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Biogas Production from a Systems Analytical Perspective

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Biogas Production from a Systems Analytical Perspective

Abstract

Anaerobic digestion and the production of biogas can provide an efficient means of meeting several objectives concerning energy, environmental and waste management policy. Interest in biogas is increasing, and new facilities are being built. There is a wide range of potential raw material, and both the biogas and digestates produced can be used in many different applications. The variation in raw materials and digestion processes contributes to the flexibility of biogas production systems, but at the same time makes their analysis and comparison more complicated.

In this thesis, the energy performance in the life cycle of biogas production is assessed, as well as the environmental impact of introducing biogas systems to replace various fuels and existing strategies for the handling of various raw materials. The energy performance and environmental impact vary greatly between the biogas systems studied depending on the raw material digested and the reference system replaced. The results are largely dependent on the methodological assumptions made, for example, concerning focus, system boundaries, and how the energy required in joint operations is allocated to the raw materials digested. Many of the environmental implications depend on how changes resulting from non-energy-related aspects of the implementation of biogas production can be taken into account. For example, changes in emission of methane and ammonia from the handling of the raw material or changes in nitrogen leaching from arable land.

There are several potential barriers to the successful implementation of biogas production. The aspect to which most attention was devoted here was the prospect of using digestate from large-scale biogas plants as a fertilizer in agriculture. Reliable and generally accepted disposal of the comparatively large amounts of digestate produced is necessary if biogas production is to be implemented. Agriculture is currently the most common, and sometimes the only suitable means of disposal of the digestate. Serious resistance to or problems associated with this use could therefore jeopardise the development of biogas systems.

Keywords

Anaerobic digestion, biogas, digestate, energy balance, energy systems analysis, environmental systems analysis, fuel-cycle emissions, indirect environmental impact

Biogas, bränslecykelemissioner, energibalans, energisystemanalys, indirekt miljöpåverkan, miljösystemanalys, rötning, rötrest

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ABSTRACT

Anaerobic digestion and the production of biogas can provide an efficient means of meeting several objectives concerning energy, environmental and waste management policy. Interest in biogas is increasing, and new facilities are being built. There is a wide range of potential raw material, and both the biogas and digestates produced can be used in many different applications. The variation in raw materials and digestion processes contributes to the flexibility of biogas production systems, but at the same time makes their analysis and comparison more complicated.

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PREFACE

The work presented in this thesis was carried out at Environmental and Energy Systems Studies, LTH (IMES), Lund University, during the years 2001–2006. The main part of the thesis, including *Papers I–III*, is based on the project “Energy and Environmental Systems Analyses of Biogas Systems” (In Swedish, ”Energi- och miljösystemanalys av biogassystem”) which started in 2001. The work was performed in collaboration with Senior lecturer Pål Börjesson. During the two first years, the project was funded by the Research Foundation of Göteborgs Energi. Their financial support is gratefully acknowledged. The last part of this thesis, including *Paper IV*, is based on the results obtained from a project carried out during 2005 regarding the prospects for the use of digestate from large-scale biogas plants on arable land.

I am truly grateful for the encouragement and patient support provided by my supervisors Professor Lars J. Nilsson and Senior lecturer Pål Börjesson. Thank you for interesting discussions and for guiding me into this broad and fascinating field of energy systems studies. Many thanks to Karin Ryde and Helen Sheppard for constructive comments on the language. I have learned a great deal.

Stort tack till alla kollegor på IMES, nya såväl som gamla! Det har varit roliga år med livliga och spännande diskussioner i köket, vid semiarier och under äppelträden. Särskilt tack till Sus som är så bra att prata med, Karin som hänger med på det mesta, och Joakim som delat med sig av sitt Lund.

Och så ett varmt tack till min stora familj i norr och till mina vänner runt om i landet! Nu, nu har jag nåt min södergräns. Tror jag i alla fall…

Lund, February 2006
Maria Berglund

LIST OF PUBLICATIONS*

This doctoral thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

I Berglund, M and Börjesson, P., 2006. "Assessment of energy performance in the life-cycle of biogas production". *Biomass and Bioenergy 30 (3): 254-266.*

II Börjesson, P and Berglund, M. "Environmental systems analysis of biogas systems – Part I: Fuel-cycle emissions". *Biomass and Bioenergy,* In press.

III Börjesson, P and Berglund, M. "Environmental systems analysis of biogas systems – Part II: The environmental impact of replacing various reference systems". Submitted to *Biomass and Bioenergy.*

IV Berglund, M. "Prospects for the spreading of digestates from biogas plants on arable land". Submitted to *Resources, Conservation and Recycling.*

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[*] My contributions to the papers:
Paper I: I performed the data collection and calculations, and wrote the paper.
Papers II–III: I performed much of the calculations, and wrote parts of the papers.
Paper IV: I performed the data collection, and wrote the paper.

SAMMANFATTNING

Intresset för biogas och rötning ökar i Sverige, bland annat beroende på att gasen är ett förnybart bränsle och att rötning kan vara en lämplig sätt att ta hand om avfall. Men hur bra är biogas egentligen ur miljö- och energisynpunkt? Finns det svårigheter eller hinder som kan äventyra framtida satsningar på biogas? Dessa frågor tas upp i denna avhandling.

Biogas bildas när specialiserade mikroorganismer bryter ner komposterbart material i syrefria miljöer. Sådan nedbrytning sker spontant i myrar och soptippar. Nedbrytningen utnyttjas även i så kallade biogasanläggningar där man rötar olika substrat, så som komposterbart avfall från jordbruk, hushåll och livsmedelsindustri.

Biogasen som bildas i dessa anläggningar samlas upp och användas för olika energiändamål. Gasen innehåller cirka 60 procent metan, som är en energirik gas, och 40 procent koldioxid. Gasen kan användas direkt för värme- och elproduktion, eller efter rening från koldioxid och trycksättning som fordonsbränsle eller distribueras i naturgasnätet.

Restprodukten som återstår efter rötningen kallas rötrest. Den innehåller bland annat all växtnäring, främst kväve, fosfor och kalium, som funnits i substraten, och används därför ofta som gödselmedel i jordbruket.

Biogas i Sverige

I Sverige finns det ett tiotal storskaliga biogasanläggningar där man framförallt rötar gödsel från svin och nötkreatur samt komposterbart avfall från livsmedelsindustrin. Det finns även ett tiotal mindre gårdsanläggningar på lantbruk och naturbruksgymnasier där man framförallt rötar gödseln från de egna djuren. Där används gasen främst för att täcka delar av gårdens värmebehov.

Varje år produceras cirka 0,1 TWh (terawattimmar) biogas i de storskaliga biogasanläggningarna, vilket kan jämföras de 9 TWh naturgas som årligen tillförs det svenska energisystemet. Dessutom samlar man upp 0,4 TWh gas från de större soptipparna. Många kommunala avloppsreningsverk rötar avloppsslammet som bildas vid rening av avloppsvatten. Denna produktion bidrar med ytterligare cirka 0,8 TWh gas.

Endast en bråkdel av alla tillgängliga substrat rötas idag. Om alla substrat kunde nyttjas fullt ut skulle produktionen kunna uppgå till mellan 15 och 20 TWh biogas. Detta motsvarar ungefär en femtedel av energiinnehållet i all bensin och diesel som används för transporter i Sverige.

Intresset för biogas och rötning ökar i Sverige. Ett tiotal biogasanläggningar planeras eller håller på att byggas. Det ligger flera olika motiv till dessa satsningar. Biogas räknas som en förnybar energikälla eftersom gasen produceras ur substrat som ständigt återbildas. Genom att ersätta fossila bränslen med biogas kan vi minska utsläppen av växthusgaser och vårt beroende av dessa bränslen. Ett annat motiv är det nya förbudet mot deponering av komposterbart avfall. Förbudet medför att kommunerna och avfallsbolagen måste hitta andra lösningar för avfallshanteringen, och då kan rötning vara ett alternativ. Genom att röta avfallen kan även växtnäring från hushålls- och livsmedelsindustriavfallet återföras till åkermarken. Ett tredje motiv är att rötresten kan vara ett bättre gödselmedel än handelsgödsel eller orötad stallgödsel. Till skillnad från handelsgödsel innehåller rötresten organiskt material. Detta kan vara bra att tillföra åkermarken för att förbättra dess egenskaper och struktur, till exempel i områden med intensiv spannmålsodling. När stallgödsel rötas ökar andelen kväve som är direkt tillgänglig för växterna. Därmed blir det lättare att dosera gödseln rätt och risken för kväveläckage kan minskas.

Är biogasproduktion energieffektiv?

Ett vanligt argument mot många energikällor är att det kan krävas mycket energi för att producera bränslet, till och med mer än vad man får ut när det sedan används. Hur ser det då ut för biogas, hur energieffektiv är produktionen?

Vid produktion av biogas används energi bland annat vid insamling och transport av substraten, drift av biogasanläggningen, rening av gasen och spridning av rötresten. Denna avhandling visar att dessa energiinsatser normalt motsvarar 20 till 40 procent av biogasens energiinnehåll. Energiinsatsen variera bland annat beroende på vilka substrat som rötas, hur gasen används och hur mycket el och värme som behövs för att driva biogasanläggningen.

Biogasutbytet från gödsel är relativt lågt samtidigt som driften av biogasanläggningen motsvarar en relativt stor andel av gasens energiinnehåll. Energiöverskottet skulle ändå räcka för att transportera gödseln upp till 200 km. För hushållsavfall och andra energirika substrat som kan transporteras mer energieffektivt, skulle energiöverskottet räcka för att transportera substraten mellan 600 och 700 km.

Biogasens miljöpåverkan

Hur stor miljöpåverkan orsakar biogasproduktionen? Kan den totala miljöbelastningen minska när rötning och biogas ersätter andra bränslen och andra sätt att ta hand om substraten?

Många gånger vill man producera biogas för att ersätta fossila bränslen, och därmed minska utsläppen av koldioxid och andra växthusgaser. Visserligen bildas det koldioxid i rötningsprocessen och när biogasen förbränns, men denna koldioxid kommer ursprungligen från växter som nyligen bundit in koldioxid via fotosyntesen. Så länge nya växter fortsätter att binda in koldioxid som producerats blir det inget nettotillskott av koldioxid till atmosfären. När fossila bränslen som kol, olja och naturgas förbränns frigörs istället koldioxid som bundits in för 50 till 500 miljoner år sedan. Eftersom återbildningen av fossila bränslen tar mycket lång tid kommer förbränning av dessa bränslen att orsaka nettotillförsel av koldioxid till atmosfären.

Mängden fossila bränslen som används vid produktion av biogas, till exempel som diesel i transporter, är mycket lägre än mängden bränsle som den producerade biogasen kan ersätta. Om biogas kan ersätta olja i ett fjärrvärmeverk eller bensin i en personbil kan utsläppen av koldioxid minska med cirka 75 procent.

Metan är den viktigaste beståndsdelen i biogas, men också en kraftig växthusgas. Utsläpp av ett kilogram metan påverkar växthuseffekten lika mycket som utsläpp av cirka 20 kilogram koldioxid. En viktig anledning till att växthusgaserna bidrar olika mycket till växthuseffekten är deras varierande förmåga att fånga in värmestrålningen från jorden.

För att minimera biogasens bidrag till växthuseffekten är det viktigt att metanförlusterna är låga. När rötresten tas ut ur biogasanläggningen innehåller den fortfarande metan och mikroorganismerna bryter fortfarande ner substratet. Gasen som bildas i rötrestlagret motsvarar så mycket som 10 till 15 procent av den totala biogasproduktionen i anläggningen, därför är det viktigt att ha gastäta rötrestlager och att samla in gasen som bildas där. Metanförluster kan även uppstå när biogasen renas från koldioxid, vid läckage i biogasanläggningen eller om oförbränd biogas släpps ut till luften vid tillfälliga produktionsöverskott.

Mängden metan som kan förloras innan biogasproduktion bidrar till mer växthuseffekt än andra bränslen gör beror till stor del på vilka substrat som rötas, vilka bränslen som ersätts och hur substraten annars skulle ha hanterats. Om biogas från gödsel ersätter olja i ett fjärrvärmeverk eller bensin i en personbil, skulle en femtedel av metanen kunna förloras innan de fossila bränslena är ett bättre alternativ. Att så höga förluster kan tolereras beror främst på att förbränning av fossila bränslen orsakar höga koldioxidutsläpp och att rötning av gödsel kan minska förlusterna av metan som vanligen sker vid lagring av gödsel. Om biogasen hade ersatt energiskog eller andra biobränslen hade biogas varit sämre ur växthusgassynpunkt även utan metanförluster eftersom dessa biobränslen ger betydligt lägre koldioxidutsläpp än vad olja ger.

När man jämför biogasens miljöpåverkan och miljöpåverkan från andra bränslen får man inte glömma att substraten som används vid biogasproduktionen måste tas omhand även när de inte rötas, och att även denna hantering kan orsaka utsläpp, som i fallet ovan om metanförluster vid lagring av gödsel. I avhandlingen visas att utsläppsskillnaderna mellan olika sätt att hantera substraten i många fall är helt avgörande för den totala miljöpåverkan, och att rötning ofta orsakar lägre utsläpp än de alternativa sätten att hantera substraten.

Om man tittar på utsläpp av försurande och övergödande ämnen visar analyserna att rötning ofta är ett bra alternativ. Genom att samla in och röta sockerbetsblast istället för att lämna kvar blasten på fälten kan kväveläckaget minskas. Blast som lämnats kvar på åkern bryts ner i marken under vintern, och då kan även kvävet som varit bundet i blasten frigöras. Om det då saknas grödor som kan ta upp kvävet kan det istället lakas ut ur marken och orsaka övergödning i vattendrag. ▪

SUMMARY

Interest in biogas and anaerobic digestion is increasing in Sweden, mainly as a result of the desire to increase the production of renewable energy carriers and to implement new and more sustainable waste management practices. But, is biogas really a good alternative from an environmental point of view? Are there any obstacles that could hinder the further development of biogas production systems? These questions are addressed in this thesis.

Biogas is formed when specialized microorganisms decompose organic matter in the absence of oxygen. This takes place spontaneously in swamps and landfills. The anaerobic digestion process is also applied at biogas plants, in which various organic waste products from households, agriculture and the food industry are decomposed.

The biogas produced in these facilities is recovered and used for energy production purposes. Typically, biogas comprises 60% methane (CH_4), an energy-rich gas, and 40% carbon dioxide (CO_2). The gas can be used directly for heat or electricity production, or, after pressurisation and removal of CO_2 (i.e. upgrading of the biogas), as a vehicle fuel or be injected into the natural gas grid.

The remaining residue is often called digestate. All plant nutrients, mainly nitrogen, phosphorus and potassium, from the raw materials digested are preserved in the digestate, and the digestate is therefore mostly used as a fertilizer in agriculture.

