Biogas in Sweden - Opportunities and challenges from a systems perspective

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Opportunities and challenges from a systems perspective

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Till min familj

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ABSTRACT

Addressing today's challenges of reducing our dependence on fossil fuels and related emissions of greenhouse gases requires measures such as increased energy efficiency and replacement of fossil energy carriers with renewable ones. Biogas is one of the fastest growing renewable energy sources in the world and the overarching purpose of the research presented in this doctoral thesis is to explore the prospects of an increased production and utilization of biogas in a Swedish context.

Biogas can be produced from various kinds of organic material such as municipal and industrial waste, which dominate the current production. This is driven by existing policy incentives, which also promote the use of biogas as vehicle fuel. However, the lion's share of the Swedish biogas potential remains essentially untapped within the agricultural sector, including feedstock such as manure, crop residues and dedicated biogas crops. If fully utilized, biogas from wastes and residues only could replace 10% of the vehicle fuels or 50% of the natural gas used in Sweden today. This implies that existing incentives must be strengthened to overcome today's barriers, especially regarding the limited profitability in biogas production based on agricultural feedstock as identified in this thesis. In addition, the techno-economic performance needs to be improved, for example by reduced feedstock costs and increased methane yields. For low-cost feedstock, such as manure, measures to reduce the cost of capital and the related cost of operation and maintenance are especially important.

In the environmental assessment presented in this thesis, it was found that biogas produced in an existing, representative co-digestion plant, reduced emissions of greenhouse gases by approximately 90% when replacing fossil vehicle fuels. Based on the current structure of the Swedish energy system, the replacement of fossil vehicle fuels with biogas would normally render the highest reduction of greenhouse gas emissions, followed by the replacement of natural gas and other fossil energy carriers, indicating that these utilization options should be prioritized. However, given the additional greenhouse gas benefits of biogas produced from manure, regardless of how the biogas is utilized, such production should also be promoted.

In conclusion, the overall findings in this thesis show that there are substantial opportunities to increase the production and utilization of biogas in Sweden, which would reduce greenhouse gas emissions significantly. However, current challenges, including the limited profitability in biogas production based on agricultural feedstock, should be met by further technology development combined with adequate and focused policy instruments.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Biogas, som i huvudsak består av metan och koldioxid produceras när mikroorganismer bryter ned organiskt material utan tillgång till syre, så kallad rötning. I princip kan alla typer av organiskt material användas för att producera biogas men vanligast är till exempel avloppsslam, olika typer av avfall från hushåll och industrier, gödsel, grödor och odlingsrester.

Biogas kan användas för att producera elektricitet och värme. Den kan också användas som fordonsbränsle eller för att ersätta naturgas i olika industriella processer.

Den svenska biogaspotentialen från restprodukter är drygt 8 TWh vilket motsvarar ungefär 10 % av den totala mängden bensin och diesel eller 50 % av den totala mängden naturgas som används i Sverige idag. I dagsläget produceras biogas huvudsakligen från avloppsslam och avfall men den stora potentialen finns inom lantbrukssektorn i form av gödsel och odlingsrester. Det är också möjligt att producera biogas från grödor. Om 5 % av den svenska åkermarken skulle avsättas för biogasgrödor skulle potentialen öka med cirka 50 %.

Ur miljösynpunkt kan produktion och användning av biogas leda till stora vinster. Biogas från avfall och restprodukter, i synnerhet gödsel, ger till exempel mycket låga utsläpp av växthusgaser. Den miljöanalys av en modern samrötningsanläggning som presenteras i den här avhandlingen visar till exempel att utsläppen av växthusgaser minskar med ungefär 90 % om biogasen används som drivmedel och ersätter bensin och diesel.

Det finns idag ett antal olika styrmedel som på olika sätt påverkar förutsättningarna för att producera biogas. Generellt är dessa styrmedel antingen inriktade på hur olika råmaterial ska hanteras eller på hur den producerade biogasen ska användas. Inom avfallsområdet har det till exempel införts ett förbud mot att deponera organiskt avfall och ett av våra nationella miljömål säger att 50 % av det organiska hushållsavfallet ska behandlas biologiskt år 2018. Produktionen av biogas från avfall ökar också kontinuerligt. Inom lantbrukssektorn, där den stora potentialen finns, är befintliga styrmedel (till exempel investeringsstöd) däremot för svaga för att stimulera en utbyggnad. De tekno-ekonomiska analyser som presenteras i den här avhandlingen visar också att produktion av biogas från grödor, odlingsrester och gödsel i de flesta fall inte är lönsam med de förutsättningar som råder i Sverige idag.

Det finns därför behov av ytterligare teknikutveckling för att effektivisera produktionen av biogas. Det kan till exempel röra sig om åtgärder för att minska kostnaderna eller öka gasutbytet för de substrat som biogasproduktionen baseras på. När biogas produceras från gödsel, som är ett relativt billigt substrat, skulle åtgärder som minskar kapitalkostnaderna också få stor betydelse. Om biogasen används som fordonsbränsle är det också viktigt att minska kostnaderna för transport av gas och tankstationer som idag kan stå för halva priset till slutkonsument. Det skulle till exempel räcka med en prisökning på 5 % hos biogasproducenten för att kunna producera biogas från grödor och gödsel med lönsamhet.

Det finns också förslag på styrmedel för att gynna en gödselbaserad produktion av biogas som skulle kunna få stor betydelse. Ett så kallat metanreduceringsstöd på 20 öre/kWh biogas skulle göra det lönsamt med gödselbaserad produktion av biogas oavsett om den används som fordonsgas eller för att göra el och värme. I många fall krävs det dock att gödsel från flera gårdar rötas i samma anläggning för att genom skalfördelar nå lönsamhet.

Sammantaget visar resultaten som presenteras i denna avhandling att det finns stora möjligheter till en ökad produktion och användning av biogas i Sverige vilket skulle kunna minska utsläppen av växthusgaser betydligt. För att möta de utmaningar som finns, till exempel dagens begränsade lönsamhet för biogasproduktion från lantbruksbaserade substrat, krävs dock en fortsatt teknikutveckling i kombination med anpassade och effektiva styrmedel.

LIST OF PUBLICATIONS

This doctoral thesis is based on the following Papers, which will be referred to in the text by their Roman numerals. The Papers are attached at the end of this thesis. Reprints are published by kind permission of the publishers concerned.

I. **Lantz, M.**, Svensson, M., Björnsson, L. and Börjesson, P. (2007) *The prospects for an expansion of biogas systems in Sweden – Incentives, barriers and potentials*, Energy Policy 35:1830-1843

II. **Lantz, M.** (2012) *The economic performance of combined heat and power from biogas produced from manure in Sweden – A comparison of different CHP technologies*, Applied Energy 98:502-511

III. **Lantz, M.**, Kreuger, E. and Björnsson, L. *Impact of energy crop selection on process parameters and economy in the production of biogas as vehicle fuel*, Submitted to Biomass and Bioenergy, December 2012

IV. **Lantz, M.** and Börjesson, P. *Greenhouse gas and energy assessment of biogas from co-digestion injected into the natural gas grid – A Swedish case study including effects on soil properties*, Manuscript

My contribution to the Papers

I. I was responsible for the layout of the article and most of the writing under supervision of Pål Börjesson and Lovisa Björnsson.

II. Sole author.

III. I contributed in the choice of scenarios and coordinated the writing of the Paper. I was responsible for the literature review of upgrading and energy input and I performed the economic assessments.

IV. I was responsible for the layout of the Paper and the literature review with the exception of soil compaction and soil carbon. I performed the environmental and the economic assessments.

Other publications by the author not included in this thesis.

I. **Lantz, M.**, Larsson, G. and Hansson, T. (2006) *Förutsättningar för förnybar energi i svensk växthusodling*, Rapport nr 57, Miljö- och Energisystem, Lunds Tekniska Högskola

II. **Lantz, M**. (2007) *Ökat utnyttjande av befintliga biogas-anläggningar*, Rapport nr 63, Miljö- och Energisystem, Lunds Tekniska Högskola

III. **Lantz, M.**, Ekman, A. and Börjesson, P. (2009) *Systemoptimerad produktion av fordonsgas – En miljö och energisystemanalys av Söderåsens biogasanläggning*, Rapport nr 69, Miljö- och Energisystem, Lunds Tekniska Högskola

IV. **Lantz, M.** and Börjesson, P. (2010) *Kostnader och potential för biogas i Sverige, Bilaga 1 till Energimyndighetens förslag till en sektorsövergripande biogasstrategi*, Rapport 2010:23, Energimyndigheten

V. Börjesson, P., Tufvesson, L. and **Lantz, M.** (2010) *Life Cycle Assessment of Biofuels in Sweden*, Report no. 70, Environmental and Energy Systems Studies, Lund University

VI. **Lantz, M.** (2010) *Gårdsbaserad och gårdsnära produktion av kraftvärme från biogas*, Rapport nr 71, Miljö- och Energisystem, Lunds Tekniska Högskola

VII. Gissén, C., Prade, T., Kreuger, E., Achu Nges, I., Rosenqvist, H., Svensson, S-E., **Lantz, M.**, Mattsson, J E., Börjesson, P. and Björnsson, L. *Comparing energy crops for biogas production – yields, energy input and costs in cultivation using digestate and mineral fertilisation*, Submitted to Biomass and Bioenergy

VIII. Tufvesson, L. and **Lantz, M.** (2012) *Livscykelanalys av biogas från restprodukter*, Rapport nr 76, Miljö- och Energisystem, Lunds Tekniska Högskola

IX. Tufvesson, L., **Lantz, M.** and Börjesson, P. *Life cycle assessment of biogas produced from industrial residues – environmental performance including competition with animal feed*, Submitted to Journal of Cleaner Production

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Chapter 1: Introduction

The world as we know it is dependent on fossil fuel to 80% for its total primary energy demand. From 1990 to 2010, global energy demand as well as the utilization of fossil fuels increased by 45%, mainly in Asia and other non-OECD countries (IEA, 2012a).

Combustion of fossil fuels also represents more than 50% of global anthropogenic emissions of greenhouse gases affecting the climate system (IPCC, 2007). Meanwhile, although the future is yet to be revealed, scenarios presented by the International Energy Agency predict a continued increase in energy demand, especially in the non-OECD countries (IEA, 2012a). Addressing this challenge requires the joint efforts of various actors. For example, the European Union has made the commitment to reduce greenhouse gas emissions by 80 – 95% by 2050[1] under certain conditions. Measures to reach this target include increased energy efficiency as well as replacement of fossil energy carriers with renewable ones (EC, 2011).

Biogas, representing 1.5% of the global renewable energy supply, is one of the fastest growing renewable energy sources in the world (IEA, 2012b). It consists of a mixture of methane (CH_4) and carbon dioxide (CO_2), and is produced when microorganisms degrade organic material in the absence of oxygen, known as anaerobic digestion. In theory, all organic material could be utilized for biogas production. Common

[1] Compared to the levels of emissions in 1990

feedstock is organic waste and residues from households and industries, sludge from waste water treatment plants and manure from livestock production. Biogas is also produced from different kinds of crop residues and dedicated energy crops. Other less conventional feedstock such as algae, seaweed and wood has also been suggested and evaluated in various studies (Jarvis and Schnürer, 2009).

Biogas has been produced and utilized for more than a century, mainly as a by-product in waste water treatment. For instance, such biogas was used in the street lights of Exeter in 1897 (Deublein and Steinhasuser, 2008). In Sweden, interest for biogas production was limited until the oil crisis in the 1970s, when biogas production was developed at municipal and industrial waste water treatment plants. At this time, some farm-scale plants were also constructed, mainly on large pig farms. In the 1980s, the recovery of landfill gas was also initiated in Sweden with the primary objective to reduce emissions of methane, which is a potent greenhouse gas (GHG). One decade later, the first, large-scale co-digestion plant was built, producing biogas from industrial waste and manure (Berglund, 2006; SEPA, 2012a).

As an energy carrier, biogas has various possible utilization pathways, such as production of heat or combined heat and power. After upgrading, it can also replace natural gas in various industrial processes and be used as a vehicle fuel.

Biogas is identified as a renewable energy carrier with a high potential to reduce GHG emissions (EU, 2009; JRC, 2011; SEA, 2010; SEA, 2012a). Anaerobic digestion could also be a part of an appropriate waste management system and a way to increase nutrient recycling from urban waste as well as improving the quality of manure already used as fertilizer (Berglund, 2006; SEA, 2010).

The production and utilization of biogas is thus affected by various kinds of policy instruments depending on feedstock and how the biogas is utilized. In a similar way, economic conditions for biogas production as well as its environmental impact can vary considerably.

1.1 Purpose, scope and delimitations

The overarching purpose of the research presented in this doctoral thesis is to explore the prerequisites for an increased production and utilization of biogas in a Swedish context. The prospects for such a development depend on feasible techno-economic conditions for various biogas systems, which may require the implementation of adequate policy instruments, in addition to documented, favourable environmental performance.

This thesis therefore includes:

- ✓ A review of the incentives, barriers and potentials for an increased production and utilization of biogas in various system applications (Paper I).
- ✓ Techno-economic assessments of selected biogas systems, including effects of policy instruments (Paper II and III).
- ✓ An environmental system assessment of an existing biogas system, including analyses of potential improvements of environmental performance (Paper IV).

1.2 Outline of the thesis

The following chapter 2 provides a brief background and overview of current production and utilization of biogas in Sweden and in the European Union as well as estimations of the biogas potential. Methods applied in this thesis are presented in chapter 3. A review of incentives and barriers for different biogas systems, focusing on former, current and suggested policy instruments are presented in chapter 4.

In chapter 5, techno-economic assessments are presented for some selected biogas systems. In chapter 6, a case study is presented where the environmental performance, focusing on greenhouse gas emissions, of an existing biogas system in southern Sweden is assessed. Finally, the results from the various Papers are summarized in some general conclusions and recommendations in chapter 7.

Chapter 2: Background

In Sweden, the total energy supply was 2 200 PJ in 2011, where the main contributions are from bioenergy (22%), fossil fuels (38%) and nuclear fuel (27%). There are, however, significant differences in energy supply between different sectors. Bioenergy is mainly used within the industrial sector and for district heating where it represents 70% of the energy supply. Power production, which amounted to 530 PJ in 2011, is dominated by hydro power (45%) and nuclear power (40%) while fossil fuel only contributes to a few per cent of the production (SEA, 2012b). The transportation sector on the other hand, with a total supply of 440 PJ annually, is dominated by fossil fuels. Renewable vehicle fuels represent 6.8% of the energy used for road transport and the main contributions are from biodiesel (46%), ethanol (41%) and biogas (12%). Biodiesel is mainly used as low blend in fossil diesel while ethanol is used as low blend in petrol (49%), E85 (85% ethanol and 15% petrol) and ED95 which is an ethanol fuel used in busses (SEA, 2012c).

In Sweden, biogas for the transportation sector is marketed as “vehicle gas” which also includes fossil natural gas. In 2011, 62% of the vehicle gas was biogas (SEA, 2012c). However, biogas is not blended with a fossil fuel in the same way as ethanol and biodiesel since some filling stations could sell 100% biogas and others could sell 100% natural gas. Regarding natural gas, the current utilization in Sweden is approximately 63 PJ used for electricity and district heating (54%), in the industry sector (22%) and in the residential and services sector (14%). Approximately 2% of the total natural gas supply is used in the transportation sector as vehicle gas (SEA, 2012b).

2.1 Production of biogas

Biogas production in Sweden

Swedish biogas production currently stands at approximately 5.3 PJ, produced at more than 230 locations (SEA, 2012d). Thus, production has increased by less than 15% over the past 6 years despite the implementation of several policy instruments, as described in Paper I and chapter 4. One reason is that production of landfill gas has dropped by 40% over this period since landfilling of organic material was banned in 2005 (Avfall Sverige, 2012). Landfill gas is biogas produced in the oxygen-free environment of a landfill, but often with a lower CH_4-content and a higher concentration of other gasses than biogas produced in biogas plants. Concerning co-digestion plants and farm-scale biogas plants, called "*other biogas plants*" in Figure 1, production has increased by more than 100% over the same period. In 2011, approximately 740 000 t of feedstock, excluding sludge from waste water treatment plants (WWTP), was used for biogas production. Although a wide variety of feedstock is used, it can be grouped into three main categories based on wet weight; manure (38%), industrial waste (32%) and municipal solid organic waste (MSOW) (27%) while energy crops represent only 4% of the feedstock (SEA, 2012c). If feedstock categories were instead quantified according to the biogas produced, these proportions are entirely different, as the biogas yield per wet weight of, for instance, MSOW is considerably higher than that of manure (Carlsson and Uldal, 2009).

