put into the technology. The energy company Göteborg Energi commissioned a pilot plant in 2013. It has an installed capacity of 20 MW and

1 The biogas share measured by volume was 74 % as an average between January and August 2015 (Statistics Sweden 2015c). Measured by energy content the share is slightly lower since biogas has a lower energy content.

may generate 180 GWh methane per year, i.e. a substantial volume in comparison with the total current use of upgraded biogas for transportation in Sweden. Göteborg Energi received financial support from the government for this first phase, an investment that amounted to SEK 1.5 billion. A new upscaled plant was originally planned with an annual capacity of 100 MW[2] that would generate 800 GWh of biogas per year (Gothenburg City 2012; Börjesson et al. 2013; Hansson & Grahn 2013).

The investment for the second phase is expected to be between SEK 2.5 and 3.0 billion, and its implementation depends on the performance of the first phase and also on the stability of policy support and regulations together with the price of competing fuels. Other companies observe this development closely, e.g. the company E.ON that has advanced plans of a full-scale plant which could produce 1 600 GWh of methane per year (Börjesson et al. 2013; Grahn & Hansson 2014; E.ON 2015). The methane production from one such large-scale plant would be more than the current use of vehicle gas in Sweden, including both upgraded biogas and natural gas (Swedish Energy Agency 2015a). Hence it is clear that methane from forest-derived biomass could have a significant impact on biogas as a fuel for the Swedish transportation sector. However, to realize this potential, the gasification technologies must be competitive compared to biogas based on anaerobic digestion and also compared to other pathways from forest biomass to transport fuels. Effects of learning-by-doing are thus necessary for this technology to be commercially viable and to overcome techno-economic constrains. In addition, systemic constrains, e.g. path dependency and competing platforms, will influence the development.

1.1 AIM

This research aims at increasing understanding of forest-derived methane as transport fuel in Sweden and its complementarity with upgraded biogas from anaerobic digestion. The *specific research questions* are:

- Which are the economic and systemic constraints for a commercial introduction?
- How could policy support address these constraints?

1.2 LIMITATIONS

The analysis of economic and systemic constraints for forest-derived methane is mainly focused on the supply side and only to a lesser extent on the demand side. This analysis includes competing production pathways from forest biomass to transport fuels. Industry actors´ perception of drivers and barriers has also been captured through interviews. The analysis of policy instruments that address barriers for renewable transport fuels covers both the supply and demand side. The review of the recent vehicle gas development in Sweden also includes the demand side.

The focus on the supply side implies that social barriers related to the users are not included, e.g. the perception of gas as a safe or unsafe fuel. Similarly, we have not included the perception of

2 In addition, the plant has capacity to generate electricity (4 MW) and to deliver heat (15 – 19 MW) to the district heating grid.

availability of vehicle gas, which might have been affected negatively of an historical lack of supply in certain regions.

2 METHODOLOGY

The study builds on interviews and a survey with industry stakeholders as well as a literature review. The literature review covers journal articles, grey literature, and information from the industries (e.g. pre-studies, conference presentations and other material available to public).

The identification of industries to be included in the interviews and the survey started with existing compilations (Börjesson et al. 2013; Grahn & Hansson 2014; International Energy Agency 2015).

The interview questions concern factors that have influenced the industries´ decision-making process: whether to make the investment or not, choice of fuel to produce, feedstock to use, location of plant, possibilities to switch to methane production. Other questions concerned the industries perception of policy instruments and their specific needs that may be attended with policy instruments. The interview questions are presented in Appendix A1.

The interview was followed up by a survey to adjust the scope of the questions and quantify the findings from the interviews. In these surveys the interviewees were asked to quantify alternatives as opposed to the open questions in the interviews. The survey is presented in Appendix A2.

3 BACKGROUND

3.1 RENEWABLE TRANSPORT FUELS IN SWEDEN

3.1.1 Recent development

Sweden achieved a 12 % share of renewables in domestic transport sector during 2013[3], the highest share in EU (Swedish Energy Agency 2015a; Eurostat 2015). Domestic transport in Sweden used 85 TWh during 2013, equivalent to nearly one-quarter of the domestic final energy use. Of this amount, 5.4 TWh (6 %) was biodiesel, 2.1 TWh ethanol (2 %), and 0.87 TWh biogas (1 %). In addition, rail transport used 2.8 TWh of electricity (3 %)[4] (Swedish Energy Agency 2015a).

Biofuels for transport have increased by 95 % from 2008 to 2013. During this period biodiesel has increased by 259 % and biogas by 167 %, while ethanol has decreased by 16 % (Swedish Energy Agency 2015a). The use of electricity as a transport fuel for personal vehicles does not enter into the official statistics by the Swedish Energy Agency, but electrical vehicles are increasing rapidly. By October 2015 there were over 13 000 electrical vehicles in Sweden (Elbilen i Sverige 2015).

Biodiesel refers to either hydrotreated vegetable oils (HVO) or fatty acid methyl esters (FAME). The use of HVO is larger than the use of FAME. One advantage is that HVO can be blended in diesel to a higher percentage than FAME if conventional diesel engines are used (Swedish Energy Agency 2014e). The possibility to blend biodiesel in conventional fossil diesel facilitates distribution, as no new infrastructure is needed.

In Sweden, ethanol was introduced as a transportation fuel in 1998 and its use grew quickly. In 2008 the consumption peaked at 2.5 TWh (Swedish Energy Agency 2015a). Ethanol is imported and also produced domestically in Sweden. The largest producing countries are USA and Brazil. In Sweden two companies produce ethanol: Lantmännen Agroetanol and Domsjö Fabriker. Ethanol is distributed as low blend-in with gasoline (E5), high blend-in with gasoline (E85), and also as high blend-in with diesel (ED95). E5 distribution can benefit from the existing infrastructure for gasoline. The infrastructure for E85 is also well developed. This is a result of a law that obligates refueling stations to offer a renewable fuel. Since the infrastructure for E85 is cheaper to install than for example the infrastructure for vehicle gas, 1808 of 1992 refueling stations affected by the law[5] opted for E85 (Swedish Energy Agency 2014e). ED95, on the other hand, is distributed through the company SEKAB directly to customers and through one public refueling station.

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3 When accounting for the EU Renewable Energy Sources Directive (RES), the use of renewable transport fuels amounts to as much as 17 % (Swedish Energy Agency 2015a). The high figure is a result of the RES's double counting for fuels produced from waste or residues. All biogas and HVO (a type of biodiesel) are counted twice (and even if the fuel is produced from energy crops). The figure also includes electricity from renewable sources in rail transport.

4 The share of renewables in electricity end-use during 2013 was 62 %.

5 The law affects refueling stations that sell a certain amount of fuel per year and not smaller stations. For this reason only 1992 of 2716 stations are affected by the law.

The use of upgraded biogas in transport is complemented with natural gas and the product is sold under the name vehicle gas[6] independent of the origin. Vehicle gas was introduced in Sweden in the early 90´s and was initially composed by natural gas, but the growth came with the introduction of biogas. The Swedish natural-gas grid is located in the southwestern part of the country; it stretches from Trelleborg in the south to Stenungssund in the north and Gnosjö in the east. Since 2011 there is a liquefied natural gas (LNG) harbor in Nynäshamn, nearby Stockholm, and since 2014 there is a terminal in Lysekil north of Gothenburg (The Linde Group 2015; Energigas Sverige 2015). There are also plans of LNG harbors in Gothenburg, Helsingborg, and Gävle (Energigas Sverige 2015; SwedeGas 2015)

The major part of the upgraded biogas, 79 %, is distributed through gas cylinders in compressed form while the remaining 21 % is distributed through the natural gas grid (Swedish Energy Agency 2014e). Almost no biogas is distributed in liquefied form (LBG). When biogas is injected to the natural gas grid this is done to the distribution and not the transmission grid (Swedish Energy Agency 2013a). Local grids exist in Stockholm, Västerås, and Linköping. Distribution through a gas grid is more cost efficient compared to distribution through gas cylinders, especially for longer distances. LBG is only produced in Lidköping (Swedish Energy Agency 2014e). The process is expensive and also energy consuming compared to other distribution forms.

The access to natural gas, through a grid or through distribution with gas cylinders, can increase security of supply for vehicle gas. During 2010 - 2011 there were regional supply problems, e.g. in Stockholm (Lönnqvist et al. 2013). These supply problems were remediated by the commissioning of the LNG harbor in Nynäshamn.

Gas is distributed through grids and cylinders to refueling stations. By October 2015 there were 158 public and 63 non-public vehicle gas refueling stations concentrated in the southern, and most densely populated, part of Sweden (Gasbilen.se 2015). The large number of non-public refueling stations can be explained by the use of vehicle gas in public transport, which often enjoys a dedicated distribution infrastructure, sometimes connected to bus pit lanes. In addition there are five LNG refueling stations. The use of LNG in the road transport has started relatively recently and it is mostly used for trucks. The public vehicle gas refueling stations are illustrated in Figure 1 (Gasbilen.se 2015).

6 A direct translation of the Swedish word fordonsgas.

Figure 1: Public vehicle gas refueling stations (Gasbilen 2015)

3.1.2 Historical experiences

Different renewable transport fuels have been tried out in Sweden, but for different reasons. During World War II, wood gas (raw syngas) was used in the Swedish transport sector due to the shortage in the supply of oil and oil products. This technology was quickly abandoned after the war when the imports of oil and oil products improved.

As a response to the 1973 oil crisis, methanol was investigated as a transport fuel. The Swedish government mainly cooperated with Volvo. The efforts were intensified as a result of the 1979 oil crisis and a low blend-in into gasoline (M15) was used by 1000 vehicles between 1979 and 1982 (Sterner et al. 1998; Ulmanen et al. 2009). The infrastructure for M15 covered a large part of the country and also parts of Western Germany, Norway, and Denmark. In 1981 the focus shifted to pure methanol (M100) and the cooperation expanded to include other partners than Volvo, but only

22 M100 light vehicles and two M100 busses circulated in Sweden (Ulmanen et al. 2009). Methanol was produced from fossil sources, but the aim was to shift to renewable sources (ibid).

3.2 POLICY BACKGROUND

3.2.1 Policy targets

Policy targets on a EU level

Policy targets for renewable energy in transport are set on a regional, national, and local level (counties and municipalities in the case of Sweden). For example, the European Union Renewable Energy Sources Directive (RES) mandates a 10 % share of renewables in the transport sector in Member States (MS) by 2020 (European Union 2009). Sweden has already met the levels stipulated in the RES; its use of renewable transport fuels amounted to 17 % during 2013 (Swedish Energy Agency 2015a). The high figure is a result of the RES's double points for fuels produced from waste or residues. All biogas and HVO are counted double (even if parts are produced from energy crops). The figure also includes electricity from renewable sources in rail transport and it considers the share of renewables in electricity generation[7]. It should be noted that the target excludes air and sea transport (Swedish Energy Agency 2014a).RES has replaced the outdated EU biofuels directive, which set a target of 5.75 % renewables in transport by 2010 and 2 % by 2005 (The European Parliament and the Council 2003).

The European Commission has proposed to update RES regarding four aspects (European Commission 2012). *Firstly*, only half of the 10 % target can be fuels produced from food or fodder crops (i.e. 5 %). *Secondly*, fuels produced from waste, residues, and other feedstocks that do not affect land use should be counted double or in some cases even four times. *Thirdly*, RES demands a calculated 35 % Greenhouse Gas (GHG) emissions reduction from a Life Cycle Analysis (LCA) perspective compared to the fossil fuel equivalence. This reduction shall increase to 60 % for fuel production plants commissioned 2017 or later. *Fourthly*, indirect land use changes (ILUC) should be considered when accounting for GHG emissions (Government of Sweden 2013; Hansson & Grahn 2013; European Commission 2012).

Policy targets on a national level/Sweden

MS may choose to set even more ambitious targets than EU and Sweden has set the target of attaining a vehicle fleet independent of fossil fuels by 2030. This target is seen as a step towards the target of zero net GHG emissions from Sweden by 2050 (Government of Sweden 2013a). However, the national legislation must be compatible with EU legislation and policy instruments may be subject to approval by the European Commission.

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7 When accounting for the RES target one can either count the share of renewable electricity in the MS or the average share in EU two years before the accounting year (i.e. 2011 if accounting the renewables in transport 2013) (Hansson & Grahn 2013). In Sweden, the share of renewables of electricity generation during 2011 was approximately 60 % (Swedish Energy Agency 2014a).

Policy targets on a regional or local level/counties and municipalities

The targets set on local level may differ from the national targets. For example, Stockholm County aims at fossil-free public transport by 2030, including road and rail traffic. Furthermore, a 90 % share of renewables in the region's public transport should be obtained by 2020 (Stockholm County Administrative Board 2010; Stockholm County Administrative Board 2012)

National goals are often implemented at the local level, particularly in countries such as Sweden, which manages a significant share of its fiscal resources within the municipalities and counties. The County Councils in Sweden are e.g. responsible for public transport and its procurement may have a significant impact on the transport fuel mix and the vehicle fleet.

3.2.2 Policy instruments

Policy instruments can be divided in four categories: economic, administrative, information, and research & development. Examples of economic policy instruments are taxes and tax exemptions, fees, subsidies, and trading systems. Examples of administrative instruments are regulations, emission limits, demands on fuel choice and energy efficiency, long-term agreements, and environmental standards. Examples of information instruments are information campaigns, counseling, education, and lobbying towards the public opinion. Finally, examples of research and development instruments are economic support to research and development at universities and companies, support to demonstration projects, and public procurement (Swedish Energy Agency 2015d). SEA has conducted over 50 public procurements since 1995 to promote technology development, e.g. heat pumps, electrical vehicles, refrigerators, and other systems (Swedish Energy Agency 2014d) .