Biogas in Sweden

There are currently some ten large-scale biogas plants in Sweden which mainly treat animal manure and organic waste from the food industry. There are also a dozen farm-scale biogas plants which mainly treat the manure produced at the farm.

The large-scale biogas plants in Sweden generate about 0.1 terawatt-hours (TWh) of biogas per year, which can be compared with the 9 TWh of natural gas supplied to the Swedish energy system per year. In addition, some 0.4 TWh of gas is recovered at landfills. Most of the sewage sludge generated at municipal wastewater treatment plants is digested. This generates about 0.8 TWh of gas.

Little of the available raw material is currently digested. The potential for biogas production in Sweden is equivalent to 15–20 TWh of biogas per year. This corresponds to one fifth of the current use of petrol and diesel in the transport sector.

Interest in biogas and anaerobic digestion is increasing. A dozen biogas plants are being planned or being built in Swe-

den. Biogas is regarded as a renewable source of energy since the raw materials are constantly regenerated. Therefore, the emission of greenhouse gases can be reduced when biogas replaces fossil fuels. In addition, the current ban on landfilling of organic waste means that the municipalities and waste companies will need new waste management strategies, and anaerobic digestion may be of interest. Anaerobic digestion will also enable the recycling of plant nutrients from organic waste. Moreover, digestate may be a better fertilizer than chemical fertilizers or undigested manure. Unlike chemical fertilizers, digestate contains organic matter that can improve soil fertility, for example, when introduced in cereal cropping systems. Digestion of animal manure improves the quality of the manure as a fertilizer due to reduced odour and increased amounts of plant-available nitrogen, for instance.

Is biogas production energy efficient?

It is sometimes argued that the production of renewable energy carriers is an energy-demanding process. Is this the case for biogas, and how energy efficient is biogas production?

In biogas production, energy is used in collecting and transporting raw materials, operating the biogas plant, upgrading of biogas, and spreading the digestate. In this thesis it is shown that the energy input normally corresponds to 20–40% of the energy content of the biogas produced. The amount of energy required in the production of biogas is largely dependent on the raw material digested, the application of the biogas, and variations in electricity and heat demand in the operation of the biogas plant.

The biogas yield from the digestion of manure is comparatively low, and the energy needed in the operation of the biogas plant corresponds to a comparatively high proportion of the biogas produced. However, the surplus energy would be sufficient to transport the manure about 200 km. The biogas yield from household waste and other energy-rich raw materials is higher and their transport more energy efficient, meaning that they can be transported for some 600–700 km until more energy is required than is generated in the production of the biogas.

Environmental impact of biogas

What about the environmental impact of implementing anaerobic digestion and biogas production? Can the negative environmental impact be reduced when anaerobic digestion is used to replace other energy carriers or waste management strategies?

Biogas is often used to replace fossil fuels, thereby reducing the emission of CO_2 and other greenhouse gases. However, CO_2 is produced in the digestion process and in the combustion of the biogas, but it originates from plants that recently incorporated CO_2 via photosynthesis. These emissions will not cause a net accumulation of CO_2 as long as new plants continue to incorporate CO_2. The combustion of oil, coal, natural gas and other fossil fuels releases CO_2 that was incorporated 50–500 million years ago. It takes a very long time to regenerate fossil fuels. Consequently, the combustion of fossil fuels contributes to a net supply of CO_2 to the atmosphere.

Considerably less fossil fuel is used in the production of biogas (e.g. diesel for transport) than can be replaced by the biogas produced. Consequently, the emission of greenhouse gases can be reduced by some 75% when biogas replaces fuel oil in district heating plants or petrol in light-duty vehicles, despite the fact that the emission from vehicles, etc. used in biogas production is included.

CH_4 constitutes the energy-carrying component in biogas, but it is also a potent greenhouse gas. From a climate change perspective, the emission of one kilogram of CH_4 to the atmosphere is comparable to the emission of about 20 kilograms of CO_2. The difference in effect of these greenhouse gases is largely due to their varying capacity to absorb heat radiated by the Earth.

Maintaining low losses of CH_4 is essential to minimize the emission of greenhouse gases from biogas systems. Digestate newly removed from the digester contains CH_4 and the microorganisms are still producing CH_4. The biogas produced during storage of digestate is equivalent to 10–15% of the biogas produced. It is therefore important to store the digestate in covered tanks and to collect the gas produced. Loss of CH_4 can also occur during upgrading of the biogas, from leakages in the biogas plant, and from the emission of un-combusted biogas to the air during occasional excess production of biogas.

The amount of biogas that can be released to the air before biogas systems become worse than their alternatives, regarding the emission of greenhouse gases, depends largely on the raw material digested, the fuels replaced and the alternative treatment of the raw material. One fifth of the CH_4 in biogas based on manure can be lost before the emission of greenhouse gases from the utilisation of biogas becomes higher than that resulting from the use of fuel oil in district heating plants or petrol in light-duty vehicles. This is mainly due to the high emission of CO_2 from the combustion of fossil fuels and the lower leakage of CH_4 from the storage of digested manure than from the storage of undigested manure. If biogas were to replace other sources of bioenergy, the emission of greenhouse gases would increase, even without the loss of methane from the biogas system. This is due to the comparatively low emission of greenhouse gases from these reference systems.

When comparing the environmental impact of different sources of energy, one must not forget that the waste has to be treated even if it is not digested, and that these treatment cause emission. This must be taken into account in order to make the comparisons accurate. Here it is shown that these indirect emissions can be of great importance for the outcome in comparisons between fuels or between waste management systems. Anaerobic digestion can often be used to reduce these emissions.

Anaerobic digestion is usually a good alternative considering emissions that cause acidification and eutrophication. For instance, nitrogen leaching can be reduced if tops and leaves of sugar beets are recovered and digested. Part of the cropping residues left on the field would otherwise be decomposed during the winter. Nitrogen is released in this decomposition, which can cause eutrophication if there are no crops to absorb it. ▪

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1 INTRODUCTION

There is an increasing interest in producing biogas from anaerobic digestion as a renewable source of energy and as means of reducing our dependence on fossil fuels. Anaerobic digestion can also be useful in achieving several environmental benefits and political objectives, such as more sustainable strategies for waste management and agricultural practices. However, biogas production systems are multifaceted and complex, due to a number of factors such as: (i) the large variation raw materials, digestion technologies and end-use applications of the biogas, as well as the digestate produced, (ii) the large variety of objectives and issues to be addressed in the implementation of biogas systems, and (iii) the many actors involved. The diversity is also reflected in the varying effects (e.g. environmental impact) and potential obstacles to the successful implementation of biogas systems. A broad systems perspective is therefore useful in order to explore the benefits and drawbacks of different biogas systems. So far, most of the research in this field has focused on specific biogas systems or parts of systems, for example, enhancing the digestion technology or use of the biogas. There are few comparative studies of biogas production that include several alternatives for anaerobic digestion, or studies that synthesise the current knowledge.

The overall objective of the work described in this thesis was to assess biogas production from a systems analytical perspective in order to identify strengths and weaknesses of this process. In this case, “biogas production” should be interpreted as the physical aspects of entire biogas systems, from the raw materials digested to the final use of the biogas and digestate produced. The systems analytical approach considers primarily the environmental impact of biogas production from a life-cycle perspective, including energy performance and emissions from the biogas production systems. The first aim was to assess when and under what conditions biogas and anaerobic digestion are good alternatives from an environmental point of view. The systems analytical approach was then broadened in order to identify factors of importance for the successful implementation of biogas production. Here, the disposal of digestate was identified to being an important factor. The second aim was therefore to analyse the prospects for the successful disposal of digestate through various means.

The research described here is motivated by the need for better information concerning biogas production from a broad systems perspective. The principal audience envisaged is firstly those who are interested in, or engaged in, biogas-related issues, including policy makers, decision makers, researchers, consultants, farmers, and operators of biogas plants, who require more information on the environmental implications of biogas production. Secondly, this thesis is directed towards those who carry out life cycle assessment, and similar analyses, of waste management, energy production, agricultural practices, etc., and who require information on the characteristics of biogas production from a systems analytical perspective.

1.1 Focus and Delimitations

The studies were carried out in a Swedish context. Nevertheless, the discussions and results may be applicable in other countries or regions with similar conditions concerning, for example, the raw materials and digestion technologies available, and agricultural production systems being utilised. The focus is on large-scale biogas plants, unless otherwise stated.

The studies were carried out mainly on the anaerobic digestion of organic waste from the food industry, source-sorted organic household waste, energy crops, manure, and cropping residues from agriculture. A clear distinction is made between these biogas plants and the digestion of sewage sludge that takes place at wastewater treatment plants (including co-digestion of sewage sludge with the raw materials mentioned above). This distinction is mainly motivated by the controversies and obstacles to the use of sewage sludge in agriculture (see *Paper IV* and Chapter 5), whereas virtually all digestates from large-scale and farm-scale biogas plants have been, and still are, used in agriculture. The use of the digested residues as fertilizer in agriculture is one of the requirements set in the energy and environmental systems analyses of biogas (see Chapter 1). Sewage sludge and sewage plants are therefore excluded from these analyses.

1.2 Overview of Papers and Outline of the Thesis

Papers I–III include assessments of the energy performance and environmental impact of biogas production from a life-cycle perspective. The calculations are based on literature reviews and refer to Swedish conditions. The results of these analyses are given for individual raw materials, and the energy demand and emissions are expressed per unit of energy carrier (regarding energy performance) or energy service (regarding environmental impact).

Paper I describes an assessment of the energy balances in biogas production systems based on eight different raw materials. The energy balance is calculated as the ratio between the total primary energy input required in the production chain of biogas and the total amount of biogas produced.

Paper II presents a description of the fuel-cycle emissions from biogas production; that is, instantaneous emissions from the entire production chain and the end-use emission from various applications of the biogas. The environmental impact of introducing biogas systems to replace various reference systems is analysed in *Paper III*. The reference systems include handling of the raw materials and production of energy services. The calculations include both the direct environmental impact of the energy conversion in the systems compared and the indirect emissions that are due to the changes in handling of the raw materials.

Swedish experience and the prospects of using digestates on arable land are assessed in *Paper IV*. Reliable disposal of the digestates produced was identified as being of great importance to ensure successful implementation of biogas systems.

The next chapter of this thesis gives an overview of biogas production in Sweden today, and the characteristics of this process. Chapters 3–4 are based on the analyses presented in *Papers I–III*. Chapter 3 gives an overview of the environmental implications of introducing biogas, and Chapter 4 was included to allow for a broader discussion of the methods applied in the energy and environmental systems analyses than was possible in *Papers I–III*. The prospects for using digestate in agriculture are discussed in Chapter 5. This chapter is based on the results presented in *Paper IV*.

2 THE ROLE OF BIOGAS AND ANAEROBIC DIGESTION

Anaerobic digestion is used in many different applications today, and the number of facilities as well as the volume of biogas produced is expected to increase in the future. Anaerobic digestion can be employed for several different reasons, for example, enhanced waste management capability, the production of renewable energy carriers, or improved management of plant nutrients. There are many different raw materials available, and the biogas and digestate produced can be used in a wide range of applications. Altogether, these factors contribute to the complexity, but also the flexibility, of biogas systems.

Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen. There are many different raw materials available, ranging from organic waste products from the food industry and households, to manure, harvest residues and dedicated energy crops from agriculture. The biogas produced contains mainly methane (CH_4) and carbon dioxide (CO_2). The residue, or digestate, that remains after the degradation process contains the plant nutrients of the raw materials digested and can be used as a fertilizer.

A number of digestion technologies are available. Biogas plants can be operated at different temperatures, usually mesophilic (approximately 30–37 °C) or thermophilic (approximately 55–65 °C), but also under psychrophilic conditions (<20 °C). In general, the higher the temperature, the faster the degradation. The digesters in which decomposition takes place can be fed in different ways. One example is the continuously stirred-tank reactor in which new raw materials can be fed to the digestate on a daily basis, replacing an equivalent amount of digested residues. The raw materials are typically treated for some 20–30 days in the case of mesophilic conditions, and for a shorter period of time under thermophilic conditions. In batch systems, all the raw material is added simultaneously, and the reactor is emptied after 3–4 weeks. In addition, the decomposition process can take place in one digester (one-phase digestion), or be separated (two-phase digestion) to enhance the decomposition (see Section 2.5).

2.1 The History of Biogas Production in Sweden

The first Swedish municipal wastewater treatment plants were built in the 1920s. By the mid 1950s, a quarter of Swedish cities had wastewater treatment plants (Agustinsson, 2003). Biogas production from the digestion of sewage sludge in wastewater treatment plants took off in the 1960s. Digestion of the sludge was primarily applied to reduce the sludge volume and to stabilize the sludge. Anaerobic digestion is currently the most common way of stabilizing sludge, in terms of the total amount of sludge produced. Anaerobic digestion is currently applied at almost all of the largest municipal wastewater treatment plants, and at a total of some 135 facilities (SBGF, 2005). Anaerobic digestion of industrial wastewater has been adopted at paper mills, sugar mills, distilleries, dairies, and in the pharmaceutical industry, etc. since the 1980s. The main objective is to reduce the content of organic substances in the wastewater (Lindberg, 1997).

Methane-rich gas is produced spontaneously in landfills when organic matter is degraded under anaerobic conditions. Most of this landfill gas is produced within the first 15–25 years after closure of the landfill, and production decreases with time. The first large-scale facilities for the recovery of landfill gas were built in the mid 1980s, with a boom some years later. The main reason was to reduce the emission of methane from landfills, and not for the purpose of recovering energy. Today, landfill gas is recovered at all large landfill sites, and the gas is primarily used for heating purposes. The gas is recovered through pipes that are placed in the landfills prior to, or as in earlier cases after, final closure of the landfill. Landfill gas contains comparatively high proportions of nitrogen gas (N_2), typically some 20% (RVF, 1996), since air enters the landfill. The total gas production in landfills will decrease in the future as landfilling of organic waste is decreasing. There are also comparatively new waste management systems for easily degradable organic waste, so-called biocell reactors, aimed at speeding up the anaerobic degradation process of the organic waste and ensuring high rates of recovery of the gas (RVF, 1996). Only a few per cent of the household waste landfilled in 2004 was treated in biocells (RVF, 2005a).

When the oil crises in the 1970s caused increased oil prices, an interest in farm-scale production of biogas from manure arose in Sweden. Some 15 farm-scale biogas plants were taken into operation between the years 1975 and 1984, many of which were located on large pig farms. These plants received government investment grants, but when these grants were no longer available, no new plants were built for several years. Most of these early Swedish plants are no longer in operation, mainly due to low profitability caused, for instance, by operational disturbances and the need for extensive maintenance (Thyselius, 2004).