Biogas production in Europe

In Europe, biogas production has increased significantly over recent years and reached 455 PJ in 2010, see Figure 2. Unlike the Swedish situation, no more than 40% of the biogas is produced at WWTP or landfills but this varies greatly from country to country, see Figure 3. In Germany, which dominates biogas production in Europe, 90% of the production originates from biogas plants based on energy crops, manure and waste. In the UK, by contrast, landfill gas represents 85% of the production.

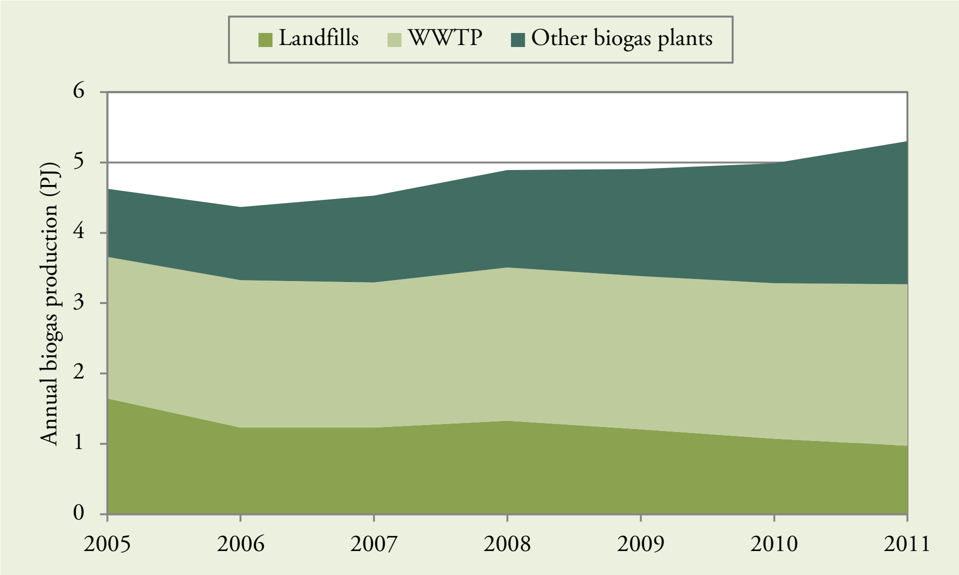

Figure 1: Biogas production in Sweden (SEA, 2012d)

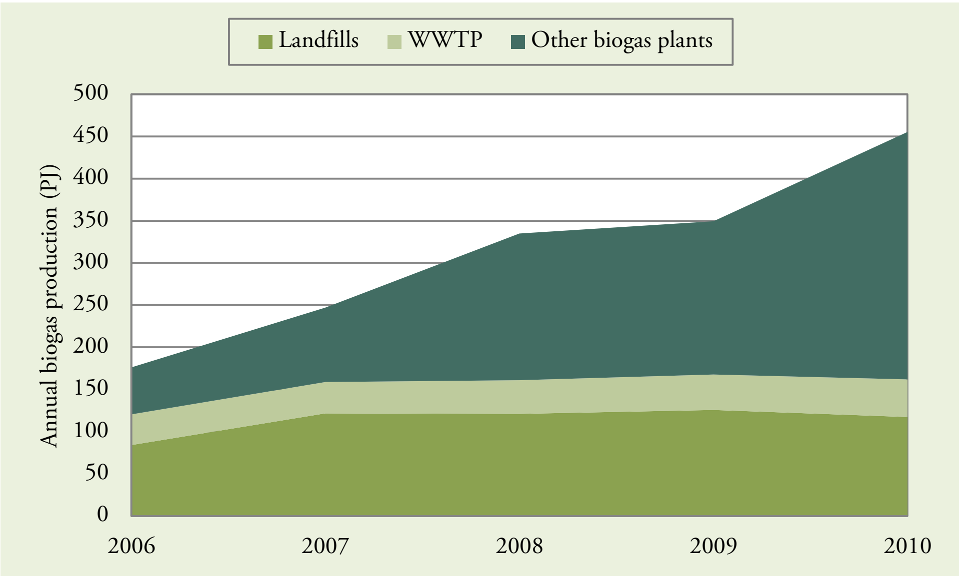

Figure 2: Biogas production in Europe (EurObserv'er, 2008; 2010: 2012)

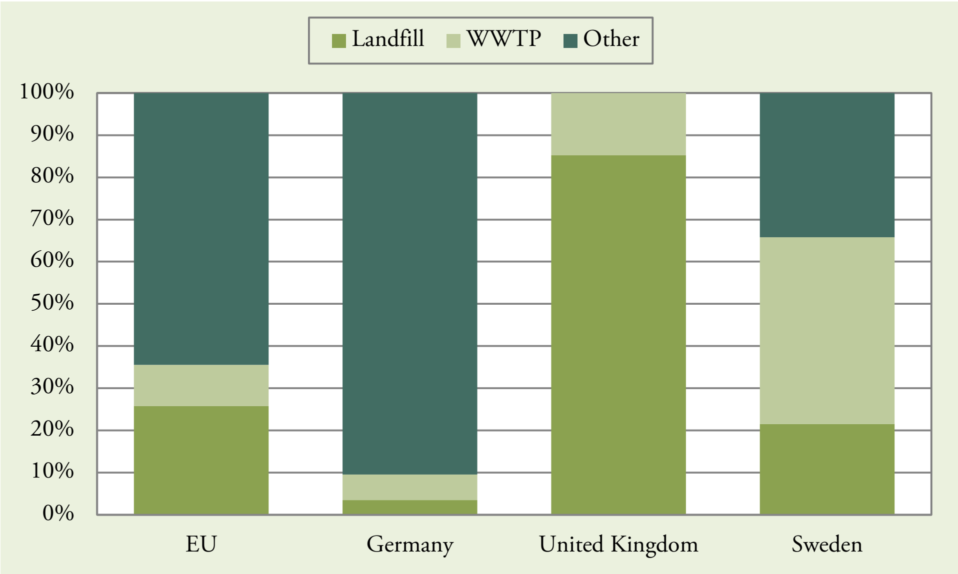

Figure 3: Source of biogas production in different countries in 2010 (EuroObserver, 2012; SEA, 2012d)

2.2 Utilization of biogas

Biogas can be utilized for the production of heat or combined heat and power, which requires limited pre-treatment focused on reducing the concentration of contaminants in the biogas. Biogas can also be used as a vehicle fuel or to replace natural gas in various applications, which requires a more extensive pre-treatment, also known as upgrading. In this process, CO_2 and contaminants are removed, increasing the methane content to 95 – 99% as required in the Swedish standard for vehicle gas (Petersson and Wellinger, 2009).

Currently, 50% of the biogas produced in Sweden is utilized as a vehicle fuel and 38% is used for the production of heat, and only a minor share is used for electricity production or is flared. As shown in Figure 4, the production of upgraded biogas has increased in proportion significantly in recent years. This is partly due to reduced production of heat and partly due to increased production of biogas in co-digestion plants, since over 90% of the biogas produced at these plants is upgraded. Upgraded biogas is primarily used as a vehicle gas for busses (37%) as well as passenger cars and light duty vehicles (SCB, 2012a). In Europe, biogas is used mainly to produce electricity and heat albeit a certain amount of vehicle gas is also produced (EuroObserver, 2012; IEA, 2013).

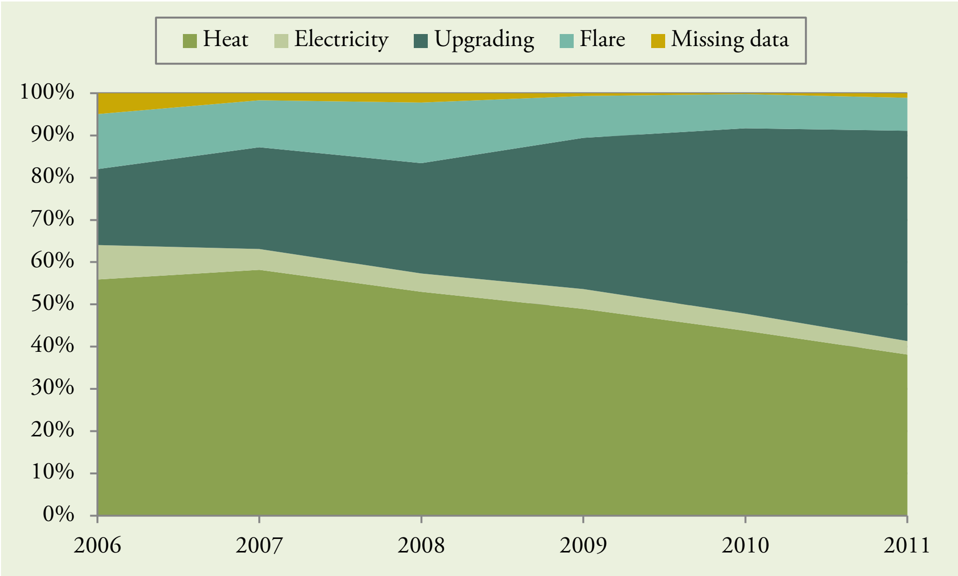

Figure 4: Utilization of biogas in Sweden (SEA, 2012d)

2.3 Distribution of biogas

When biogas is used for the production of heat or combined heat and power, the utilization normally takes place on site or in the vicinity of the biogas plant. In fact, a large proportion of the heat produced from biogas in Sweden today is probably used as process heat at the biogas plant, although there are also examples of biogas being utilized for district heating. In these cases, biogas is distributed in dedicated, low pressure grids. When utilized as a vehicle fuel in Sweden, the upgraded biogas is transported from the production site to a filling station. In 2011, there were 133 public filling stations, 21 non-public filling stations and 33 bus depots in Sweden (SCB, 2012a). There are several examples of filling stations close to the biogas plant where the gas is distributed via dedicated gas grids. In 2009, it was estimated that 49% of the biogas used as vehicle fuel would be distributed in this way in 2010. The remaining vehicle gas was estimated to be distributed over longer distances via the natural gas grid (29%) or by truck (22%) (Benjaminsson and Nilsson, 2009). In 2011, 25% of the upgraded biogas, injected at 8 locations, was distributed via the natural gas grid (SEA, 2012d). When biogas is distributed by trucks to the filling station it is normally compressed to 200 bar, also known as compressed biogas

(CBG). An alternative is to cool the biogas to -162 °C and transport it as liquefied biogas (LBG). In this way, the energy density is more than twice that of CBG (Benjaminsson and Nilsson, 2009). In Sweden, LBG is currently produced on a commercial scale at one location (SEPA, 2012a).

In other parts of Europe, where biogas is used mainly for electricity and heat, biogas is normally utilized on site or in the vicinity of the biogas plant. However, from being a mainly Swedish phenomenon, the number of upgrading plants in Europe is now increasing rapidly, as presented in Figure 5. In fact, installations in Germany now represent 70% of the total upgrading capacity in Europe (IEA, 2013). The reason for upgrading is, however, mainly to inject biogas into the natural gas grid so that it can be utilized more efficiently, while its use as vehicle gas is still less common.

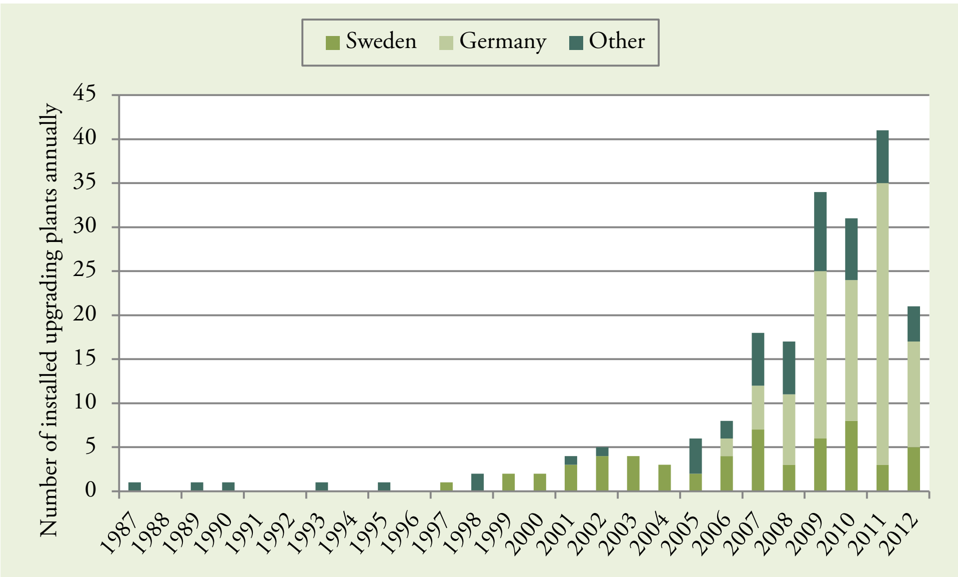

Figure 5: Number of annual installations of biogas upgrading plants in Europe (IEA, 2013)

2.4 Production and utilization of digestate

In addition to biogas, the anaerobic process will also result in a liquid effluent, the digestate. This digestate contains all the nutrients in the feedstock. It will also contain all undegradable contaminants that were present in the feedstock, like heavy metals, while pathogens and unwanted organic compounds are degraded to varying extent during the process. In Sweden, 94% of the digestate produced at co-digestion plants and farm-scale biogas plants is utilized as fertilizer. Regarding sludge from WWTP, only 24% is used as fertilizer (SEA, 2012d).

2.5 The biogas potential

Studies on the biogas potential, as any other bioenergy potentials, are based on a number of assumptions affecting the final result. For instance, estimates of the potential contribution of biomass to the global energy supply in 2050 vary from less than 100 EJ to more than 400 EJ annually (Berndes *et al.*, 2003). Different studies could also refer to the theoretical, the technical, the economic or the market potential etc. (Egnell and Börjesson, 2012).

Studies of the biogas potential in a certain region often start with an inventory of the amount of feedstock that can be utilized for biogas production. As previously mentioned, this could include all organic material which potentially could be used as feedstock. Combining this inventory of feedstock with the maximum theoretical production of CH_4, which can be calculated if the composition of the feedstock is known or can be estimated (Symons and Buswell, 1933), gives the theoretical potential.

The practical amount of feedstock available is, however, reduced due to technical and economic limitations. Some organic residues and waste are currently used as feed. Others are treated in competing waste management systems (Linné *et al.*, 2008). Some feedstock, such as manure and crop residues, does not require any additional treatment. Thus, the biogas producer may need to cover parts of or the entire cost of handling and transport of the feedstock. The impact of assumptions made on the economic conditions for biogas production is especially apparent for biogas crops where the biogas producer competes with the market for food and feed. If the biogas producer can offer the farmer a compatible price, the biogas crop potential could be very high compared to other kinds of feedstock. If the biogas producer's ability to pay is not high enough, the market potential is, however, negligible. This could also be the case if regulations are implemented, limiting the use of agricultural land for bioenergy production. Also, in today's commercial, full-scale biogas plants, the theoretical methane potential is not reached, and the achieved methane production will depend on the technology used and operational parameters. The methane potential of a specific feedstock may also be limited by economic conditions. For instance, the biogas producer will not apply a longer retention time in the reactor than motivated from an economic perspective. Thus, it may be feasible to optimize biogas production per volume reactor instead of the biogas production per volume of feedstock.

Waste and Residues

The Swedish biogas potential from waste and residues has been estimated to be in the vicinity of 60 PJ assuming that no competing utilization pathways exist and that all municipal organic waste and all crop residues are collected etc. Including some limitations, such as competing utilization pathways (e.g. industrial residues used as feed and ecological restrictions on how much straw can be collected etc.) the practical potential has been estimated to approximately 30 PJ (Linné *et al.*, 2008; Lantz and Börjesson, 2010). The corresponding potential in Europe has been estimated to 1 825 PJ (Aebiom, 2009), see Table 1.

Table 1: The biogas potential in Sweden and EU-27 (Linné at al., 2008; Lantz and Börjesson, 2010; Aebiom, 2009)

Origin of feedstock	Sweden		EU-27	
	PJ	%	PJ	%
Agricultural				
- Crop residues	11.1	37	403	22
- Manure	9.9	33	738	40
Household and industry				
- Household	2.7	9	360	20
- Industry	3.8	13	108	6
- Sludge from WWTP	2.5	8	216	12
Total biogas potential	**30**		**1 825**	

Dedicated biogas crops

The biogas potential presented in Table 1 is based on waste and residues that are produced whether biogas production is implemented or not. Dedicated biogas crops, on the other hand, are produced to be utilized for biogas production only. The biogas potential depends on the amount and type of arable land utilized and the type of crop that is cultivated. Different potential studies in Swede have, for example, assumed that energy crops could be cultivated on approximately 10 – 40% of the arable land (SOU, 2007). This can be compared to the situation in Germany where 5% of the agricultural land was used for the cultivation of biogas crops in 2009 (Delzeit *et al.*, 2012). The European Biomass Association also presents an example where 5% of the arable land in the EU is utilized for energy crop cultivation (Aebiom, 2009). In Sweden, this would represent some 130 000 ha (SCB, 2012b).

