System studies of Biogas production

Comparisons and performance

Emma Lindkvist

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System studies of biogas production - comparisons and performance

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Till

Stella & Linus

ABSTRACT

Biogas has the potential to be part of the transition towards a more sustainable energy system. Biogas is a renewable energy source and can play an important role in modern waste management systems. Biogas production can also help recirculate nutrients back to farmland. Besides all this, biogas is a locally produced energy source with the potential to increase global resource efficiency, since it can lead to more value and less waste, as well as decreased negative environmental effects. However, biogas production systems are complex, including different substrates, different applications for biogas and digestate, and different technology solutions for digestion, pre-treatment and for upgrading the raw gas. To increase the development of biogas production systems, knowledge sharing is a key factor. To increase this knowledge sharing, comprehensible analysis and comparisons of biogas production systems are necessary. Thus, studies are needed to verify the resource efficiency of biogas production systems from different perspectives.

The aim of this thesis is to perform a systems analysis of biogas production systems and to explore how to analyse and compare biogas production systems. An additional aim is to study biogas production systems from a systems perspective, with a focus on environment, energy and economy. Studying biogas production systems from different system levels, as well as from different approaches, is beneficial because it results in deeper knowledge of biogas systems and greater opportunities to identify synergies.

Systems studies of biogas are important, since biogas systems are often complex and integrated with other systems. In this thesis, biogas systems analyses are performed at different levels. In the widest system study, classifications of different biogas plants are analysed and classifications in different European countries are compared, with the prospect of paving the way for a new common classification for biogas plants in Europe. Today, classifications vary between countries, and hence comparisons of plants in different countries are difficult. In the narrowest system study, a new methodology for analysing energy demand at different biogas production plants has been developed. The aim was to develop a methodology that is applicable for all kinds of biogas plants with energy inputs. The methodology describes the process of analysing energy demand and allocating energy to sub-processes and unit processes.

Further, an approach for assessing the resource efficiency of different treatment options for organic waste was designed. The approach includes environmental, economic and energy perspectives, and was applied to five different regions with several food manufacturing companies. A study of treatment options for organic waste from a single food company was also conducted. The results showed that biogas production is a resource-efficient way to treat waste from the food industry. The approach enables a wider analysis of biogas systems, and the results from the applications show the complexity of assessing resource efficiency. It is also shown that it is important to understand that the resource efficiency of a system is always in relation to the substituted system.

In this thesis, three different approaches to analysing biogas production systems are presented: categorization, resource efficiency analysis and energy demand analysis. These approaches all contribute to the understanding of biogas systems and can help, in different ways, to increase knowledge about biogas systems in the world. If knowledge about different biogas systems can be easily disseminated, more of the unused potential of biogas production may be realized, and hence more fossil fuels can be replaced within the energy system.

SAMMANFATTNING

Biogas har potentialen att vara en del av övergången till ett mer hållbart energisystem. Biogas är en förnybar energikälla som kan spela en viktig roll i moderna avfallshanteringssystem. Produktion av biogas kan även hjälpa till att återcirkulera näringsämnen tillbaka till jordbruksmark. Förutom allt detta är biogas en lokalt producerad energikälla med potential att öka resurseffektiviteten i världen, eftersom det kan leda till ökat värde och mindre avfall samt minskade negativa miljöeffekter. Dock är biogasproduktionssystem komplexa, inklusive exempelvis olika substrat, användning för biogasen och rötresterna, olika tekniska lösningar för rötresterna såväl som förbehandling av substrat och uppgradering av rågas. För att öka utvecklingen av biogasproduktionssystem är kunskapsdelning en nyckelfaktor. För att öka kunskapsdelningen är tydliga analyser och jämförelser av biogasproduktionssystem nödvändiga. Därför behövs studier för att verifiera resurseffektiviteten för biogasproduktionssystem från olika perspektiv.