Interest in farm-scale biogas production is increasing again, thanks to improved technology and predicted better economical outcome. Experience in Germany, and the technology development that has taken place there, may also be beneficial for Swedish farm-scale biogas production. Farm-scale biogas production has grown rapidly in Germany over the past few years, and the total number of facilities in 2005 was estimated to be about 4 000 (Edström & Nordberg, 2004). Farm-scale biogas production can, for example, be motivated by concerns about increasing energy costs or the demand for a nitrogen-rich fertilizer for use in organic farming. There are currently a dozen farm-scale biogas plants in Sweden, of which a handful are located at agricultural colleges and schools (Edström & Nordberg, 2004). Farm-scale biogas production is usually based on manure from the farm and possible fodder residues or organic waste from the food industry. Typically, less than 10 000 tonnes of raw materials is treated annually at each farm-scale biogas plant.

Since the mid 1990s, a dozen large-scale biogas plants have been taken into operation in Sweden (Svärd & Jansen, 2003). They are primarily located in the southern part of Sweden in agricultural areas, close to food processing plants. Many of these facilities are intended for the digestion of various liquid raw materials, such as manure and organic waste from the food industry (e.g. slaughterhouse waste). Most biogas plants use the same digestion technology as is traditionally used at sewage plants; that is, continuous, single-stage tank reactors. Some 20 000–70 000 tonnes of raw material are treated per year at such a biogas plants. Other biogas plants are intended primarily for the digestion of organic household waste and other solid waste products. Some 10 000–20 000 tonnes of waste could be treated per year at such a plant (RVF, 2005a; NV, 2005). Some organic waste from households and the food industry is digested at sewage plants; either separately, or co-digested with sewage sludge.

Approximately 220 000–250 000 tonnes of raw material have been digested annually in large-scale biogas plants in recent years (RVF, 2005a). The digestion capacity of these plants is reported to exceed 400 000 tonnes annually, and this capacity would increase by some 70% if planned biogas plants were included (RVF, 2005a; NV, 2005). Manure and slaughterhouse waste are the main raw materials, each category amounting to some 100 000 tonnes per year (NV, 2005). Approximately a quarter of the organic waste from households and the food industry is subjected to biological treatment, composting (NV, 2004a; RVF, 2005a). Organic household waste used for biogas production amounts to approximately one fifth of the raw material digested (expressed as dry matter), and this is likely to increase since many of the new biogas plants are intended for comparatively high proportions of household waste (NV, 2005).

Biogas production in Sweden totals some 1.5 TWh[1] of gas per year, including landfill gas (see Table 1). Most of the biogas is produced in sewage plants. However, the figures are somewhat uncertain and not up-to-date for some of the categories (Millers-Dalsjö, 2004). New statistics on gas production and the number of facilities are expected in 2006.

***Table 1:** Current biogas production in Sweden.*

Category	Gas production (TWh/year)
Municipal wastewater treatment plants [a]	0.81
Landfills and biocells [b]	0.42
Large-scale biogas plants [c]	0.12
Industrial wastewater treatment [a]	0.09
Farm-scale biogas plants [d]	<0.02

[a] Production in 2001 (SBGF, 2005).

[b] Production in 2004 (RVF, 2005a). Most of the gas is used for heating purposes, but about 25 GWh is used in the production of electricity and 50 GWh of the gas is flared.

[c] Production in 2004 (RVF, 2005a).

[d] Estimate based on reported or expected biogas yields from some farm-scale biogas plants (e.g. Bortz, 2005; Edström & Nordberg, 2004; Gustavsson & Ellegård, 2004)

2.2 What Are the Reasons for Biogas Production?

Biogas production systems are often implemented to fulfil a combination of several objectives. These objectives span a wide range of issues, and can be divided into three main categories: (i) appropriate waste management, (ii) the production of renewable energy carriers, and (iii) improved management of plant nutrients. There are also several policy instruments that support anaerobic digestion, directly or indirectly. Several existing and planned biogas plants have received investment grants from the local investment programmes (LIP) during the period 1998–2002, and recently the climate investment programmes (KLIMP) since 2002. These programmes are funded by the Swedish Government and their purpose is to speed up the transition to a more sustainable society. The grants awarded to biogas plants through LIP total about SEK170 million, or some €18.7 million (NV, 2005).

Waste management

Many large-scale biogas plants were built to meet the demand for appropriate treatment of organic waste products, such as liquid waste from local food processing plants or organic household waste (Bjurling & Svärd, 1998). Landfilling might

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[1] In this thesis, energy units are used to denote physical amounts of energy carriers. Thus, 1 m^3 of methane (0 °C, 1 bar) would be expressed as 9.8 kWh (Mörtstedt & Hellsten, 1994).

not have been a suitable option for some waste products due to their properties, e.g. low dry matter content. There is also a political ambition to reduce the landfilling of waste demonstrated, for example, by the current ban on landfilling organic waste (SFS, 2001; NV, 2004b). This ban calls for new waste management strategies, such as anaerobic digestion. Exemption from the ban can be granted by the County Administrative Board when there is not sufficient capacity for treatment of the waste (NV, 2004b). A waste tax is levied for waste that is landfilled or stored for more than three years at waste plants (SOU, 2005). The tax rate is SEK435 (i.e. approximately €48) per tonne of waste from the year 2006 (SFS, 1999).

The ban on landfilling of organic waste favours not only biological treatment, but also combustion. However, there is a political ambition to increase the biological treatment of waste. One of the national environmental quality objectives adopted by the Swedish Parliament, namely "A Good Built Environment", includes interim targets for biological treatment of food waste to improve material recovery and the recirculation of plant nutrients. According to this objective, at least 35% of the food waste from households, restaurants, catering establishments and retail premises, and 100% of the food waste from the food industry should be treated biologically by the year 2010 (Swedish Government, 2005b). To achieve these targets, an additional 130 000 tonnes of household waste must be composted or anaerobically digested annually compared with the 430 000 tonnes in 2004 (RVF, 2005a). In addition, combustion of organic waste is sometimes not an option due to limited or irregular demand for heat, especially during the summer, or a lack of means of distributing the heat. Combustion may also prevent the recirculation of plant nutrients if the ash is landfilled.

Renewable energy carriers

Several biogas plants, not least farm-scale plants, are designed to produce renewable energy carriers. For instance, anaerobic digestion can be preferable to composting because of the economical benefits of producing biogas. The biogas can be used in a wide range of applications and can be distributed in the existing infrastructure for gas, for example, by injection into the natural gas grid or at landfills at which landfill gas is recovered. There may also be an increased demand for energy gases locally, which can be met by biogas production. Using the biogas to replace fossil fuels, e.g. oil and coal, can have many environmental benefits, such as reduced end-use emissions of carbon dioxide, particles, hydrocarbons and sulphuric compounds.

There are several political instruments that promote biogas as an energy carrier. Biogas, as well as other renewable fuels, is exempt from the energy and CO_2 taxes applied to fossil fuels in Sweden (SFS, 1994). In 2006, the taxes on energy and CO_2 are SEK263 and SEK74 per MWh for diesel, and SEK316 and SEK236 per MWh for petrol, respectively (Skatteverket, 2006). However, these taxes are not fully enforced in all sectors. For instance, the manufacturing industry pays no energy tax and only 21% of the CO_2 tax on diesel. In 2003, an electricity certificate system came into force in Sweden. This aims to gradually increase the production of electricity from renewable sources by 10 TWh by the year 2010 compared with the production in 2002. Biogas-based electricity production can be granted certificates (SFS, 2003). In 2005, the average market price for the certificates was SEK216 per MWh of electricity (Svenska Kraftnät, 2006). The use of renewable fuels for transport, such as biogas and ethanol, is promoted within the EU, for example, through national indicative targets on minimum proportions of renewable fuels on the market (EC, 2003). According to new Swedish legislation, all large petrol filling stations (i.e. those selling more than 3 000 m^3 petrol and diesel per year) must provide renewable vehicle fuels from April 2006 (Swedish Government, 2005a; 2005c). More filling stations will be subject to this eventually. Policy measures will be taken to ensure that several renewable energy carriers are promoted (Swedish Government, 2005c).

Plant nutrients and the digestate

There are several advantages of using digestate as a fertilizer in agriculture. All the plant nutrients in the raw materials digested are preserved in the digestate. Anaerobic digestion can therefore allow for recirculation of plant nutrients in urban waste products, and potentially reduce the demand for chemical fertilizers.

Anaerobic digestion can also improve the quality of the raw materials as fertilizers. The digestate contains a higher proportion of plant-available nitrogen, i.e. ammonium, than the raw materials, which can improve the nitrogen efficiency. This is due to the mineralization that takes place during the degradation process, in which organic compounds are degraded and, for example, organic-bound nitrogen is converted into ammonium. For example, digestion of pig manure was reported to increase the proportion of ammonium from 70% of the total content of nitrogen to 85% in digested manure (Sommer et al., 2001). In addition, digested manure is easier to spread than undigested manure due to, for instance, reduced viscosity and increased homogeneity. The digestion process also reduces the odour, as well as the occurrence of pathogens and weed seeds (RVF, 2001; RVF, 2005c; Hansson & Christensson, 2005).

Anaerobic digestion can allow for improved management of plant nutrients, especially nitrogen. An increased proportion of plant-available nitrogen allows for better precision in the application of the fertilizer, and for a higher proportion of the nitrogen to be used by the crop. If less plant-available nitrogen is left in the soil during the winter, nitrogen loss, through leaching and/or denitrification, is likely to be reduced. The amount of plant-available nitrogen left in the fields during the winter season can be reduced by the recovery of nitrogen-rich harvest residues, such as tops and leaves of sugar beets, which can be used for anaerobic digestion. One of the large-scale biogas plants (that in Laholm) was constructed for the digestion of manure primarily to reduce nitrogen leaching from arable soils and thereby reduce the eutrophication of the sea in the Laholm Bay. Digestion of the manure would enable better precision in the application of the manure (Bjurling & Svärd, 1998). Cultivation of annual ley crops used as green manure can be employed at organic farms without animals to provide plant nutrients to the cropping system. The ley crop is cut frequently during the cropping season and the plant material is left on the fields. However, much of the nitrogen in the cut plant material may not be available in the following year due to leaching processes, formation of ammonium, etc. (Malgeryd & Torstensson, 2005). Recovery and anaerobic digestion of ley crops could therefore decrease these losses and improve the nitrogen efficiency (Lantz et al., 2006).

Anaerobic digestion can also be employed to increase the content of organic matter in arable soil, for example, by the spreading of digestate rich in organic matter. Increased soil organic matter can improve the soil structure, and the capacity of the soil to retain water. Improved soil structure reduces the vulnerability to compaction of the soil, and facilitates root penetration, drainage and aeration. An important reason for building one of the large-scale biogas plants (that in Västerås) was to improve the poor soil structure by introducing ley crops intended for anaerobic digestion in cereal-based crop sequences and by spreading digestate rich in organic matter on arable land (Khan, 2003; Vafab, 2003). Cultivation of ley crops can also increase soil organic matter because of the harvest residues, including roots, left in the field. Cultivation of a perennial crop may also reduce soil tillage, which triggers mineralization and thus decomposition of soil organic matter.

2.3 Use of the Biogas

The biogas consists mainly of CH_4 (some 60–70%) and CO_2 (some 30–40%), but also water vapour and traces of, for example, nitrogen (N_2), hydrogen sulphide (H_2S) and ammonia (NH_3). These proportions, as well as the biogas yields, are largely determined by the raw materials digested and the digestion technology applied. For instance, the digestion of a raw material with a high fat content can provide a higher gas yield and a higher proportion of methane than the digestion of a raw material rich in carbohydrates. Since methane is the energy carrier in both biogas and natural gas, they can be used in the same applications. Methane is a potent greenhouse gas, and the emission of one kg of methane leads to the same global warming effect as the emission of 21 kg of carbon dioxide, calculated for a period of 100 years (Baumann & Tillman, 2004). The losses of methane from biogas systems should therefore be minimized.

Much of the biogas is used at the same location as it is produced. However, biogas is usually produced continuously during the year whereas the demand can vary considerably. For example, the heat demand on farms can vary greatly due to variations in outdoor temperature, periodical need for drying of crops, etc. Distribution of biogas via the natural gas grid allows for reliable disposal of the gas throughout the year. So far, biogas from one of the large-scale biogas plants is distributed on the natural gas grid (i.e. that in Laholm) (Svärd & Jansen, 2003; NV, 2005). The main gas grid runs along the west coast, from Trelleborg, in the south, to Stenungsund, north of Gothenburg, with branches to regional and local networks. To be distributed on the natural gas grid and to meet the quality standards set, biogas must be upgraded. This includes the removal of carbon dioxide to increase the heating value, and the removal of particles, water vapour and corrosive components, mainly hydrogen sulphide. Odorants are added to make leakages traceable, and heavy hydrocarbons are added to increase the heating value of the biogas to natural gas quality. There are several upgrading technologies available, most of which entail adsorption or absorption of CO_2 (Persson, 2003).

Heat production is the most common and simple way of using biogas (SBGF, 2004). It can be used in boilers developed for natural gas with minor adjustments of the boiler, and generally without more pre-treatment of the gas than the removal of water. Biogas can be used for district heating purposes when applicable, or for heating of buildings close to the biogas plant, for example, at farms. Access to a boiler for a district heating system can provide a means of reliable disposal of the gas throughout the year, whereas biogas production can exceed the heat demand in smaller systems, such as farms, during the summer. Any excess gas should be flared off to reduce the emission of methane. Most digesters are heated by combustion of some of the biogas produced in the biogas plant. This usually corresponds to about 10% of the biogas produced in large-scale biogas plants and 30% in farm-scale plants (Berglund & Börjesson, 2003).

Biogas can also be used for combined heat and power production (CHP). There are many technologies available for CHP, for example, diesel engines, gas turbines and Stirling engines. The conversion efficiency is generally high, and may correspond to about 30–40% of electricity and 50% of heat, depending on plant size and conversion technology (*Paper III*). The pre-treatment demands are often higher for CHP than when the gas is used for stand-alone heat production. In addition to the removal of water vapour, the pre-treatment should include removal of particles and corrosive components such as H_2S and chlorinated hydrocarbons (SBGF, 2004). Electricity generation from biogas is not as widely applied in Sweden today as in other countries within the EU, e.g. Germany. This is mainly due to the relatively low revenue for electricity in Sweden compared with heat, whereas electricity from biogas in Germany is supported by generous feed-in tariffs at the moment.

There is increasing interest in Sweden for the use of biogas as a vehicle fuel. Biogas can be used in distribution systems and vehicles adapted for natural gas. Biogas intended for this application is upgraded to natural gas quality and pressurised. The gas is distributed to filling stations, either to public, quick-filling stations or slow-filling stations mainly intended for heavy-duty vehicles. The number of filling stations selling natural gas and biogas has increased by about 20–30% per year since the late 1990s, and total today approximately 85 stations. Most of these filling stations are located along the west coast, or between Gothenburg and Stockholm. Approximately 160 MWh of biogas is currently used per year as vehicle fuel, including biogas from wastewater treatment plants. This corresponds to nearly half of the gas used in vehicles. The number of gas-fuelled vehicles is also increasing rapidly, and totals approximately 7 900 vehicles today. Heavy-duty vehicles represent a comparatively high proportion of these gas-driven vehicles (Persson, 2005; Mathiasson, 2006).