In Paper III, some possible biogas crops are analysed from an economic point-of-view. Although none of them was economically feasible under current Swedish conditions, some were found to be more cost-efficient than others. In Table 2, crop and methane yield are presented for the four most cost-efficient crops if cultivated in the southern part of Sweden (Gissén *et al.*, 2012). Assuming that these crops were cultivated for biogas production on 5% of the arable land, one quarter each, results in a biogas potential of 15 PJ, equivalent to 50% of the biogas potential from residues presented in Table 1. Thus, energy crops could play an important role in a future biogas system. The corresponding potential in Europe has been estimated to be 980 PJ, which also corresponds to approximately 50% of the potential from residues (Aebiom, 2009).

Table 2: Crop and methane yield for energy crops (Gissén *et al.*, 2012).

Energy crop	**Crop yield**	**Methane yield**	**Methane yield**
	t DM*/ha	GJ/t DM*	GJ/ha
Sugar beet**	13.6	12.5	170
Maize	9.9	11.0	109
Triticale	7.9	12.2	97
Wheat grain	6.7	13.2	89

* Dry matter

** Including roots and tops

Summary

In Sweden, current biogas production, including landfill gas, amounts to less than 20% of the biogas potential based on waste and residues. Although feedstock from the agricultural sector represents 70% of the potential, its current contribution to biogas production is limited. By including dedicated energy crops, the agricultural sector's share of the potential biogas production increases even further. Thus, any substantial increase in Swedish biogas production will be based on agricultural feedstock.

Given the energy supply in Sweden, the biogas potential of 30 – 45 PJ could, for example, replace 10 – 15% of the fuel used within the transportation sector, excluding aviation and bunker oil, or 48 – 71% of the natural gas consumed.

Chapter 3: Methods

The research presented in this thesis is based on a broad systems perspective. As argued by Miser and Quade (1985) this approach does not imply specific methods or techniques. Instead, it is a way of approaching a problem and carrying out decision-oriented research. This thesis thus includes complementary methods and assessment techniques in the various papers.

Paper I includes a systematic review of policy instruments and other incentives and barriers affecting the implementation of various biogas systems in Sweden. Identified incentives and barriers were categorised according to how they influence i) the production of biogas from different types of feedstock, or ii) the utilisation of the biogas for heat, electricity or vehicle fuel production. The review in Paper I includes a system expansion approach also taking into account associated systems of, for example, waste handling, agriculture production and energy generation, and their related policy implications on the development of biogas systems.

Based on the findings in Paper I, techno-economic assessments were performed for selected biogas systems in Paper II and III, including evaluations of suggested and implemented policy instruments. The methods applied in the techno-economic assessments are further described in section 3.1. In Paper IV, an environmental systems assessment was performed for an existing biogas system, focusing on greenhouse gas emissions, but also involving economic aspects. The assessment was based on the methodology for Life Cycle Assessments (LCA), which is described in section 3.2.

3.1 Techno-economic assessments

The techno-economic assessments presented in this thesis are based on an evaluation of the technical and economic performance of the different biogas systems analysed. The technology assessments include parameters such as process energy requirements, energy conversion efficiency and methane losses. These parameters are used, for example, to evaluate biogas production on different scales, from different feedstock and by different process concepts or to compare different technologies to produce combined heat and power and to upgrade biogas into vehicle fuel.

The economic assessments are based on traditional investment analysis where the economic conditions for biogas production and utilization are evaluated from an economic point-of-view. In Papers II – IV, the investment analysis is based on the annuity method where the initial investment is presented as an annual cost of capital during the lifetime of the investment. This annuity cost is calculated by multiplying the initial investment by the annuity factor (A), which is calculated according to Equation 1. An alternative, commonly used method is to calculate the Net Present Value of an investment. By this method, the present value of a future cash flow is calculated and compared to the original investment. When comparing different investments, these two methods will give the same result and they are both highly dependent on the discount rate (Persson and Nilsson, 1999; Yard 2001).

$$A = \frac{r}{1-(1+r)^{-N}} \qquad \text{(Equation 1)}$$

A = Annuity factor

r = Discount rate (%)

N = Time (year)

Discount rate

An investment analysis is performed based on nominal (including inflation) or real (excluding inflation) economic conditions. Thus, an investment analysis based on a nominal cash flow considers price changes over time, including inflation, whereas an analysis based on real terms should consider only real price changes over time. When nominal conditions are applied, the discount rate should also be nominal and vice versa (Persson and Nilsson, 1999; Yard 2001). The assessments presented in Papers II – IV are based on real terms with fixed real prices but in the sensitivity analysis different price levels are addressed.

The discount rate could be based on the investor's actual cost of capital, such as the interest rate on commercial loans. The discount rate could also indicate the minimum rate of return required by an investor. With this approach, the investors also consider the rate of return from alternative investments and the risks involved compared to other investments. The discount rate is often decided by calculating the weighted average cost of capital (WACC) taking into consideration the fact that different providers of capital may require different rates of return. Thus, the discount rate could vary depending on the project and the investors.

For example, the European Commission's guide to cost benefit analysis of investment projects presents an indicative average real discount rate of 4.8% based on a portfolio of different securities (EU, 2008). In Sweden, The Transportation Administrations guidelines for cost benefit analysis within the transportation sector, suggest an interest rate of 5% for commercial loans and a WACC of 10% as a required rate of return for businesses in general if the actual requirement is not known (STA, 2012).

Considering different biogas projects, it is relevant to compare the discount rate with those applied for investments in the agricultural sector and the energy sector. In the agricultural sector, applied real discount rates given in the literature vary from 6 - 7%, with reference to conventional production of crops for food and feed, milk and meat as well as energy crops (Agriwise, 2013; Gissén *et al.*, 2012).

When calculating the production cost for power production in new facilities in Sweden, Nyström *et al.* (2011) use a real discount rate of 6%. Regarding the transmission of electricity and natural gas, these grids may be operated by private companies in Sweden but this infrastructure is based on local monopolies. Thus, network tariffs are monitored and supervised by the Energy Market Inspectorate which applies a real discount rate of 5.2% (Energimarknadsinspektionen, 2011). For investments in gas grids, Gustafsson and Ottosson (2012) estimate the real WACC to be 5.5 – 6.7% for 2010. In Papers II – IV, the real discount rate is set to 5 – 6%.

3.2 Environmental systems assessments

The environmental assessment presented in Paper IV is based on the methodology for Life Cycle Assessments (LCA) as described in the ISO standard 14040 – 14044 (ISO, 2006). In a LCA, the environmental impact of a product, process or service is calculated and includes the complete life cycle; from *the cradle to the grave*. The life cycle perspective is often applied in various contexts although not always in full compliance with the ISO standard. For example, the Renewable Energy Directive (RED) requires a certain reduction of GHG emissions when biofuels replace fossil fuels calculated from a life cycle perspective (EU, 2009).

A LCA may include various impact categories such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical creation potential (POCP), toxicity and use of energy (Tufvesson, 2010). The assessment performed in Paper IV focuses on the GWP and the use of energy. Some key parameters in the LCA method are the functional unit, the system boundaries and allocation, which are briefly described here.

Functional unit

In a LCA, the functional unit (FU) defines what is produced in the system analysed to which all input and output can be related. The FU can, for example, be defined as 1 kg of product or 1 MJ of fuel. The definition of the FU should, in addition to quantity, also address the quality of the production and, if relevant, the time horizon (Tufvesson, 2010; Ekman, 2012).

In Paper IV, the FU is defined as 1 MJ of upgraded and compressed biogas distributed via the natural gas grid. The FU could also have included the utilization of the biogas as a vehicle fuel where the environmental impact is presented per km of distance driven instead. This approach is recommended by Sing *et al.* (2010) and Cherubini and Strømman (2011) in order to make possible a comparison and evaluation of different fuels. However, this type of approach also requires assumptions on what kind of vehicle and engine is used as well as driving behaviour and speed. In Paper IV, the primary objective is to evaluate a specific biogas system and not to compare the biogas produced with other vehicle fuels and applications. Thus, the FU does not include the utilization of the biogas, although the result can be used in such analyses.

System boundaries

The technical system boundaries define the system analysed and the processes that are or are not included in the assessment. In Paper IV, the system analysed includes the transport of feedstock, biogas production and upgrading as well as gas grid injection and compression at the filling station. Thus, the environmental impact of the biogas produced is calculated from *well to tank*. System boundaries should also include a geographical area and a time frame. The biogas plant analysed in paper IV was established in 2006, is thus an existing production system having an expected technical life time of approximately 15 to 20 years. It is located in the southern part of Sweden which also defines the geographical system boundary applied. The time frame is also important for the calculation of the environmental impact. For instance, the GWP is calculated using characterisation factors to recalculate emissions of different greenhouse gases into emissions of CO_2-eqvivalents. In a 100 year perspective (GWP_{100}), 1 kg of CH_4 would correspond to 25 kg of CO_2-eqvivalents, while in a 20 year perspective; 1 kg of CH_4 would correspond to 72 kg of CO_2-eqv. (Forster *et al.*, 2007). The production and utilization of biogas could lead to losses of CH_4 but, when produced from manure, biogas production could also reduce CH_4 emissions from conventional manure storage. Thus, this time aspect could make a great impact for the analysis of biogas systems. In general, the 100 year perspective is the most commonly used today (Tufvesson, 2010) and is also applied in Paper IV.

Allocation

The biogas system analysed in Paper IV, produces not only biogas but also digestate that is used as fertilizer. Thus, the environmental impact can be *allocated* between these different products. Such allocation can be based on the physical or the economic properties of the various products. However, according to the ISO-standard (ISO, 2006), allocation should be avoided by system expansion when applicable. This means that the system being analysed is expanded so that it also includes an alternative production of the co-product or a product with a similar function. In Paper IV, system expansion is applied by including the production and application of mineral fertilizers which are replaced by the digestate produced.

Input data

The input data utilised in the LCA in Paper IV are to a high degree based on site-specific measurements in connection to the existing plant. Some average data are also utilised in the assessment, for example regarding energy carriers used in the biogas system. This approach is also known as an accounting LCA, evaluating an existing production system, using average data. However, the LCA also apply a system expansion approach, e.g. by including the mineral fertilizer replaced by the digestate produced, which leads to different indirect environmental effects. The system expansion also include changed in soil properties, both positive and negative, on the local farmland. The quality of the various input data utilised are critical assessed and the consequences of changing input data and key parameters is shown in sensitivity analyses. This is referred as the interpretation phase in LCA methodology (ISO, 2006).

Chapter 4: Incentives and barriers

Biogas can be produced from a wide variety of feedstock, by different actors and on various scales. The biogas produced can be utilized for various energy services by different consumers. The conditions for the use of digestate can also vary depending on feedstock and scale of production. The prospects for biogas production and utilization are thus affected by a wide range of policies, objectives and undertakings within different sectors, resulting in a variety of incentives and barriers (Paper I).

This chapter provides an overview of incentives and barriers, focusing on policy instruments affecting; (i) the production of biogas and (ii) the utilization of biogas. In Paper I, this distinction is justified by the fact that some incentives and barriers affect the availability of different feedstock and production of biogas as such but do not take into account the actual utilization of the biogas. Other incentives and barriers affect the utilization of biogas with minor or no concern of how the biogas is produced. From the time when Paper I was published in 2007, there have been some changes in existing policy instruments as well as suggestions of new or modified ones which in some cases focus on a specific feedstock-utilization pathway. Nevertheless, the distinction between production and utilization of biogas regarding incentives and barriers is still valid in most cases. In this chapter, the current situation is presented, with some recap to the situation described in Paper I.

4.1 Incentives and barriers for biogas production

In this section, incentives and barriers for biogas production are presented based upon three main categories of feedstock; i) waste from households and industries, ii) agricultural residues and iii) dedicated energy crops. Incentives and barriers for the utilization of digestate and for investments in biogas plants, not connected to a specific feedstock, are also addressed.

Waste from households and industries

There is a wide variety of waste and residues where the variable composition affects the prerequisites for using them as a feedstock for biogas production. A common denominator is, however, that this kind of feedstock must be treated or disposed of in some way. Thus, the prospects for biogas production depend on the competitiveness of anaerobic digestion versus other waste treatment methods such as incineration, composting and landfilling. Waste or by-products from the food industry can also in some cases be an attractive feed, posing as a barrier for biogas production (Tufvesson and Lantz, 2012).

In 2011, 51% of Swedish municipal waste was incinerated, 33% was treated by material recirculation, 15% was treated biologically and 1% was landfilled. Compared to the situation in 2004, incineration of waste has increased, but the major difference is the reduction of the amount of waste landfilled and the increased amounts of the biologically treated waste (Avfall Sverige, 2012; Paper I). Landfilling has decreased dramatically the past decade due to the implementation of various policy instruments. In the year 2000, a tax on landfilled waste was introduced and in 2005, landfilling of organic waste was banned (Avfall Sverige, 2012). These instruments favour alternative treatment methods, though not specifically biological treatment or anaerobic digestion.

As presented in Paper I, the dominating treatment method could act as a barrier against alternative methods due to lock-in effects. In order to favour methods other than incineration, Sweden imposed a tax on incineration of waste in 2006. However, this tax was abolished in 2010 since no significant effect on waste production or treatment methods applied could be identified (Avfall Sverige, 2012; SOU, 2009).

Of the municipal waste treated biologically in 2011, 30% was used for biogas production and 70% was composted. Thus, the proportion of the biologically treated waste used for biogas production has increased, as compared to the situation presented in Paper I. However, more than 80% of the composted waste is garden waste. Currently, 40% of the total amount of food waste produced is treated biologically by anaerobic digestion (24%) or by composting (15%) (Avfall Sverige, 2012; SEPA, 2012b). One of Sweden's national environmental objectives states, however, that at least 50% of municipal food waste should be treated biologically by 2018, enabling recycling of the nutrients in the waste. Further, it states that 40% of food waste should also be treated for energy recovery (Miljömålsportalen, 2013a). This is an increase compared to previous objectives, presented in Paper I, and it also favours anaerobic digestion versus composting.

However, the Swedish environmental objectives do not include any regulations, taxes or other incentives. In fact, current gate fees imply that anaerobic digestion is the most expensive treatment method, see Table 3, which was also found in Paper I. Despite this economic barrier, anaerobic digestion of municipal waste is increasing and the Swedish Waste Association reports that a majority of municipalities, that have not implemented source separation of food waste already, is planning to do so (Avfall Sverige, 2012). In this context, it is worth mentioning that municipalities in Sweden are responsible for the collection and treatment of household waste and the cost is covered by fees, decided by the local authorities.

Table 3: Average gate fees for municipal waste for different treatment methods in Sweden in 2011 (Avfall Sverige, 2012) (maximum and minimum values within brackets)

Treatment	**Gate Fees (€/t)**
Anaerobic digestion	59 (24 – 73)
Composting	54 (38 – 74)
Incineration	51 (42 – 86)

Regarding industrial waste, gate fees are normally not publically available. However, the fact that by far the greatest part of the organic industrial waste in Sweden is treated by anaerobic digestion (Jenssen *et al.*, 2011; SEA, 2012d) indicates, that the current conditions are economically feasible, both for the waste producer and for the biogas producer.

Agricultural residues

Residues from the agricultural sector, such as manure and crop residues, are produced regardless of whether they are used for biogas production or not. However, there is no legislation requiring any treatment of manure and crop residues. In fact, one of the conclusions in Paper I was that there were few and weak incentives for biogas production from manure and crop residues despite the environmental benefits achieved in biogas systems based on these feedstocks. Generally, biogas production based on feedstock from the agricultural sector also suffers from limited profitability under current Swedish conditions (Paper II and III).

However, regarding manure for biogas, efforts have been made to increase the incentives for such systems over recent years. Since 2009, a specific investment subsidy is available for biogas plants where manure is the dominating feedstock. The investment subsidy has been implemented within the EU-funded Rural Development Program, which means that it is available only to farmers. Also, the maximum subsidy is limited to 200 000 €, or 30 – 50% of the investment (SJV, 2009). Thus, it does not affect the prospects for large-scale production of biogas from manure, nor does it increase the incentives for actors outside the agricultural sector to invest in such production. In 2010, the Swedish Energy Agency also suggested a production subsidy for biogas from manure corresponding to approximately 6.2 €/GJ (SEA, 2010). So far, this subsidy has not been implemented. However, in December 2012, the Swedish EPA suggested that this policy instrument should be further analysed as one measure to reduce methane leakage from manure storages, and contribute to the efforts of attaining zero net emissions of GHGs in Sweden by 2050 (SEPA, 2012c).