Policy instruments on EU level

There are examples of policy instruments on an EU level that address barriers for an increased use of renewable transport fuels. According to the European Commission, important barriers are high vehicle prices, low acceptance among consumers, and lack of refueling and recharging stations (The European Parliament and the Council 2014).

The directive 2014/94 on the deployment of alternative fuels infrastructure demands that member states provides renewable fuels distribution infrastructure and refueling/recharging points along a core network corridor denominated TEN-T (The European Parliament and the Council 2014).

The transport fuels affected by the directive are: CNG for road transport, LNG for road and maritime transport, electricity, and also – although voluntary– hydrogen. The Swedish trajectory of TEN-T is illustrated in Figure 2 (European Commission 2015).

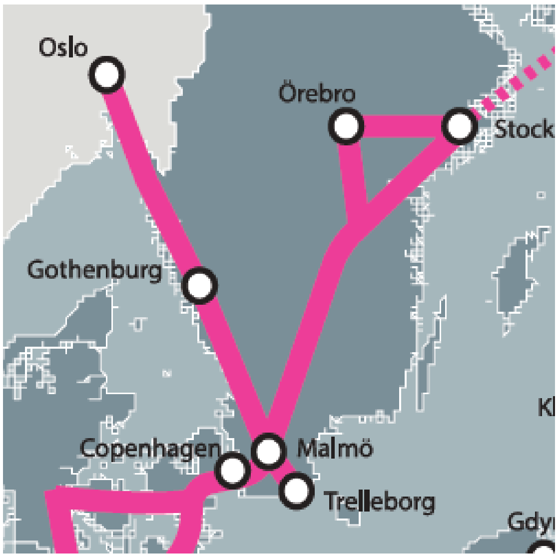

Figure 2: Swedish trajectory of TNT-T(European Commission 2015)

The Swedish part of TEN-T has two trajectories. The first trajectory follows the existing natural-gas grid (from Trelleborg to Stenungssund) and continues towards Oslo. The second trajectory goes from Malmö towards Stockholm. The second trajectory covers an area with a vehicle gas market but with no access to a natural-gas grid and it ends in a triangle with Stockholm in the east and Örebro in the west. This part partially coincides with a planned pipeline for natural gas and biogas in Mälardalen. Regional actors are discussing a stepwise construction of a gas grid and the directive may have a positive effect on this development. The directive stipulates that MS shall assure refueling/recharging points with an indicated lowest distance in between them along the TEN-T. For CNG the indicated distance is set to 150 km and for LNG it is 400 km (The European Parliament and the Council 2014). Targets for public transport are also set in the directive. Public transport has been, and is still, very important for the local biogas development (Vernay et al. 2013). Local agreements have guaranteed supply and demand in public transport over long time.

The demands on LNG infrastructure for maritime transport stipulated in the directive may also affect gas demand and, indirectly, have an effect on vehicle gas development (The European Parliament and the Council 2014). The maritime transport sector is facing new regulations for sulfur emissions which may force them to switch fuels and LNG may be an attractive option (International Maritime Organization 2015). The targets in the directive shall be fulfilled by 2025 (The European Parliament and the Council 2014).

A well-developed distribution infrastructure is a pre-requisite for actors both on the supply and demand side of renewable transport fuels, as pointed out by the Commission. In this regard the directive addresses important barriers. However, the indicated distances for CNG along the TNT-T network in Sweden are essentially already fulfilled and the directive´s effect is thereby limited, at least domestically. It may be necessary to complement with local and national initiatives that promote more refueling points along TNT-T and also refueling points beyond the network, especially in scarcely populated areas.

The fuel quality directive, 2009/30/EC, regulates low blend-in. It stipulates what shares[8] of low blend-in that are permitted from a technical perspective. A maximum volume share of 10 % ethanol can be blended in gasoline. For methanol in gasoline this share is set to 3 %. The permitted share of FAME in diesel is set to 7 % (Hansson & Grahn 2013). The directive does not set any limits for HVO, which is the largest and most quickly growing biofuel in Sweden (Swedish Energy Agency 2015a). This because HVO is a “pure diesel-like hydrocarbon”, which thus can be blended in fossil diesel in any share (The European Parliament and the Council 2009). Furthermore, the directive treats Fischer-Tropsch diesel in the same way.

The fuel quality directive also stipulates how large GHG emissions reductions should be achieved. It is the obligation of the fuel supplier to achieve this through blend-in of biofuels. The level is set to a calculated 6 % GHG emission reduction per energy unit by 2020 compared to 2010 (Hansson & Grahn 2013; Government of Sweden 2013). The emission reductions stipulated in the fuel quality directive refers to both the fossil and renewable part. The emission reductions stipulated in RES, on the contrary, only refers to the renewable part. The fuel quality directive and RES can be seen as complementary since the former concentrates on emission reductions and the latter concentrates on the share of renewables.

The Energy tax directive 2003/96/EC regulates minimum levels for energy taxes in EU (European Union 2003). The directive is expressed as euros per liter fuel in case of liquid fuels and euros per GJ in case of gaseous fuels. This has two major implications. Firstly, both fossil fuels and renewable fuels are taxed with the same rate. Secondly, since the tax for liquid fuels is set per liter, e.g. ethanol that has lower energy content will be taxed higher per kWh compared to gasoline. Thus the directive does not incentivize the use of renewables and it even disincentivizes the use of liquid renewables with lower energy content than their fossil alternative.

Tax-exempts for renewables is considered as state aid and only allowed in certain cases. The support (i.e. the tax exempt) may not exceed the difference between the levelised production cost and the market price. Furthermore, the production cost must be updated at least once per year (European Commission 2014).

The European Commission has proposed a new energy tax directive which would incentivize the use of renewables (European Commission 2011). The Parliament voted against it in 2012 and the directive is again discussed among the MS. The proposed directive has two tax components: a tax based on energy content and a CO_2 tax (20 euros per ton). Biofuels would be exempted from the second component if they comply with sustainability criteria defined in RES and in the fuel quality directive. The proposed directive sets minimum levels, like the present directive, and MS may set higher tax levels.

General Swedish policy instruments

MS largely adopt their own policy instruments to reach targets. Sweden has used general and specific policy instruments to promote renewable energy. The most important general policy instruments have been the energy and the CO_2 taxes, which were introduced in the 1950´s and

8 Measured by volume, not by energy content.

1990´s, respectively. These two taxes also apply on transport fuels and together they are called the transport fuel tax. The exact tax component for each fuel during 2015 can be seen in Table 1 (Swedish Petroleum and Biofuels Institute 2015; Swedish Tax Agency 2015a; Swedish Tax Agency 2015b).

Table 1: Transport fuel taxes in Sweden by June 2015

Fuel	Energy tax		CO2 tax		Total*
	SEK / kWh	SEK / liter SEK / Nm3	SEK / kg CO2	SEK / liter SEK / Nm3	SEK / liter SEK / Nm3
Gasoline	0,36	3,25	1,10	2,60	5,85
Diesel, 1 **	0,19	1,83	1,27	3,22	5,05
Natural gas	0	0,00	1,18	2,41	2,41
Biogas	0	0,00	0	0	0,00
Ethanol (E5)	0,06	0,36	0	0	0,36
Ethanol (E85, ED95)	0	0,00	0	0	0,00
FAME ***	0,18	1,68	0	0	1,68
FAME ****	0,11	1,02	0	0	1,02
HVO	0	0	0	0	0,00

* These taxes do not include VAT. VAT of 25 % should be added after adding transport fuel taxes.
** Environmental standard 1
*** Up to 5 % blend-in
**** Pure or high blend-in

It can be seen from Table 1 that the transport fuel tax is substantial on fossil fuels. The transport fuel tax together with VAT was as much as 57 % of the final gasoline price in 2014 (Ekonomifakta 2014a). The tax has two functions. The first function is to obtain fiscal resources. As much as 4 % of total fiscal resources in Sweden were obtained from energy and environmental taxes during 2014 (Ekonomifakta 2014b). The second function is as a policy instrument to promote renewables and reduce energy consumption. These two functions may conflict; the government may lose fiscal resources when tax exemptions are given to promote biofuels. The energy tax exemption for biofuels amounted SEK 3.4 billion during 2014 and is expected to increase to SEK 4.2 billion by 2017 (Government of Sweden 2015b). The tax exemption for e.g. HVO was only granted up to 15 % blend-in into conventional diesel. This limitation was removed (retroactively) from May 1st 2014. However, the EU fuel quality directive sets no limitations for the HVO levels in conventional diesel. The Swedish limitation for HVO thus may have been for fiscal rather than technical reasons.

It can be seen from Table 1 that energy tax is also applied to some renewables, although to a lesser extent compared to fossil fuels. This is because Sweden, alike other MS, is not allowed to give state aid. Thus tax exemptions, which are considered as a form of state aid, may only be granted if biofuels are more expensive to produce than their fossil equivalence. Biofuels should not be overcompensated, i.e. be cheaper than their fossil equivalence by means of state aid. For this reason fuel suppliers report twice a year to the Swedish Energy Agency (SEA) who monitors if state aid has been provided.

SEA compares the production cost of each renewable transport fuel to their fossil equivalence. For example the production cost for ethanol entails: purchasing cost, labor costs, capital costs, processing costs, transport costs, and profits. The final result is adjusted for the energy content of ethanol so that it will be comparable with gasoline (Swedish Energy Agency 2015c). If the production cost is found to be lower than the gasoline price it is considered as overcompensation. SEA states in their monitoring report that E5 and E85 probably have been overcompensated during 2014, but this was not the case for ED95 (Swedish Energy Agency 2015c). The explanation for the overcompensation is that the costs for ethanol were low during 2014. The energy tax exemption for ethanol (E5 and E85) is consequently planned to be reduced by December 2015 (Ministry of Finance 2015). When comparing the cost structure of E5 and E85 it can be noted that E5 has lower capital costs but higher purchasing price. The lower capital costs may be because this drop-in fuel can be used in existing infrastructure. The production cost entails the separate storage facilities for E85 but it does for example not entail the separate pumps for E85 at refueling stations. This is because the tax point is when the fuel leaves the storage. The higher purchasing price is because the Swedish regulations favor European ethanol to be used as E5, which is more expensive than ethanol imported from outside Europe. Ethanol, which is imported to Sweden and used as E5, should not be denatured in order to obtain the energy tax exemption. At the same time EU has higher duty tariffs on non-denatured ethanol: 192 euros/m^3 compared to 102 euros/m^3 for denatured ethanol. As a result only European ethanol is used in E5 and the purchasing price is higher compared to ethanol to be used in E85 (Swedish Energy Agency 2012).

SEA states in their monitoring report that low blend-in and pure FAME have been overcompensated as well during 2014 (Swedish Energy Agency 2015c). The explanation is a high reference price for fossil diesel during 2014 and decreased production costs for FAME. The tax exemptions for FAME have been adjusted accordingly. The energy tax for low blend-in FAME was adjusted from 0.28 to 1.68 SEK/liter January 1st 2015. High blend-in FAME was previously completely exempted from energy tax but is now taxed with 1.02 SEK/liter. SEA concludes that overcompensation is not likely for 2015 since the diesel price has decreased. HVO, on the contrary, has been more expensive than fossil diesel and no adjustments of its tax exemption are planned (Swedish Energy Agency 2015c).

SEA also monitors the market for biogas in transport and concluded that no overcompensation has occurred. In fact SEA has calculated an upgraded biogas cost, which is almost twice as large as the natural gas cost, after adjusting for the lower energy content; 12.3 SEK/Nm^3 compared to 6.3 SEK/Nm^3 (Swedish Energy Agency 2015b). However, an agreement between the vehicle gas suppliers keeps the biogas level above 50 % in spite of the considerably higher costs for biogas. No energy tax is charged for natural gas or biogas when used for transport purposes. Until 2014 natural gas used in transport also received a partial CO_2 tax exemption: 1.85 SEK/Nm^3 instead of 2.41 SEK/Nm^3.

SEA states that the system of monitoring overcompensation and adjusting the energy tax accordingly gives shortsighted and unstable signals to the market (Swedish Energy Agency 2015c). It is the fuel suppliers that bear the financial risk of refunding overcompensation. In addition, The Ministry of Finance has announced plans to increase the energy tax on diesel and gasoline by January 2016. When the energy tax on these fuels increases the reference price, used in the monitoring of over compensation, also increases. As a result of increased fossil reference prices, the energy tax on renewables may have to be adjusted again (Ministry of Finance 2015).

Specific Swedish policy instruments on vehicle ownership, distribution, and production

A premium of SEK 10 000 was given to private consumers when purchasing a so-called *environmental car* (Swedish: miljöbil) between April 2007 and June 2009. An environmental car was according to a definition a car that emitted less than a calculated value of 120 g CO_2 per km for gasoline or diesel. For cars running on renewable fuels, limitations were instead set to the fuel consumption. The premium was given for 169 000 vehicles and amounted 1.7 billion SEK during the period. The premium was replaced with a five years long vehicle tax exemption in 2010 (Swedish: befrielse från fordonsskatt). In 2013, a new definition of what was an environmental car was introduced. It relates the CO_2 emissions to the vehicle´s weight and permits higher emission levels for ethanol and gas vehicles. For electrical cars, a limit was instead set for fuel electricity consumption. A so-called *super environmental car premium* was also given out from 2012 until 2014. A super environmental car was defined as a car emitting less than 50 g CO_2/km and the premium was SEK 50 000 for private car buyers. For companies and other organizations some additional restrictions applied to the premium. In practice, only electrical vehicles and plug-in hybrids can qualify for the super environmental car premium. Since 2009 an administrative authority (Swedish: myndighet) may only purchase or lease environmental cars (Hansson & Grahn 2013). This also applies for companies financed by and providing certain services to the government, e.g. school transports or mobility services (ibid).