2.4 Use of the Digestate

The production of digestate at large-scale biogas plants has been 200 000–220 000 tonnes per annum for the past few years. More than 90% of the digestate produced is currently used as fertilizers on arable land (RVF, 2005a). This is often regarded, not least by the operators of biogas plants, as the most suitable means of disposal due, for instance, to the lack of other options that are as economically and practically feasible (see *Paper IV*). One of the main reasons for building biogas plants can actually be to produce digestates intended for agriculture, for example, to meet the demand for organic fertilizers or to reduce nitrogen leaching by digesting manure.

The properties and characteristics of digestates are largely determined by the raw materials digested and the digestion technology applied. Virtually all digestates from large-scale biogas plants used in agriculture are liquid (approximately 2–7% dry matter), and can be spread using the same equipment as is used for liquid manure. However, the high water content leads to comparatively high costs for transport and spreading of the digestate. The digestates contain high proportions of nitrogen (typically >100 kg N per dry tonne, of which about 75 kg is in the form of ammonium), phosphorus (about 15 kg per dry tonne) and potassium (about 50 kg per dry tonne) (RVF, 2005c). The exact proportions can vary greatly depending on the raw materials digested. Digestate can often be used as a complete fertilizer and can replace chemical fertilizers. Field trials indicate that similar nitrogen efficiency is obtained from the application of digestates based on various waste products as from chemical fertilizers (RVF, 2005c). During the digestion process, the concentration of ammonium increases as does the pH. This increases the risks of loss of ammonia during storage and spreading of the digestate. This loss can be reduced by covering the storage tanks, and by using appropriate spreading techniques, e.g. immediate incorporation of digestate into the soil. Appropriate covering is important since the crusts formed on digestate are rarely as thick as those formed on undigested manure (Berg, 2000). Environmental and health risks from the spreading of digestate on arable land, i.e. transmission of pathogens and undesirable organic compounds, are considered to be negligible, provided that the systems are functioning properly (*Paper IV*).

The prospects for using digestate in various applications, primarily agriculture, are discussed further in Chapter 5.

2.5 Potential and Future Applications

Biogas production in Sweden has the potential to increase considerably. The theoretical biogas potential is estimated to correspond to 14–17 TWh per year, including digestion of sewage sludge and assuming current digestion technology (Nordberg et al., 1998; Linné & Jönsson, 2004). Digestion of agricultural by-products and dedicated energy crops constitutes the main part of this estimate (Figure 1). Some 11–14 TWh could be produced annually from the digestion of harvest residues (e.g. tops and leaves of sugar beets), manure from cattle, pigs and fowl, and dedicated energy crops (e.g. ley crops, corn, sugar beet and cereals) cultivated on 10% of the available arable land. Only a small fraction of these raw materials is currently being used for biogas production. On the whole, barely any agricultural by-products are used for energy production purposes. Slightly less than 100 000 tonnes of animal manure are digested annually, which can be compared with the 17 million tonnes of manure spread on arable land (NV, 2005; SCB, 2004). So far, biogas production from harvest residues and dedicated energy crops is almost non-existent. The first large-scale biogas plant intended for digestion of ley crops has recently been taken into operation, and there are also a few farm-scale and pilot plants intended for this kind of raw material. Regarding urban organic waste, a comparatively high proportion is already treated by biological means. The equivalent of 0.8 TWh in biogas is produced annually at sewage plants; the biogas potential for sewage sludge is estimated to correspond to 1 TWh (Linné & Jönsson, 2004; SBGF, 2005).

The actual increase in biogas production will not necessarily match the theoretical potential. The raw materials are distributed unevenly across the country, and all raw materials are not currently economically feasible for anaerobic digestion due, for instance, to costly transport to centralised biogas plants or high production costs for cultivation of energy crops. Previous assessments regarding potential location of large-scale biogas plants (i.e. production >10 GWh per year) indicate that sufficient amounts of raw material could be available in some 35–50 municipalities, depending on the level of production cost deemed acceptable (Nordberg et al., 1998). This biogas production would correspond to 1.4–3.4 TWh per year, or up to 7 TWh if high proportions of energy crops were affordable.

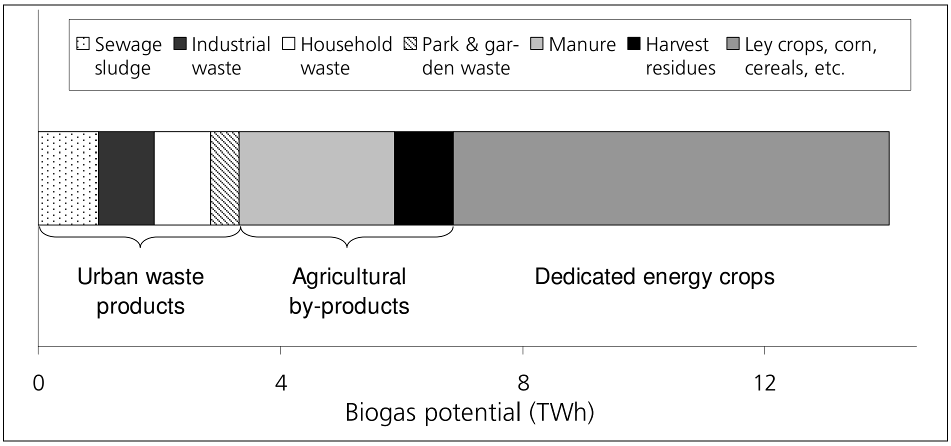

Figure 1: *Biogas potential in Sweden. "Harvest residues" refers to tops and leaves of sugar beets. The potential is based on a report by Linné & Jönsson (2004).*

The raw material and arable land can be used more efficiently in other applications than the production of biogas. For example, the digestion of straw could contribute considerably to the biogas potential, but the biogas yield and degradability of straw are low due to its high content of lignin (Linné & Jönsson, 2004). Combustion of the straw would provide a much higher heat output than digestion. This heat could be used, for instance, for heating of the digester. Cultivation of willow (Salix) for heating purposes would provide much higher heat output per hectare of arable land than cultivation of ley crops for anaerobic digestion (see *Paper III*). However, biogas compares better regarding options for the production of vehicle fuel. This is due to the higher conversion efficiency in the combustion of solid biofuels than in the production of vehicle fuels (e.g. methanol) from these biomasses (L-B-Systemtechnik, 2002). However, there may be other reasons for choosing anaerobic digestion than the production of as much energy carriers as possible (see Section 2.2). Such aspects are often not considered in potential studies or technology assessments.

New potential raw materials may also emerge. Attention has recently been drawn to the production of ethanol from cereals. The residues from this process could be used for biogas production. This would increase the net energy yield per tonne of cereals by about 60%, taken into consideration the energy required in the production of the energy carriers (Börjesson, 2004). For every TWh of ethanol produced from cereals, an additional 0.4 TWh of biogas could be produced from the digestion of the residues.

Biogas production can be increased by more efficient use of existing digestion capacity and improved digestion technology, including improved monitoring and control of the digestion process. As mentioned in Section 2.1, the digestion capacity in large-scale biogas plants is reported to exceed the current digestion rate by some 60%. In addition, the digesters at wastewater treatment plants, at which most of the biogas is produced, were primarily designed for the reduction of sewage sludge volume and the stabilization of the sludge; the production of an energy carrier may be of secondary importance. They are generally run at a comparatively low organic load rate to avoid overload and to ensure high availability. There is potential to use these digesters more efficiently, for example, via co-digestion with various organic waste products, and improved monitoring and control. Laboratory studies indicated that the current organic load in the digesters investigated could be tripled (Murto et al., 2004). The digestion capacity at sewage plants is often over-dimensioned (Lantz et al., 2006). Such excess digestion capacity has been utilised by assigning digesters to separate digestion of other raw materials than sewage sludge (e.g. in Kalmar) (Nilsson et al., 2001). Co-digestion of various raw materials can be favourable since it may improve the nutrient balance (e.g. provide trace elements or a suitable ratio between carbon and nitrogen) and reduce the effects of toxic compounds. Thus, the biogas yield could be increased significantly.

Digestion technology is still evolving, and new concepts and applications are being investigated. Digestion in slurry-based, single-stage tank reactors is the most common technology applied in Sweden today. Dry digestion technologies may be preferable for the digestion of dry raw materials which require extensive pre-treatment to form a slurry or of raw materials that can cause problems such as foaming and crusts when digested in slurry-based reactors (Lantz et al., 2006). There are several reactor designs available in which, for example, the raw materials can be fed to a bed and the leachate produced is recycled to enhance decomposition. The anaerobic degradation process involves several steps, for example, fermentation in which volatile fatty acids are formed, and the methanogenesis in which methane is formed. The microorganisms involved in these steps differ regarding pH optima, nutrition requirements, etc. Two-phase digestion, in which acid formation and methane formation are performed separately, allows for optimisation of both steps and thus enhanced degradation (Nordberg, 1996). New applications for anaerobic digestion are also emerging in Sweden. Large-scale biogas production based on dedicated energy crops, such as ley crops and cereals, is now being implemented. Research is also being carried out on the development of farm-scale biogas production systems suitable for the digestion of crop residues from cropping farms (Department of Biotechnology, 2006). Farm-scale anaerobic digestion could be useful in making more raw materials economically feasible for biogas production since transportation can be reduced (Lantz et al., 2006).

2.6 The Economics of Biogas

The economics of biogas is complex, and can not be compared directly with the economics of other energy production systems. In contrast to many other energy production systems, anaerobic digestion is often applied to address more issues than the demand for energy carriers. The production of energy carriers can even be of secondary importance. Anaerobic digestion can be applied to meet legal requirements (such as the ban on landfilling of organic waste), to reduce the environmental impact of existing waste management strategies or agricultural practices, or to provide a good fertilizer. The aim here is to highlight important issues related to the economics of biogas production in general, rather than to give exact figures on the economical outcome of biogas production.

Virtually all raw materials digested today are either delivered and treated free of charge at the biogas plants (e.g. manure), or gate fees are charged for the treatment of waste products. The gate fees vary considerably between different categories of waste, and between biogas plants (NV, 2005). The gate fee for household waste at some biogas plants is reported to be approximately SEK500–750 per tonne, and for various categories of slaughterhouse waste SEK50–300 per tonne (NV, 2005). The gate fees are partly determined by the alternative cost of treatment of the waste; today, primarily the cost associated with the delivery of waste to combustion plants. Previous interviews with operators of biogas plants indicate that the gate fees are mostly to their satisfaction, and that there is great interest in the food industry and among municipalities in delivering waste products to biogas plants (NV, 2005). However, plant operators experience competition from other waste management facilities, such as incineration plants (NV, 2005). Experience from Danish co-digestion plants, which digest large proportions of manure, indicates that the addition of waste products from the food industry, or similar material, is essential for the economics of the plants. Co-digestion with waste products, which would normally constitute some 20% of the raw material digested, increases the biogas yield significantly, and the gate fees provide extra revenue which can amount to as much as a quarter of the income (Hjort-Gregersen, 2003). Increasing competition concerning waste products can affect the profitability of the plants if less waste is available for digestion or the gate fees decrease.

The greatest potential for biogas production lies in the cultivation of dedicated energy crops (see Figure 2). The x-axis in Figure 2 indicates the estimated biogas potential based on Linné & Jönsson (2004). The y-axis indicates the current revenue in the form of gate fees reported by some large-scale biogas plants (NV, 2005), or the estimated cost of recovery of harvest residues and for cultivation and harvesting of ley crops and cereals (Hakelius (Ed.), 2005b; Berglund & Börjesson, 2003; Svensson, 2005). The cost estimates do not include the cost of transportation. Manure is assumed to be delivered free to the biogas plants. The higher cost for dedicated energy crops refers to ley crops, and the lower to cereals[2]. The cost of these crops can be reduced if the cultivation cost decreases and the benefits of introducing ley crops in to cereal-based cropping rotations are accounted for. However, a considerable expansion of biogas production may imply a shift from regarding raw materials as a potential income to an expense.

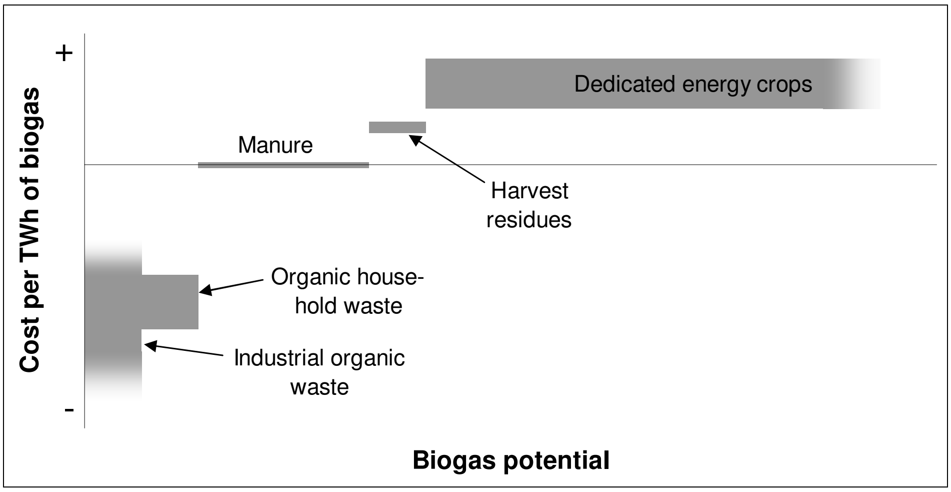

Figure 2: *Current income (-) and potential cost (+) of various raw materials available for biogas production.*

The investment cost for large-scale biogas plants varies greatly (Svärd & Jansen, 2003; NV, 2005). Available data indicate, although with a high level of uncertainty, that the investment cost is roughly SEK800–1 600 per tonne of raw material digested per year at biogas plants at which large proportions of liquid raw material are digested. The investment cost is higher, greater than SEK6 000 per tonne of raw material per year, for facilities intended for high proportions of solid waste, such as organic household waste, which requires extensive pre-treatment.

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[2] Assuming a production cost of ley crops of approximately SEK1200 per dry tonne and a biogas yield of 2.8 MWh per dry tonne, results in a production cost of SEK0.40/kWh of biogas. Assuming the production cost of cereals to approximately SEK900 per dry tonne and a biogas yield of 3.5 MWh per dry tonne, results in a production cost of SEK0.25/kWh. Assuming a gate fee of SEK600 per tonne of organic household waste and a biogas yield of approximately 1 MWh per tonne, results in revenue of SEK0.60/kWh of biogas.