The economic effect for the biogas producer of implementing such policy instrument has been analysed in Paper II and III, and is further discussed in chapter 5. For comparison, Germany has implemented a feed-in tariff of 0.25 €/kWh_{el} for electricity based on biogas from manure when produced in small- scale applications (<75 kW_{el}) (EEG, 2012). Assuming an electric efficiency of 30%, see chapter 5, this corresponds to 21 €/GJ biogas. For larger installations, the feed-in tariff is slightly reduced.

One barrier identified for biogas from manure is related to the utilization of the digestate. As presented in Paper II, the prospects for biogas production from manure could be improved, by efficiency of scale, if the biogas plant uses manure from several farms. However, such an approach requires that the manure is hygienized according to EU regulation (EU, 2002) and as implemented in Sweden (Paper II). Due to the extra cost for such a hygienization unit, this could be a barrier against small and medium-size biogas plants based on manure.

Dedicated energy crops

The incentives and barriers for utilization of energy crops for biogas production, or any production of energy carriers based on crops, has changed significantly over time. Previously, there were several policy instruments favouring the production of energy crops, as described in Paper I. Within the Common Agricultural Policy (CAP), cultivation of energy crops was granted a subsidy of up to 45 €/ha. Currently, there are no production subsidies available for energy crops suitable for biogas production in Sweden, neither are requirements on a certain share of set-aside land applied. Thus, there are no policy instruments favouring the cultivation of energy crops as compared to other crops. The Swedish Agricultural Agency suggests, however, a new policy instrument within the Rural Development Program favouring ley crops in the southern part of Sweden. The suggested cultivation subsidy is approximately 300 €/ha. The subsidy is motivated by reduced leaching of nitrogen, improved soil quality and biodiversity, but also allows production of energy, thus acting as an incentive for biogas production from ley crops (SJV, 2012). However, as presented in Paper III, this incentive might, not be big enough if the biogas is to be utilized as a vehicle fuel.

There has also been a shift in EU Policy from a situation where energy crops were considered as one of the key parameters to reach the Union's objectives on renewable energy (EC, 1997), to a suggestion from the European Commission that biofuels from cereals and other starch-rich crops, sugars and oil crops should be limited in favour of biofuels from waste, residues and non-food crops (EC, 2012a). The background to this suggestion is the debate on indirect land use changes (iLUC) addressing the issue of energy crops grown on agricultural land and used for biofuel production, see also Chapter 6. However, perennial ley crops are apparently not included in this limitation, thus presenting a potential incentive for biogas production compared to other kinds of biofuels based on starch, sugar or oil crops.

Biogas production

As presented in Paper I, subsidies for investments in biogas production and utilization were previously available in Sweden within the Climate Investment Program (KLIMP), and before that the Local Investment Program (LIP). An evaluation of the climate investment program states that the investment subsidy was important for many projects both from an economic point-of-view and as a "moral", support sending the signal that "biogas is seen as a desired and preferred technique at a national level" (Tamm and Fransson, 2011).

An additional investment subsidy, introduced in 2009, focus specifically on investments that could contribute to an efficient and increased production, distribution and utilization of biogas and other renewable energy gases (SFS, 2009a).

This policy instrument only subsidise the additional cost for new technology compared to conventional technology. However, biogas production in continuous stirred tank reactors (CSTR) or upgrading of biogas with the technologies normally used is not considered as new technology even thou such investments are not commercially competitive.

Thus, the subsidy focuses on improvements of existing biogas systems and new technical solutions, such as, for example, the production of liquefied biogas (LBG). Since the subsidy does not consider the economic challenges for biogas production based on proven technology but using feedstock from the agricultural sector, as presented in Paper II and III, it is difficult to see how it should contribute to a significant increase of biogas production in Sweden.

Utilization of digestate

As presented in chapter 2, almost all digestate produced at Swedish biogas plants outside the waste water treatment sector are utilized as fertilizer. Previously, there was a tax on nitrogen in mineral fertilizers (Paper I), favouring alternative organic fertilizers such as digestate. However, this tax was abolished in 2009 (SFS, 2009b) which reduced the price of commercial fertilizers, thus also reduced the economic benefits of using digestate.

4.2 Incentives and barriers for biogas utilization

In this section, an overview of incentives and barriers for biogas utilization, with its focus on policy instruments, is presented for the following utilization pathways; i) heat, ii) combined heat and power and iii) vehicle gas. There are also some general policy instruments, not focused on a specific kind of utilization, such as the energy- and CO_2-taxes applied in Sweden and the EU Emissions Trading System (EU ETS).

In 2009, the European Union decided that 20% of the gross energy supply in the Union should be renewable in 2020, with a national target for Sweden at 49%, as presented in the Renewable Energy Directive (RED) (EU, 2009). However, the Swedish Government (2009a) suggests that 50% of the gross energy supply in Sweden should be renewable in 2020. Also, the Swedish parliament has decided that GHG emissions should be reduced by 40% by 2020 compared to the emissions in 1990, excluding the sectors included in the EU ETS (Miljömålsportalen, 2013b).

In the EU ETS, a maximum amount of CO_2, a cap, is allowed to be emitted from power plants and various industries in the EU. The system covers approximately 45% of the total GHG emissions in the Union (EC, 2012b). In this system, some emission allowances, each giving the right to emit one tonne CO_2, will be auctioned and some will be granted to polluters free of charge. Each year, participating actors must report their emissions and deliver the corresponding amount of emission allowances. In order to fulfil their obligation, actors can buy and sell emission allowances. In 2008, the first year after implementation, the market price varied from 20 – 30 €/t CO_2. Thereafter, the price dropped to 5 – 10 €/t in 2012 due to a surplus of allowances (EC, 2012b). Currently, the market price is approximately 6 €/t on the spot market (EEX, 2013) which corresponds to approximately 0.4 €/GJ natural gas and 0.5 €/GJ heating oil (SEPA, 2013). The fine for not surrendering enough allowances is 100 €/t in 2013 (EC, 2012b).

For comparison, the CO_2 tax applied for fossil fuels in Sweden was just over 110 €/t in 2012 (STA, 2012). Fossil fuels are also subject to an energy tax, as presented in Table 4. These taxes affect all areas of utilization but to different degrees. Fossil fuels utilized within the domestic sector are charged the full tax, as well as VAT. The agricultural and the industrial sector are, however, entitled to a tax reduction of 70% for fuels not used as vehicle fuel, and some of the tax for diesel used in working machines in the agricultural sector is reimbursed. In addition, industries participating in the EU ETS are entitled to a reduction of 100% of the CO_2 tax (SFS, 1994).

To summarize, the policy instruments described here favour renewable energy in general, as compared to fossil energy carriers, and especially renewable energy used as fuel for transportation or within the domestic sector.

Table 4: Energy and CO2 taxes in Sweden in 2013 (€/GJ) (SFS, 1994)

Fuel	Energy	CO_2	Total tax in different sectors		
			Domestic	Agricultural	Industry
Heating oil	2.4	9.1	14.3	3.4	0.7 [b] – 3.4
Petrol	10.1	8.1	22.7	18.2	18.2
Diesel	5.2	9.1	17.8	9.3	14.2
Natural gas[a]	–	4.9	6.1	4.9	4.9
Natural gas	2.4	6.1	10.6	2.6	0.7 [b] – 2.6

[a] When used as a vehicle fuel
[b] Included in the EU ETS

Heat

As presented in chapter 2, production of heat was previously, the most common utilization pathway for biogas in Sweden. The seasonal changes in heat demand can, however, pose a barrier for biogas as compared to liquid and solid fuels, which are easier to store. This is also indicated by the previously high proportion of flared biogas in combination with a high production of heat, (SEA, 2012d). Heat production in the domestic sector, where the tax exemption has the highest impact, is also dominated by solid biomass-based energy carriers, such as wood chips and pellets, and electricity. These systems may act as a techno-economic barrier to an increased utilization of biogas for heat production (Paper I). Also, biogas utilization for heat, not produced on site, normally requires investments in gas grids, an infrastructure which is currently available only in parts of Sweden. However, at some locations, biogas could be injected into the existing gas grid and thereby replace the natural gas used within the domestic sector, which amounted to 8.8 PJ in 2011 (SEA, 2012b). There are, however, some potential barriers to biogas distributed via the natural gas grid, which is described later in this section.

Combined heat and power

Power production in Sweden is not subject to any energy- or CO_2 taxes since the consumer of the electricity pays a tax on the electricity used (Paper I). Also, heat from combined heat and power (CHP) in power plants included in the EU ETS is only charged 30% of the energy tax and no CO_2 tax (SFS, 1994). Thus, renewable power production cannot be favoured by a tax reduction compared to fossil fuels. Instead, renewable power production is favoured by a certificate system which was implemented in Sweden in 2003. Since January 2012, the electricity certificate system also includes Norway. This is a market-based system aiming at an increased production of renewable electricity, where one MWh of electricity entitles the producer to one certificate. These certificates can be sold to the highest bidder. A demand is established by a quota obligation for electricity suppliers. If the electricity supplier fails to fulfil his quota obligation, he must pay a quota obligation charge which is 150% of the average market price the previous year. From 2003 – 2011, the annual, volume weighted, average market price varied from 18 – 31 €/MWh_{el} (SEA, 2012e). For the biogas producer, the economic value of this policy instrument thus depends on the current market price as well as the electricity generation efficiency in the power production system used. As presented in chapter 5, the electric efficiency in micro- and small-scale, biogas-based CHP applications could vary from approximately 30 – 40% while large-scale applications could reach well over 50%. If biogas is utilized for CHP with an electric efficiency of 40%, the value of the electricity certificates corresponds to approximately 2.2 €/GJ biogas, given a market price of 20 €/certificate.

When producing CHP, local utilization of energy is not as important as in the production of heat only since electricity can always be sold via the electric grid. However, a limited local demand for heat could act as an economic barrier to the production of CHP from biogas.

Vehicle fuel

In addition to the objectives on renewable energy in general presented earlier, the EU has also decided that 10% of the energy used in the transportation sector shall be renewable by 2020 (EU, 2009). The Swedish Government (2009b) also suggests that Sweden should have a vehicle fleet independent of fossil fuels in 2030.

To be accounted for, when it comes to the fulfilment of the 10% target, renewable vehicle fuels must fulfil some sustainability criteria's. In Sweden, these criteria's are also mandatory in order to receive exemption from energy and CO_2 taxes (SFS, 2010). In brief, these criteria set requirements on how and where biomass feedstock is produced as well as the resulting reduction of GHG emissions when compared to fossil vehicle fuel. Currently, the reduction of GHG emissions must reach 35% which is increased to 50% in 2017. The biodiesel, ethanol and biogas currently used in Sweden reduce GHG emissions by 38%, 62% and 71% in average (SEA, 2012a). Thus, the current production of ethanol and biogas would also be sufficient in 2017 but not the current production of biodiesel.

Biogas from waste, manure and crop residues is also favoured in the RED by which biofuels produced from such feedstock is counted twice when countries report their share of renewable energy in the transportation sector (EU, 2009). The European Commission also suggests in a revised version of the RED that biofuels from manure and straw should be counted four times instead of twice which, if implemented, could increase the prospects for biogas production from such feedstock (EC, 2012a). Still, this mechanism only affects the accounting of the share of biofuels and has no direct effect on biogas production, unless additional policy instruments are implemented.

There is also an additional policy instrument currently being investigated on a national level which consists of a quota system for biofuels. The Swedish Energy Agency (SEA, 2009) has delivered a suggestion on how this system could be designed, including separate quota obligations for petrol and diesel and the introduction of an energy tax also for renewable, low-blended fuels (as presented above). However, the final presentation of this potential quota system is so far not publically available, so the potential impact is uncertain.

However, the Swedish parliament has decided that ethanol and biodiesel should be subject to 11% and 16% respectively of the current energy tax. Also, considering low blended biofuels, the tax exemption should only be applied up to 5% of the total amount of fuel (petrol or diesel). Thus, ethanol and biodiesel above this limit does not receive any tax exemption. For biogas and high blend fuels such as E85, the tax exemption is still applied (SFS, 1994).

The suggestion from the Energy Agency also states that biogas can be used to fulfil the quota obligation for both kinds of fuels. The suggestion also includes the opportunity to count biogas from waste and residues etc. twice, in accordance with the RED (EU, 2009). Thus, it appears that this shift in policy instruments could favour high blend biofuels and biogas. However, the Swedish Gas Association has expressed concerns that there will be a disadvantage for biogas since oil companies could fulfil their quota obligation with low-blend biofuels only. Also, although positive for biogas, the double counting of selected biofuels reduces the actual amount of biofuels introduced to reach the target share of renewable vehicle fuels.

Barriers to the utilization of biogas as a vehicle fuel, as identified in Paper I, are, for example, the additional cost for adapted vehicles, the limited number of filling stations and the competition with other renewable alternatives. Meeting these barriers, several policy instruments have been implemented in addition to the tax exemptions presented here. Some of these instruments favour renewable vehicle fuel in general, and some are focused on biogas in particular (Paper I).

The barrier in the form of additional investment costs for bi-fuel vehicles (vehicles that can use vehicle gas and petrol), compared to conventional vehicles, has been addressed by incentives such as investment subsidies, tax reduction, free parking and exemptions from congestion charges as described in Paper I. However, investment subsidies and exemption from congestion charges are not available anymore, and the reduced tax for cars provided by the employer is available only until the end of 2013 (Skatteverket, 2012). Thus, several incentives, reducing the price barrier between bi-fuel and conventional passenger cars are no longer available.

This additional cost for bi-fuel vehicles is also reflected in the price for vehicle gas at public filling stations which is approximately 10% and 20% lower, respectively than the price of diesel and petrol, per energy unit (SPBI, 2013a; Gasbilen, 2013).

The limited number of filling stations for renewable vehicle fuels was also identified as a barrier in Paper I. In 2005, there were, for instance, only 62 filling stations for vehicle gas and 300 filling stations selling E85, as compared to the 3 839 filling stations in total (SPBI, 2013b). To reduce this barrier, an obligation for large petrol filling stations to sell a renewable vehicle fuel was introduced in 2006 (SFS, 2005). This obligation increased the number of filling stations supplying E85 to almost 1 700 stations in 2011 (SPBI, 2013b). However, few filling stations chose vehicle gas as their renewable fuel due to the extra investment compared to an E85 pump. Therefore, a special investment subsidy was implemented for investments in vehicle gas filling stations, which was available until 2009 (SEPA, 2010). In the end of 2010, when these subsidised filling stations should be in operation, there were 122 filling stations for vehicle gas. Since then, another 10 filling stations have been constructed (SPBI, 2013b). Thus, some filling stations are still being established even without an investment subsidy.

In a European perspective, biogas in combination with natural gas is seen as one of several alternative fuels which increased utilization could reduce the transportation sectors dependence of oil as well as reduce GHG emissions. To reduce the barriers connected to the limited infrastructure, the European Commission has also proposed a new directive on the deployment of alternative fuels infrastructure including an obligation for member states to ensure that filling stations for CGB are publically accessible with a maximum distance between stations of 150 km (EC, 2013a; b).

Gas grid injection

The Swedish natural gas grid is located on the west coast and is currently used to transport approximately 60 PJ of natural gas annually. Regardless of the final utilization, upgraded biogas could be injected into the natural gas grid and distributed to the final consumer (assuming that a "green gas system" is applied to keep track of injected and sold amounts of biogas). Thus, the local biogas producer could reach a regional market and is not dependent on the local market. As presented in Paper I, actors within the natural gas industry also call attention to the synergetic effects between biogas and natural gas. There are, however, some technical limitations which may act as a barrier to the distribution of biogas via the natural gas grid. When biogas is injected into the natural gas grid, the heating value must be adjusted so that it corresponds to that of the natural gas distributed in the grid. This is achieved by addition of LPG (Liquefied Petroleum Gas), resulting in an additional cost and environmental impact (Paper IV, Nelsson, 2012).

Also, the gas grid consists of one high-pressure grid and a number of low-pressure grids to which most natural gas consumers are connected. Currently, biogas is only injected into these low pressure grids. The amount of gas distributed in these low-pressure grids varies between different grids but also over time. A biogas plant, which normally seeks an even production throughout the year, must thus consider the base load in the gas grid in question since it is currently not possible to inject more gas than is actual used in that specific grid. Thus, distribution of biogas via the natural gas grid may in some cases require additional investments in gas grids and pressurization in order to inject the biogas into the high-pressure grid, even though a local distribution grid may be close by (Colnerud Granström, 2010; Nelsson, 2012). This additional cost as well as the LPG addition could act as a barrier as compared to alternative distribution alternatives described in chapter 2.