Syftet med denna avhandling är att utföra systemanalyser av biogasproduktionssystem och att undersöka hur man analyserar och jämför biogasproduktionssystem. Vidare är syftet också att studera biogasproduktionssystem ur ett systemperspektiv med fokus på miljö, energi och ekonomi. Det är fördelaktigt att studera biogasproduktionssystem på olika systemnivåer och utifrån olika tillvägagångssätt, eftersom kunskapen om biogassystem fördjupas och möjligheterna att hitta synergier ökar.

Systemstudier av biogas är viktigt eftersom biogassystem ofta är komplexa och integrerade i andra system. I denna avhandling utförs analyser på olika nivåer av biogassystemen. På den högsta systemnivån analyseras klassificeringar av olika biogasanläggningar. Klassificeringar i olika europeiska länder jämförs, med förhoppningen att bana väg mot en ny, gemensam klassificering för biogasanläggningar i Europa. Idag varierar klassificeringarna mellan länder och därför är jämförelser av anläggningar mellan länder svåra. På den lägsta systemnivån utvecklades en ny metod för analys av energibehov vid olika biogasproduktionsanläggningar. Syftet var att utveckla en metod för alla typer av biogasanläggningar. Metodiken beskriver processen för att analysera energibehov och fördela energin till delprocesser och enhetsprocesser.

Vidare utformades en metod för att bedöma resurseffektiviteten hos olika behandlingsalternativ för organiskt avfall. Metoden inkluderar miljö, ekonomi och energi och tillämpades i fem olika regioner med flera livsmedelsindustriföretag. En studie av behandlingsalternativ för organiskt avfall från ett enda livsmedelsföretag genomfördes också. Resultaten visade att biogasproduktion är ett resurseffektivt sätt att behandla avfall från livsmedelsindustrin. Metoden möjliggör en bredare analys av biogassystem och resultaten från tillämpningarna visar komplexiteten i att utvärdera resurseffektiviteten. Det visas också att det är viktigt att förstå att ett systems resurseffektivitet alltid är i förhållande till det substituerade systemet.

I denna avhandling presenteras tre olika metoder för analys av biogasproduktionssystem: kategorisering, resurseffektivitetsanalys och energibehovsanalys. Dessa tillvägagångssätt bidrar alla till att förstå biogassystem och kan på olika sätt bidra till att öka kunskapen för biogassystem i världen. Med bra system för att sprida kunskap om olika biogassystem kan mer av den outnyttjade potentialen för biogasproduktion realiseras och därmed kan fler fossila bränslen i energisystemet ersättas, samtidigt som de övriga fördelarna med biogas också kommer samhället till nytta.

Appended papers

This thesis is based upon the work described in the five papers listed below. In the thesis the papers are referred to with roman numerals, and the papers are appended at the end of the thesis.

- I. Lindkvist E., Karlsson M. (2017) Biogas production plants; existing classifications and proposed categories. *Journal of Cleaner Production*, 174, 1588-1597.
- II. Lindkvist E., Karlsson M., Ivner J. (2019) Systems Analysis of Biogas Production – Part I Research Design. *Energies*, 12, 926.
- III. Lindkvist E., Johansson M., Rosenqvist J. (2017) Methodology for Analysing Energy Demand in Biogas Production Plants – A Comparative Study of Two Biogas Plants. *Energies*, 10, 1822.
- IV. Lindkvist E., Karlsson M., Ivner J. (2019) Systems Analysis of Biogas Production – Part II Application in Food Industry Systems. *Energies*, 12, 412
- V. Broberg Viklund S., Lindkvist E. (2015) Biogas production supported by excess heat – A systems analysis within the food industry. *Energy Conversion and Management*, 91, 249-258.

A co-author statement for each paper is presented in chapter 1.3.

Other publications not included in the thesis:

Lindkvist E., Karlsson M., Ivner J. (2016) Biogas production feasibility in food industry clusters. ECEEE Industrial Summer study – Industrial Efficiency 2016. (early version of papers II and IV).