The difference in total production cost is smaller as the revenue from gate fees and the comparatively high biogas yield from household waste are included. The general experience is that the total investment cost has tended to be higher than projected in the planning phase.

Many biogas projects have received government investment grants from the Swedish local investment programmes (LIP), which have now been replaced by the climate investment programmes (KLIMP) (NV, 2006). Grants from LIP were typically about one fifth of the investments in the biogas projects in question (NV, 2005). These grants are reported not to have been of crucial importance for the implementation of the projects, but they may have acted as a catalyst in the realization of the projects (NV, 2005).

Most digestates intended for agriculture are delivered for free to the farmers. In cases when the farmers are charged, the price may be based on the content of plant nutrients and the price for chemical fertilizers. Farmers who deliver manure to the biogas plants are not charged for the corresponding amount of digestate they receive (RVF, 2005c). The willingness to pay for digestate as a fertilizer is low in general, but is estimated to be higher if approved for organic farming (RVF, 2005c; *Paper IV*). Some digestates are intended for other applications than agriculture. One reason for this can be the possibility to receive an extra income from the production of soil improvers or soil for civil engineering purposes.

Much of the biogas produced has traditionally been used for heating purposes, but there is a rapid increase in the demand for biogas as vehicle fuel. There is greater willingness to pay for biogas used for transport than for heat due to the higher prices of alternative fuels in the transportation sector. The alternative fuel in district heating plants is often solid biofuels of low cost. For example, the price of wood chips from forest residues was reported to correspond to SEK0.14 per kWh in 2005 (STEM, 2005). Upgrading of the biogas can expand the market for the gas. The current price of petrol is approximately SEK11 per litre, or some SEK1.20 per kWh, including taxes. However, there is a cost for upgrading the biogas, which is reported to range from approximately SEK0.10–0.20, up to SEK0.40 per kWh of purified biogas for some Swedish upgrading plants (Persson, 2003). In general, the cost is higher for small upgrading plants and for facilities at which the upgrading capacity can not be fully utilised, for example, due to a limited number of gas-driven vehicles.

3 BIOGAS FROM AN ENVIRONMENTAL POINT OF VIEW

In *Papers I–III*, the energy performance and environmental impact of biogas production and utilisation were analysed. The studies showed that biogas systems have the potential to provide a good source of energy from an environmental point of view and to be a useful tool in addressing several environmental problems. The environmental impact of introducing biogas systems varies greatly depending on the raw materials digested, the energy services provided, and the fuels and handling systems for the raw material that are replaced. Hence, no general conclusions on the average environmental impact and energy performance of biogas production can be drawn without accurate specification of the biogas system considered.

As discussed in the previous chapter, anaerobic digestion can be adopted in a wide range of applications regarding raw material, digestion technology, and the use of the biogas and digestate produced. The design of the biogas system will largely depend on the local conditions, for example, regarding the raw materials available and the disposal of the biogas and digestate, but also on the objectives to be fulfilled or environmental concerns to be addressed. These factors must be considered when the energy performance and environmental impact of biogas production are assessed.

Biogas systems have been analysed using an energy and environmental systems analysis approach. The analysis includes assessment and quantification of energy flows and emission during the entire life cycle of biogas production and utilisation. One aim was to identify factors that have a decisive impact on the energy and environmental performance of the systems analysed, and to identify the most promising applications for biogas systems from an environmental point of view.

The calculations were performed for individual raw materials to ensure transparency of the results and to clearly reflect the variations between raw materials. In practice, various raw materials are usually co-digested to obtain well-functioning digestion processes and to utilise the digestion capacity and the raw materials available efficiently. The raw materials were also assumed to be co-digested in these calculations, if necessary to obtain the pre-set biogas yield or to fulfil the conditions set by the design of the system.

The calculations were based on literature reviews and refer to Swedish conditions and current technologies. A base scenario was defined by using the figures identified as the "best estimate" from the literature review. These best estimates were assumed to be valid as mean values for groups of raw materials (e.g. regarding biogas yield, or energy demand of the recovery of harvest residues, collection of organic waste, cultivation of ley crops) or for joint processes (e.g. regarding energy input in the operation of the biogas plant). The results presented here are based on the figures used and the assumptions made in the base scenario (see *Papers I–III*).

Attention was focused on the production of energy carriers. The energy performance is expressed as the ratio between the sum of all energy inputs in a biogas system, and the biogas yield expressed in terms of MJ. Emissions from the biogas systems analysed are given in mg per MJ of biogas produced. When the analysis involved comparisons between a biogas system and a reference system, the emissions were expressed per MJ of energy service provided (that is, heat, heat and electricity, and kinetic energy) to account for differences in conversion efficiency between end-use applications. An overview of the biogas systems analysed is given in Figure 3. Emission from and energy used in the transport and spreading of the digestate are included in the biogas systems studied since appropriate disposal of the digestate is essential to provide a well-functioning biogas system and agriculture is the primary disposal option today.

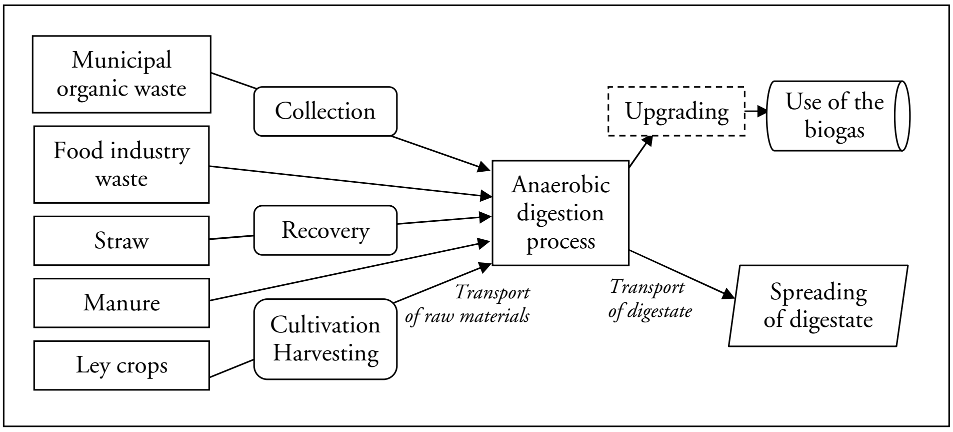

Figure 3: *Overview of the biogas systems studied. The arrows indicate material flows.*

Since the calculations were performed for individual raw materials, the energy input into joint processes (i.e. the operation of biogas plant and the spreading of digestate), and consequently the emissions from these processes, must be distributed between the raw materials digested. These processes include operation of the biogas plant, and transport and spreading of the digestate. In the base scenario, the heat and electricity used in the operation of the biogas plant are expressed as MJ per tonne of substrate mixture (10% dry matter (DM)) added to the digester. The dry matter content required is assumed to be obtained by mixing raw materials of different dry matter contents, or by adding fresh water. Dry raw materials (i.e. >10% DM) were assumed to be diluted by mixing with raw materials of lower dry matter content or by the addition of fresh water. One tonne of ley crops (23% DM) is therefore assumed to correspond to 2.3 tonnes of substrate mixture and to 2.3 tonnes of digestate to be transported and spread on arable land. Consequently, 1 tonne of manure (8% DM) is assumed to correspond to 0.8 tonnes of substrate mixture and 0.8 tonnes of digestate, since some excess water is assumed to be used for diluting drier raw materials. Weight loss during the degradation process is considered negligible in relation to the amounts of digestate to be transported and spread.

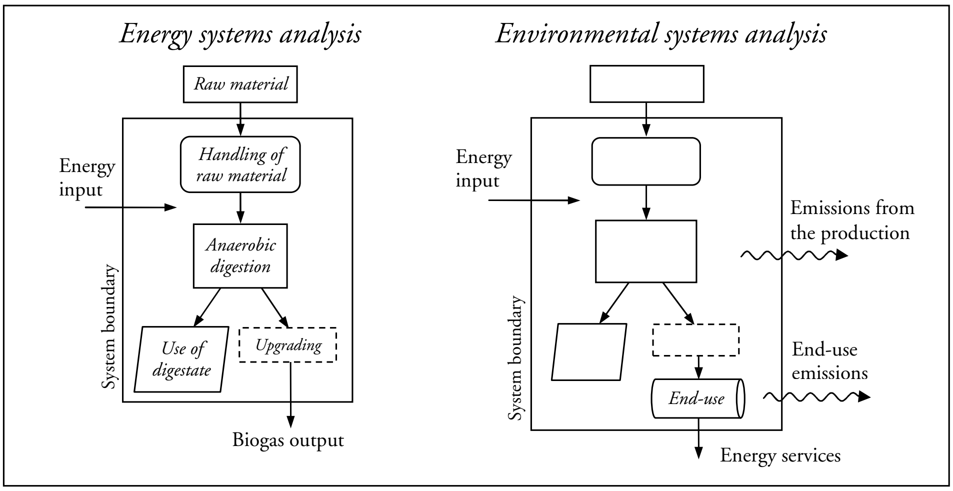

Figure 4: *System boundaries applied in the energy and environmental systems analyses. The arrows represent material and energy flows, or emissions from the systems. The sum of the emissions from the production and the end-use emissions are denoted fuel-cycle emissions.*

3.1 Energy Performance

In the energy systems analysis (*Paper I*), all energy inputs in the biogas systems were summed and compared with the biogas yield (see Figure 4 for the system boundaries applied). Energy needs are determined for all the operations required to run the biogas system. Consequently, handling of the raw materials is included when necessary to make them available for biogas production (e.g. recovery of harvest residues, collection of organic waste or cultivation and harvesting of energy crops). All energy inputs are calculated as primary energy inputs; that is, unconverted and untransformed natural resources. These figures include the energy needed in the production of energy carriers, chemical fertilizers, vehicles, etc., and the energy embodied in these products. For example, the electricity used in the biogas systems is assumed to be produced from natural gas in condensing plants, the conversion efficiency being 50%. The use of 1 MJ of electricity is thus assumed to correspond to 2.2 MJ of primary energy, including the production and distribution of natural gas, and distribution losses in the electricity grid.

The calculations show that the primary energy input in large-scale production of biogas typically corresponds to 25–40% of the energy content in the biogas produced, depending on the raw material digested. If upgrading of the biogas is required, the figures are estimated to increase by 11 percentage points. Typically, the higher figure relates to raw materials that generate comparatively low biogas yields, such as manure and straw, or to raw materials that require extensive and energy demanding handling, such as ley crops. Ley cropping corresponds to slightly less than half of the total energy input in ley crop-based biogas production systems. Operation of the biogas plant is generally the most energy demanding process in the systems studied, and accounts for some 50–80% of the energy input. The assumptions made regarding the allocation of the heat and electricity demand to raw materials will therefore affect the results significantly (for further information on different allocation methods, see Section 4.3). In the base scenario, the raw materials and digestate are assumed to be transported 10 km. The calculations indicate that the transport distance for municipal organic waste and slaughterhouse waste could increase to 580 and 750 km, respectively, before the energy input exceeded the biogas yield (the digestate is still assumed to be transported 10 km). For manure, the transport distance between the farm and biogas plant could increase to 200 km before the energy balance becomes negative.

3.2 Environmental Impact

In the first part of the environmental systems analysis (*Paper II*), the fuel-cycle emissions from biogas systems were evaluated. The fuel-cycle emissions include emissions from the production and the end use of the biogas (see Figure 4 for a description of the systems analysed). The calculations included both large-scale and farm-scale biogas production. The emissions studied included carbon dioxide of fossil origin, carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), hydrocarbons (HC, methane excluded), methane and particles. The gas could be used in large- and small-scale boilers (heat production), large- and small-scale gas turbines (combined heat and electricity generation), and light- and heavy-duty vehicles. The calculations included emissions from the production chain for energy carriers, chemical fertilizers, etc.

The calculations indicate that the emission from the production of biogas can vary greatly between biogas systems. The contribution of various operations to the total emission varies between emission categories. In general, extensive handling of the raw materials leads to comparatively high emissions. The emissions are generally highest in biogas systems based on ley crops, in which ley cropping contributes a large part to the emissions (mainly from diesel used in tractors and the production of chemical fertilizers). For instance, the emissions of SO_2 from biogas systems based on ley crops are 4–13 times higher than from systems based on other raw materials. This is mainly due to the production of phosphorus fertilizers. The emissions from ley crop-based biogas systems are likely to decrease if digestate can replace chemical fertilizers.

There are large variations in fuel-cycle emissions between raw material and end-use applications. Generally, the production chain accounts for the highest fuel-cycle emissions of CO_2, NO_x and SO_2, particularly when the biogas is based on ley crops. On the other hand, the end-use emissions accounts for the highest contribution to the fuel-cycle emissions concerning emission of particles, or emission from biogas based on various waste products.

In addition to the CH_4 emissions resulting from energy conversion in the systems, varying amounts of CH_4 can be released to the atmosphere through losses of CH_4 from the biogas systems. These losses can be caused by leakage or deficient technology, or excess production of biogas when the energy demand is low. Such losses affect the environmental characteristics of the systems studied in two ways: (i) they increase the emission of greenhouse gases substantially since CH_4 is a potent greenhouse gas, and (ii) they increase all fuel-cycle emissions in proportion to the losses since the emissions are expressed per MJ of energy service or MJ of usable biogas. If the loss of CH_4 corresponds to 2% of the biogas produced, the fuel-cycle emission of CH_4 increases 10–100 times, depending on the raw material studied and end-use technology employed. The loss of CH_4 during upgrading of biogas is reported to normally correspond to less than 2% of the biogas produced, but may vary between 0.2–4%, even up to 11–13% (Persson, 2003; RVF, 2005b). If the loss corresponded to 10% of the biogas produced, the fuel-cycle emissions would increase 50–540 times. The biogas produced during storage of the digestate is reported to amount to roughly 5–10%, and even up to 20%, of the total biogas production from biogas plants (Bjurling & Svärd, 1998; Sommer et al., 2001).

3.3 Comparing Biogas Systems with Reference Systems

The fuel-cycle emissions from biogas production systems were compared with the emissions from reference systems based on other energy carriers (*Paper III*). The reference systems included alternative handling of the raw materials or arable land, such as combustion of the raw material, composting of waste products or cultivation of willow. See Table 2 for an overview of the comparisons carried out. Data on the environmental impact of the reference systems were based on literature reviews. In addition to *Paper II*, the comparisons included emissions of ammonia, nitrous oxide (N_2O), and of nitrate (NO_3^-) to water. Additionally, the losses of methane from the biogas systems were estimated to correspond to 1% of the biogas yield when the gas is used for the generation of heat or electricity, and to 2% when upgraded and used as a vehicle fuel. The emissions were classified into the environmental impact categories: global warming potential (GWP_{100}), acidification potential (AP), eutrophication potential (EP) and photochemical oxidant creation potential (POCP).