Another tax-related specific policy instrument that affects the cost for owning a car is the Swedish vehicle tax. Since 2006 the vehicle tax is based on calculated CO_2 emissions and due to the calculation basis the tax is lower for renewable fuels vehicles. Before 2006 it was based on the vehicle´s weight (Hansson & Grahn 2013; Government of Sweden 2013). The *taxable value of fringe benefits* (Swedish: förmånsvärde) is also reduced for gas and electrical vehicles. A smaller reduction is obtained for ethanol and non-plug-in hybrid vehicles (Government of Sweden 2013a; Hansson & Grahn 2013).

Local policy instruments have also been important to promote the use of renewable transport fuels. In the municipality of Stockholm, a *traffic congestion fee* is charged since 2006. The congestion fee currently varies between 10 and 20 SEK and it is limited to 60 SEK per vehicle and day. Until 2009 environmental cars were exempted from the fee and for some cars the exemption lasted until 2012 (Government of Sweden 2015a; Government of Sweden 2013; Hansson & Grahn 2013). This economic incentive probably had an effect on the local demand for environmental cars. However, the main purpose of the fee is to limit congestion and to obtain fiscal resources. Thus it made sense to remove the exemption as the number of environmental cars increased. Although the congestion fee is primarily addressing traffic congestion, it may thus also have an effect on the CO_2 emissions.

Another local instrument is parking fees. Over 30 municipalities have offered a parking fee exemption or reduction for environmental cars (Swedish Association of Green Motorists 2011). However, many municipalities have removed the exemption since the number of environmental cars have increased (Hansson & Grahn 2013). In Stockholm the exemption was given between 2005 and 2008, in Malmö between 2006 and 2009, and in Gothenburg between 1998 and June 2015 (Gothenburg City 2015; Hansson & Grahn 2013).

In 2006, Sweden introduced a law to *promote a renewable transport fuels infrastructure* (Swedish: lag om skyldighet att tillhandahålla förnybara drivmedel, 2005:1248). The law mandates refueling stations above a certain annual sales volume to provide at least one renewable fuel (Government of

Sweden 2005). The law initially included refueling stations with a sales volume above 3 000 m^3. In 2009 the volume was adjusted to 1 000 m^3 and in 2014 the volume was adjusted again to 1 500 m^3 (Government of Sweden 2013a; Government of Sweden 2014a). The reason for the last adjustment was to protect small refueling stations, which may not be able to afford the investment. The consequence of the law was an ethanol infrastructure expansion. This is because ethanol infrastructure implies a lower investment compared to other renewable transport fuels (Government of Sweden 2013a). Vehicle gas infrastructure implies an investment cost that is approximately 20 times higher compared to ethanol: SEK 4 000 000 compared to SEK 200 000 (Swedish Environmental Protection Agency 2012). As a response to the unbalanced ethanol infrastructure expansion, the Government introduced a support to other renewable transport fuels infrastructure in 2007 (Swedish Environmental Protection Agency 2012; Government of Sweden 2013a). The support was equivalent to 30 % of the difference between an investment in an ethanol pump and the renewable fuel that the refueling stations had chosen. For a typical vehicle gas pump the support would be (Swedish Environmental Protection Agency 2012):

$$(\text{SEK } 4\,000\,000 - \text{SEK } 200\,000\,) \times 30\% = \text{SEK } 1\,140\,000$$

Although the support was directed to all renewable transport fuels except ethanol, it led to an expansion of vehicle gas infrastructure and 57 vehicle gas pumps received support between 2007 and 2010 (Swedish Environmental Protection Agency 2012). The average support was approximately one million SEK. The government reserved SEK 145 million for the support and applications for SEK 114 million were approved. In the end only SEK 59 million was paid, because many actors withdrew their applications. The reasons for withdrawal were failure to finance the complete investment as well as to obtain necessary permits, uncertainties regarding demand from public transport, or that a competing actor established a refueling station before the applicant. As much as 92 % of the funds was granted to five large actors: E.ON, Fordonsgas Sverige, AGA, Svensk Biogas, and Stockholm Gas. The location of the supported refueling stations was concentrated to the most populated counties that already have a vehicle gas market: Stockholm County, Västra Götaland, Skåne, and Östergötland. Prior to the support, Sweden had 62 vehicle gas refueling stations compared to 158 stations in October 2015 as shown in Figure 1. It is therefore obvious that one of the reasons that the EU infrastructure directive from 2014 does not affect Sweden to a large extent is that it is predated by these Swedish laws have been from 2006 and 2007.

The climate investment program KLIMP entailed almost two billion SEK between 2003 and 2008. Almost 20 % of these funds went to biogas production and upgrading and an additional 8 % went to infrastructure investments (refueling stations and pipelines) and vehicles (Hansson & Grahn 2013). Prior to KLIMP the local investment program for ecological sustainability (LIP) distributed SEK 6 billion between 1998 and 2002 (Government of Sweden 2013a). LIP also supported biogas production and use.

The Swedish Government passed a law in 2013, which *mandates a low blend-in quota*. The law was later abolished since the Government did not obtain the necessary permission for state aid from the European Commission (Government of Sweden 2014b). The Government is currently preparing a new proposal. The law from 2013 mandated a low average blend-in quota for gasoline and diesel. For gasoline the quota was set to 4.8 % biofuels by May 2014 and 7 % by May 2015. For diesel the quota was set to 9.5 % of which 3.5 % should be biofuels with special benefits (Government of Sweden 2013b). Energy tax applies to the mandatory low blend-in biofuels. At the same time, pure or high blend-in biofuels are exempted from energy tax. According to Grönkvist et al. (2013) the policy instrument was designed to easily control the share of renewables (through the quota), to avoid tax losses for low blend in fuels, and to maintain the market for pure or high blend-in biofuels. The reason that the European Commission did not give the permission for state aid was the combination of the quota system together with the CO_2 tax exemption for biofuels. In addition, the energy tax on low blend-in biofuels would be equal to the energy tax on fossil fuel per energy unit. This is not consistent with the EU energy tax directive, which establishes an energy tax per volume. The European Commission did not give the permission and decided to undertake an investigation, which may take up to 18 months. Thus the Swedish Government decided to withdraw the law to create stability. If the Commission would not grant permission, the risk will be passed on to the fuel providers that retroactively may have to pay the compensation for state aid (Government of Sweden 2014a).

Policy instruments suggested in the FFF inquiry

The Government commissioned an *inquiry* in 2012 to *evaluate the possibilities to obtain a vehicle fleet independent of fossil fuels by 2030. This is seen as a first step towards the target of zero net GHG emissions by 2050* (Government of Sweden 2013a). In 2013 Thomas B Johansson et al. presented their thorough inquiry (hereafter called FFF after its Swedish abbreviation) in 2013, which treats the current situation and the policy instruments in place. The report also analyses the challenges ahead and proposes policy instruments to reach the goals. The report received much attention in media and by the research community. However, two years later the proposed measures have not been implemented.

FFF defines a vehicle fleet independent of fossil fuels as: 1) the vehicle fleet can technically function without fossil energy carriers and 2) fossil-free energy carriers are available in sufficient quantities. Furthermore, FFF states that high blend-in biofuels may also be considered as fossil free. The target is thus vague; a vehicle fleet independent of fossil fuels does not necessarily mean fossil free. However it is clear that the current share of fossil transport fuels – 88 % during 2013 – is far from “independent of fossil fuels”. FFF states that the total energy demand in the transport sector must decrease through both decreased transport demand and more energy efficient transport and that this should occur in combination with an increased share of biofuels and electricity that may decrease the GHG emissions and the fossil dependency.

FFF states that the CO_2 tax has been an efficient instrument, but that an increased CO_2 tax would not be sufficient to reach the targets by 2030 or 2050. Further on it states that policy instruments should be general, cost efficient, technology neutral, consider multiple benefits and costs (e.g. air pollution, noise, congestion, security of supply, and oil dependency) and also compatible with EU legislation (Government of Sweden 2014c). However general policy instruments may also be complemented with specific policy instruments for promising technologies during a limited period of time. This is because promising technologies, which are in the beginning of their learning curve, commonly cannot compete with technologies that already have reached commercial scale and the economy of scale that follows from this. [9] The inquiry proposes policy instruments affecting both the supply of renewable transport fuels and the transport demand.

Among the policy instrument proposed in FFF are a *mandatory biofuel quota* and *a price premium model*. The first policy instrument, in combination with CO_2 tax alleviations, affects the biofuels demand while the latter is directed at the technology development. It is proposed that the mandatory quota includes high blend-in fuels and that biofuel certificates for the transport sector are introduced. The certificates are suggested to function as a market mechanism where a fuel supplier with a high share of renewables, e.g. a vehicle gas supplier, would have a certificates surplus. A fuel supplier with a low share of renewables, e.g. gasoline with low blend-in of ethanol, would have a deficit of certificates. The certificates would be traded on a market and benefit the supplier with a high share of renewables[10].

The FFF also proposes that energy tax should be paid for all transportation fuels. However, a low quota for blend-in fuels in combination with energy tax on all bio-fuels may make the pure or high blend-in biofuels non-competitive. Two alternative paths are suggested to overcome this problem. The first alternative is to from the start set the quota so high that low blend-in is not sufficient to fulfill the requirements. The quota can then be increased gradually to obtain a fossil-free fleet in the long run. The other alternative is to modify the relation between CO_2 tax and energy tax so that the high blend-in fuels are competitive. Furthermore, it is proposed to base the quota on emission reductions instead of volume share. This would benefit energy from waste and second-generation biofuels over first-generation biofuels based on energy crops. FFF also proposes the introduction of energy tax on natural gas in connection to the mandatory quota (natural gas is currently exempted from energy tax when it is used as a transportation fuel, see Table 1). However a gradual introduction is proposed as the production capacity of biogas increases in order to maintain the competiveness of vehicle gas.

The *price premium model* is a complement to the mandatory quota to support new technology based on waste and residues. Food crops are explicitly excluded. In addition, FFF suggests that anaerobic digestion should not be supported with this instrument, although it is normally based on waste. However technologies such as gasification are mentioned and the plant Gobigas is specifically mentioned. The price premium model guarantees a premium to the producer during a twelve-year period. The size of the premium depends on which year operations started. If operations start in 2015 a premium of a certain size will be obtained for twelve years (until 2027). If operations start in 2016 a smaller premium will be obtained for twelve years (until 2028) and so

9 Learning curves can illustrate cost reductions of a technology as a function of accumulated experiences. Past cost reductions are extrapolated to future cumulative production levels to indicate a future production cost. The concept illustrates the advantages of policy support to emerging technologies until they become competitive with incumbent technologies (Wiesenthal et al. 2012).

10 Sweden has a similar system since 2003 to promote renewable electricity production: the tradable green certificate system (in Swedish: gröna elcertifikat). Producers obtain a certificate for each MWh produced. A market for these certificates is generated since the electricity supplier has a quota obligation. In the end it is the electricity consumer that pays for the support and the system is not considered as illegal state aid by the European Commission.

on. The higher premium for the first years may incentivize investors to start as soon as possible which is intended to create learning effects in the industry, which later investors may benefit from. The premium is adjusted according to the current diesel production cost and to the current CO_2 tax applied on diesel. This implies that the producer is liberated from risks related to the diesel cost (i.e. the oil price) and to changes in the CO_2 tax. Operations that are initiated in 2015 receive a premium of 12 SEK per liter diesel equivalence. If the diesel production cost is e.g. 5 SEK per liter and CO_2 tax is 4 SEK per liter diesel the producer will receive a premium of SEK (12 – 5 – 3) = SEK 4 / diesel liter equivalence. However, the producer only receives the premium when the fuel is sold on the market, which means that the producer must carry the market risk. This model is meant to distribute risks. The transport fuel distributors would share the cost for this support to new technologies. The model is thus not financed by the government, which according to FFF should mean that it should not be considered as illegal state aid by the European Commission.

FFF also proposes instruments to increase the demand for renewable transport fuels and the demand for vehicles adopted for these fuels. So-called feebates or bonus-malus are discussed to promote low emitting vehicles. The word feebate is a combination of fee and rebate thus providing a rebate for low emitting vehicles and a fee for high emitting vehicles. The idea is that the system is self-financed, balancing the fees and rebates. The Latin term bonus-malus for “good” and “bad” is used in the Swedish debate. The feebates would promote cars emitting a calculated maximum of 95 g CO_2/km by 2020. Feebates are directed at the purchase of vehicles and is thus of a “one time character”, just like environmental car premiums and the registration tax for new vehicles. These instruments can be combined with continuous instruments such as a differentiated vehicle tax that is applied every year. FFF states that the purchase price affects the consumer much more than the expected yearly cost during the vehicle´s lifetime. For this reason instruments directed at the purchase of vehicles are the most effective.