Feiz R., Johansson M., Lindkvist E., Moestedt J., Pålédal Nilsson S., Svensson N. (2020) Key performance indicators for biogas production – Methodological insights on the life-cycle analysis of biogas production from source-separated food waste. *Energy*, 200, 117462

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Thesis outline

This thesis is divided into two parts. Part 1, the kappa, gives an introduction to and a summary of the five papers that form the basis of this thesis. Part 2 contains the appended papers.

Part 1 is structured as follow:

Chapter 1 gives an introduction to the kappa. It also includes the aim, research questions, scope and delimitations as well as a paper overview and co-author statement to the appended papers.

Chapter 2 serves as an introduction to biogas production systems.

Chapter 3 gives an introduction to the food industry

Chapter 4 introduces the key concepts of the thesis, together with some earlier system studies of biogas production systems.

Chapter 5 describes the different systems studied.

Chapter 6 presents the methods used.

Chapter 7 provides a summary of the main results from the appended papers, as well as answers to the two research questions.

Chapter 8 includes discussion, conclusion and suggestions for further work to be done.

“The only true wisdom is in knowing you know nothing”

- Socrates

“How could I look my grandchildren in the eye and say I knew what was happening to the world and did nothing”

- David Attenborough

Abbreviations

AP	Acidification Potential
BAU	Business as usual
CHP	Combined heat and power
EP	Eutrophication potential
GHG	Greenhouse gas
GWP	Global warming potential
IO	Investment opportunity
IPCC	Intergovernmental panel on climate change
LBG	Liquified Biogas
LCA	Life cycle analysis
PEF	Primary energy factor
RES Directive	Renewable energy directive
SDGs	Sustainable development goals

Chemical Compounds

CH₄	Methane
CO₂	Carbon dioxide
H₂O	Water
NH₃	Ammonia
NO₃⁻	Nitrate
N₂O	Nitrous oxide
NO_x	Nitric oxide

O_2	Oxygen.
PO_4^{3-}	Phosphate
S_2	Sulphur
SO_2	Sulphur dioxide

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PART 1

THE KAPPA

INTRODUCTION

1

The world is facing many environmental problems connected to human activities. Global warming is probably the best known, and is caused by emissions of greenhouse gases (GHGs) such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). In the Paris Agreement (UNFCCC, 2015), which entered into force in November 2016, the goal of a limited global temperature increase of 2°C relative to pre-industrial levels was reaffirmed. As at February 2020, 189 of 197 parties have ratified the agreement (UNFCCC, 2020). According to a report from the IPCC (Intergovernmental Panel on Climate Change) (Hoegh-Guldberg et al., 2018), global warming is accelerating, and the rise in temperature should be stopped at 1.5°C instead. According to Xu et al. (2018), one way to reduce global warming would be to reduce emissions of e.g. CH₄, which has 25 times the impact of CO₂ on global warming. Besides global warming, there are also increasing global problems relating to the acidification of both water (Hoegh-Guldberg et al., 2017) and soil (Dai et al., 2017), as well as eutrophication (Le Moal et al., 2019). The acidification of soils can lead to decreasing soil quality and reduced crop yields (Dai et al., 2017). Acidification in oceans is a result of more CO₂ dissolving in the water, thus lowering the pH, which affect e.g. corals (Hoegh-Guldberg et al., 2017). Eutrophication is occurring in many of the world's lakes, coastal areas and rivers, and is mainly caused by emissions of nitrogen and phosphorus (Le Moal et al., 2019).