Table 2: *Overview of the comparisons carried out between biogas systems and reference systems. Letters indicate whether large-scale ("L") and/or farm-scale ("F") biogas systems were investigated.* [a]

Biogas system *Reference system*	Heat	Heat and electricity	Heavy- and light-duty vehicles
Ley crops			
Fallow land & fossil fuel	L & F	L & F	L
Willow[b]	L		L
Straw			
Not recovered & fossil fuel	L & F	L & F	L
Combustion	L & F		
Tops and leaves of sugar beets			
Not recovered & fossil fuel	L & F	L & F	L
Manure			
Conventional storage & fossil fuel	L & F	L & F	L
Organic waste			
Composting & fossil fuel	L	L	L
Combustion	L		

[a] "Fossil fuel" refers to fuel oil used for heat production, natural gas for combined heat and electricity production, petrol in light-duty vehicles and diesel in heavy-duty vehicles.

[b] Wood chips from willow were assumed to be used in the heat reference system, whereas methanol from willow was assumed to be used in the transportation alternatives.

The comparisons also included potential indirect environmental effects due to the replacement of existing alternatives for the handling of raw materials or management of arable land. The effects considered here were: (i) changes in the emissions of CH_4, NH_3 and N_2O from the storage and handling of raw materials (e.g. storage of manure or composting of waste products), and (ii) changes in nutrient leakage from arable land due to changes in cropping practice (e.g. introduction of new crops in the crop sequence, introduction of recovery of harvest residue, or replacement of undigested manure by digested manure). These indirect environmental effects are not directly related to the replacement of energy systems, but can affect the results significantly as discussed below. Emissions that are categorised as causing indirect environmental impact are given as the difference between the two systems compared. This difference is always assigned to the system that causes the highest emissions.

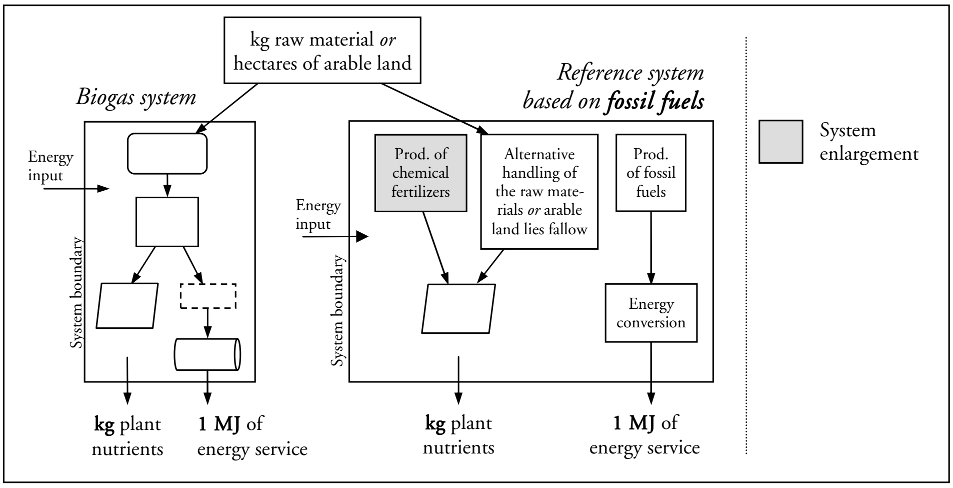

Figure 5: *Comparing biogas systems and reference systems based on fossil fuels.*

To make a biogas system and a reference system comparable, the basis of comparison (i.e. kg of raw materials or hectare of arable land) and the output (i.e. fertilizers and energy services) must be similar in both systems. When the alternative handling of the raw materials does not generate any usable energy services, fossil fuels are assumed to be used in the reference system to provide the same energy output as in the biogas system ("Reference system based on fossil fuels" in Figure 5). The same applies to the management of arable land when the land lies fallow in the reference system. The fossil fuels considered are fuel oil for heating, natural gas for combined heat and electricity production, petrol for light-duty vehicles, and diesel for heavy-duty vehicles. The reference system includes emissions from the production and end-use of these fossil fuels. The alternative handling options for the raw materials (for example, composting of waste products, conventional storage of manure, and harvest residues being left on the fields) may generate a usable fertilizer, but less nitrogen is likely to be available to the crops than in the comparable biogas system. This difference is assumed to be compensated for by additional production and utilisation of chemical fertilizers in the reference system. This is here denoted "system enlargement".

The alternative handling of the raw materials or management of arable land can also generate a usable energy service via combustion of waste products or straw for heat recovery, or cultivation of willow for heat recovery or production of methanol ("Reference system based on bioenergy" in Figure 6). In these bioenergy-based reference systems, less raw materials or arable land is generally needed to provide 1 MJ of energy service than is needed in the corresponding biogas systems. Combustion of the raw materials generates higher energy output per tonne than combustion of the biogas provided by anaerobic digestion. In addition, the biomass yield is assumed to be higher in the cultivation of willow than of ley crops. The difference in energy output is assumed to be compensated for by additional use of fossil fuels in the biogas systems. Typically, this addition of fossil fuels would be equivalent to about 30–50% of the energy output in the biogas systems. Combustion of the raw materials or cultivation of willow is assumed not to generate any fertilizers. Hence, production and use of chemical fertilizers is included in the reference systems to compensate for this difference.

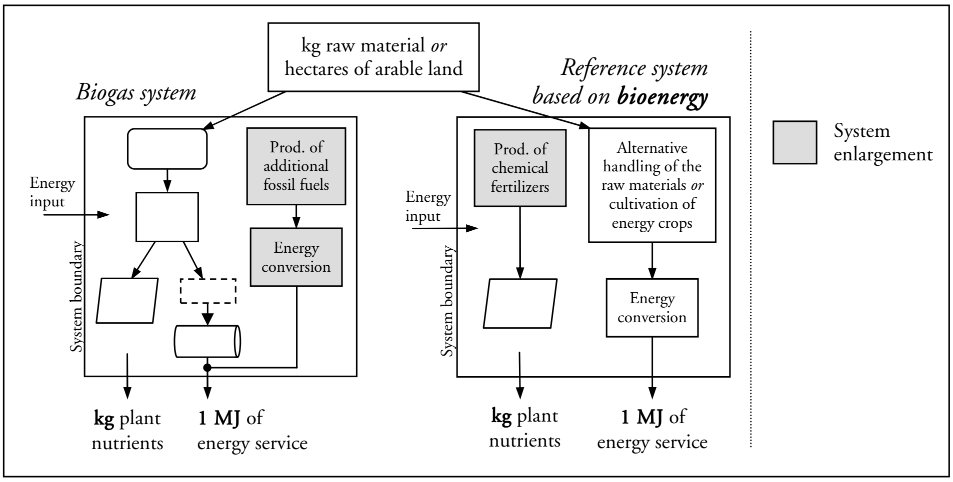

Figure 6: *Comparing biogas systems and reference systems based on bioenergy.*

The calculations show that the introduction of biogas systems often leads to environmental improvements, especially when the indirect environmental effects are accounted for. However, the effects on the environmental impact vary considerably between the comparisons considered, and the outcome is largely due to the raw materials studied and the energy carriers and handling operations replaced.

It was also found that the indirect environmental impact can be of great importance for the results, especially regarding the acidification and eutrophication potentials. In these cases, the emissions defined as causing indirect environmental impact may contribute some 50–95% to the total emissions from a system. The AP and EP for reference systems that include conventional storage of manure or composting of waste can be ten times higher than from the corresponding biogas system, including the indirect environmental impact. The conclusion regarding which of the systems compared causes the lowest emissions can be totally determined by whether the indirect environmental impact is included or not. As for the comparisons with reference systems based on willow, the introduction of biogas would generally reduce the AP and EP when the indirect emissions are included (i.e. decreased nitrate leaching), whereas willow is better if these emissions are not considered. The GWP and POCP can also be affected by emissions that cause indirect environmental impact, i.e. emissions of CH_4 from the storage of manure and of CH_4 and N_2O from composting.

The results of the analyses indicate that the emission of greenhouse gases could be decreased by about 75–90% if biogas were used to replace fossil fuel for heating, by 60–90% for CHP, and by 50–85% when petrol and diesel used in vehicles are replaced by biogas. The loss of methane from the biogas systems could typically amount to some 10–20% of the biogas yield before the emissions of greenhouse gases would exceed those from the corresponding fossil-fuel-based reference systems. On the other hand, the emissions of greenhouse gases from biogas systems could be 50–500% higher, or even 25 times higher (for large-scale combustion of straw), compared with reference systems based on bioenergy. This is mainly due to the need for additional fossil fuels in the biogas systems to compensate for lower energy output per tonne of raw materials or hectare of arable land.

3.4 When is Biogas Production Advantageous?

The analyses show that anaerobic digestion and biogas production can have several potential environmental advantages, depending on the raw materials digested, and the fuels and waste management practices replaced. In general, anaerobic digestion is likely to be most advantageous in the following cases.

- When biogas is produced from raw materials that are not normally used for energy conversion, for example, liquid manure and tops and leaves of sugar beets – in these cases, biogas is assumed to replace fossil fuels;

- when the indirect environmental impacts are accounted for, for example, (i) reduced emissions of methane and ammonia from the storage of manure, (ii) reduced nitrogen leaching and field emissions of ammonia from the recovery and digestion of nitrogen-rich crop residues, and (iii) reduced emissions of ammonia from composting of organic waste; and

- when biogas replaces fossil fuels. This could reduce the emissions of greenhouse gases in general, but could also reduce the contribution to the POCP, EP, AP and emission of particles, for example, when biogas is used as a vehicle fuel.

However, biogas in not always the best alternative when compared with other bioenergy systems. For example, if there is a demand for heat and the raw materials can be combusted, or the arable land can be used for the cultivation of willow, the introduction of biogas could increase the emission of greenhouse gases. This is mainly due to the higher energy conversion efficiency from combustion of a raw material. This inherent difference is difficult to influence. High losses of methane or ammonia from the biogas system can significantly affect the environmental performance. This can be remedied, for example, by appropriate covering of the storage tank for digestate and flaring of excess biogas to reduce the losses of methane, or by employing an appropriate spreading technique for the digestate to reduce the loss of ammonia.

The main reason for implementing a biogas system should be clear to allow for proper interpretation of the results. For example, if the main purpose of cultivating energy crops is to obtain as high a heat yield as possible per hectare arable land, then cultivation of energy crops intended for combustion, e.g. willow or reed canary grass, would be better than cultivation of crops intended for anaerobic digestion, e.g. ley crops. On the other hand, if the main objective is to improve soil fertility and soil structure, then ley cropping and anaerobic digestion provide a good alternative to achieve these goals.

Large variations were found between the biogas systems compared concerning energy performance and environmental impact. Hence, it is not possible to draw any general conclusions on the average environmental impact of biogas production and utilisation without defining the biogas system considered.

4 REFLECTIONS ON METHODS

The results presented in the previous chapter largely depend on the choices and the assumptions made regarding input data, system boundaries, allocation methods, etc. Awareness of the implications of these methodological aspects is therefore important in interpreting the results from this and previous studies properly. These aspects are discussed in this chapter, as well as potential differences between the approaches applied in *Papers I–III* and previous studies.

4.1 Focus

One overall aim of the studies described here (*Papers I–III*) was to broaden our understanding of the energy performance and environmental impacts of potential biogas production systems. Several different raw materials were therefore investigated, and they were studied individually in order to make the calculations and results as transparent and general as possible. Since the production of energy carriers is the common denominator of these systems, the functional unit was set to one MJ of biogas, or energy services. This energy-related perspective is in line with previous research carried out at Environmental and Energy Systems Studies concerning various renewable energy systems.

Other approaches can be used to analyse biogas production from a life-cycle perspective. Previous life cycle assessments[3] concerning Swedish conditions have focused on entire waste management systems, from local to national level, for example, in studies based on the ORWARE model (Eriksson, 2006) and the MIMES/Waste model (Ljunggren Söderman, 2000). In these cases, anaerobic digestion was one of several different treatment options for some of the waste.

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[3] Life cycle assessment (LCA) is a standardized tool (ISO 14040) for systematic assessment of the environmental impact of a product or a service, from its cradle (e.g. extraction of natural resources) to its grave (i.e. its disposal). The assessment includes goal and scope definition, inventory analysis, and impact assessment. The analyses performed here are founded on similar basic ideas, and similar terminology is applied. For further information on LCA, see, for example, Baumann & Tillman (2004).

These models can include both environmental and economical aspects, and can be expanded to include wastewater treatment. In addition, environmental systems analyses have been performed in which anaerobic digestion and other options for the treatment of specific substrates are compared, for example, organic household waste (e.g. Nilsson, 1997) and common reed, *Phragmites australis* (Fredriksson, 2002). Analyses have also been carried out of the environmental impact of specific biogas plants (e.g. Nilsson et al., 2001) and the consequences of introducing ley crops for anaerobic digestion on conventional or organic cropping farms (Sundberg et al., 1997). These studies have to a higher extent focused on the treatment of various by-products and waste products, or the management of arable land. For example, the functional unit was tonnes of the raw material studied, or the environmental impact was expressed as the sum of all impacts for the waste management systems studied.

The results from such studies are valid for different aspects depending on the focus chosen and systems studied. The purpose of the studies presented in this thesis was to improve our general understanding of the environmental implications of biogas production and to demonstrate how such analyses can be performed, rather than to give exact figures for the environmental impact of a specific biogas production system. Nevertheless, the calculations and methods used here can be applied to the evaluation of the environmental impact of real biogas applications, but site-specific data should be used when available to better reflect the actual situation. Differences in focus between studies will also affect the implications of the aspects discussed below, for example, regarding system boundaries and the need for allocation of energy input and emissions, as discussed in Section 4.3.

4.2 System Boundaries

The system boundaries applied in environmental systems studies define which processes are included in the analysis. The biogas systems analysed here include handling and transport of raw materials, operation of biogas plants, transport and spreading of digestate, and upgrading when necessary and use of the biogas produced. The calculations included the production of inputs used in these processes, such as energy carriers, chemical fertilizers, and vehicles and machinery used for transport and handling of raw materials and digestates.

Handling and transport of raw materials include the actions necessary to make the raw materials available for anaerobic digestion. The ley crops included in these analyses are considered to be cultivated primarily for biogas production purposes. Hence, the energy needed and the environmental impact of cultivation and harvesting are included in the analyses. If the ley crops were assumed to be residues from a green manuring system, the system boundaries for the biogas system were narrowed so that sowing and management of the green manure crop were excluded. This would resemble with the preconditions set for other harvest residues studied here. However, excluding sowing and management of the ley crops would require that the reference systems compared included green manuring in order to make the comparisons accurate. This is not considered an option here. Chemical fertilizers were assumed to be used in the cultivation of ley crops. Digestate could be used to replace chemical fertilizers, as is likely in reality. This is not considered here since it would diverge from the basic system settings assumed for biogas production. The remaining raw materials are considered to be by-products. Hence, no environmental impact associated with the production of the main product is included in these systems.