Biogas import

The biogas import to Sweden from Germany amounted to 2 % of the total use in 2012 (Swedish Energy Agency 2013a). The companies AGA, E.ON, and Modity imported biogas through the natural gas pipeline from Denmark. Companies that provide biogas produced in Sweden, e.g. Göteborg Energi and Kraftringen, perceives the import as a problem (Mattias Paijkull 2014). This is because the imported biogas may have received subsidies in both Germany and Sweden and because this would be a distortion of competition and possibly state aid in Germany, according to Göteborg Energi. Sweden incentivizes biogas use through exemption from energy and CO_2 tax. Germany provides support to some, but not to all, biogas producers through premiums and feed-in tariffs (Ganslandt & Beltramo 2013). Facilities that upgrade and inject all biogas to the grid do not receive subsidies in Germany, but facilities that generate electricity and also inject some biogas may receive a premium. The support is also conditioned to which substrate that is used. It is thus possible that some imported biogas has received support both in Germany and Sweden. The Swedish Energy Agency believes that the importing companies have misinterpreted the meaning of the sustainability law 2010:589 (Swedish Energy Agency 2013b). The agency states on their homepage “*Biogas for transport purposes must be traceable to be considered sustainable according to the sustainability law. This implies that biogas imported through the natural gas grid to Sweden cannot be considered as sustainable*” (ibid). SEA believes that tax exemption should not be granted for imported biogas since there is no intra-national register or control body to check in- and outflows of biogas. The Swedish Tax Agency has a contrary view to SEA; imported biogas should be exempted from tax in the same way as domestic biogas as long as the importer has purchased the corresponding amount elsewhere (Swedish Tax Agency 2014). In addition, SEA has tools to affect the biogas import; SEA may withdraw the sustainability certificates (Swedish: hållbarhetsbesked) without which the companies would not obtain tax exemption. The reason SEA has not used this tool may be because the company Modity has been certified through the EU certificate RED and thus is not dependent on SEA´s certification (Eleonor Grundfeldt 2015-03-18). This certification could also be a possibility for the importers AGA and E.ON.

It is unclear if the imported biogas obtains support in both Germany and Sweden, but it is likely that the import cost is lower than the domestic production cost (Personal communication with Eleonor Grundfeldt, Energigas Sverige, 2015-03-18). The regulations are currently unclear and Göteborg Energi and Kraftringen are waiting with investment decisions for their large-scale facilities for second-generation biomethane (Mattias Paijkull 2014).

4 COMPETING PATHWAYS: TRANSPORT FUELS FROM FOREST BIOMASS

A variety of transport fuels can be obtained from forest biomass and the feedstock potential is large in Sweden. The realistic conversion technologies are however not yet commercially mature and there is an uncertainty about which conversion technologies, fuels, infrastructure, and type of vehicle engine that are most feasible to realize. This review includes feedstock potential, conversion technologies and transport fuels, as well as identified synergies between bioenergy production and forest industry in Sweden.

4.1 LARGE FEEDSTOCK POTENTIAL FROM FOREST BIOMASS

Forest is the base for large industries branches in Sweden like pulp and paper (P&P), sawn wood products, and also solid fuels. The forest industry is the fifth largest export sector and represented 12 % of exports or 1.1 billion EUR during 2014 (Statistics Sweden 2015a; Statistics Sweden 2015b). However, the forest industries are currently under pressure. P&P is a global market and competition for forest biomass is also increasing. Sweden is a net exporter of P&P and a net importer of raw material for P&P. Approximately 35 million m^3 of wood are used per year in P&P and a similar amount is used in sawn wood products (Staffas et al. 2013). Forest biomass is a limited resource, but Sweden has currently a net growth and its use for different applications could thus increase (Staffas et al. 2013). In addition forest yield could increase with new practices and as an effect of climate change[11] (Government of Sweden 2007; Staffas et al. 2013).

New uses of forest biomass include liquid and gaseous transport fuels but also textiles, bioplastics, and other applications (Staffas et al. 2013). Woody biomass contains cellulose, hemicellulose, and lignin that can be made use of in transport fuel production. Staffas et al. (2013) have compiled 24 estimates of forest biomass potential. The total biomass energy potential by 2020 is estimated between 110 and 180 TWh. By 2030 the estimates are between 140 and 200 TWh. Black liquor (BL), which is a residue from chemical pulp mills, is estimated to between 45 and 50 TWh by 2020 and between 50 and 55 TWh by 2030. There is a large spread among the compiled estimates.

Transport fuels can be produced from a variety of woody biomass. The competition for biomass creates a high price for timber, and the most attractive parts for fuel production is, due to the current price and legislation, rather process residues from the forest industries and parts of the trees which are not used today. Residues from pulp mills include black liquor, tall oil, and methanol condensate (Staffas et al. 2013). Saw mills also generate residues like wood chips, bark, and saw dust, and harvesting residues, such as twigs, tops and stumps, can also be applied in fuel production. These less attractive parts of a tree constitute a large part of the total biomass. Tops and branches constitute between 10 and 35 % of the tree. Some of these residues, such as stumps, are sometimes left in the forest after the harvest. This means that a low cost can be assumed. However, if this biomass is removed from the forest, nutrients have to be added to the forest to avoid depletion. This may be achieved by recycling of ash. Different parts of the tree and wood of inferior quality can be converted to wood chips which can vary in size from 5 - 50 mm. Energy products like wood chips, briquettes, wood powder, or pellets are available as on established

11 Although climate change may cause increase forest yields it may also increase damage from insects, fungi, and storms.

markets. Other intermediate products for biofuel production can be torrefied biomass, pyrolysis oil, and lignin extract. Converting biomass into an intermediate product facilitates logistics since the energy carrier then will be more homogenous with a higher energy density.

BL is a large potential biomass source. It is generated at Kraft pulp mills when lignin and hemicellulose are extracted in the Kraft process. BL contains lignin and cooking chemicals that are fed to a recovery boiler (Tomlinson boiler) where process steam and green liquor containing the cooking chemicals is generated. The cooking chemicals are returned to the pulping process (digester) through further processing in a recovery process. The lignin can be used in energy applications and a medium sized pulp mill (300 000 tons of pulp per year) generates 1.7 TWh of BL per year (Staffas et al. 2013). Today the majority of BL is used in the recovery boiler for internal energy needs, although modern mills generate a surplus of thermal energy. If large quantities of BL would be used for fuel production it must be replaced with another biomass source. There is normally a surplus of bark at a mill, which partially could replace BL in the recovery boiler. Chemical pulp is used for production of more high value paper compared to mechanical pulp. Mechanical pulp is normally used for newspapers and similar products since it will bleach with time. The reason is that lignin and hemicellulose are not extracted from mechanical pulp. For the same reason there is no BL or much other biomass residues generated from mechanical pulp, which can be applied in fuel production (i.e. all the wood pulp is used to produce pulp). In addition a mechanical pulp mill has a higher electricity demand compared to a chemical pulp mill.

Tall oil derives from pine but also spruce. A modern pulp mill generate approximately 35 kg of tall oil per ton of pulp (Staffas et al. 2013). It is used for a number of products including energy products. 10 kg of methanol condensate is also generated per ton of pulp produced. This residue is used internally at the mills today but could also be used as a biofuel.

4.2 CONVERSION TECHNOLOGIES AND FUELS

A variety of transport fuels can be produced from forest biomass. The conversion technologies are not yet commercially mature, in spite of large research and development efforts. Figure 3 shows pathways for different feedstock, conversion technology and transport fuels (Grönkvist et al. 2010; Zhang 2010; Bojler Görling et al. 2013)

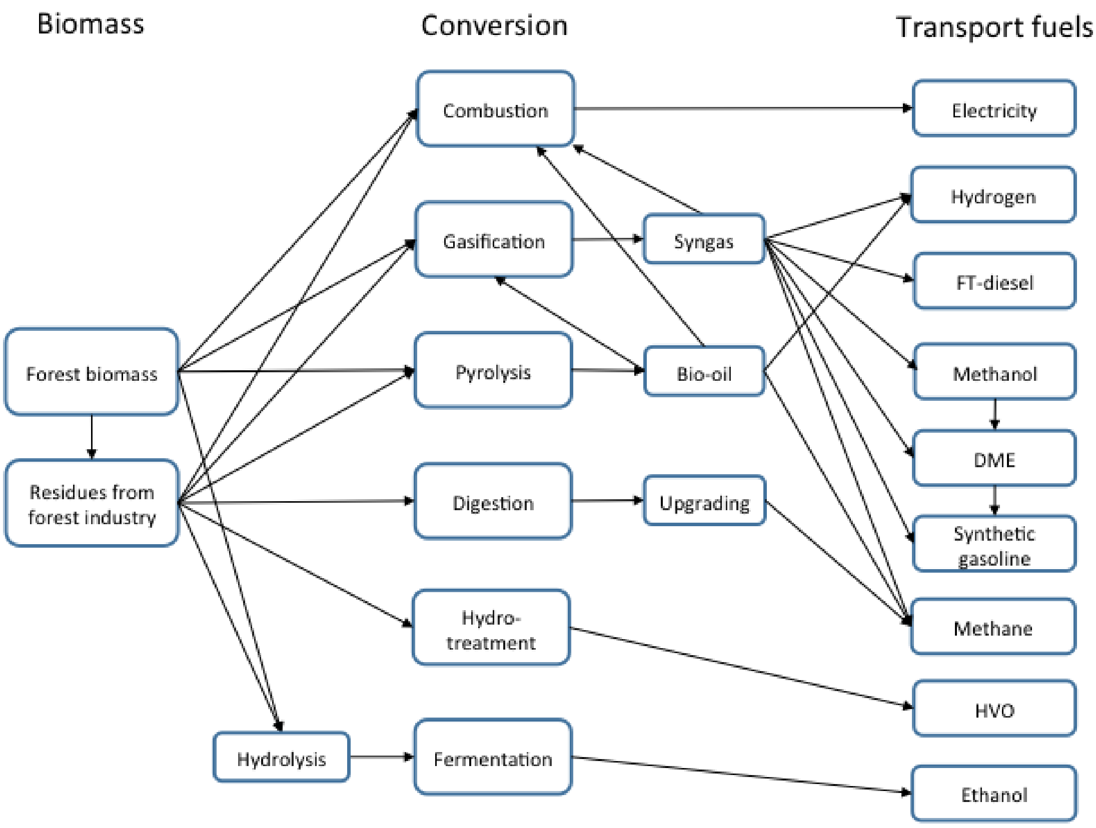

Figure 3: Pathways for different feedstock, conversion technology and transport fuels

Figure 3 includes raw forest biomass and also residues from forest industries. Five types of conversion technologies are illustrated: combustion, gasification, pyrolysis, digestion, and fermentation.

Combustion

Heat and power can be obtained from forest biomass through combustion. Combined heat and power facilities are often connected to the district heating grid and can receive different types of biomass, including municipal solid waste. Heat is excluded from Figure 3 since the figure only includes transport fuels. For this reason, it is most interesting to use cheap biomass in combustion. This biomass could be residues from forest such as stumps, barks, twigs and tops, although densified wood fuel also is used.

Gasification

Syngas can be produced from forest-derived biomass through gasification. The gas mainly contains H_2 and CO but also CH_4, CO_2 and H_2O. Syngas can be used to produce a variety of transport fuels such as hydrogen, methane, methanol, dimethyl ether (DME), and, Fischer-Tropsch (FT) diesel. Relatively dry biomass (10-15 % water content) must be used in the gasification process (Grönkvist et al. 2010). When liquid fuels are produced from syngas the whole process is called biomass to liquid (BTL). Gasification can be combined with processes that require heat, e.g. district heating, pellets production, or biorefineries, increasing the overall efficiency.

DME can be produced from syngas through a process involving a catalyst. One promising pathway is to convert the syngas from black liquor gasification (BLG). This pathway has almost reached commercial maturity. DME has a high energy density, may achieve large GHG emission reductions, and is thus seen as an attractive transport fuel (Joelsson & Gustavsson 2012). The fuel has a boiling point of -25 °C and can be liquefied at 6.1 bar. It is tried out in pilot scale for heavy duty transport in Sweden by Volvo and LTU Green Fuels (initiated by Chemrec and based on technology developed by Chemrec) (Chemrec 2014; Zhang 2010). Chemrec (2014) is also developing a concept in which bio-oil from pyrolysis is co-gasified with BL which widens the resource base.

FT-diesel can be obtained from syngas. This process involves several different conversion steps performed at different temperatures and using different catalysts. One advantage of this synthetic diesel is that it is free from N and S. In addition valuable by-products, chemicals of different forms, may be obtained through the processes (Dry 2004). FT-diesel may also be obtained from natural gas or gasified coal. The latter process was used by Germany during the Second World War and has been – and is still– used in South Africa (Zhang 2010). However the most expensive part of the process is to clean the syngas and conversion of biomass to FT diesel is currently more expensive than coal-based FT-diesel.

Hydrogen (H_2) can be obtained from syngas through water gas shift (WGS) reaction. The main components of syngas are H_2 and CO. Through the WGS H_2O and CO react and form H_2 and CO_2 and this reaction is also used to balance the H2 to CO composition for other products that may be produced from a syngas. The H_2 content of the syngas is increased and the CO2 is subsequently removed. The process requires certain temperatures and it also involves a catalyst (Graciani & Sanz 2015). H_2 can be used as transport fuel in fuel cells or directly in combustion engines.

Methane can be obtained from syngas through a methanation process in which the methane (CH_4) content is increased through a reaction where H_2 from the syngas react with CO and CO_2, forming CH_4 and H_20.The methane produced from a syngas is commonly referred to as synthetic natural gas (SNG)[12] of bio-SNG. Before the methanation process, a WGS reaction can be pursued to increase the level of H_2 and CO_2, thus permitting a higher formation of CH_4 during the methanation. After methanation, CO_2 can be removed at one or two stages to further increase the concentration of CH_4 (Duret et al. 2005; Molino & Braccio 2015). The facility Gobigas in Gothenburg is based on gasification technology and has an installed capacity of 20 MW and may generate 160 GWh biogas for transport purposes per year (Gothenburg City 2012).

Methanol can be produced from syngas through a process including a catalyst. The process has high conversion efficiency but the energy density of the fuel is relatively low. Methanol can be blended with gasoline or used to produce DME or synthetic gasoline through a process including zeolite catalysts (Zhang 2010). Methanol is thus an intermediary step for DME.