The UN's 17 Sustainable Development Goals (SDGs), which were adopted by all members of the United Nations in 2015, are the blueprint for a more sustainable future (UNDESA, 2015). The SDGs include e.g. life on land, climate action and affordable and clean energy. According to Bhatta (2018), biogas can contribute to eight of the SDGs, whilst the World Biogas Association (2017) estimates that biogas can contribute to nine of the SDGs. However, Hagman and Eklund (2016)

claim that biogas can contribute to all 17 of the SDGs. The main purpose of producing biogas through anaerobic digestion of organic material is often to produce a renewable energy carrier that can replace fossil fuels. The European Union has launched targets for 2030 of reducing GHG emissions by 40%, relative to 1990 levels, and achieving a proportion of at least 27% renewables in the energy system (European Commission, 2014). Biogas can contribute to fulfilling both of these targets. Anaerobic digestion is also a sustainable waste management option for organic waste, in contrast to landfilling. In the European Union, Directive 1999/31/EU on the landfill of waste (European Parliament, 1999), establishes a goal of reducing biodegradable waste sent to landfill. An amendment to the Directive ((European Parliament, 2018a), states that all waste suitable for recovery or recycling should not be landfilled by 2030. Directive 2008/98/EC on waste (European Parliament, 2008) presents the waste management hierarchy, an order of prioritization for waste management. At the top of the hierarchy is the prevention of waste, followed by reuse, recycling, recovery and, at the bottom, disposal (landfilling) (European Parliament, 2008). The remaining solid material after anaerobic digestion is called digestate and is rich in nutrients and can be used as fertilizer on farmlands. Thus, anaerobic digestion corresponds to the recovery level, since both energy and nutrient recovery are possible with biogas production systems. However, biogas production systems also contribute to many more benefits. According to the Renewable Energy Directive (the RES Directive)(European Parliament, 2018b), biogas production can contribute to a sustainable development. The RES Directive promotes biogas as an option in the transport sector to reduce greenhouse gas emissions in the European Union (European Parliament, 2018b). Anaerobic digestion of organic waste can reduce greenhouse gas emissions as well as water, soil and air pollution, compared to landfilling (European Parliament, 2018a). According to the RES Directive, biogas can also contribute towards innovations, jobs and economic growth, as well as reducing reliance on energy imports (European Parliament, 2018b).

As described above biogas production systems are more than just a waste management system or the production of a renewable energy carrier. To grasp more of the advantages of biogas production systems, systems analyses need to be carried out from different perspectives. One way could be to study the resource efficiency of biogas production systems. According to *Roadmap to a Resource Efficient Europe*, resource efficiency implies that greater value can be

delivered with less input, that resources can be used in a more sustainable way and that the impact on the environment can be minimized, as well as minimizing waste (European Commission, 2011). Ersson (2014) relates the concept of resource efficiency to energy, environmental and economic perspectives.

Systems analyses of biogas production system have been performed previously. For example, Börjesson and Mattiasson (2008) studied the resource efficiency of biogas as a vehicle fuel, with a focus on energy. Their conclusion is that biogas has the potential to become one of the most sustainable vehicle fuels. Tufvesson et al. (2013) performed a lifecycle assessment (LCA) of biogas production from industrial waste for vehicle fuel. The results showed reduced GHG emissions from the biogas system compared to fossil fuels. However, the study did not include an economic evaluation. Wu et al. (2016) performed a systems analysis of three different utilization options for biogas: combined heat and power (CHP), biomethane and fuel cell. Three different perspectives were used: environment, energy and economy. The results showed that the most preferable option for biogas utilization depended on the perspective. The environmental perspective included nine different impact categories; however, the results were transformed to a “green degree” and thus, no results were shown for the individual impact categories. Moreover, utilization of digestate was not included in this study. Uusitalo et al. (2013) also compared three different utilization options: raw gas to CHP, biomethane to CHP and biomethane as a vehicle fuel. The electricity produced at the CHP plant was assumed to be used for electric cars. The options with biomethane as a vehicle fuel resulted in the highest amount of output and were the most profitable from an energy perspective. Furthermore, the biomethane for vehicle fuel option resulted, together with the biomethane to CHP option in the largest decrease in GHG emissions. However, as for the study by Wu et al. (2016), digestate utilization was not included in this study.