Transport and spreading of the digestates on arable land were included in the analysis since this is the main disposal option for digestates today, and appropriate disposal of the digestates was considered to be of great importance to enable well-functioning biogas systems. In addition, the reason for building biogas plants is often the demand for an organic fertilizer in agriculture. Some previous studies have not included transport and spreading of the digestate, but regarded it as a by-product that be used as a fertilizer in agriculture (e.g. Nilsson et al., 2001). In such cases, no energy demand or environmental impact resulting from the production of biogas has been allocated to the digestate. The present calculations showed that the potential environmental benefits of the biogas systems analysed depend largely on the use of digestate on arable land. Hence, it is important to ascertain whether the handling of the digestate is included or not when comparing systems analyses of biogas systems.

The time horizon applied can affect the results. Here, the focus was basically on short-term effects of introducing biogas systems, such as changes in the loss of nitrogen due to changes in the management of harvest residues or animal manure. Long-term effects, for example, changes in soil organic matter, are not generally included in the studies presented here. The long-term effects of increased soil organic matter resulting from introducing ley crops in cereal-based crop sequences were assessed in *Paper I*. These effects were expressed as indirect energy savings due to a reduced demand for chemical fertilizers. However, to make an accurate assessment of the long-term effects of the implementation of biogas production, more details about local conditions and better definitions of the biogas system and the reference systems are needed than were generally possible and available for the analyses performed here.

The analyses described in this thesis refer mainly to Swedish conditions. Regarding the agricultural issues included in the systems, we have primarily considered the southern region of the country. This includes, for example, crop yields, available crops (e.g. sugar beets and willow), nitrogen loss, and estimated emissions of ammonia and methane from the storage of manure or harvest residues left in the fields. Much of the biogas produced in Sweden is currently produced in the southern region, and there is also considerable potential for increased biogas production here. The potential supply of raw materials from Skåne (the southernmost province) is estimated to correspond to some 20% of the theoretical biogas potential in Sweden (Nordberg et al., 1998).

The electricity required in the systems analysed was assumed to be produced in condensing plants using natural gas. Natural gas was assumed to reflect the long-term, marginal electricity production in the Scandinavian countries (Mattsson et al., 2005). Other sources of electricity, or mixtures of sources reflecting the average means of electricity production in a region, could have been used as well. The source of electricity chosen is dependent on the scope of the study. Marginal electricity production was chosen rather than average data since the studies were performed to reflect the impact of implementing biogas production. In change-oriented studies, for example within LCA, marginal data is often considered the most relevant since this change can be expected to cause marginal effects on the production of inputs, such as the generation of electricity (Mattsson et al., 2005). The effects of choosing electricity from CHP based on biogas were evaluated in the sensitivity analysis presented in *Paper II*. The greatest effect was seen on the emission of CO_2, which decreased by 20–40%, excluding upgrading of the biogas, and 35–60%, including upgrading, in the large-scale biogas systems analysed. Changing the source of electricity will affect all the biogas systems similarly since the proportion of electricity used in the systems is similar. However, greater effects may be seen when the biogas systems are compared with various reference systems since the electricity intensity can vary considerably between reference systems.

Different criteria were used to account for the environmental impact of capital goods (i.e. vehicles, machines, buildings, etc.) in the biogas systems. Construction, maintenance and demolition of biogas plants or of infrastructure used for gas distribution were not included. Their contribution to the environmental impact of biogas production systems was deemed to be low, especially considering the large material and energy flows handled in these facilities during their lifetime. The environmental impact of the production and maintenance of vehicles and machinery was estimated to be higher, based on previous experience (e.g. Sundqvist et al., 2002). Production and maintenance included vehicles and machines used in the transport and handling of raw materials, and in the transport and spreading of digestate. The calculations showed that this would generally contribute to about 1–8%, occasionally more, to the emissions from the transport, the handling of raw materials, and the spreading of digestate, respectively. The question of whether to include capital goods was therefore considered not to have a significant effect on the results.

System enlargement

System enlargement, also referred to as “system expansion” in the literature, was adopted to make two systems comparable and to ensure that the systems included similar bases for comparison and provided similar outputs. System enlargement was important mainly because two usable outputs were to be provided (i.e. fertilizer and energy) and their proportions differed between the systems studied. The systems could be enlarged since both outputs can be provided separately, i.e. the production of chemical fertilizers, and extraction and use of fossil fuels. In some cases the implications of system enlargement were of considerable importance, especially concerning emissions of greenhouse gases when comparisons included combustion of the raw materials for heat recovery.

A clear distinction is made here between the environmental effects resulting from system enlargement, and the emissions related to what is here called indirect environmental impact. The latter category is here defined to include emissions that are not directly related to energy conversion in the systems studied. Other definitions of indirect effects can be found in the literature.

4.3 Allocation Methods

When a process has several inputs (e.g. the co-digestion of several raw materials), the environmental impact of this process must be divided between the various inputs if they are further analysed separately. The same applies to processes in which several products are produced (e.g. the production of biogas and digestate at biogas plants, or co-generation of heat and electricity) and the further analyses only include some of the products. In the studies described here, allocation of environmental impact to the raw materials is necessary concerning the operation of biogas plants, and transport and spreading of digestate. The basic idea was to find values of the energy demand for these processes that could be used for the various raw materials studied in order to make the calculations as transparent and general as possible. These processes, mainly operation of the biogas plant, use a large part of the energy input to the biogas systems studied. The allocation method chosen can therefore significantly affect the results.

In the base scenario (see Chapter 3), the energy input and emissions from these processes were divided between the raw materials studied according to their dry matter content; that is, the energy input and emissions were expressed as a mean value per tonne of substrate mixture having a 10% dry matter content. Other allocation methods were investigated in which differences regarding dilution requirements and biogas yields were dealt with differently (see *Paper I*). These methods resulted in different ways of expressing the mean energy input required for the operation of the biogas plants, and the amount of digestate produced per tonne of raw material. The following two allocation methods were investigated in addition to the method applied in the base scenario.

1. The energy needed for the operation of the biogas plant and the handling of digestate was expressed as a mean value per tonne of raw material, regardless of its dry matter content. As a result, no consideration is taken of the potential need for diluting dry raw materials or the potential benefits of using liquid raw materials to dilute dry ones. One tonne of raw material is assumed to correspond to 1 tonne of substrate added to the digester and 1 tonne of digestate to be transported and spread.

2. The mean energy requirement for the operation of the biogas plants is expressed as a percentage of the biogas yield. As in the base scenario, the energy requirements for the transport and spreading of the digestate are determined by the dry matter content of the raw materials. Consequently, 1 tonne of ley crops (23% dry matter) corresponds to 2.3 tonnes of digestate to be transported and spread, while 1 tonne of manure (8% dry matter) corresponds to 0.8 tonnes of digestate. The mean energy demand for the operation of biogas plants is often reported as a percentage of the biogas yield.

The different allocation methods were found to affect the calculated energy performance of the biogas systems significantly. Ignoring differences in dry matter content and thus dilution demands has the greatest effect on raw materials that have very high or very low dry matter contents (alternative 1 above). In contrast to the base scenario, the energy input associated with the handling of water, fresh water or liquid raw material, required to obtain suitable dry matter content in the digester is not allocated to the dry raw materials. This will also reduce the amount of digestate from dry raw materials to be transported and spread. The calculated energy input in biogas systems based on municipal organic waste is almost half that of the base scenario. On the other hand, raw materials that have very low dry matter contents are not credited for their potential use for dilution of drier raw materials. The energy input calculated for the digestion of grease separator sludge is almost doubled, including the increased demand for transport and spreading of the digestate.

When the energy input is expressed as a percentage of the biogas yield (alternative 2 above), the raw materials that have the highest biogas yields are disadvantaged. This allocation method implies that the energy input in the operation of the biogas plant corresponds to a fixed percentage of the energy output of the system, regardless of the properties of the raw materials digested or their biogas yields. In the base scenario, the energy needed in the operation of the biogas plant corresponds to a lower proportion of the biogas yield for high-yielding raw materials than the fixed percentage assumed in the latter allocation method. The energy input for the digestion of grease separator sludge is estimated to double when this allocation method is applied.

The allocation method applied in the base scenario was chosen since it was regarded as the best estimate of reality, considering that the raw materials were studied individually. This allocation method the characteristics of the raw materials and biogas plant to be taken into account in a better way than would be possible if the energy input was expressed as a percentage of the biogas yield. The heat demand depends, from, on the amount of insulation, use of heat exchangers, and the need for sanitization of the raw materials, rather than the biogas yield. However, the allocation method described as alternative 1 above could be used if dry raw materials were to be added to the digester without the need to add more fresh water or wet raw materials to obtain the appropriate digestion conditions. Increased dry matter content in the digester can in some cases be preferable since the biogas yield per unit volume of the digester could be increased and less water would have to be handled and transported.

When the environmental impact of entire co-digestion plants or systems is assessed, there is no need to divide the energy demand between the raw materials digested as discussed above. However, if results from such assessments are extracted for individual raw materials, consideration should be given to how the environmental impact is allocated to the raw materials. Such considerations are rarely seen in the literature.

Allocation may also be necessary when a process generates different products, as is the case in the co-generation of heat and electricity. Here, the emissions from CHP were instead expressed per MJ of heat *and* electricity. Similar end-use technologies were assumed for both biogas and for natural gas used in the corresponding reference systems. Hence, the conversion efficiencies and proportions between heat and electricity will be similar in both systems. Allocation may be necessary if biogas-based electricity generation is to be compared with other production alternatives in which no or other proportions of heat were produced. Allocation can be avoided if the system providing less heat is expanded to include additional heat production to make up the difference.

4.4 Input Data

The applicability, characteristics and quality of the input data found in the literature and used in these studies vary. The sensitivity analysis performed (e.g. in *Papers I–II*) indicates that the results depend on the input data and system design.

Some data depend greatly on local conditions. The availability of various raw materials, transport distances and potential crop yields, etc. vary depending on the location of the biogas plant, which in turn affects the energy demand and the environmental impact of the operations. For example, the cultivation of ley crops is assumed to represent average-yielding (tonnes per hectare) cultivation in southern Sweden. Other locations or cultivation intensities would affect the energy demand, environmental impact, and the area of arable land needed. The local conditions will also have a great impact on the indirect environmental impact (see the section below). Although high-quality data may be available for specific sites, there may be large differences between sites. The location of the biogas system and its characteristics should therefore be stated clearly in such environmental systems analyses, and borne in mind when comparing different systems. However, some emissions may be difficult to measure or to model, for example, the formation of N_2O in arable land, which in turn may lead to unavoidable uncertainties.

There are other details and site-specific data that can not be considered in the general studies described here. For instance, there may be large differences between raw materials digested regarding pre-treatment demands, sanitization requirements, viscosity, etc., that will affect the heat and electricity demand in the operation of the biogas plant. There will also be differences between biogas plants regarding the system design, for example, insulation, heat exchangers, and equipment used for stirring, maceration, etc. When real biogas systems are evaluated, site-specific data should therefore be used when available.

Variations and uncertainties may also arise due to defective or old data, or the fact that accurate data are lacking. Whenever possible, the values used in the analyses were based on mean values or best estimates from different references in order to reduce these uncertainties. New, higher-quality data have become available since the calculations presented here were preformed, for example, concerning emissions from various end-use applications (e.g. Nylund et al., 2004), and leakage of CH_4, N_2O, etc. from biogas plants and upgrading plants (e.g. RVF, 2005b). New measurements at some biogas plants indicate that the loss of CH_4 corresponds to some 0.5–1% of the biogas produced, and that the losses at upgrading plants correspond to 1–4% of the biogas purified. In the calculations presented here it was assumed that the loss of CH_4 corresponded to 1% of the biogas at the biogas plant and an additional 1% at the upgrading plant.

Indirect environmental impact

The potential indirect environmental impact of implementing biogas production was shown to often be of great importance for the results, although these indirect effects are associated with a comparatively high degree of uncertainty. These effects arise mainly from the reference systems assumed in the comparisons and the non-energy-related aspects of the systems compared (e.g. handling of harvest residues and management of organic waste or arable land). Good knowledge of these issues and well-defined systems are therefore needed in order to reduce the uncertainties and to draw accurate conclusions. Many of these uncertainties are difficult to address since they can vary greatly and are highly dependent on local conditions. The soil type and the climate differ between regions, affecting the indirect emissions. For example, nitrogen leaching is higher from sandy soils than from clay soils, and when the precipitation is high. Low temperature slows down many biological processes and reduced the evaporation of gases. The emissions of ammonia and methane from storage of manure will therefore be lower further north. Emissions of ammonia from the composting of organic waste can vary greatly due to, for example, the functioning of gas cleaning equipment potentially used and the carbon/nitrogen ratio. The amount of data may be limited, for example, regarding how the implementation of biogas production affects emissions of methane and ammonia from the storage of manure or the handling of harvest residues.

To conclude, the indirect environmental impact of implementing biogas systems can be difficult to assess and the magnitude is often uncertain. However, the indirect environmental impact should be included in environmental assessments of biogas since it can be of great importance to the results, and biogas systems can rarely be regarded as energy conversion systems solely. In this thesis, the emissions categorised as causing indirect environmental impact are presented separately from other emissions, for example, by showing them in separate segments in the figures. This was done to clarify the distinction, and the different levels of uncertainty, between these categories, and to enable the reader to exclude indirect environmental impact when appropriate.

4.5 Comparability

The environmental impact of introducing a biogas system depends largely on the reference system chosen for the comparison. The main area of interest in these studies was biogas production systems, and it was not possible to perform as detailed calculations regarding the reference systems. Therefore, previous studies were used, and where possible the values were adjusted to resemble the conditions in the biogas systems. For example, the electricity used in the biogas systems is assumed to be based on natural gas. When other sources of electricity were used in the reference systems, the emissions from the production of electricity were recalculated to match the assumptions made in the biogas systems.

The reference systems were chosen to represent realistic alternatives to biogas production systems of today or in the near future. Regarding organic waste (i.e. industrial organic waste and municipal organic waste), combustion or composting of the waste are considered to be the most realistic alternatives for the near future. Landfilling of these waste products is decreasing steadily (RVF, 2005a), and the ban on landfilling of organic waste calls for other waste management strategies. For some raw materials, for example, manure and tops and leaves of sugar beets, anaerobic digestion is essentially the only realistic alternative to conventional option. Tops and leaves of sugar beets can be used as fodder, but this is rarely practiced today and was not included in this study.