12 Synthetic Natural Gas (SNG) from biomass is sometimes denominated Bio Natural Gas (BNG) or Bio Synthetic Natural Gas (Bio SNG) to emphasize that it is renewable.

Pyrolysis

Pyrolysis of woody biomass generates three products: charcoal, bio-oil, and syngas. Approximately 10 % if the lower heating value (LHV) is used for the heating demand of the pyrolysis process. Pyrolysis is usually categorized in three different types of processes that favor different compositions of the three products: slow, intermediate and fast pyrolysis. Slow pyrolysis is performed at a temperature of approximately 400 °C and favors a high yield of charcoal. Fast pyrolysis or flash pyrolysis is performed at a temperature of approximately 500 °C and favors a high yield of bio-oil. Bio-oil ages rapidly and must be used within a short period of time. However, there may be methods to alleviate this problem and make it last longer, e.g. by mixing it with methanol. However bio-oil has higher energy density than the original biomass which facilitates logistics for production of other biofuels (Bojler Görling et al. 2013). It can thus be seen as an intermediary product. If bio-oil is gasified a syngas is obtained which can be used in Fischer-Tropsch, methanol synthesis, or other processes (Ng & Sadhukhan 2011a; Ng & Sadhukhan 2011b). The entire fraction of bio-oil can also be mixed with methanol and then upgraded to H_2 via steam reforming (Heracleous 2011). The reformation step is not represented in Figure 3 to simplify the schematic representation. Görling et al. (2013) have investigated another pathway based on slow pyrolysis. This pathway makes use of both the bio-oil and the syngas from pyrolysis to produce methane. By-products from that process are heat and charcoal.

Digestion

Biogas can be obtained through anaerobic digestion of residues from forest industry. The raw biogas obtained contains CH_4, CO_2, and other components. It can be upgraded to a high CH_4 content. Anaerobic digestion is performed in an oxygen free environment. The process involves different bacteria depending on the process temperature. The two main types are thermophilic digestion and mesophilic digestion. In the forest industry, it is mainly the digestion of sludge from pulp mills that is of interest. The biogas potential from sludge deriving from pulp and paper industry is estimated to between 700 and 1000 GWh in Sweden (Jansson et al. 2013).

Hydrotreatment

Hydrogenated Vegetable Oils (HVO) can be produced from vegetable oils and fat through *hydrotreatment* (also called hydrogenation). Possible feedstock for HVO production is tall oil, slaughterhouse residues, rapeseed, soy, or palm oil (f3 2015). Tall oil is a residue from P&P industry which is processed to tall diesel before hydrotreatment (Grahn & Hansson 2014). Hydrotreatment reduces the oxygen content of tall diesel through use of H_2. After this an isomerization processes can be done to improve the fuels´ performance in cold conditions (Swedish Energy Agency 2014e). In this process the straight hydrocarbon chain is transformed to a branched chain. HVO is a drop-in fuel meaning that it can be used in a high blend without adjusting infrastructure or vehicles. HVO has grown quickly since its introduction in Sweden 2011 and represented a 33 % share of renewable transport fuels during 2013 (Swedish Energy Agency 2014e).

Hydrolysis and fermentation

Ethanol can be produced from woody biomass through hydrolysis and fermentation. There are two types of hydrolysis: enzymatic and weak acid. The *enzymatic hydrolysis* process uses enzymes to catalyze cellulose and lignocellulose into sucrose (saccharification). The sucrose can then be fermented to obtain ethanol (Hahn-Hägerdal et al. 2006). Saccharification and fermentation can be performed in two steps or in one combined step. Research on enzymatic hydrolysis is performed in USA, Canada, and Sweden (Grönkvist et al. 2010; Zhang 2010). *Weak acid hydrolysis* and fermentation can also be used to obtain ethanol from woody biomass. In this process lignin is obtained as a byproduct. Ethanol from hydrolysis is also called second-generation ethanol to distinguish it from first-generation ethanol, which generally is based on an edible feedstock and only includes the fermentation step. There are no large scale facilities in Sweden but a few pilot scale facilities for second generation ethanol exist (Staffas et al. 2013). US Government have supported large-scale plants with investment subsidies (Grönkvist et al. 2013; Stephen et al. 2014). If ethanol production is combined with a process that requires heat, e.g. district heating or pellets production, the overall efficiency can increase. Combined systems can have a total efficiency of 50-90 % while the ethanol production alone has a conversion efficiency of 35-45 % (Staffas et al. 2013).

Other processes

Lignin can be separated from black liquor by precipitation achieved with carbon dioxide. The process is commercially known under the name LignoBoost and it may have several advantages depending on the industrial context. Firstly, the capacity of the recovery boiler at the Kraft pulp mill is increased since less material is entering. Secondly, the separated lignin may be used for energy purposes. It could either be combusted in internal processes or used as a feedstock for biorefineries.

Biorefineries is an umbrella term for processes that convert biomass into a variety of products. The International Energy Agency (de Jong et al. 2009) defines a biorefinery as: *"the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)."* Biorefineries will enable an efficient use of biomass resources and the concept could be used by the traditional forest industry to diversify its product mix. However, several of the proposed biorefineries are at a level of development and are not yet commercially mature (de Jong et al. 2009). The term is so widely defined that it may encompass a vast variety of biomass conversion possibilities. One such possibility is to use lignin as a feedstock for transportation fuels. The primary oil refinery company of Sweden, Preem, has also investigated the possibilities of separating lignin from BL and using the lignin as a feedstock in the refineries (Government of Sweden 2014c).

4.3 INDUSTRIAL SYNERGIES AND DYNAMICS

Although more abundant than cultivated biomass, forest biomass is a limited resource with many applications. An increasing competition implies that the biomass ought to be used efficiently. The energy density of forest biomass is relatively low; large volumes are needed for fuel production and large facilities must be used in order to obtain economy of scale (Wetterlund et al. 2013). These constraints imply logistical challenges. As a result, fuel production from forest biomass must be planned in synergy with incumbent forest industry to make use of its residue flows and its established supply chains.

An increased competition for forest biomass may lead to increased costs for forest industries (ceteris paribus). However, the existing forest industries can also adapt to a new situation and become bioenergy producers. Forest industry may produce multiple products and thus become a biorefinery, to a larger extent than today. Adding value to the residue flows may support the Nordic forest industry in the increased international competition.

Integration with a heat sink can increase efficiency in fuels production, since virtually all biofuel processes generate a surplus of heat. Appropriate heat sinks may be district heating, production of other fuels e.g. pellets, or internal energy needs in the industry where the residue was originally generated. Available heat sinks limit the availability of appropriate locations for biofuel production. Wetterlund et al. (2013) have investigated the integration of production of DME from BLG and ethanol from enzymatic hydrolysis with the forest industry and appropriate heat sinks. Investigated heat sinks were P&P mills, sawmills, and district heating systems. Pulp mills have a thermal surplus (at low temperatures) while paper and integrated P&P mills have a thermal deficit. Chemical pulp and paper mills were found to be the most appropriate heat sink according to their model and district heating was found to be the least appropriate heat sink. This result is not only due to low heat prices, but also for logistical reasons; the modeling results favored locations in northern Sweden for logistical reasons since this is where most of the forest biomass and most possibilities for integration are located. The authors also stress the importance of intermediate products with an increased energy density to facilitate logistics. These can be torrefied biomass, pyrolysis oil, and lignin extract from chemical P&P mills.

There is an uncertainty about which pathway to take among potential biofuel producers. As has been shown in Figure 1, there is a variety of pathways resulting in different transport fuels. According to Börjesson et al. (2013) methanol and BNG are the options with the lowest costs among transport fuels from forest biomass. Cellulosic ethanol is much discussed as it may provide larger volumes than first-generation ethanol (from crops). Cellulosic biofuels (in practice ethanol from enzymatic hydrolysis) are also incentivized by policy instruments in USA who set targets expressed a certain minimum volume. However these volume have not been reached, partly because the technology is not yet commercially mature (Grönkvist et al. 2013).

DME from BLG is much discussed and actors such as Volvo and Chemrec pursue this pathway. The vehicle manufacturer Volvo and the energy conversion technology provider Chemrec have performed field tests including heavy duty vehicles (Chemrec 2014). Although DME have been a favored option in these tests, BLG can also be used to provide many different transportation fuels, as illustrated in Figure 3. Chemrec sold their test facility to LTU Green fuels in 2013 that continues the research efforts. The only conversion process used for BL is currently the recovery boilers (Tomlinson boilers) where the BL is combusted and the steam is used for electricity production and thermal energy needs in P&P industry. If BLG would be applied and much of the energy would leave the plant as a biofuel, the internal thermal energy needs would have to be covered with other fuels. The use of additional biomass should be considered when evaluating the economic and environmental performance of the fuel production. BL can be replaced with harvest residues, e.g. bark, stumps, roots and tops. Some bark will naturally be available at the P&P mills, and this fuel is commonly utilized in in other boilers at the mills. Existing supply chains could in most cases be used for the additional forest biomass. The biomass replacing BL is of low value and there is hence an interesting business opportunity to pursue. Those P&P industries that choose to become biorefineries with a more diversified product mix may have better possibilities to deal with the increased competition for biomass.

4.4 COMPETING PATHWAYS? FROM ENERGY CROPS TO METHANE

Crop cultivations dedicated for energy generation are called energy crops. There are different pathways from energy crops to methane. Energy crops such as sugar beets or ley crops may be cultivated and applied in anaerobic digestion to produce methane. Other energy crops, such as salix, are not suitable for anaerobic digestion but can be applied in gasification or pyrolysis to obtain methane, as described in section 4.2. Thus, gasification and pyrolysis may be alternatives to anaerobic digestion. This means that there are different pathways from arable land to methane. These alternative pathways may compete for resources, i.e. arable and fallow land. This means that two different pathways may compete for land resources for methane production. Currently there is no competition between gasification and anaerobic digestion for land resources in Sweden. This is because only small volumes of energy crops are used in anaerobic digestion and because the little production based on gasification that exists is based on forest residues.

Globally, energy crops are sometimes discussed as a “food vs. energy” issue. This debate is less common in Sweden because the area of arable land has been decreasing during recent decades due to declining agricultural activity. Energy crops cultivation for biogas is still a marginal phenomenon; according to SEA, 29 700 tons of energy crops were digested during 2013 (Swedish Energy Agency 2014c). This can be compared with 307 000 tons of food waste or 5 900 000 tons of sewage sludge that were digested during the same year. Currently, biogas production through anaerobic digestion of residues and waste dominate and it is possible to increase the production based on residues (Lönnqvist et al. 2013).

Salix is currently not used for methane production. It is mostly cultivated for heat and power generation (European Willow Breeding 2015). Furthermore the plants for production of transport fuels from forest biomass that we have surveyed (see chapter 6), are mostly planning to use forest residues since this is a more economic alternative compared to energy crop cultivations.

The methane yield per hectare and year for different pathways can be compared. Biogas crops – e.g. a mix of sugar beets, corn, grain and grass – may render 27 MWh/ha/year (Linné & Jönsson 2005). However, crops like sugar beets may render as much as 50 MWh/ha/year (ibid). Linné & Jönsson (2005) present an analysis based on 14.6 ton dry substance (DS) per hectare and year from sugar beets. They further assume a methane yield of 340 Nm^3 CH_4 /ton DS (ibid) resulting in 50 MWh/ha/year. However, sugar beets cannot be cultivated in the entire country for climate reasons and other crops with lower yield may therefore be more interesting to use in other areas. The authors present a yield of 36 MWh/ha for corn, 23 MWh/ha/year for lay crops and 20 MWh/ha/year for cereals (ibid). Furthermore the authors make assumptions of what share of arable that could be used for different types of crop cultivations: 10 % sugar beets, 20 % corn, 40 % lay crops, and 30 % cereals (ibid).[13] This assumption results in an average yield of 27 MWh/ha/year.

Görling et al. (2013) have shown that cultivation of salix and production of methane by pyrolysis may produce 25 MWh/ha/year of methane and 6,5 MWh/ha/year of char coal (Bojler Görling et al.

13 Linné & Jönsson (2005) have further assumed that 10 % of arable and fallow land in Sweden could be used in energy crops cultivation. The mix of crops they present reflects that some crops can not be cultivated in the whole country.

2013). A comparison of the methane yield per hectare and year between pyrolysis of salix and anaerobic digestion of a mix of crops will in this case indicate a slight advantage for anaerobic digestion. Comparing digestion of sugar beets with pyrolysis of salix gives a clear advantage for digestion. One underlying factor that explain much of the difference is that the cultivation of sugar beets give a much higher yield of dry substance per hectare and year compared to cultivation of salix; 14.6 ton DS/ha/year compared to 7 DS/ha/year. However, these comparisons do not consider how much input energy is needed to produce the crops, run the conversion process etc. It is likely that cultivation of biogas crops requires more energy than cultivation of salix per hectare and year, since the former is harvested every year, as opposed to salix, which is harvested every four years. Furthermore, as pointed out by Linné & Jönsson (2005), the most attractive biogas crops cannot be cultivated in the whole country.

However, the biomass yield from salix may be even higher than what Görling et al. (2013) have assumed (7 ton DS/ha/year). According to the Swedish Board of Agriculture (2013) higher yields can be achieved, up 9 ton DS/ha/year. However, the first harvest from salix cultivations is lower than the subsequent harvests, 7 ton DS/ha/year (Swedish Board of Agriculture 2013).

In summary, there is currently no competition between these pathways for arable land to produce methane. Production through anaerobic digestion may increase based on residues and waste, which are cheaper feedstock than energy crops. Similarly, our survey of plants using forest biomass to produce transport fuels in section 5 indicates that production is planned based on forest residues and not on cultivated woody biomass such as salix. However, should such competition come about, it appears that cultivation of biogas crops render more methane per hectare compared to pyrolysis. This is because cultivation of these crops produces more DS per hectare compared to salix. Pyrolysis and gasification are currently less commercially mature conversion technologies compared to anaerobic digestion.