Chapter 5: Techno-economic assessments

Based on the findings in chapter 2, 3 and 4, it can be concluded that feedstock from the agricultural sector will play an important role in increasing the Swedish biogas production. The current magnitude of such production indicates, however, that existing incentives, reviewed in chapter 4, are not strong enough to overcome potential barriers.

The Swedish biogas potential from manure originates from thousands of farms spread across the country, all with different features regarding the amount of manure, internal energy demand and prospects to find external demand for the biogas produced. In some parts of Sweden, livestock production is concentrated to a relatively small area with many producers and a high density of animals. In such areas it is possible to use manure from several farms in one biogas system. Such a system could consist of one large-scale co-digestion plant to which manure is delivered from a number of farms and the biogas is utilized for CHP or upgraded and sold as a vehicle fuel. A second option is that several farm-scale biogas plants are connected by a gas grid to one upgrading plant or a CHP plant. A third option is farm-scale biogas plants where the biogas is utilized on site which could also be applied in areas with low density of animals.

Crop residues have similar prerequisites as are applicable for manure concerning the availability of feedstock, which is produced independent of any biogas production, all over the country. Dedicated biogas crops could also be grown in all parts of the country although some crops could be more regionally adapted. However, biogas crops and crop residues require transportation from the field to the biogas plant, even in the case of farm-scale biogas plants. Thus, the potential benefits of farm-scale production of biogas are not as clear when it comes to biogas from crops and crop residues as compared to biogas from manure. Otherwise, similar biogas systems could be applied for this kind of feedstock, as for manure.

In order to explore the economic feasibility of biogas produced from agricultural feedstock, techno-economic assessments were performed for selected biogas systems based on manure (Paper II and III) and dedicated energy crops and crop residues (Paper III).

The overall objective of these studies was to assess the conditions under which biogas production and utilization from agricultural feedstock could be economically feasible. Another aim was to evaluate the impact of different policy instruments, existing and suggested. To further increase the understanding of the economic conditions for different biogas systems, each study also included more specific issues. In Paper II, the features of different CHP technologies, efficiency of scale and process temperature in the biogas reactor were also evaluated. In Paper III, different energy crops and crop residues were compared based on their properties and how these properties affect the biogas process. Also, the impact of the economic value of the digestate on the overall economic performance was evaluated.

The techno-economic assessments performed in Paper II and III, are here presented as the following cases:

Case 1: Farm-scale production of biogas, based on liquid manure, utilized for CHP (Paper II).

Case 2: Expanded farm-scale production of biogas, based on liquid manure from 2 – 3 farms, utilized for CHP (Paper II).

Case 3: Large-scale production of biogas, based on liquid manure from several farms, utilized for CHP (Paper II).

Case 4: Large-scale production of biogas, based on liquid and solid manure, utilized as a vehicle fuel (Paper III).

Case 5: Large-scale production of biogas, based on various energy crops and crop residues, utilized as a vehicle fuel (Paper III).

5.1 Biogas from manure, crops and crop residues

Feedstock cost

Techno-economic assessments of farm-scale biogas plants normally assume that manure is available free of charge and that existing manure storage tanks are used to store digestate. When manure is used in biogas plants not located at a farm, it is often assumed that the biogas producer can "borrow" the manure from the farmer, assuming that the cost of transportation of manure and digestate is covered. However, at some farms investments in additional storage tanks, reinforcement of access roads, etc. may also be necessary. It could also be argued that the added truck traffic may cause inconvenience. Thus, as long as no tax, fee or other policy instrument are imposed to limit GHG emissions from manure, an economic incentive will probably be necessary to motivate the vast majority of farmers to deliver, or "lend out" their manure.

Dedicated energy crops are produced for biogas production only. Thus, the biogas producer must cover all costs associated with the feedstock production, including the farmer's potential profit margin from alternative crops. The biogas producer must also cover the cost of transport and storage (ensiling in most cases) which could be substantial, as presented in Gissén *et al.* (2012). If biogas production is based on crop residues such as sugar beet tops, the biogas producer must cover only the additional cost for gathering, transport and storage. However, as presented in Figure 9, these costs could be comparative to those of dedicated energy crops.

The total feedstock cost, including storage and transport, for various energy crops, crop residues and manure are shown in Figure 9. Comparing the feedstock cost for manure, energy crops and crop residues, it is clear that manure is considerably cheaper. For example, manure can be transported for almost 150 km and still be cheaper than the cheapest energy crop evaluated in Paper III. However, if the total biogas production cost, including cost of capital, process energy, operation and maintenance etc., is taken into account, the difference is reduced.

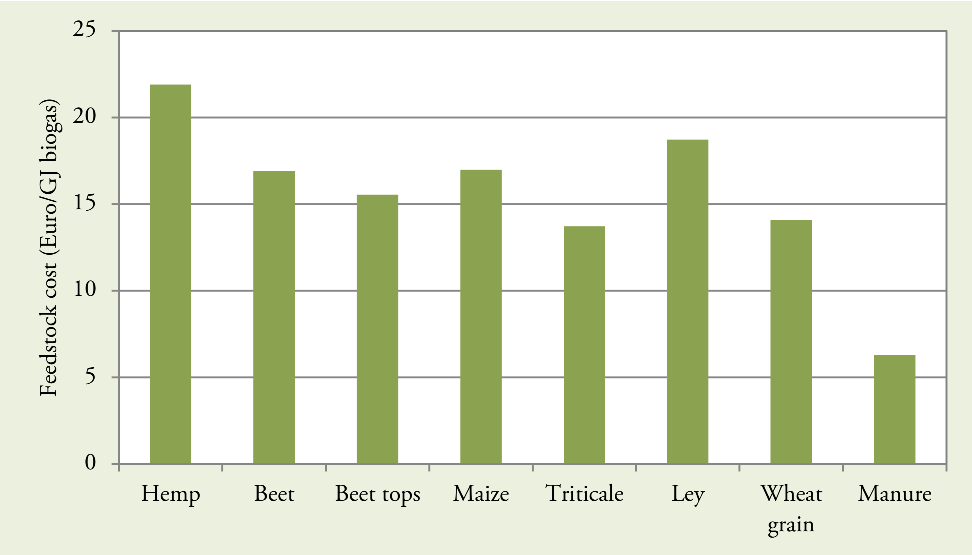

Figure 6: Feedstock cost for various biogas crops and manure transported (Paper III)

Investment cost

The biogas plants analysed, as described in Paper II and III, are all based on the continuous stirred tank reactor (CSTR). Comparing similar biogas plants, efficiency of scale has a great effect on the investment cost (Christensson *et al.*, 2009; Lantz and Börjesson, 2010; FNR, 2010; Urban *et al.*, 2008), also demonstrated in Figure 10. However, when comparing actual biogas plants, the efficiency of scale might not be so clear since choices regarding plant design, level of automation and redundancy, the kind of feedstock that can be treated and installation of pre-treatment equipment etc. all effect the investment cost. This is demonstrated in Paper II, where biogas plants on different scales and with different features is compared. For example, in case 1 and 2, where biogas is produced in a farm-scale plant, the investment cost is based on a basic biogas plant, designed to treat liquid feedstock only, and using existing infrastructure such as storage tanks, access to the electric grid as well as personnel facilities. In case 3, the biogas plant has the same general design but also a hygienization unit and is built as a stand-alone facility, increasing the investment as compared to farm-scale biogas plants. Thus, the investment cost is slightly higher per m^3 reactor even though the reactor is almost twice the size of the reactor in case 2.

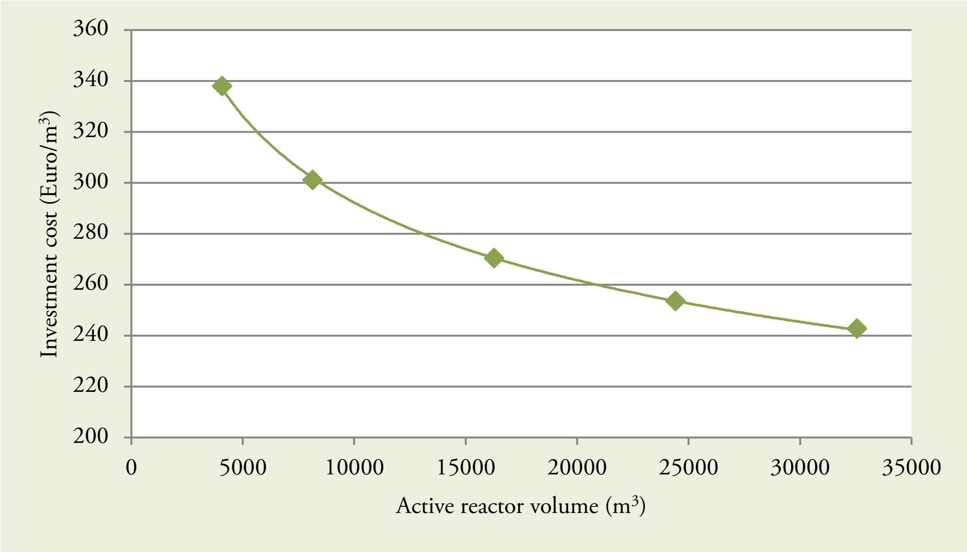

Figure 7: Investment cost for biogas plants designed to treat energy crops (Paper III).

Cost of operation and maintenance

In addition to the cost of capital and feedstock, there are also other costs related to the production of biogas such as process energy, personnel and maintenance. In the analyses presented in Paper II and III, electricity is bought from the grid although it could also be produced internally. When the biogas produced is utilized for CHP (Paper II), process heat is delivered from the CHP unit. When biogas is utilized as a vehicle fuel (Paper III), process heat is assumed to be produced in a wood chip boiler.

The cost of operation and maintenance, for example, depends on the feedstock utilized, the design of the biogas plant and the quality of the equipment installed. For example, a high level of automation and redundancy in the biogas plant design could increase the investment cost while decreasing the cost for personnel and downtime. Thus, the cost will vary for different biogas plants. In the literature reviewed, the cost of operation and maintenance, excluding process energy but including personnel, is set to 4% – 10% of the investment (Paper II and III).

5.2 Combined heat and power

Cogeneration, or the production of CHP, is a process where heat and power are produced simultaneously. Thus, overall efficiency can be enhanced compared to processes in which the same amount of heat and power is produced separately (EU, 2004; IVA, 2002; IEA, 2009). In Swedish legislation, CHP is defined as a process in which the heat produced is utilized and the electric efficiency is at least 15% (SFS, 1994). In this thesis, the definition of CHP is applied also when only a part of the heat produced is utilized as process heat in the biogas process.

In Europe, more than 50% of the total biogas-based power production takes place in Germany where biogas was produced at more than 7 200 agricultural biogas plants in 2011 (Linke, 2012). For individual biogas plants, the installed capacity can vary considerably although few biogas plants exceed 1 MW_{el} (FNR, 2005; 2009). The average installed load has, however, increased from 60 kW_{el} in 1999 to 125 kW_{el} in 2004 and 400 kW in 2011 (FNR, 2012). Thus, CHP from biogas is mainly produced in micro-scale (<50 kW_{el}) and small-scale (<1 MW_{el}) plants according to the definition in EU (2004). It is, however, also possible to utilize biogas in large-scale power plants, with an installed capacity of several 100 MW_{el}.

There are several technologies available for micro- and small-scale production of CHP from biogas. Most common are internal combustion engines with sparkplug ignition (SI) or compression ignition (CI) as described in Paper II. Other applications available on the market are micro gas turbines, Stirling engines and fuel cells. As presented in Figure 10 and 11, efficiency varies for different engines and different scale. Typically, SI engines have an electric efficiency of 30% – 40% and CI engines have, in general, a somewhat higher efficiency than SI engines. Also, as shown in Figure 11, a higher electric efficiency normally results in a lower thermal efficiency.

Comparing SI and CI engines, it should be noted that a mix of air and biogas does not contain enough energy to ignite when compressed. Thus, the CI engine, also known as the dual-fuel engine, requires an ignition fuel, representing less than 10% of the fuel in a modern engine (Paper II). Normally, this fuel is either diesel, biodiesel or in some cases vegetable oil. In Paper II, fossil diesel was applied as ignition fuel since it was previously found to be the most economic choice under Swedish conditions (Lantz, 2010).

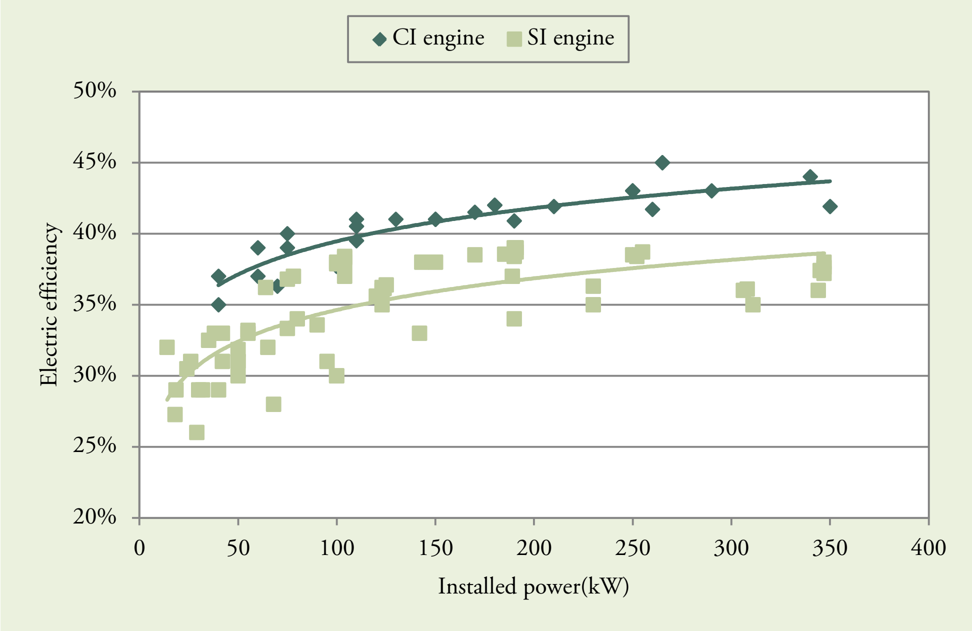

Figure 8: Electric efficiency for compression ignition (CI) and sparkplug ignition (SP) engines (Paper II)

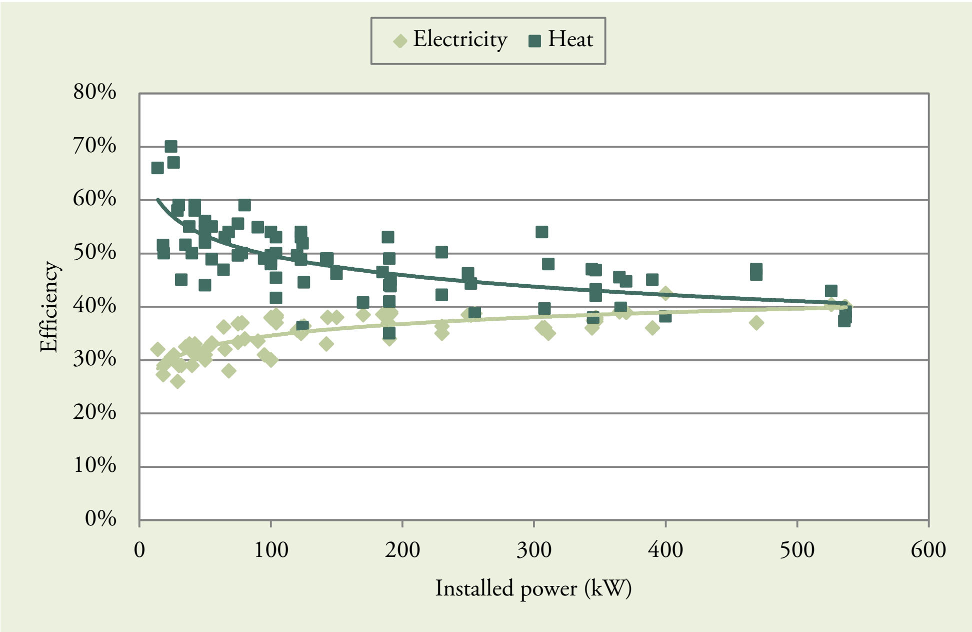

Figure 9: Electrical and thermal efficiency of sparkplug ignition (SI) engines (Paper II)

Revenues from electricity, electricity certificates and heat sales

Electricity and electricity certificates can always be sold on the market although the price may vary considerably over time, as presented in Figure 13. The economic value may also be higher if the biogas producer can use the electricity internally. In that case, reduced transmission fees and the electricity supplier's profit margin could be added to the economic value. Also, feed-in of electricity on the low voltage grid entitles the producer to a small fee from the grid operator (Paper II).