Havukainen et al. (2014) evaluated methods for examining the energy performance of biogas production systems. Their conclusion was that the studies were difficult to compare, due to the use of different system boundaries and different approaches. In the *Country Report Summary* by IEA Task 37 (Fagerström and Murphy, 2018), biogas production in 15 countries is presented. Even though the task group tried to apply a common classification of biogas plants to compare biogas production in the countries, at least seven different classifications appear in the report for the different countries. Diverse classifications make it difficult to

make comparison between countries, and may thus hinder the development of efficient biogas production systems.

The EU is the largest exporter and the second largest importer of food and drink products in the world (FoodDrinkEurope, 2018). According to Pazera et al. (2015), organic waste from the food industry in Europe offers an untapped potential for biogas production. Biogas production from waste has the potential to increase the world's resource efficiency, since it can lead to more value and less waste as well as decreased negative environmental effects, including decreased GHG emissions. However, biogas production systems are complex, including, different substrates, different applications for biogas and digestate, and different technology solutions for digestion, pre-treatment and upgrading of the raw gas. Knowledge sharing is a key factor for increasing the development of biogas production systems. To increase knowledge sharing, comprehensible analysis and comparisons of biogas production systems are necessary. Thus, studies are needed to verify the resource efficiency of biogas production systems from different perspectives.

1.1 Aims and research questions

The main aim of this thesis is to explore how to compare and analyse biogas production systems. A further aim is to study the performance of biogas production systems, with a focus on environment, energy and economy. The aims of the thesis are achieved by answering two research questions:

1. How can comparison and analyses of biogas production systems be realized at different system levels? (RQ1)
2. How can organic waste from the food industry be treated in a resource-efficient way? (RQ2)

The connections between the appended papers and the research questions can be found in Table 1.

Table 1. Connections between the research questions and the appended papers.

	Paper I	Paper II	Paper III	Paper IV	Paper V
RQ 1	•	•	•		
RQ 2		•		•	•

1.2 Scope and delimitation

The scope of this thesis is systems analysis of biogas production systems. ‘Biogas production systems’ refers to anaerobic digestion of organic material, and related processes. Other technologies for transforming organic material into biogas, such as gasification, are outside the scope of this thesis. The production of substrates is not included in the scope of this thesis. Nor are analyses of the performance of microorganisms within the biogas digester. The studies are performed in a Swedish context. However, the results are assumed to be applicable to biogas production systems in a European context and other similar contexts.

In the economic evaluations performed, prices for fuels and other materials have been retrieved from Swedish sources. The environmental assessment includes global warming potential, acidification potential and eutrophication potential for two of the papers (II and III). In one paper (IV), the environmental assessment is limited to GWP.

When the term ‘resource efficiency’ is used, only the environmental, economic and energy perspective are considered. Resource efficiency could also include other perspectives, but is delimited in this thesis to the three perspectives mentioned, as defined by Ersson (2014).

In two of the papers (I and V), the utilization of biogas is included in the analysis. For the other papers, the utilization of biogas, digestate or other products included in the systems (e.g. animal fodder) is not included. However, upgrading biogas to biomethane is included in two papers (III and IV).

1.3 Paper overview and co-author statement

This thesis is based on six papers. A brief description of the papers, together with a co-author statement, is found below.

Paper I

Lindkvist, E., Karlsson, M. (2017) Biogas production plants; existing classifications and proposed categories. *Journal of Cleaner Production*, 174, 1588-1597.

This paper investigates different classifications of biogas production systems in certain countries in Europe. Large differences are found between the classifications. Ten Swedish biogas plants are used to visualize the differences between the classifications. A Framework for Categorization is proposed, including seven categories. The developed framework is an attempt to find a common international classification for biogas production systems.

I had responsibility for data collection and for writing the paper. The planning of the paper and the analysis were carried out together with Magnus Karlsson. Magnus Karlsson and Mats Söderström supervised the work.