5 FACTS ABOUT SURVEYED PLANTS

This mapping of forest biomass to transport fuels includes 12 plants and projects, which are described in detail in Table 2. All of the selected plants and projects utilize thermal conversion of biomass and this means that they are relevant to study as possible conversion steps for forest biomass to methane. Four of these plants are currently in operation. Five projects are in planning phase or on hold. Two projects have been canceled and one plant has stopped operations. The feedstock varies from different types of residues – twigs, tops, stumps, black liquor and bark – to more high value forest biomass – round wood and wood chips.

The conversion technologies varies; mostly different types of gasification technologies: indirect gasification (IG), entrained flow biomass gasification (EFBG), circulating fluidized bed gasification (CFBG), air-fed circulating fluidized bed gasification (air-fed CFBG), pressurized entrained flow biomass gasification (PEFBG), and atmospheric circulating fluidized bed gasification (ACFBG) are employed. One of the cancelled projects planned to utilize pyrolysis. This plant is included in the survey, in spite on not being a gasification technology, since its output, pyrolysis oil, is an important input for other gasification plants included in the survey. Pyrolysis has also been proposed for methane production without gasification (Bojler Görling et al. 2013; Larsson et al. 2013).

The project locations are rather spread across the country. Several projects are located in northern Sweden, where the majority of the forest biomass is located. However projects also exist in the south and Skåne, Västergötland, Värmland, Östergötland, Närke, Västmanland and Småland are represented. These counties also have access to forest biomass. However the plant Bio2G is planned in Skåne, an area in the very south of Sweden, which does not have large forest resources. This plant, however, will depend on boat shipments of biomass.

The plants are planned in relation to available infrastructure for feedstock supply and for distribution of produced feedstock. Those plants that plan to produce methane are located nearby the natural gas pipeline. Some plants can use a district heating grid to distribute surplus heat, but not all of them. Well-developed roads, harbors, and railways have also been determining factors.

Three of the projects aim at producing methane, while the other ten aim at producing other transport fuels, e.g. DME or methanol. One plant, Biorefinery Norrtorp, has evaluated the option of combining methane and methanol production. Heat is normally obtained as a by-product and some of the projects plan to distribute it as district heating while others plan to use it internally to dry the incoming biomass. Different fuels, conversion technologies, and types of feedstock will in many cases represent competing pathways. This report focuses on methane from forest biomass for use in the transport sector. The first three projects in Table 2 represent this pathway

Table 2: List of Gasification plants in Sweden

Plant; Owner; Location	Tech	Input	Output	Capacity (MW)	Production (GWh_{pa} fuel)	Infra	Comment	Ref
1 Gobigas Phase 1; Göteborg Energi; Gothenburg (Phase 2 in parenthesis)	IG	Solid biomass *	Methane, heat **	20 (80 – 100)	180 (1000)	Gas, DH & electricity grid	Phase 1: Demonstration plant operating since 2013. Co-financed by SEA Phase 2: Commercial plant. Implementation depends on phase 1. NER 300 approved.	A,B, C
2 Bio2G; E.ON; Malmö or Landskrona	IG	Chips mainly from forest residues	Methane	200	1500 - 1600	Gas & DH grid	Ready 4 years from decision. Pending due to uncertainty of policy support. Approved NER 300: SEK 1.9 billion.	A,B, D
3 Biorefinery Norrtorp; Sakab et al; Kumla	G	Forrest residues & round wood	Methanol, methane & heat	250	1300 methanol & 480 methane		Currently on hold. Earliest 2023. Many actors involved. Choice between methanol, methane, or both.	A
4 Värmlandsmetanol AB; Hagfors	CFBG	Wood chips	Methanol, heat	110	600***	DH grid	Searching for funding	A,B, E
5 LTU Green fuels; LTU (2013-) Chemrec (-2013); Piteå	EFBG	BL & pyrolysis oil	DME	3	6	10 trucks, 4 refilling stations	Operating since 2010. Cooperation with Volvo and Preem	A,B
6 Chemrec/Domsjö; Domsjö Fabriker; Örnsköldsvik	EFBG	BL	DME or methanol	200	960		Project discontinued due to lack of long-term policy decisions (A).	A,B
7 Vallvik Biofuel; Rottneros AB; Söderhamn	G	BL	Methanol	200	750		Ready 4-5 years from decision. Cooperation with Chemrec.	A,B
8 Rottneros biorefinery; Rottneros AB; Värmland	G	Lignocellulosic biomass	Methanol	200	750		Cooperation with Tyréns and 2genAB. Needs financing and "conducive long term political decisions" for investment.	A,B

Plant; Owner; Location	**Tech**	**Input**	**Output**	**Capacity (MW)**	**Production (GWh_{pa} fuel)**	**Infra.**	**Comment**	**Ref**
9 Pyrogrot; Billerud Korsnäs AB; Skärblacka Bruk in Östergötland	P	Twigs, tops, & stumps	Pyrolysis oil		750		Approved NER 300. Later canceled because not considered as commercially feasible at present conditions	A,B F
10 Växjö Värnamo Biomass Gasification Center; Linnaues University	Air-fed CFBG	Wood chips	Originally electricity	18		Electricity grid	Commissioned 1996. Not in use. Granted financing from SEA for reconstruction but industry co-financing failed.	A,B
11 Pilot; SP (formerly ETC); Piteå	PEFBG (IVAB)	Forrest residues, torrefied biomass, pyrolysis oil	DME/ methanol	1			Try-outs started in 2013	B
12 Värö bruk; Södra; Värö south of Gothenburg	ACFBG	Bark****	Syngas	28	Internal use in lime kiln		Operating since 1987	B,F

* Pellets in phase 1, chips, twigs & tops in phase 2 ** Also electricity in phase 2 *** Ap. 100 000 ton methanol. 60% of energy in methanol and 40% in heat
**** The demand on feedstock is less demanding, since it is an air-blown gasification used for internal purposes and not transport fuel production
A (Grahn & Hansson 2014); B (Börjesson et al. 2013); C (Swedish Energy Agency 2014b); D (E.ON 2015); E (Gillberg 2008); F (Held 2011)

6 RESULTS FROM SURVEYS AND INTERVIEWS

Surveys and interviews with the actors mentioned in Table 2 were conducted in cooperation with the project "Examining systemic constraints and drivers for production of forest-derived transport biofuels"[14]. Interviews with actors representing the three projects in Table 2 that produce or aim at producing methane from forest biomass are specified in Table 3.

Table 3: Interviews with methane producers

Plant	Interviewee	Interviewer	Date, place
Gobigas	Lars Holmquist (LH), business strategic planner, and Ingemar Gunnarsson (IG), development engineer. Technical background information was obtained from Malin Hedenskog (MH), project manager.	Tomas Lönnqvist, KTH	2015-10-06, Gothenburg
Bio2G	Björn Fredriksson Möller (BFM), project leader biogas	Philip Peck and Yuliya Voytenko, Lund University	2015-09-29, Malmö
Biorefinery Norrtorp	Göran Eriksson (GE), former president of Sakab	Tomas Lönnqvist, KTH	2015-09-22, via telephone

The main findings from the individual interviews are presented below. This is followed by an analysis of common themes in the interviews in section 7, *discussion & concluding remarks*.

6.1 GOBIGAS

Gobigas phase 1 is a 20 MW methane output gasification plant in Gothenburg producing methane and heat. Methane is injected to the natural gas grid and heat is distributed through the district heating grid. The demonstration plant is currently in a commissioning phase. Pellets are currently used as feedstock, but the company plans to switch to chopped wood of lower quality. The plan is to eventually use branches and tops (In Swedish: grenar och toppar, GROT). This is because it is easier to commission the plant on pellets but also because a terminal to receive pellets already existed on the site. The plant will need 32 MW biomass (LHV). A pilot plant preceded the demonstration plant. The demonstration plant is meant to show that the technology works and pave the way for Gobigas phase 2, a full-scale commercial plant of 100 MW methane output. The methane efficiency is 65 % (LHV) and the total efficiency is over 90 % due to the district heating deliveries. Phase 1 is planned to deliver 160 GWh_{pa} (8000 h of operation pa) and phase 2 is planned for 800 GWhpa. According to the interviewees the determining factors for the realization of phase 2 are: a sufficient performance of the operations, a market for the product, the presence of beneficial policy instruments, and an adequate financing. According to the interviewees, the last factor should not be problematic if the previous factors are in place. Sensitivity to economies of scale is clear when comparing phase 1 and 2. Phase 2 is planned with five times the capacity (100 MW compared to 20 MW), but the investment is roughly estimated to be only twice as high (3 billion SEK compared to 1.5 billion SEK). Effects of learning-by-doing can also be seen; the

14 The project "Examining systemic constraints and drivers for production of forest-derived transport biofuels" is also financed by f3 The Swedish Knowledge Centre for Renewable Transportation Fuels. The project is coordinated by Lund University in cooperation with IVL and KTH.

interviewees state that they could build a plant of the same size as phase 1 today for 2/3 of the cost. Phase 1 became 350 MSEK more expensive than the original budget and the interviewees state that "you take a risk when you build something no one has built before".

One determining factor for the realization of phase 1 was an R&D support of SEK 222 million from SEA in 2009 (15 % of the total investment). The final decision was taken in 2010 when the European Commission approved the support (legal state aid). Since the decision was taken, the conditions for profitability of Gobigas have changed. The oil price has dropped dramatically[15] and policy support has not developed as expected. GE states that they did not base their investment decision on any specific policy instrument, however they did count on rather stabile, or even increasing, oil prices.

LH and IG believe that a production support is more suited than an investment support to promote production of transport fuels from forest biomass in Sweden. This is because a production support reduces the risk for the producer and also because it "creates a market" by sending the right signals. LH and IG highlights that the price premium model suggested by Thomas Kåberger in FFF is a well designed production support (Government of Sweden 2013a). The price-premium-model distributes the risks well, according to LH and IG. The model liberates the producer from the oil price risk and also the effects from changes in the CO_2 tax. This is obtained by guaranteeing a premium to the producer. The premium is based on a reference price (for 2015: 12 SEK / liter diesel equivalence). The production cost of diesel and CO_2 tax applied on diesel is later deducted from the premium. However the premium is only paid if the fuel is sold on the market and the producer thus has to assume the market risk[16]. LH and IG believe that the model would fit the current situation well, considering the oil price drop and changes in taxation for biofuels. The quota obligation, on the other hand, is believed to mainly favor low blend-in and thus not be very appropriate for producers of pure biofuels like Göteborg Energi. The current exception from energy and CO_2 tax are mentioned as important for the profitability of renewable methane in general and for Gobigas in particular. The interviewees underline that these tax exemptions are only guaranteed for a few more months. They further stress that an investor doesn't make decisions under such uncertainties. They perceive the German and French support systems as stabile and predictable. However, in these countries, policy instruments for biogas are directed at electricity generation and thus the industry has opted for this end-product. The most profitable use for methane in Sweden is in the transport sector due to policy instruments, according to the interviewees. One disadvantage with the French and German systems is that they are too detailed and that they support small and unprofitable production "they cover costs instead of promoting profitable production". However, their feed-in tariff system is perceived as an efficient support system and a feed-in tariff inspired by these countries may also work in Sweden, according to the interviewees. Other important Swedish instruments are the support to the end-user, e.g. reduced fringe benefit tax for the cars that the government defines as environmental cars of which biogas cars are one category. The interviewees

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15 The WTI (Western Texas Intermediate) oil price was approximately 90 USD/barrel by the end of 2010 compared to the current price of 48 USD/barrel. The price peaked at 155 USD/barrel in 2011 according to www.nasdaq.com.

16 See section 3.2.2 for a more detailed description.

perceive that these instruments reach companies and other segments, which may afford the more expensive vehicles that use renewable fuels. Although these instruments, supporting the end-user, have been substantial they have also been unpredictable. LH states that taxes are more predictable than support systems such as the environmental car premiums.

The interviewees express a careful optimism that Sweden might become the leader in biomass gasification. Gasification of forest biomass can be used to produce a multitude of fuels. Göteborg Energi opted for methane since it fits well with their core activity. The company has dealt with gas since the mid 19th century and it currently owns upgrading capacity for biogas. They previously owned 50 % of the vehicle gas distribution company Fordonsgas Sverige. They perceive that forest biomass is more accessible today compared to when the project started.

Göteborg Energi co-operates with Chalmers University of Technology who operates the pilot plant. They also co-operate with Fordonsgas Sverige that is an important vehicle gas distributor. Pellets are received from the combined kraft pulp mill and sawmill Värö bruk. However there is no co-operation with the vehicle producers in the region. LH comments that the co-operations related to Gobigas are a true example of triple helix[17].

The primary reasons for the location of the plant, in central Gothenburg, was the access to: railways, a good harbor, a natural gas pipeline, the demand for methane, available land owned by the company, the valid environmental permits in connection to the site, an existing terminal to receive pellets, as well as the demand for heat and distribution possibilities through the district heating grid.

6.2 BIO2G

E.ON has rather advanced plans on a large-scale gasification plant in Southern Sweden. E.ON was involved in the Gobigas project at an early stage but left it as they decided to continue with their own plant, Bio2G. Bio2G is planned to have twice the capacity of Gobigas phase 2: 200 MW. The investment is estimated to be between SEK 4 and 5 billion. A comparison of the estimated investment and planned capacity between Bio2G and Gobigas Phase 2 demonstrates sensitivity to economies of scale; the capacity is twice as large, but the investment is only 33 % to 66 % larger. E.ON would take approximately half of the investment themself. At least one billion SEK (20 % - 25 % of the total investment) is needed in governmental support according to the interviewee (BFM). E.ON has also been approved for NER 300 funding of 1.9 billion SEK, which would be obtained during the first five years of operations. E.ON has also discussed the possibility of co-financing with external actors, including local heat producers, gas distributors, forest owners, different segments of the forest industry, and technology suppliers with an interest in a reference plant.