In Paper II, calculations are performed for a combined value of electricity and electricity certificates of 80 – 100 €/MWh$_{el}$ when the production is based on biogas only. In the case of dual-fuel, the number of granted electricity certificates is reduced in relation to the amount of diesel used in the CI engine.

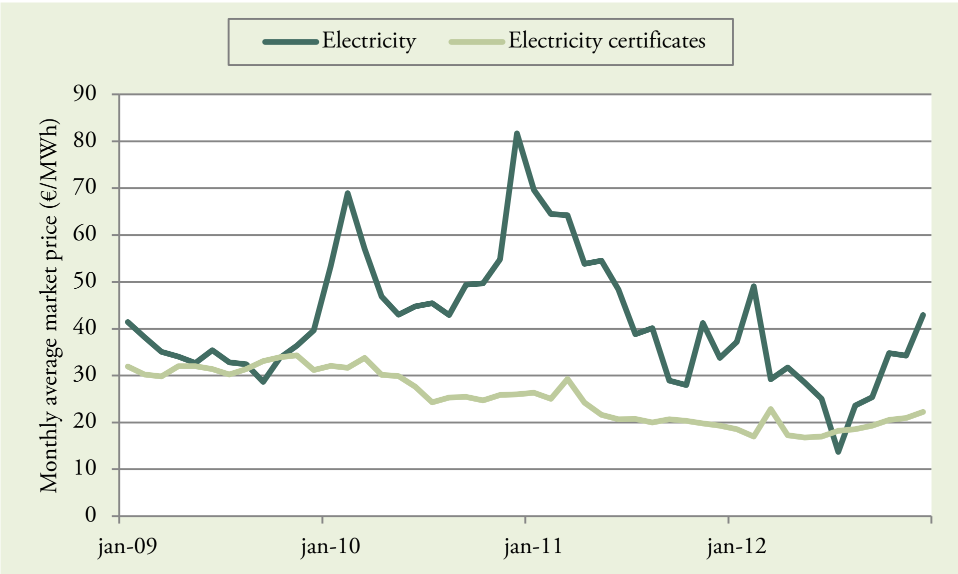

Figure 10: Average market price for electricity and electricity certificates in 2009 – 2012 (Nordpool, 2013; SVK, 2013).

Revenues from the heat produced depend on the energy carrier that is replaced and how much of the heat that can be utilized. During the summer, the income from the heat produced may be negligible due to limited heat demands, as mentioned in chapter 4. Also, the amount of heat available could vary depending on how much is used internally at the biogas plant. In Paper II, the result is presented, assuming a value of the available heat (after heating the biogas process) of 0 – 11 €/ GJ.

Sparkplug ignition, compression ignition or micro gas turbines

In Paper II, different CHP technologies are compared under Swedish conditions. The result shows that the feasibility is affected by a number of parameters which can vary between different locations but also over time. For example, a high electricity price favours technologies with a high electric efficiency while favourable conditions for utilization of heat could favour CHP technologies with a high total efficiency. Also, the cost of ignition fuel and the income from electricity certificates affect the comparison of SI and CI engines, where the CI engine is favoured by a low cost for the ignition fuel and a low income from electricity certificates. The result is also affected by the cost of operation and maintenance, where the cost of operation and maintenance of the micro gas turbine could compensate for the lower electric efficiency as compared to SI and CI engines. For example, with the lower electricity income applied in Paper II, the micro gas turbine was closest to profitability, but with a higher income from electricity and electricity certificates, other technologies were found to be more feasible. Thus, it was not possible to identify a specific technology with the highest economic outcome at all times. However, on the assumptions made in Paper II, it was found that the SI engine was the best choice for the farm-scale biogas plant utilizing manure from one farm only (Case 1).

5.3 Vehicle gas

Biogas produced from energy crops and manure has a methane concentration that typically varies in the range of 50 – 65%. Thus, the biogas must be upgraded to fulfil the Swedish standard for vehicle gas.

Currently, there are several upgrading technologies available on the market and used in Sweden today, such as the water scrubber, the pressure swing adsorption and the chemical scrubber (Paper III). Other technologies currently available are based on membranes or cryogenic separation (IEA, 2013).

Although is it possible to upgrade biogas to vehicle fuel in farm-scale plants, and that there are such applications available on the market today, the efficiency of scale favours large-scale upgrading plants (Biogas Syd, 2011; Paper III). In Figure 14, the upgrading cost is presented for different technologies used in Sweden today, indicating minor differences between different technologies from an economic point-of-view. However, the efficiency of scale is clear up to an installed biogas treatment capacity of approximately 1 000 m^3/h. A further increase in scale seems to have a limited effect on the upgrading cost. As summarised in Table 5, parameters such as process energy requirements and methane losses vary depending on technology, which affects the feasibility of different technologies when site-specific conditions are considered. For example, the chemical scrubber has a relatively high energy demand albeit mostly as heat. Thus, this technology is favoured if heat is available at a low cost and the cost of electricity is high. The comparison is also affected by the possibility to utilize waste heat, which is especially important for the chemical scrubber, although other technologies can also deliver waste heat. Finally, the methane losses and the methane concentration in the upgraded biogas affect the outcome of a techno-economic comparison. A high market price of methane favours solutions with low methane losses, increasing the amount of methane that can be sold. With a lower price on methane, these losses are not as important in a techno-economic assessment, but minimizing them will still be important to attain a good environmental performance. The methane concentration is especially important when the biogas is injected into the natural gas grid, as described in chapter 2 and 4. A high methane concentration reduces the need for additional LPG, which is an economic as well as an environmental burden as described in chapter 6 and Paper IV.

In this thesis, the techno-economic analysis in Paper III includes a chemical scrubber and the environmental assessment in Paper IV is performed for a biogas plant using the pressure swing adsorption (PSA).

Table 5: Process energy requirements and methane losses for various biogas upgrading technologies (Paper III; Petersson and Wellinger, 2009)

	Electricity (kWh/m^3)	**Heat (kWh/m^3)**	**Methane losses (%)**	**Methane content[a] (%)**
Water scrubber	0.2 – 0.9		< 1 – 4.7	>96
Pressure swing adsorption	0.24 – 1.0		< 3 – 10	>96
Chemical scrubber	0.12 – 0.15	0.44 – 0.55[b]	< 0.1	>99

[a] In the upgraded gas
[b] Of which 70 – 80% could be available as waste heat

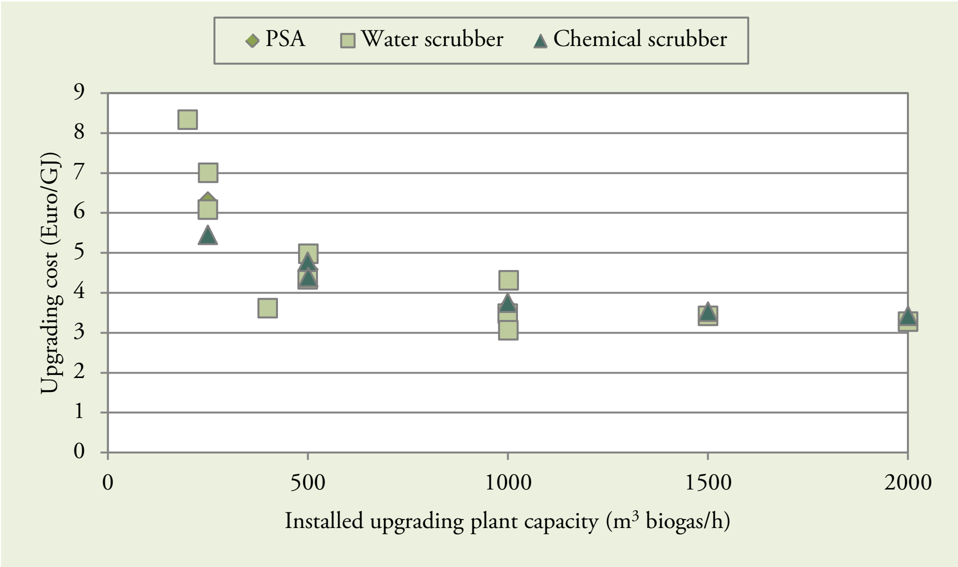

Figure 11: Cost for upgrading biogas by different technologies and at different scale (Paper III)

Revenues from vehicle gas sales

When biogas is utilized as a vehicle fuel, the revenue is affected by the current market price for alternative fuels, both fossil and renewable. In Figure 14, the average market price for vehicle fuel sold at public filling stations is presented. However, these prices include distribution, filling stations and profit margin for the distributer. In Paper III, it is assumed that the biogas producer is paid 20 €/GJ for CBG at the biogas plant, indicated by CBG* in Figure 14. This represents 60% of the price paid by the consumer excluding VAT. Thus, the competitiveness of biogas as a vehicle fuel is not only connected to a cost-efficient production of biogas, but also to a cost-efficient distribution to the final consumer.

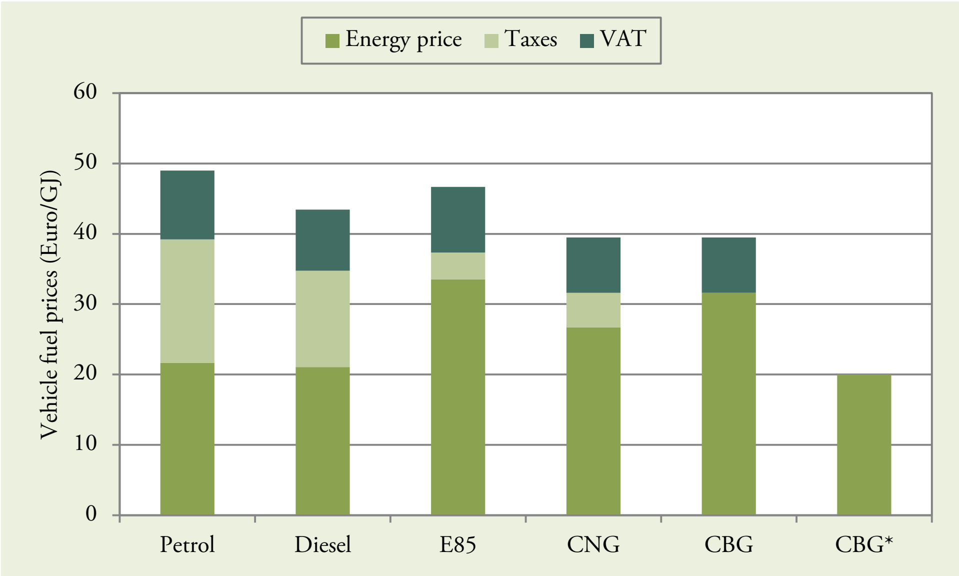

Figure 12: Average price at public filling stations in 2012 for liquid fuel and in January 2013 for gaseous fuel (SPBI, 2013a; Gasbilen, 2013) and assumed market price for CBG* at the biogas plant (Paper III).

5.4 Digestate

The digestate produced from anaerobic digestion includes all nutrients in the utilized feedstock. Given that there are no contaminants, the digestate could be used as fertilizer which is also applied for almost all digestate currently produced in co-digestion plants as presented in chapter 2. When addressing the economic value of digestate from agricultural feedstock, it is relevant to distinguish digestate based on manure from digestate based on crops.

In the anaerobic digestion process, some of the organically bound nitrogen is mineralized to NH_4-N which is easier available for crops (Jarvis and Schnürer, 2009). Other nutrients such as Phosphorus and Potassium are not affected. Thus, when biogas is produced from manure, already used as a fertilizer, the economic value is mainly increased due to the higher proportion of NH_4-N. If biogas production is based on liquid and solid manure as in Paper III, the economic value of the digestate is also increased by the reduced cost for spreading liquid digestate compared to solid manure. When biogas is produced from energy crops, the feedstock was previously not used as fertilizer. Thus, the value should include all nutrients available. However, the value should also be reduced by the additional cost of storage and spreading compared to when mineral fertilizers are applied. In Paper III, the maximal value of the digestate was estimated based of the current market price on mineral fertilizers including the cost for spreading of digestate compared to mineral fertilizers and solid manure. The cost for transport and storage of the digestate was included in biogas production costs. When produced from liquid and solid manure, the maximal value was calculated to 6.9 €/t where the reduced cost for spreading of solid manure contributed to 1/3 of this value. When produced from energy crops and crop residues, the value of the digestate was calculated to 2.1 – 6.3 €/t. For comparison, Smyth *el al.* (2010) estimate the value of digestate based on grass to 4 €/t while Brown *et al.* (2011) states that a conservative assumption is that the value of the digestate should equal the cost for transport and spreading.

In Paper III, the cost for biogas production was calculated both using this maximal value and excluding the value of the digestate. Thus, the impact of the digestate value on overall production cost was illustrated. Using the maximal value reduced total production cost with 2 – 13% the systems analysed.

5.5 Economic performance

The biogas systems analysed in this thesis, where production is based on agricultural feedstock only, was not found to be economically feasible under current conditions (Paper II and III). However, the economic performance of the different systems did vary considerably. In Figure 15, the total production cost per GJ biogas-based electricity and heat, or vehicle gas, is presented excluding the value of the digestate. In the case of CHP, data is presented for SI engines and the amount of heat produced is reduced by the heat used in the biogas process. For comparison, the estimated revenues, as presented in section 5.1 and 5.2, for electricity, heat and vehicle gas are also included (dashed lines or squares). For CHP, the interval presented indicates the income with and without any utilization of the heat produced.

Regarding the production of CHP from manure, efficiency of scale was found to affect the economic outcome when comparing a farm-scale biogas plant (Case 1) with a farm-scale plant using manure from 2-3 farms (Case 2). However, this effect was reduced by the investment subsidy described in chapter 4 since it is limited to 200 000 € or 30% of the investment. Thus, only the smallest plant received the full subsidy of 30% in these calculations (Paper II). The effect was also counteracted by the cost of transportation of the manure. However, it was not found to be motivated, from an economic point-of-view, to collect manure from a number of farms to a large co-digestion plant (Case 3) with an installed capacity of approximately 250 kW_{el} compared to farm-scale digestion on a smaller scale (Case 1 and 2). The reasons are mainly the increased investment due to hygienization requirements and the increased transportation costs for the feedstock. For comparison, Walla and Schneeberger (2008) calculated the optimal size of biogas plant production CHP was in the range of 575 kW_{el} to 1150 kW_{el} when biogas production was based on maize.

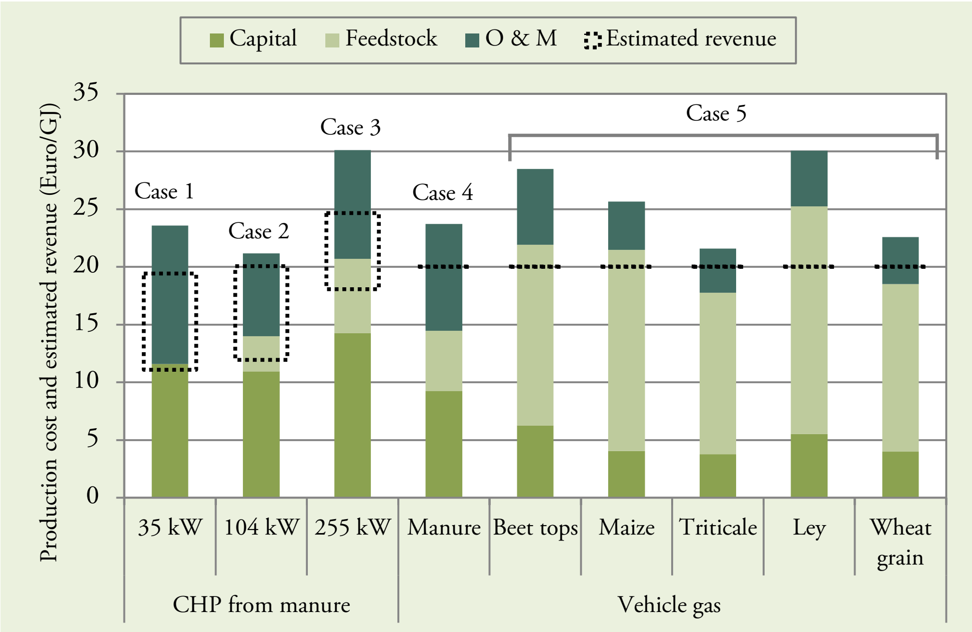

Figure 13: Calculated production cost and estimated income for electricity, heat and vehicle gas. The interval indicates the income with and without any utilization of the heat produced in addition to the heat used in the biogas process (Paper II and III).