When there were different alternatives to choose between, the alternatives representing the best case and the worst case were selected, to show the range between different alternatives. For example, set-aside arable land was assumed to be used for energy production purposes, either for cultivation of ley crops for anaerobic digestion or the cultivation of willow. Willow was chosen since it is estimated to be the crop that can provide the highest heat yield per hectare of arable land, under Swedish conditions (Hakelius (Ed.), 2005a). In addition, methanol from willow has been estimated to be the most energy efficient biofuel based on cultivated crops, regarding the transportation service, per hectare of arable land, taking into consideration the energy used in the production of fuels (STEM, 2003). In contrast, the worst case was assumed to be represented by the use of fossil fuels for energy production purposes, implying that arable land lies fallow.

Fossil fuels were assumed to be used for energy production purposes in reference systems in which the handling of the raw materials did not generate any usable energy carriers. Biogas is often produced to reduce the use of and dependence on various fossil fuels, for example, petrol or diesel in the transportation sector, or fuel oil for heating purposes on farms. Natural gas was assumed to be used for combined heat and electricity production in the reference systems since: (i) the same end-use technology can be used for both biogas and natural gas, (ii) it complements the assumptions made regarding the generation of electricity used in the biogas systems, and (iii) natural-gas-based electricity is assumed to be the long-term method of marginal electricity production in the Scandinavian countries (Mattsson et al., 2005). Concerning district heating, biogas may replace various solid biofuels. However, the only bioenergy-based reference systems considered here are those that include the same raw material or area of arable land as is used in the corresponding biogas system. If the reference systems were to be based on other biofuels, the comparability between systems would be reduced since this implies that some alternative use of the biofuel needs to be included in the corresponding biogas system.

The analyses performed take their starting point in calculations of energy flows in the systems studied. In order to allow different energy flows to be summed, they are all given as primary energy inputs; that is, unconverted and untransformed natural resources. The accuracy of summing different natural resources can be questioned and different criteria or conversion coefficients can be used, but this approach was considered to be the most appropriate way of presenting the total energy use in the systems analysed. The energy input in the biogas systems is given for each process to allow for other conversion coefficients to be used. Differences in environmental impact between energy carriers are then accounted for in the environmental systems analyses as these analyses include emissions from the production and use of the energy carriers. In this way, it is possible to account for the different emissions of fossil CO_2 from renewable energy carriers and fossil fuels.

5 PROSPECTS FOR THE USE OF DIGESTATE

There are several potential obstacles and problems related to biogas production that must be addressed. To date, much of the focus has been on technical and economical aspects, such as the development and improvement of digestion technologies, or evaluation of the use of biogas in vehicles, exemplified by the collaboration project on biogas in vehicles, administrated by the Swedish Biogas Association (SBGF, 2006). Large-scale co-digestion is a fairly new practice in Sweden, and new concepts are being developed and adopted in practice. Problems reported from these large-scale biogas plants have included: (i) mechanical operation problems regarding the pre-treatment of organic waste (e.g. separation of plastics, high content of organic matter in the reject), stirring (e.g. failing equipment, thick crusts), and dewatering of digestate (e.g. high concentrations of nitrogen in the reject water), (ii) process-related problems including formation of scum and failing digestion process due, for example, to overload, and (iii) odour, which has been a common worry among local residents and has led to resistance against the construction of new biogas plants (Khan, 2004; NV, 2005). Some of these problems can be regarded as teething troubles, and may be better dealt with when new plants are built. In addition, there are many actors from different sectors involved in biogas production systems, for example, actors within agriculture, waste management, energy production and local authorities. For example, in the planning and siting of biogas plants several actors have different interests which must be reconciled in this complex project (Khan, 2004).

Regarding digestate, much attention has been focused on risk assessment, for example, concerning transmission of pathogens, and the occurrence and fate of undesirable organic compounds (e.g. RVF, 2005d; RVF, 2005e; Sundh (Ed.), 2004). Studies have also been carried out regarding practical experience of the disposal and utilisation of digestate in agriculture (e.g. Berg, 2000; RVF, 2005c).

A reliable and generally accepted means of disposal of the comparatively large amounts of digestate produced was identified to be of great importance if the whole biogas system is to work as anticipated. If there is no demand, any excess biogas can be, and often is, flared off. This technology is easy to apply and it is inexpensive, though flaring leads to loss of income. More than 90% of the digestates produced in large-scale biogas plants are currently used as fertilizers in agriculture (RVF, 2005a). There are rarely any other disposal options as practical and economically feasible as agriculture, and this will probably continue to be the case in the future. The analyses presented in *Papers I–III* show that many of the environmental benefits, especially the indirect environmental benefits, of biogas production are due to the digestates being used on arable land. The above motivated the study presented in *Paper IV* concerning the prospects for using digestate from large-scale biogas plants on arable land.

Digestates are generally seen as good fertilizers and there have been few obstacles to their use in agriculture. However, one occasion was in the summer of 2001 when Cerealia, the largest cereal-based food producer in Sweden, for a period of time did not recognise digestate as an approved fertilizer (Andersson, 2001).

Regarding sewage sludge from wastewater treatment plants, there has been a more enduring and lively debate regarding its use as a fertilizer on arable land. This use has suffered many setbacks over the years, and doubts have been repeatedly raised regarding the feasibility of using sludge in agriculture, for example, due to alarming reports. In 1999, there were reports on the risk of the accumulation of various heavy metals in arable soils, risks to health, and an indicated increase in brominated flame retardants in sewage sludge. The latter initiated the Federation of Swedish Farmers (LRF) to recommend its members to stop using sewage sludge due to reduced confidence in sludge as a fertilizer (Agustinsson, 2003). In addition, most actors within the food industry did not allow the use of sewage sludge as fertilizers in food or fodder production (Berglund, 2001). This was primarily motivated by concerns regarding undesirable substances in the sludge (e.g. PCB and cadmium), consumer attitudes towards sewage sludge, and customer demands. Above all, there were few economical incentives for the actors within the food industry to allow the use of sewage sludge, whereas the reduced confidence in their products might lead to significant economical risks if the products were associated with the use of sewage sludge (Berglund, 2001).

A clear distinction is made here between digestate from biogas plants and sewage sludge from wastewater treatment plants. This is in part motivated by the scepticism regarding the use of sewage sludge on arable land while the use of digestate has been relatively successful in Sweden. Secondly, it is motivated by their different characteristics and the differences in legislation and certification systems for their agricultural use. Legislation concerning the use of digestate on arable land includes, for example, restrictions on when, where and how organic fertilizers can be applied arable land, and regulations on the pre-treatment, sanitization, and application of animal by-products intended as fertilizers. The legislation covers application rates of plant nutrients, but not heavy metals. In this case, current legislation regarding sewage sludge is often applied to digestate. A voluntary certification scheme for digestate from organic waste was introduced some years ago. So far, digestates from five plants has been granted certificates by the Swedish Testing and Research Institute (SP), and other plants are applying for certification. The certification criteria concern, for instance, the origin and quality of the raw materials digested, transport and handling of the materials, chemical analyses, documentation of the digestion process and the digestate, and quality requirements regarding the digestate.

Sustainable use of digestates on arable land requires awareness of the risks involved. Regarding the possible transmission of pathogens and undesirable organic compounds to the environment via digestates, the risks to human health and soil organisms are considered to be negligible (e.g. RVF, 2005d; RVF, 2005e; Sundh (Ed.), 2004). Other sources may be much greater contributors to their presence in the environment. Regarding heavy metals, much of the metals in digestate originate initially from arable soils. Recycling of these metals would therefore not cause an accumulation in the soils.

Some actors in the agricultural sector and food industry have stated their views on the recirculation of digestate or other urban waste products to arable land. In principle, they support the use of digestate, but have generally made more extensive demands than those stipulated by legislation and certification criteria (see below and *Paper IV*). For instance, the LRF, the Federation of Swedish Food Industries (LI) and the Swedish Society for Nature Conservation (SSNC) have jointly stated their views on the recirculation of plant nutrients from urban organic waste (LRF, 2002). According to this policy, plant nutrients should be recycled in the long run, but without the accumulation of heavy metals and organic pollutants in arable soils or the transmission of pathogens. Widespread confidence in this use is required to achieve sustainable use of various waste products as fertilizers. In addition, Cerealia now allows the use of approved organic waste products that stem from the food chain as fertilizers in agriculture. The conditions include origin, sanitization and certification. In addition, recirculation must not cause undesirable changes in the concentration of, for instance, heavy metals and plant nutrients in the soil.

Although the use of digestate on arable land is widely acknowledged today and the risks discussed above are considered to be negligible, we should be aware of other ways of interpreting information about potential risks. Perceived risks and alarming reports are difficult to predict, but established relations between actors, confidence in this use of digestates, as well as certification systems can serve as pre-emptive measures. Concerning sewage sludge, the mere thought of the undesirable substances present or that their concentrations were increasing was enough to cause reduced confidence in the use of sludge as a fertilizer. However, there are fundamental differences between digestate and sewage sludge that can mitigate potential problems. In relation to sewage sludge, the link between digestates and agricultural production is clearer since most of the raw materials digested originate directly from food production without being mixed with other waste flows. Many biogas plants have been built to meet the demand for appropriate treatment of waste from the food industry, and spreading the digestate on arable land is included in the concept. The food industry can influence, and they have influenced, the terms for biogas systems.

Digestate from most large-scale biogas plants is intended for use as fertilizers on arable land. These digestates are primarily based on manure and organic waste from the food industry. In these cases, the use of the digestates in agriculture is often regarded as the most appropriate application, and even the only suitable application. This use enables recirculation of plant nutrients, and can also be one of the main reasons behind the biogas systems. According to operators of these biogas plants, all digestates intended for agriculture have been used there, presupposing that the biogas plant works as intended (*Paper IV*). The demand for digestate is even reported to exceed the supply in some cases. According to the operators, the lack of other disposal options may force them to close down in the case of a long-term stop similar to the current situation regarding sewage sludge. However, the risk of ending up in the same situation is considered to be negligible. Current quality requirements are met, and frequent measurements will allow for measures to be taken in cases of high concentrations of undesired compounds or inadequate sanitization. Digestate from most of these biogas plants is, or is intended to become, certified by SP. This is required by some branches of the food industry, and may therefore be essential to ensure confidence among the actors involved and the disposal of the digestate.

Farmers who receive digestate from large-scale biogas plants are reported to be satisfied with it (Berg, 2000; RVF, 2005c). The odour is reduced and the nitrogen efficiency is considered to be higher than in animal manure. Digestates are also considered to be easy to spread. The digestates are usually delivered free to the farmers, and the willingness to pay for digestate is generally low (see Section 2.6).

There is some interest in getting digestate approved as a fertilizer in organic farming. Approval of the digestate for organic farming may lead to economical benefits for the biogas plants since the market would expand, and such an approval is estimated to increase the willingness to pay for digestate. Some operators of biogas plants state that there is an interest in digestate approved for organic farming, for example, among farmers who used to receive digestate but subsequently become KRAV-certified producers. However, KRAV (the largest control organisation for organic farming in Sweden) has not, so far, approved digestate from any large-scale biogas plant. Current KRAV standards exclude much of the potential raw materials (e.g. manure from cattle raised in slatted-floor boxes or from pigs that are not certified by KRAV) and prescribe, for instance, higher levels of sanitization of slaughterhouse waste than is generally applied at biogas plants today. Hence, approval by KRAV may never become more than a niche for some of the digestates produced.

Some digestate is used in other applications than agriculture, for example, in the production of soil improvers or soil for civil engineering purposes to be used in gardens, parks, on roadsides, etc. These digestates may be based on comparatively high proportions of organic household waste, and are generally dewatered and composted with garden waste and similar material. There are several reasons for choosing other applications than agriculture. Biogas production and appropriate waste management can be in focus in some biogas systems, whereas the digestates are seen as by-products. Demands on quality may be higher when the digestates are to be used in agriculture, and considerations can be raised on whether these demands can be met. For example, some of the digestates based on household waste are reported to be used on landfills instead of on arable land due to the comparatively high content of plastics (NV, 2005). Production of such soils can provide a higher income than would be probable if the digestates were used in agriculture. There may also be a demand for such products over a long period of time, for example, for closure and final coverage of old landfills. Agriculture may be a limited market in some regions, due, for example, to limited demand for fertilizers other than the manure produced at the farm, or scepticism regarding the use of various by-products.

6 DISCUSSION AND CONCLUSIONS

Anaerobic digestion can be applied to a wide range of raw materials, and the biogas and digestate produced can be used for different purposes. There may also be considerable differences between the digestion technologies employed and the scale of the process. The design of a particular biogas system will be largely determined by local conditions, but also by the objectives to be fulfilled or environmental concerns to be addressed. This large variety in raw materials and technologies, the many potential combinations, and the need to dispose two products make biogas production systems very complex to study from an energy and environmental point of view. It also makes comparisons between systems difficult.

Biogas systems can rarely be regarded as fuel production or waste management systems alone. The production of a good organic fertilizer can be as important as the production of biogas, or may even be the main reason for building a biogas plant. The importance of appropriate disposal of the digestate was therefore highlighted and assessed in this work. Many biogas plants are intended for the treatment of both organic waste products from food industry and household, which must be treated by some means, and of agricultural by-products that would have been used on arable land in any case. The variety and flexibility is one of the main strengths of biogas production systems. They are often intended to solve several problems simultaneously and can provide many benefits, as discussed in this thesis. However, the variety and complexity may also present a challenge. This concerns not only how to account for the environmental impact or how to make different systems comparable, but can also mean complexity in terms of the many actors and stakeholders involved.

The energy and environmental systems analyses presented in this thesis indicate that the environmental impact of biogas production can vary greatly depending on the raw materials digested and the system design. The results concerning environmental impact will also be highly dependent on the methodological assumptions made, as discussed in Chapter 4. In addition, the reason or reasons for establishing the biogas plant in question must be considered in such analyses in order to ensure that all the relevant aspects are included. This is especially important when anaerobic digestion and biogas production are compared with other waste management strategies or energy carriers since the systems compared may not overlap completely, but may require system enlargement or that the comparisons has to be restricted to parts of each system.

Only a few analyses of existing or planned biogas plants can be found in the literature (see, for example, Uppenberg et al. (2001) for a compilation of analyses performed). The methodological differences between these studies regarding focus, system boundaries, input data, etc., affect the comparability of the results. In the studies presented in this thesis, the environmental impact of biogas production was expressed as the effect per MJ of energy carrier or energy service produced, including the transport and spreading of digestates. Hence, biogas and digestate could be regarded as one entity and there was no need to allocate emissions or environmental benefits to the two products. However, when energy production is the main goal and the disposal of the digestate is not included, the results may be quite different, and other considerations regarding allocation of the environmental impact may be needed.

Based on the results presented in *Papers I–III* and the experience gained concerning the large variety of environmental impact between biogas systems, no general conclusions regarding average impact of biogas production can be given. When information on environmental impact is required, analyses should be performed for the specific case and the methodological assumptions made should be stated clearly. However, the results of the analyses show that biogas production may bring about many environmental improvements when designed and managed properly. The method of calculation, and the data and results presented here may also be useful in future assessments of biogas production and provide operators with valuable background information.

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