The primary motive for the plant is the increasing demand for renewable fuels. Since biogas for anaerobic digestion will be not enough to cover the demand, BFM pointed out the methane from gasification may be an alternative. E.ON currently manages 500 GWh vehicle gas or 1/3 of the

17 The concept of triple helix is used to characterize co-operation between industry, government, and academia.

Swedish market. If the taxation continues as present there will be a demand for an additional 1.5 TWh biogas by 2025 and then Bio2G "would be needed".

Several locations have been evaluated and the main alternatives are currently Landskrona and Malmö. Both alternatives receive local political support, and have land available. However the demand for district heating is already satisfied in both these locations. Another important factor is the infrastructure for biomass supply and in particular the possibilities to store large boat shipments of biomass in a safe way.

The investment in Bio2G is delayed by the market risk; E.ON does not know if there will be a market for biogas in the future transport sector. Hence, there is a need to create new market segments and to increase some market segments. Heavy transport may be a new segment. The gas consumption by taxi, company cars, business cars, and private cars may also grow to diversify the demand side. There has also been some discussion between E.ON and local industrial companies regarding sales of biogas. Different vehicles may use gas in different ways, according to BFM. Business cars (transport cars of smaller size, e.g. VW Caddy) may be hybrids with gas and electricity. Small cars may run exclusively on gas. Trucks may also run on gas for short distances (within cities), but liquefied biogas (LBG) that has much higher energy density may be more appropriate for longer distances. BFM perceives that electrical cars currently are hyped in media and there is a trend to change to electrical busses. He also says that there is a myth that biogas busses are expensive, which is not true according to BFM. He underlines that we need both biofuels and electricity.

BFM points out that there is an uncertainty about the policy instruments and that E.ON does not know what the rules will be like by 2020 when the plant could be in operation if they took an investment decision today. BFM discusses existing policy instruments and mentions reduced fringe benefit taxation, which has now been prolonged to 2019. He also discusses benefits for environmental cars. BFM underlines that there are many uncertainties with the current policy instruments and how long they will last.

He suggests a permanent tax exemption combined with a quota obligation to increase the share of renewables in the Swedish transport sector. A quota should start at 15 % or 20 % according to BFM. He also discusses the compatibility between the EU and Swedish policy and that there is no CO2 tax in other EU countries. Biofuels in countries, which currently lack a CO_2 tax, may instead be exempted from energy tax to promote their development. BFM states that E.ON has uncertainty about which platform to opt for, different pathways have different advantages and disadvantages, and the stability of policy instruments are unclear.

6.3 BIOREFINERY NORRTORP

The idea behind Biorefinery Norrtorp was to produce methanol and/or methane from forest residues and round wood. Heat would also be obtained as a by-product. A feasibility study was performed and it considers production of methanol, liquefied methane, or a combination of both, without giving a clear recommendation. The interviewee, GE, states that the group slightly favored methanol production. The plans concern a large-scale plant – up to 1.8 TWh_{pa} of transport biofuels. There are many actors involved in the project including Sakab, E.ON, Kumla Municipality, Värmlandsmetanol, Structur, and PEAB. The last two had minor roles. The project Biorefinery Norrtorp is currently on hold. The group received financial support from SEA for the feasibility study but has not proceeded after the study (Fredriksson Möller et al. 2013). A steering group has a meeting every second month to evaluate the situation.

The project group started from a “hypothesis” that combined methane and methanol production may be efficient. Other fuels, e.g. DME, were thus not considered. It is worth mentioning that the project members of Biorefinery Norrtorp have been involved in three other methane and methanol projects, Gobigas, Bio2G, and Värmlandsmetanol. This is because Sakab was a daughter company to E.ON. The interviewee, GE, was participating in the pre-study of Gobigas on behalf of E.ON. However none of these previous projects concerned the combined production of methane and methanol. The project members considered the possibilities to sell methanol to the chemical industry, e.g. Perstorp, but transport fuels were still the main focus.

A combination of forest residues and round wood were considered as feedstock. A forest company, Sveaskog, investigated the possibilities to supply the plant with local feedstock on behalf of the project and concluded that there were not enough residues in the area. Thus round wood was also considered and another reason for this is that Sveaskog expected the price on round wood to drop since the pulp & paper industry is experiencing problems.

The main actor Sakab is based in Kumla, which influenced the location of the plant. GE mentions that this would be yet another income for Sakab on which they could spread their fixed costs. This is rather unexpected statement by the interviewee since the investment is very larger. It might be explained by that Sakab did not have a major share of the investment. There are also other motives behind the location and one is that the area is an old industrial area with good access to infrastructure, not least railway terminals. There is also certain know-how in the area from previous gasification activities (Supra and Skifferoljebolaget), although GE stresses that this was not one of the major motives since this knowledge is hard to exploit tin this project. Initially there were plans to sell heat as district heating to Örebro[18]. GE was personally lobbying for this to happen. However, there was competition from another heat supplier in the municipality of Örebro. As a result, the project Biorefinery Norrtorp determined to use the surplus heat to dry the incoming biomass.

The interviewee (GE) stated that the predictability for policy instruments in Sweden is very low – too low to make any investment decisions. GE has the impression that policymakers are fond of supporting the “next thing” which right now is electric vehicles and to some extent also fuel cells. For this reason gasification of forest biomass does not receive the attention of policy makers any longer.

It is worth noticing that the pre-study for this plant was made in September 2013. This is only two months before the results from the governmental inquiry regarding a vehicle fleet independent of fossil fuels (FFF) were presented. The interviewee mentions that there were great expectations on FFF and that it influenced their process. At this time the oil prices were also more than twice as high as when the interview was conducted (the pre-study is dated 2013-09-17 and the interview was conducted 2015-09-22) (Nasdaq 2015).

18 E.ON owns a heat and power plant in Örebro.

When GE is asked to propose a policy instrument he suggests a quota obligation that is guaranteed for a longer period of time, as long as 15 to 20 years. This decision should, according to GE, be taken by political parties from both blocks to guarantee stability. He believes that EU cannot consider it as state aid since it is the consumers that pay. According to him the green electricity certificates are an example of a quota obligation that works[19].

The interviewee expressed skepticism towards the general possibilities of producing transport fuels from forest biomass in Sweden as well as towards the specific possibilities of realizing the plans of Biorefinery Norrtorp. GE considers the life-length of policies in Sweden as very short – too short for any investment decisions. GE returns to this topic throughout the interview. The FFF inquiry is mentioned as something they had expectations on and something that affected their process. Prior to the interview, he mentioned Gobigas and that its value has been written down to zero[20]. According to him this is an example of how bad the possibilities are for transport fuels from forest biomass.

By the end of the interview GE receives a question regarding how the oil price has affected the investment decision (to not invest). He stated that it had a strong influence since the natural gas price dropped 40 % from the time of the pre-study until the time of the interview. However, GE considers the low predictability of policy instruments to be a more major obstacle than the oil price drop. The low predictability signifies “that it is not an issue of price anymore”, according to GE. This comment may be interpreted as if the changing possibilities due to policy instruments may completely change the conditions for a profitable production. A low oil price may be dealt with; it could be balanced with an efficient production, according to the interviewee.

The interview had some similarities with an interview with Värmlandsmetanol[21]. Both interviewees stated that they are not interested in investment supports like NER 300 and that knowledge sharing, which is required by NER 300, is a problem. For the same reason they do not co-operate with academia. The interviewee from Värmlandsmetanol mentioned that Biorefinery Norrtorp is an upscaled version of Värmlandsmetanol.

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19 GE is currently the president of Kumbro Vind, which deals with wind energy.

20 http://www.kemivarldenbiotech.se/nyheter/gobigas-anlaggningens-varde-noll/

21 Värmlandsmetanol is one of the partners of Biorefinery Norrtorp. The president of Värmlandsmetanol, Björn Gillberg, was interviewed by the author 2015-10-08 for the project f3 2014-002370.

7 DISCUSSION & CONCLUDING REMARKS

Production of methane from forest biomass for use in transport sector is not profitable today and there are no plants of commercial scale. There is only one demonstration plant equipped with this technology, Gobigas phase 1 in Sweden. The plant is currently in a commissioning phase. The project has experienced technical challenges and the investment has also become larger than initially planned. Many actors, in Sweden and also internationally, are observing the development of Gobigas.

This report lists twelve projects, which intend to produce transport fuels from forest biomass. They represent different technical conversion pathways, which may compete for raw materials, investments, research & development funds, and attention from policy makers. Ultimately the different pathways also compete for the end-users of transport fuels. Three of the listed projects represent the pathway forest biomass-to-methane and representatives from these three projects have participated in a survey and interviews.

One common factor for the identified projects is that the conditions for transport fuels from forest biomass have changed significantly since the projects were initiated. The projects were initiated before the oil price dropped in 2014. In addition, the policy support has been unpredictable, according to the interviewees. The unpredictable policy support has, together with other factors, affected the decision making process of the examined projects. The former president of Sakab states that the lack of stability in policy support is the most important factor that has influenced their decision to put the project Biorefinery Norrtorp on hold. He also states that the oil price drop was important for that decision. E.ON states that they have put their project Bio2G on hold because they are not sure if there will be sufficient demand for their large-scale plant (1.5 TWh_{pa}). The market development is of course also related to stable and predictable policy support as well as the relative competitiveness vis-à-vis fossil fuels. Göteborg Energi states that the presence of beneficial policy instruments is one of the determining factors for the realization of Gobigas phase 2. This company also expected the oil price to stay at the high level when they initiated Gobigas phase 1 in 2010. Thus, all the interviewed actors request stable and predictable policy support and express that the oil price drop has affected them negatively.

The interviewees have suggested different policy instruments to promote transport fuels from forest biomass in Sweden: a compulsory blend-in quota, a system inspired by the tradable green certificate system, and a price premium model. The compulsory blend-in quota was suggested in FFF. However, the quota was considered as illegal state aid by the European Commission, if implemented together with the current CO_2 tax in Sweden. Hence, it could not be introduced in the suggested form. The tradable green certificate system was implemented in 2003 and it has successfully supported electricity producers by giving them a certificate for each MWh produced renewable electricity[22]. A market for these certificates is generated since the electricity supplier has a quota obligation. In the end it is the electricity consumer that pays for the support. The system has not been considered as illegal state aid by the European Commission.

22 Up to 15 years from start of operation.

The price-premium model was suggested in the FFF inquiry by Thomas Kåberger (Government of Sweden 2014c). The model would assure a production support to certain producers of renewable fuels, i.e. advanced or second generation biofuels[23]. The producer would receive a premium, which is financed by all fuel distributors. The fact that the government does not pay the premium should make it compatible with the EU legislation regarding state aid, according to Kåberger (Government of Sweden 2014c). The premium should be set in accordance with what year the plant starts to operate, the current diesel price, and the current CO_2 tax on diesel. Thus, the producer receives a premium and is liberated from risks related to changes in the diesel price (i.e. oil price risk) and changes in CO_2 tax. However the premium is only paid when the producer sells the fuel on the market and pays energy tax, i.e. it is the producer that carries the market risk[24]. One interviewee stated that this model would have fitted the current situation quite well considering the oil price drop and the uncertainty regarding taxes on biofuels.

The proximity to infrastructure affects the investment decision and location of the plant, especially for very large plants such as the ones in this study. The interviewed potential producers of methane are all expressing that it is important to have access to natural gas pipelines. Gobigas feeds methane to the grid and Bio2G plans to do the same. Biorefinery Norrtorp evaluated production of methane, methanol, or a combination of both. They concluded that the lack of a gas pipeline is a strong disadvantage and evaluated liquefaction of methane (LBG) as a distribution model. A demand for heat and possibilities to distribute it through a district heating grid is also an important albeit not determining factor. Other infrastructural needs that were mentioned are the access to railways and a port.

E.ON has received approval for NER300 support by the European Commission, which may cover between 38 % and 48 % of the estimated investment for Bio2G. Göteborg Energi obtained an R&D support from SEA, which covered 15 % of the total investment for Gobigas phase 1. Biorefinery Norrtorp, on the contrary, is not counting on these types of support. This is because Biorefinery Norrtorp and their technology providers cannot comply with the NER 300 requests regarding knowledge-sharing. For the same reason Biorefinery Norrtorp is not co-operating with academia. This may be related to patents that the technology provider for Biorefinery Norrtorp holds.

The sensitivity to economies of scale is obvious for methane from forest biomass technologies. We have received data regarding planned capacity and estimated investments. In the case of Gobigas phase 1, the numbers refer to the actual outcome and not to estimates. These numbers can be seen in Table 4.

23 Second generation biofuels is sometimes defined as technologies using residues as feedstock. The definition used in FFF for which producers that would receive a premium includes gasification technologies but excludes e.g. biogas from anaerobic digestion, although it normally uses residues as feedstock.

24 See section 3.2.2 for a more detailed description of the price premium model.

Table 4: Specific investments for methane from forest biomass

Project	Investment [billion SEK]	Capacity [MW]	Specific investment [million SEK/MW]
Gobigas phase 1	1.5	20	75
Gobigas phase 2	3*	100	30
Bio2G	4 - 5	200	20 - 25
Biorefinery Norrtorp	6.6 - 6.8	250	26 - 27

* The interviewee states that this number is a rough estimate.