In Paper II, the conditions for a biogas process operating under thermophilic conditions (50 – 60 °C) was also evaluated compared to the mesophilic (35 – 37 °C) operation evaluated as a base scenario. In Sweden, less than 10% of the biogas plants are operated under thermophilic conditions (SEA, 2012d). However, it is a common mode of operation in Danish manure based biogas plants (Angelidaki and Ellegaard, 2003). Due to the higher conversion rate in the thermophilic process, the retention time and thus reactor volume could be reduced (Angelidaki and Ellegaard, 2003;

Deublein and Steinhauser, 2008). In Paper II, the reactor volume was, however, not reduced due to the already small-scale biogas plants analysed. Instead, the amount of feedstock was increased, reducing the retention time and thus the biogas production per m^3 reactor. Such a solution was found to improve the profitability for the analysed biogas systems if none or limited amounts of heat could be utilized externally. However, the potentially increased risk of process disturbances and their impact on the overall result were not taken into account in the calculations.

In Paper III, it was found that price and properties of the feedstock has a great effect on the total production cost when biogas is produced from crops and crop residues while the cost of capital has a minor affect. Despite the high feedstock cost, it was also found that the production cost was similar, and in some cases even lower, than for vehicle gas produced from manure. The reason is that biogas production based on manure requires significantly higher investments to produce the same amount of biogas compared to when crops are used as a feedstock. Also, the cost for operation and maintenance was found to be higher when the production was based on manure.

5.6 Evaluation of suggested policy instruments

Since none of the biogas systems analysed here was found to be economically feasible, an increased production of biogas from agricultural feedstock performed under the conditions investigated here requires additional incentives or reduced barriers. In Paper II and III, calculations have been performed to identify the additional revenue or the cost reduction required for the biogas systems to be feasible.

Investment subsidies

Currently, small-scale biogas plants primarily based on manure, can receive an investment subsidy of 30 – 50%, up to 200 000 €. This investment subsidy was included in the calculations in Paper II. The impact of a similar investment subsidy for large-scale biogas plants was evaluated in Paper III. A general conclusion of this analysis is that investment subsidies have a relatively low impact on biogas systems based on energy crops due to the low proportion of the capital cost in the total production cost, see Figure 15. The production systems based on *Triticale* and wheat grain would, however, be feasible with an investment subsidy of 13 – 23%, including the economic value of the digestate. Regarding manure, a large-scale system as the one investigated here would require an investment subsidy of 40% to be feasible.

Production subsidies

As an alternative to investment subsidies, reducing the production cost, the biogas producer's economy could also be improved by an increased income. Here, this approach has been analysed by calculating the required production subsidy for electricity (Paper II) and biogas (Paper II and III).

When biogas is utilized for CHP, production of electricity is already favoured by the electricity certificate system. In Paper II, the required net income for electricity was calculated to 98 – 170 €/MWh depending on the biogas system and the income from the heat produced. The income required from electricity could be compared to the feed-in tariff applied in Germany, presented in chapter 4, where electricity from manure receives approximately 20 – 25 €/MWh on the scale analysed here.

In Paper II, the average revenue from electricity and electricity certificates was set to be 90 €/MWh with a certificate value of 35 €/MWh. With the exception of the farm-scale biogas plant, one additional electricity certificate would thus make the investigated biogas systems profitable. Granting two certificates for electricity from biogas based on manure would also be in line with the double-counting system presented in chapter 4 regarding biofuels from manure. However, the result depends on the current market price for electricity and certificates, which vary over time.

In Paper II and III, the required production subsidy based on the biogas produced has also been calculated. When biogas is produced from manure, the required subsidy is 1 – 6.4 €/GJ, which can be compared to the suggested methane reduction subsidy of 6.2 €/GJ presented by the Swedish Energy Agency. Thus, if this subsidy was implemented, all biogas systems analysed in this thesis would be profitable with the exception of the farm-scale plant if no heat could be utilized externally.

When biogas is produced from energy crops, the required production subsidy varies from 0.5 – 11 €/GJ biogas albeit less than 6 €/GJ for most biogas systems. However, there are no suggestions for a production subsidy for biogas based on crops.

Finally, a potential production subsidy for the cultivation of energy crops was also analysed in Paper III. The required subsidy would vary from 50 – 850 €/ha, and the cultivation of ley crops would require a subsidy of 500 €/ha to give feasible production costs as biogas feedstock under the conditions investigated (Paper IV). This can be compared to the suggested subsidy of 330 €/ha for the cultivation of ley crops in Southern Sweden presented in chapter 4. Thus, this suggested subsidy would not be sufficient to motivate biogas production from ley crops if the farmer doesn't consider any additional positive effects from ley crop cultivation that could be included in the economic.

Chapter 6: Environmental assessment

The environmental performance of biogas production and utilization has been analysed in various studies (e.g. Berglund, 2006; Börjesson and Berglund, 2007; Börjesson *et al.*, 2010; Börjesson and Tufvesson, 2011; Tufvesson and Lantz, 2012; JRC; 2011; Palm and Ek, 2010; Poeschl *et al.*, 2012; Jury *et al.*, 2010; Lansche and Müller, 2012). The results of different studies may vary depending on the method used, such as the applied system boundaries and approaches to allocation described in chapter 3. The results may also vary depending on the assumptions made regarding the technical performance of the biogas system, or assumptions regarding the production of the process energy carriers required. The overall environmental impact also depends on how the biogas is utilized, on the energy carriers replaced, and the assumptions made regarding the utilization of the digestate. Finally and above all, the environmental performance of any biogas system depends on the kind of feedstock utilized.

Focusing on GHG emissions, it is in general found that biogas production and utilization reduces these emissions, albeit to different extents depending on the feedstock used. In Figure 14, a brief overview of calculated GHG emissions from biogas systems based on different feedstock, where biogas is upgraded and utilized as a vehicle fuel, is presented. Some of the key parameters affecting the environmental impacts of different feedstock are further described in the following sections.

6.1 Impact of various feedstock

Sludge and Waste

Sludge from waste water treatment plants, municipal solid organic waste as well as waste and residues from industry, are produced whether biogas production is implemented or not. Thus, the environmental assessment normally starts with transport and, if relevant, the pre-treatment of the waste and residue. It should also, if applicable, include alternative treatment options for the various wastes. Some residues could also be utilized as feed, in which case replacement by other fodder products could have a significant effect on the overall GHG balance (Tufvesson and Lantz, 2012).

Manure

The common agricultural practise is to store liquid manure for several months in storage tanks with a floating crust. Due to the anaerobic environment in these tanks, methane is produced and released to the atmosphere. If the manure is utilized for biogas production, these methane emissions could be significantly reduced (Paper IV). Depending on the assumptions made on the amount of methane emissions that are avoided, this affect could be as important from a GHG perspective as the replacement of fossil fuels by the biogas produced. The reason is that methane is a much more potent GHG than carbon dioxide, as presented in chapter 3. Although it could be argued that this effect depends on bad agricultural practise, the reduction of methane emissions is often included in environmental assessments of biogas production from manure. Thus, the reduction of GHG emissions is particularly marked in the case of manure-based biogas production, as presented in Figure 14.

Dedicated biogas crops

When biogas is produced from dedicated biogas crops, the environmental impact of the biogas system also includes the production of the crop. Thus, the reduction of GHG emissions is normally lower compared to the case when biogas is produced from waste and residues. However, as presented in Figure 14, the environmental impact varies depending on the crop. The environmental assessment of biogas from energy crops can also consider direct and potentially indirect land use changes. For example, if previous grassland is used for annual energy crops cultivation, the direct land use change could reduce the amount of soil carbon with a negative impact on the overall GHG balance. However, this affect would be marginal if the agricultural land was already cultivated with annual food crops (Börjesson and Tufvesson, 2011).

The cultivation of energy crops on agricultural land could also result in indirect land use changes (iLUC) if the previous activity on that land is moved to another location. For example, the cultivation of pasture land could result in an increase of pasture land in another part of the world possibly leading to deforestation. The potential indirect effects cannot be observed directly but only estimated by different models. Current models show, however, several limitations in their availability to assess the potential iLUC from an increased production of biofuels, leading to a significant variation in the results (Ahlgren and Börjesson, 2011; Di Lucia *et al.*, 2012; Van Stappen *et al.*, 2011). Despite this, the European Commission suggests that iLUC factors are implemented in the RED as added default values per fuel energy unit, independent on the individual biofuel produced system but with a different value depending on crop category (EU, 2012a). If implemented, it could act as a new type of barrier against an increased production and utilization of biofuels from annual food crops. However, it will not directly affect biogas produced from waste and residues.

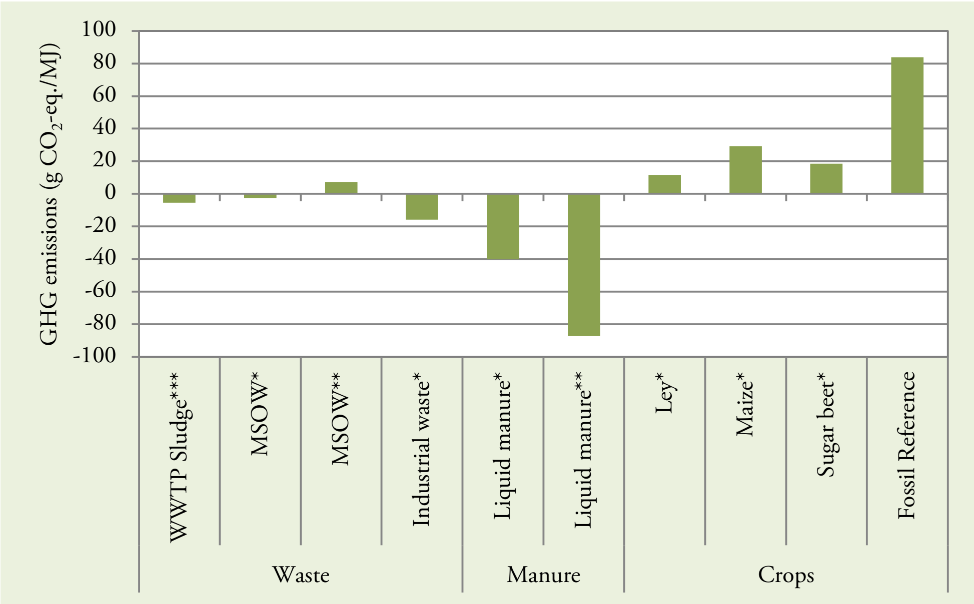

Figure 14: GHG emissions from the production of upgraded biogas based on different feedstock (Börjesson *et al.*, 2010*; JRC, 2011**; Palm and Ek, 2010***)

6.2 Co-digestion of waste and residues

Presenting the environmental performance of different biogas feedstock individually can be motivated in order to identify feedstock that should be prioritized from a GHG perspective. It also provides the possibility to compare biogas production from a certain feedstock with other alternatives. However, the majority of the biogas plants currently established in Sweden is co-digestion plants, utilizing a wide variety of different and complementary feedstock. Thus, the actual environmental impact of the biogas produced and utilized in Sweden today should also be addressed by plant-specific environmental assessments.

In Sweden, there were 19 co-digestion plants in operation in 2011 (SEA, 2012d). Although they are similar to each other regarding the technology applied, there are also differences concerning the kind of feedstock treated and how the biogas is utilized. The assessment presented here, based on Paper IV, represents one of these plants. Thus, the result is site-specific although the approach and main conclusions could, to a certain degree, be general applicable.

The co-digestion plant analysed in Paper IV was established in 2006 and produces approximately 980 TJ upgraded biogas annually. The biogas production is mainly based on sludge and vegetable waste from a local food processing industry, but also slaughter house waste, manure and other kinds of feedstock are used. The upgraded biogas is injected into the natural gas grid, which requires the addition of LPG, as described in chapter 4. The analysis includes the transport of feedstock, biogas production, upgrading, distribution and compression as well as the transport, storage and spreading of digestate. The indirect effects of the replacement of conventional storage of manure, mineral fertilizers and feed are also included (Paper IV).

Calculated net emissions of GHG's for the analysed co-digestion plant amount to 8.2 g CO_2-eqv./MJ, reducing the GHG emissions by approximately 90% compared to fossil vehicle fuels, see Figure 15. In the following sections, some of the key parameters identified in the analysis are further addressed.

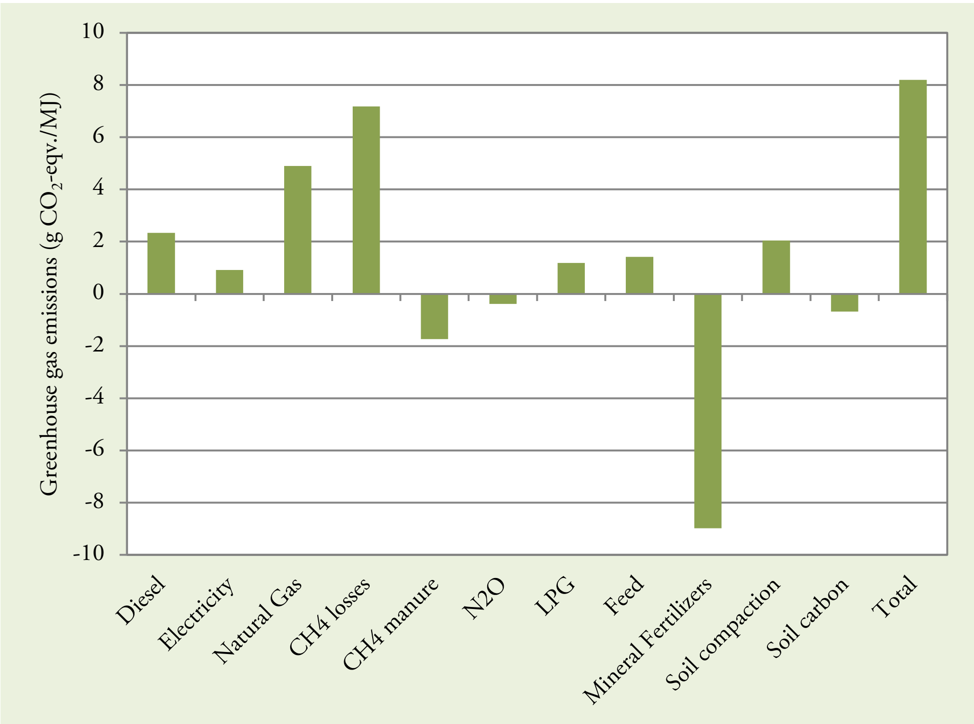

Figure 15: Calculated GHG emissions (Paper IV)

Process energy

In the biogas system analysed, electricity is used to operate the biogas process, to upgrade the biogas produced and compress the gas at filling stations. Data on GHG emissions presented in Figure 15 are based on the average Swedish electricity mix which has a low carbon footprint (Paper IV). Thus, the electricity consumption represents only 5% of directly emitted GHGs from the biogas system. If the biogas production was based on electricity representing average Nordic or European power production, the total emissions of GHGs will increase by 27 – 120%. Thus, system boundaries and choice of input data regarding electricity production has a large effect on the overall result. However, the biogas produced will still reduce GHG emissions by 77% compared to fossil vehicle fuels even if emissions related to the use of electricity are based on the average power production in Europe.

In this particular biogas plant, process heat is generated by incineration of natural gas, which is the second most important source of GHG emissions. It could be argued that the biogas plant should use biogas instead, reducing the direct GHG emissions. However, this would also, to some extent, reduce the production of upgraded biogas replacing diesel and petrol as vehicle gas. Another option is that the biogas plant could use other renewable energy carriers for heat generation, such as wood chips, which is evaluated in Paper IV and further described in section 6.3.

Methane losses

The single most important source of GHG emissions from the biogas system are methane losses from the upgrading unit, corresponding to roughly 1% of the biogas produced. Together with methane losses from the digestate storage tanks and the handling of feedstock at the biogas plant prior to biogas production, emissions amount to 1.4% of the biogas produced, equivalent to 42% of directly emitted GHGs from the biogas system.

Methane losses vary between different upgrading technologies as presented in section 5.3. For a number of Swedish upgrading plants, that were in operation in 2007 - 2008, methane losses have been measured. Average losses were 0.4% for the chemical scrubbers, 1.5% for the PSA and 3.1% for the water scrubbers in operation (Avfall Sverige, 2009). The upgrading units were of different age and size, and measured losses are thus not necessarily representative of new installations of the specific technologies, although it seems clear that the chemical scrubber has the lowest methane losses. As presented in section 6.3, it is possible to reduce methane emissions also when other upgrading technologies are applied.