The sensitivity to economies of scale is clear and the specific investment decreases as the capacity increases. We advise against using the exact values for the specific investment in Table 4. This is partly because the values used are estimates (except for Gobigas phase 1) and partly because there are only data from four projects. We have presented the specific investment only to show the tendency: that the plants are sensitive to economies of scale.

Although the values for Biorefinery Norrtorp seem to confirm the tendency, it is difficult to compare that project to the other three. This is partly because it concerns combined methanol and methane production and partly because it is for production of liquefied methane (LBG), as explained in section 6.3. However the sensitivity to economies of scale was mentioned in interviews regarding this project as well. In another interview with Värmlandsmetanol, the interviewee mentioned that Biorefinery Norrtorp is basically an upscaled version of Värmlandsmetanol[25]. The interviewee also stated that in some cases it may be more expensive to downscale components. That project works with a specific technology provider, ThyssenKrupp Industrial Solutions.

In the case of Gobigas the interviewees also mentioned the effects of learning-by-doing and that they estimate that they could build a plant with the same capacity as phase 1 for 2/3 of the cost. It is reasonable to expect further learning-by-doing effects if production of transport fuels from forest biomass takes off.

Concluding remarks

Sweden is well positioned for production of transport fuels from forest biomass. However the conditions to invest are not favorable at the moment, because of low oil prices and a perception of unstable policy support. We have mapped twelve actors, which have planned production, made pre-studies and/or set up test facilities. Three of these actors aim at methane production. Methane may be a “winning” pathway among the various fuels that can be produced from forest biomass. One

25 Värmlandsmetanol is one of the partners of Biorefinery Norrtorp. The president of Värmlandsmetanol, Björn Gillberg, was interviewed by the author 2015-10-08 for the project f3 2014-002370.

advantage for this pathway is the momentum built up by biogas from anaerobic digestion, including the demand in the transport sector and the distribution infrastructure. Lönnqvist et al (Lönnqvist et al. 2013; Lönnqvist et al. 2015) have shown that the demand for vehicle gas in the transport sector may exceed the practical production of biogas from anaerobic digestion. Thus, methane from gasification of forest biomass may complement biogas from anaerobic digestion in the transport sector, since it is the most realistic option for renewable methane. However the market for vehicle gas was only 1.61 TWh during 2014 (Gasbilen.se 2015). 0.87 TWh of the vehicle gas was upgraded biogas and the rest was natural gas, during the same year (Swedish Energy Agency 2015a). The market for methane in transport is thus very small compared to the size of a gasification plant; only one plant of the size like the Bio2G may meet the entire demand for vehicle gas (currently met by upgraded biogas from anaerobic digestion and natural gas). A smaller plant, of the size of Gobigas phase 2, would still be as large as the entire use of upgraded biogas in the Swedish transport sector during 2014. At the same time the technology for methane from forest biomass is sensitive to economies of scale. These circumstances – large plants compared to the current market as a result of the sensitivity to economies of scale – should be evaluated in relation to the low oil price and the perception of unstable policy support. The industry has suggested several policy instruments to promote transport fuels from forest biomass, e.g. a compulsory quota or a price premium model, and these instruments have also been evaluated in the FFF inquiry. However, more important than the type of policy instrument is that the support is substantial and predictable. If policy support for these technologies is insufficient there is a risk that an increased demand for vehicle gas is met by natural gas – implying fossil lock-in effects – or that the promising developed with regard to vehicle gas from forest-based biomass stagnates.

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APPENDIX A1: SURVEY AND INTERVIEW GUIDE

Intervju: svenska drivmedelsanläggningar (skogsråvara)

Syftet med intervjuer: Att undersöka förutsättningarna för drivmedel från skogsråvara i Sverige och skapa underlag för utformning av styrmedel.

Varför ska ni delta i intervjun? Huvudfinansiärer för forskningsprojektet är Energimyndigheten och Svenskt kunskapscentrum för förnybara drivmedel (f3) från vilka information når en bred krets av svenska beslutsfattare med anknytning till produktion och användning av förnybara drivmedel i Sverige. Genom att bidra med er organisations syn och specifika behov kan ni synliggöra dessa och i förlängningen även komma att påverka utformningen av styrmedel som berör drivmedelsproduktion baserad på skogsråvara.

Medverkande: Intervjuerna vänder sig till befintliga, planerade och nedlagda anläggningar som bedömts som centrala för en utveckling mot skogsbaserade drivmedel i Sverige. Intervjustudien utförs av Lunds universitet (Internationella miljöinstitutet) i samarbete med KTH (Avdelningen för energiprocesser) och IVL (Enheten Klimat och hållbara samhällsystem).

Intervjustudien genomförs inom ramen för två forskningsprojekt: *"Analys av systembarriärer för produktion av skogsbaserade drivmedel"* samt *"Hur kan metan från skogsbaserad biomassa komplettera metan från anaerob rötning som transportbränsle i Sverige?"*. Resultaten kommer i första hand att sammanfattas i en lättillgänglig f3-rapport, men även att presenteras i andra sammanhang där beslutsfattare med anknytning till svensk biodrivmedelsproduktion nås.

* 1. **Kontakt och information**

förnamn ______

efternamn ______

adress ______

företag/organisation ______

telefon (arbete) ______

epost ______

* 2. **Har du redan lämnat FULLSTÄNDIGA uppgifter (till KTH, IIIEE eller IVL) för detta f3 projekt om: BASDATA för anläggningen, och MOTIVERING för anläggningen?**

Om Ni väljer NEJ, då kan Ni lägga till ytterligare uppgifter nedan. Annars gå vidare till sidan 3.

O Yes
O No

Additional Comments

____

3. **Vänligen fyll i information från företag/organisation (om inte pre-intervju enkät har ifyllts)**

Investeringens storlek	______
Ev. investeringsstöd (hur mycket och från vem)	______
Ev. driftsstöd (hur mycket och från vem)	______
Planerad produktionskapacitet, GWh drivmedel (LHV)/år	______
Nuvarande produktionskapacitet, GWh drivmedel (LHV)/år	______
Planerad råvaruåtgång, GWh råvara (LHV)/år	______
Nuvarande råvaruåtgång, GWh råvara (LHV)/år	______

4. **Vänligen svara på följande frågor (om inte pre-intervju enkät har ifyllts)**

Vem/vilken part var initiativtagare för anläggningen?	______
Vem/vilken part tog beslutet om investeringen?	______
Grundade sig investeringsbeslutet på några specifika omständigheter?	______
Har några specifika omständigheter bidragit till att minska den	______

finansiella eller tekniska risken?

Planeras en utbyggnad eller ytterligare en anläggning av samma typ?

5. **Kommentarsfält: Basdata/Motivering för anläggningen**

* 6. **Vilka faktorer har påverkat er beslutsprocess kring det drivmedel (t.ex. metan,metanol eller DME) ni valt att producera?**

	5 Mycket starkt	4 Starkt	3 Neutral/i viss mån	2 Svagt	1 Mycket litet eller inget	vet ej
Förväntad marknadsutveckling och avsättning för drivmedel	O	O	O	O	O	O
Marknadsrisker	O	O	O	O	O	O
Styrmedel (ange vilka i kommentarsfält)	O	O	O	O	O	O
Synergier eller potentiella synergier med andra aktörer	O	O	O	O	O	O
Möjlighet till – och/eller existerande samarbete med annan organisation	O	O	O	O	O	O
Organisationens kunskap och know-how kring den tekniska processen	O	O	O	O	O	O
Erfarenheter från andra drivmedelsanläggningar (liknande/annorlunda?)	O	O	O	O	O	O
Befintlig infrastruktur för att distribuera drivmedlet	O	O	O	O	O	O
Valet av drivmedel passar väl in i organisationens kärnverksamhet och tidigare satsningar	O	O	O	O	O	O
Miljö- och klimatprestanda	O	O	O	O	O	O

7. **Kommentarsfält: faktorer som har påverkat beslutsprocess**

____

____

____

____

8. **Om ni inte producerar metan idag: Ser ni tekniska möjligheter att konvertera (och-eller utöka) processen till produktion av metan?**
Om ja: har dessa möjligheter varit av betydelse för beslutsprocess.

____

____

____

____

* 9. **Vilka faktorer har påverkat er beslutsprocess kring den råvara (t.ex. flis, pellets eller GROT) ni valt att använda?**

	5 Mycket starkt	4 Starkt	3 Neutral/i viss mån	2 Svagt	1 Mycket litet eller inget	vet ej
Tillgång på råvara, konkurrens om råvara, samt infrastruktur för tillförsel	O	O	O	O	O	O
Pris	O	O	O	O	O	O
Processtekniska skäl	O	O	O	O	O	O
Styrmedel (ange vilka i kommentarsfältet)	O	O	O	O	O	O
Möjlighet till samarbete/synergi	O	O	O	O	O	O
Uppfattningar om råvaran hos allmänheten och även uppfattningar inom leverantörskedjan	O	O	O	O	O	O
Miljö- och klimatprestanda	O	O	O	O	O	O

10. **Kommentarsfält: råvara och beslutsprocess**

____

____

____

____

* 11. **Vilka faktorer har påverkat er beslutsprocess kring anläggningens lokalisering?**

	5 Mycket starkt	4 Starkt	3 Neutral/i viss mån	2 Svagt	1 Mycket litet eller inget	vet ej
Tillgång på råvara och infrastruktur för tillförsel	O	O	O	O	O	O
Lokal avsättning för drivmedel	O	O	O	O	O	O
Infrastruktur för producerat drivmedel	O	O	O	O	O	O
Lokal avsättning för biprodukter (t.ex. värme)	O	O	O	O	O	O
Möjlighet till ekonomiskt stöd	O	O	O	O	O	O
Närhet till befintlig verksamhet	O	O	O	O	O	O
Existerande eller potentiella synergier med andra aktörer	O	O	O	O	O	O

12. **Kommentarsfält: lokalisering och beslutsprocess**

____

____

____

____

* 13. **Ett stort antal direkta och indirekta styrmekanismer kan tillämpas av staten för att påverka biodrivmedelsmarknader.**

Ofta klassificeras dessa som:
indirekt deltagande i marknaden (t.ex. lagar/reglering, skatter, subventioner osv.);
direkt deltagande i marknaden (t.ex. agerande som köpare, eller som leverantör av varor/information, m.m.)

Hur har följande styrmedel/styrmekanismer påverkat Er beslutsprocess kring att genomföra investeringen?

	5 Mycket starkt	4 Starkt	3 Neutral/i viss mån	2 Svagt	1 Mycket litet eller inget	vet ej
FoU stöd till producenter	O	O	O	O	O	O
Investeringsstöd	O	O	O	O	O	O
Energiskatter	O	O	O	O	O	O
Koldioxidskatt	O	O	O	O	O	O
Stöd till konsumenter (t.ex. miljöbilspremie)	O	O	O	O	O	O
Offentlig upphandling (t.ex. länstrafiken köper drivmedel)	O	O	O	O	O	O
Information från organisation inom offentlig verksamhet (t.ex. Energimyndigheten)	O	O	O	O	O	O
Erfarenheter från andra drivmedelsanläggningar	O	O	O	O	O	O
Möjlighet till långsiktiga avtal, t.ex. med köpare av drivmedel	O	O	O	O	O	O
Lagar och regleringar (ange i kommentarsfält [(t.ex. krav på tankstationer, %inblandning, m.m.])	O	O	O	O	O	O
Samarbete eller informationsutbyte med forsknings-, utvecklings- och demonstrations-projekt på företag och högskola.	O	O	O	O	O	O

14. **Kommentarsfält: Styrmekanismer**

____

____

____

____

* 15. **Hur värderar ni ett driftsstöd gentemot ett investeringsstöd i beslutsprocessen att genomföra en investering?**

	5 Mycket starkt	4 Starkt	3 Neutral/i viss mån	2 Svagt	1 Mycket litet eller inget	vet ej
Investeringsstöd	O	O	O	O	O	O
Driftsstöd	O	O	O	O	O	O

16. **Kommentarsfält: Driftstöd/investeringsstöd**

17. **Vilka styrmedel bedömer du vara de viktigaste för att realisera en storskalig uppbyggnad av produktionskapacitet för drivmedel från skogsråvara?**
Beskriv hur ett sådant skulle kunna vara utformat.

18. **Har ni redan ”räknat in” någon framtida förändring av styrmedel i underlaget för er beslutsprocess? Om Ja, kan du beskriva det?**

* 19. **Hur tror ni att nya och förändrade styrmedel kommer påverka förutsättningarna för drivmedelsproduktion från skogsråvara inom de närmsta fem åren?**

O Gynnsamma förändringar i stor utsträckning

O Gynnsamma förändringar i mindre utsträckning

O Oförändrat

O Ogynnsamma förändringar i mindre utsträckning

O Ogynnsamma förändringar i stor utsträckning

O Har ingen uppfattning

Kommentarsfält

* 20. **Hur har förutsägbarheten/stabiliteten, eller avsaknad av detta, påverkat Er beslutsprocess, under de senaste fem åren, kring följande områden:**

	5 Starkt positivt	4 Positivt	3 Oförändrat	2 Negativt	1 Starkt negativt	vet ej eller ingen uppfattning
Att genomföra investeringen i anläggningen	O	O	O	O	O	O
Investering i infrastruktur för t.ex. råvarutillförsel eller drivmedelsdistribution	O	O	O	O	O	O
Att ingå långsiktiga avtal	O	O	O	O	O	O
Val av drivmedel att producera	O	O	O	O	O	O
Annat beslut (ange i kommentarsfält)	O	O	O	O	O	O

21. **Kommentarsfält: förutsägbarheten/stabiliteten**

22. Hur har utvecklingen av världsmarknadspriset på energi påverkat beslutet att inte gå vidare.

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