In addition to the losses in the upgrading plant, methane is also lost from the digestate storages. As presented in Paper IV, these losses vary depending on temperature and digestate composition which is affected by feedstock and level of degradation in the biogas process. Therefore, methane loss from the digestate storages will vary for different biogas plants, but it could also vary over time for one specific biogas plant.

As presented in Paper IV, measured methane losses from the upgrading unit in the analysed biogas plant has varied 0.7 – 1.4% and 1% was used in the calculations presented here. If these measured values were used as minimum and maximum, total GHG emissions for the biogas produced would be found to vary from 6.7 to 9.6 g CO_2-eqv/MJ.

There are also reports of biogas plants with methane losses as high as 10% of the biogas produced or more (Avfall Sverige, 2009). Even if these biogas plants are few, and measures are being taken to reduce these emissions, it may be relevant to calculate the maximal level of methane losses that are acceptable before the biogas system is found to emit more GHG emissions than comparable fossil fuel systems. The exact level will vary depending on the features of each biogas system and the feedstock utilized (Berglund, 2006). For the biogas system analysed here, the limit is approximately 16% of the biogas produced, which is more than 10 times the current losses.

Mineral fertilizers

The digestate produced are used as a fertilizer on the agricultural land surrounding the biogas plant, partly replacing the mineral fertilizers that were previously used. The production of mineral nitrogen fertilizers requires fossil energy which causes CO_2 emissions, but the production also emits N_2O which is an almost 300 times more potent greenhouse gas than CO_2 (Jenssen and Kongshaug, 2003; Forster *et al.*, 2007).

When included in the system expansion, the replacement of mineral fertilizers with digestate has a great effect on the GHG balance for the biogas system. This is shown in Figure 15, where this replacement is presented as “mineral fertilizers”.

However, the effect varies depending on how the mineral nitrogen fertilizer is produced. As presented in Paper IV, emissions could vary from 4.2 – 7.7 kg CO_2-eqv./kg NH_4-N depending on whether the producer has installed catalytic N_2O reduction or not. The result presented in Figure 15 is based on the assumption that 50% of the mineral fertilizer replaced was produced with such N_2O reduction.

If all mineral nitrogen fertilizers replaced were produced with N_2O reduction, the net GHG benefit of the biogas system would be reduced, equivalent to approximately 12.7 g CO_2-eqv./MJ. Nevertheless, the biogas produced would reduce GHG emissions by 85% compared to fossil vehicle fuels.

Soil properties

The replacement of mineral fertilizers by digestate is normally included in environmental assessments of different biogas systems when a systems expansion approach is applied, but normally only in terms of reduced emissions from the production of the fertilizer (Berglund, 2006; JRC, 2011; Börjesson and Tufvesson, 2011). However, replacing mineral fertilizers with digestate can also affect soil properties and, as a consequence, indirectly the GHG balance. In Paper IV, the effect on soil properties was found to be both positive and negative from a GHG perspective.

The negative impact is caused by increased soil compaction, which can occur due to heavy machinery operating in the fields. Such compaction is known to influence crop yields negatively. This is a general problem in crop cultivation, but especially for heavy clay soils, such as the ones surrounding the biogas plant analysed in Paper IV. Since the machinery used to spread digestate is heavier than that used for mineral fertilizers, replacing mineral fertilizers with digestate could lead to increased soil compaction and thus reduced yields. However, as presented in Paper IV, the risk of soil compaction can be minimized by using alternative spreading technology systems, such as the “umbilical slurry spreading system”, which has been introduced at the actual farm. This change in spreading technology system will reduce the field machinery weight from 50 – 60 t, representing conventional spreading technology by tractor and liquid manure spreader, to approximately 12 t. This new slurry spreading equipment is only slightly heavier than a comparable mineral fertilizer spreader. Thus, the replacement of mineral fertilizers with digestate may result in only a minor increase in soil compaction and reduction of crop yields, which in turn leads to an indirect increase in GHG emissions, which is shown in Figure 15. However, the risk of soil compaction and its consequences on crop yields and GHG emissions depend on a number of different parameters and the result is therefore uncertain (Paper IV).

In addition to the risk of increased soil compaction, soil properties are also enhanced by the increased input of organic matter in the fields from the digestate. This will lead to an increase in the soil carbon content, compared with when mineral fertilizers are used, and thereby improved GHG performance of the biogas system.

The carbon content in the digestate can be determined, although it will vary depending on feedstock and process. However, the portion of the carbon that will form long-term stable organic matter in the soil is difficult to determine, and will be influenced by a range of parameters. Due to lack of data, a conservative estimate used in this study was that 10% of the carbon in the digestate ends up as stable organic matter in the soil (Paper IV). However, this is an aspect for which further investigations would be highly relevant, together with monitoring of the long-term effects on soil properties. There are also models that assess long-term changes in soil organic carbon, which are calibrated against outcomes from long-term field studies in Northern Europe when biofertilizers are applied (Andrén and Kätterer, 1997; Petersen *et al.*, 2005). For example, an evaluation of Swedish long-term field experiments on application of manure and sludge has shown that 31-47% of the carbon applied through these biofertilizers will remain as soil organic matter after 5to 10 years (Andrén and Kätterer, 1997). Assuming that 40% instead of 10% of the carbon in the digestate formed stable soil organic matter, the impact on GHG emissions would be a reduction of 2.8 g CO_2-eqv./MJ instead of 0.7 g CO_2-eqv./MJ in the biogas system analysed in paper IV, reducing emissions from the production of biogas with 25%. Thus, this is a factor connected to the utilization of digestate that should be integrated in environmental assessments of biogas systems.

6.3 Improving greenhouse gas efficiency

Even though the biogas system analysed in Paper IV have a good GHG performance, reducing the GHG emissions by some 90% compared with fossil vehicle fuels, there are still opportunities for improvements. In Paper IV, different measures that could reduce GHG emissions were identified and quantified regarding their emission reduction potential and costs.

The two measures with the highest reduction potential were the replacement of natural gas by wood chips for the generation of process heat and the reduction of methane losses from the upgrading unit by regenerative thermal oxidation. These two measures would reduce emissions by 850 t CO_2-eqv. annually, resulting in an overall "negative" GHG balance for the biogas systems equivalent to -1.1 g CO_2-eqv./MJ biogas.

From an economic point-of-view, the replacement of natural gas with wood chips could be profitable for the biogas producer due to reduced fuel costs, implying a measure that should be further considered. However, oxidising the methane losses in the upgrading process is not profitable since it does not result in any extra income or cost reduction. Other measures identified, with minor impact on the overall GHG performance, were covering the digestate storage tanks that are currently uncovered and using electricity produced by wind power instead of average Swedish electricity.

The cost of implementing these measures was found to vary from 0.14 (covering of digestate storage tanks) to 0.6 (purchasing of wind power) €/kg CO_2-eqv. For comparison, the mitigation of CO_2 emissions is valued at 0.11 – 0.15 €/kg CO_2-eqv. by the Swedish authorities such as the Swedish Environmental Agency and the Swedish Transport Administration performing cost benefit analyses within the transportation sector (STA, 2012). In comparison with these values of GHG mitigation, covering of digestate storage tanks is motivated from a socio-economic point of view, whereas methane oxidation and the purchase of electricity from wind power are not. However, covering digestate storage tanks are not profitable from a commercial point-of-view and thus the practical implementation of such a measure calls for adequate policy instruments.

6.4 Vehicle fuel versus combined heat and power

Biogas can be utilized not only as a vehicle fuel but also for the production of heat or CHP. Heat and CHP can be produced on site, but the biogas can also be transported in gas grids to other locations with better conditions for an efficient utilization of the biogas produced.

In the biogas system analysed in Paper IV, the biogas produced is utilized as a vehicle fuel, replacing fossil fuels that emit 83.8 g CO_2-eqv./MJ (EU, 2009). Annual net GHG savings for this system is presented in Figure 16. For comparison, annual net GHG savings are also calculated for two alternative utilization pathways for the biogas produced, one where the biogas is utilised to replace natural gas, and one where the biogas is utilised for electricity production.

In the case where biogas is utilized to replace natural gas, emitting 69 g CO_2-eqv./MJ (Gode *et al.*, 2011), the biogas produced is upgraded and injected into the natural gas grid. All energy input and emissions related to biogas production and transportation is included except the electricity used for compression of biogas at the filling station.

In the case where the biogas produced is utilized for CHP it is assumed that the production takes place on site with an electric efficiency of 40% (Paper II). Upgrading, injection into the natural gas grid and compression at the filling station are thus excluded from the biogas system. Also, process heat is drawn from the CHP unit to replace natural gas for heating the biogas process.

As presented in Figure 16, the utilization of biogas as a vehicle fuel, replacing diesel and petrol, results in the highest reduction of GHG emissions. The reduction is approximately 20% lower when natural gas is replaced and 80 – 90% lower when electricity is produced on site replacing Swedish or Nordic average electricity production.

If GHG emissions from average power production in the EU were used in the system analysis, the replacement of fossil vehicle fuels did still result in the highest reduction. The reduction is approximately 20% lower when natural gas is replaced and 30% lower when electricity is produced. The average Swedish, Nordic and European power production emits 10, 35 and 119 g CO_2-eqv./MJ, respectively (Gode *et al.*, 2011; SEA, 2011; IEA, 2012c).

Thus, the production of electricity from biogas is more favourable in an European context, than in a Swedish and Nordic context. If heat could be utilized outside the biogas plant, the emission reduction would be higher. For the biogas system evaluated in Paper IV, this possibility is currently not feasible, given the location of the biogas plant. Also, as presented in chapters 2 and 4, the production of heat in Sweden is already generally based on bio-based fuels. Thus, the effect on GHG emissions of replacing such heat production is limited.

Thus, in a Swedish context, biogas should primarily be utilized as a vehicle fuel or to replace natural gas or other fossil energy carriers, from a GHG perspective.

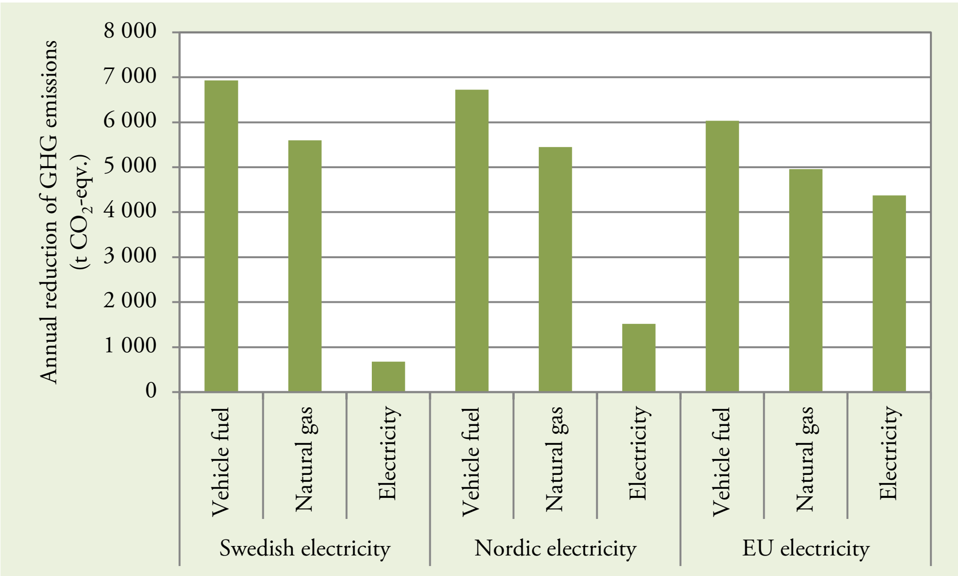

Figure 16: Annual GHG emissions from the biogas system analysed in Paper IV depending on the origin of the electricity used and how the biogas produced is utilized, including the replacement of petrol and diesel as vehicle fuels, natural gas or for the production of electricity.

Chapter 7: Conclusions and recommendations

The production and utilization of biogas in Sweden has to some extent been favoured by different policy instruments during the past decade. However, the total production of biogas has increased only by a few per cent annually over the past six years. At the same time, several assessments show a significantly higher biogas potential from organic wastes and residues. Thus, at first glance, it may seem that the existing policy instruments are too weak to promote a large-scale development of new biogas production systems. However, the actual outcome is partly hidden by the fact that the production of landfill gas decreased significantly during this period. If only dedicated biogas plants are considered, not including landfills and waste water treatment plants, the production is found to have increased by more than 100%, although it is still limited in absolute numbers.

The biogas produced at the existing dedicated biogas plants is based mainly on municipal and industrial organic waste and residues. The biogas is almost entirely utilized as vehicle gas. Several waste water treatment plants have also been changed from producing biogas-based heat or combined heat and power to the production of vehicle gas. This development is also in line with the incentives and barriers identified in this thesis, where taxes and other policy instruments especially favour the production and utilization of bio-based vehicle fuels. It also reflects the fact that current incentives for anaerobic digestion are primarily focused on municipal organic waste. Here, the national environmental objective on increased biological treatment of organic waste appears to give the intended effect even though not at present linked to any additional taxes, fees or obligations. Regarding industrial organic waste, no specific policy instrument was identified, although current economic conditions seem to favour biogas production compared to alternative waste treatment methods.

However, the lion's share of the Swedish biogas potential remains essentially untapped within the agricultural sector, including feedstock such as manure, crop residues and dedicated biogas crops. This implies that existing incentives must be strengthened to overcome today's barriers, especially regarding the limited profitability in biogas production based on agricultural feedstock.

In the techno-economic assessments presented in this thesis, the production cost of biogas based on manure was found to be similar to the production cost of biogas based on crops or crop residues. However, the relation between capital cost and feedstock cost is different for these various kinds of feedstock. Manure is a relatively cheap feedstock which, however, requires higher investments compared to crops and crop residues where the situation is the reverse, a higher feedstock cost but lower investment cost.

These different challenges should be considered when further research and development is deployed in order to improve the prospects for profitable production of biogas from agricultural feedstock. For expensive feedstock, such as energy crops, focus should primarily be on reduced feedstock cost and ways to increase the methane yield. For low-cost feedstock, such as manure, measures to reduce the cost of capital and the related cost of operation and maintenance would be especially important.

The prospects for an increased production of biogas from the agricultural sector could be improved by implementing adequate policy instruments. If the suggested compensation for reduced methane losses from manure storage were implemented, it would make many manure-based biogas systems profitable. This would be the case regardless of scale and how the biogas was utilized, with the exception of farm-scale production of CHP with no external utilization of the heat produced. For CHP based on biogas from manure, an alternative approach could be to strengthen existing policy instruments by granting the biogas producer additional electricity certificates. This would be in line with the double-counting of biofuels based on manure in the EU Renewable Energy Directive.

Farmers and other actors interested in the production of CHP from biogas based on manure should also explore the possibility to use manure from several farms to improve profitability by efficiency of scale. It is also important to find an efficient utilization of the heat produced, and if there is no external heat demand, a thermophilic biogas process could be considered.

When biogas is utilized as vehicle gas, an overall cost efficiency also requires efficient distribution of vehicle gas, which currently could represent 50% of the total price paid by private consumers. Thus, measures to reduce the cost of distribution and filling stations should be further developed.

In the assessment of the environmental performance of an existing co-digestion plant producing vehicle gas, it was found that the GHG emissions were reduced by approximately 90% when compared to fossil vehicle fuels. The analysis also shows opportunities for further improvements. Two kinds of improvements were identified to be beneficial from a commercial or a socio-economic point-of-view; namely the production of process heat by wood chips instead of natural gas, and the covering of digestate storages. The latter would, however, require additional policy instruments to be profitable from a commercial point-of-view.

Based on the current structure of the Swedish energy system, the replacement of fossil vehicle fuels with biogas would normally render the highest reduction of GHG emissions, followed by the replacement of natural gas. The reduction of GHG emissions by utilizing biogas for combined heat and power production is by comparison lower under Swedish conditions.

Thus, from an environmental point-of-view, political attention should primarily focus on systems in which the biogas produced can be utilized as a vehicle fuel or to replace natural gas and other fossil energy carriers. However, given the additional GHG benefits of biogas produced from manure, regardless of how the biogas is utilized, such production should also be promoted by new and strengthened political incentives.

In conclusion, the overall findings in this thesis show that there are substantial opportunities to increase the production and utilization of biogas in Sweden, which would reduce greenhouse gas emissions significantly. However, current challenges, including the limited profitability in biogas production based on agricultural feedstock, should be met by further technology development combined with adequate and focused policy instruments.

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