Paper II

Lindkvist, E., Karlsson, M., Ivner, J. (2019) Systems analysis of biogas production – Part I Research design. *Energies*, 12, 926.

This paper presents a research design for assessing the resource efficiency of biogas production systems. The research design includes identifying cases to study, defining scenarios, developing studied systems and a systems analysis. The analysis is performed from three different perspectives: economy, energy and environment.

I was responsible for writing the paper, and Jenny Ivner and Magnus Karlsson commented on the manuscript. The development of the research design was carried out in cooperation between Jenny Ivner, Magnus Karlsson and me.

Paper III

Lindkvist, E., Johansson, M., Rosenqvist, J. (2017) Methodology for analysing energy demand in biogas production plants – A comparative study of two biogas plants. *Energies*, 10, 1822.

In this paper, a methodology for analysing the energy demand at a biogas plant is presented. In the methodology, the allocation of energy carriers is presented in three different ways: by sub-process (e.g. pre-treatment, anaerobic digestion, gas cleaning), by unit process (e.g. heating, mixing, pumping, lighting), and as a combination of the two. The combination of allocation is recommended for a thorough energy analysis. To validate the methodology, two different biogas plants were studied. The plants differed in terms of substrate composition and only one of the plants had a hygienization step. The validation showed that the methodology is applicable to different kinds of biogas production systems.

The methodology was developed in cooperation with Maria Johansson and Jakob Rosenqvist. I collected the energy data at the first plant together with Jakob Rosenqvist. Energy data from the other plant was collected by a master's student and Jakob Rosenqvist, and I supervised the work together with Maria Johansson. I analysed the energy demand of the two biogas plants in cooperation with Maria Johansson and Jakob Rosenqvist. This paper was written jointly with Maria Johansson and Jakob Rosenqvist.

Paper IV

Lindkvist, E., Karlsson, M., Ivner, J. (2019) Systems analysis of biogas production -Part II Application in food industry systems. *Energies*, 12, 412.

In this paper, the research design for assessing the resource efficiency of biogas production systems in Paper II was applied. Five different areas involving food companies were studied, all with different prerequisites. In the areas, all larger food companies were contacted and the volumes of organic by-products available for biogas production were identified. All areas were studied based on three different scenarios: the business-as-usual scenario and two potential biogas scenarios. In the business-as-usual scenario, the organic by-products are not used for biogas production, instead being incinerated, composted or used for animal fodder production. All areas, and all scenarios, were analysed from three different perspectives: economy, energy and environment. The results showed

that it would be more resource efficient in almost all areas to change the treatment method for the organic by-products from the business-as-usual scenario to one of the biogas scenarios.

In this paper I identified the cases, together with Jenny Ivner. Jenny Ivner supervised the master's students responsible for the data collection. I was responsible for analysing the data and writing the paper, with input from Jenny Ivner and Magnus Karlsson. Magnus Karlsson supervised the work.

Paper V

Broberg Viklund, S., Lindkvist, E. (2015) Biogas production supported by excess heat – A systems analysis within the food industry. *Energy Conversion and Management*, 91, 249-258.

This paper investigates the potential for internal biogas production at a food company. The focus is on the effects on greenhouse gas emissions and economics when the company's organic waste is used for internal production, and use, of biogas. In the baseline system the waste is used at an external biogas plant and oil is used for internal processes. The potential for using excess heat instead of biogas for the heat demand at an internal biogas plant, was also studied. The results showed that internal production of biogas, in combination with utilization of excess heat, was advantageous both environmentally and economically.

The paper was planned and written jointly, and the data collection was carried out together with Sarah Broberg Viklund, with some additional help from Jakob Rosenqvist. Sarah Broberg Viklund was responsible for the parts on excess heating and I was responsible for the parts on biogas production. Magnus Karlsson and Mats Söderström supervised and commented on the work.

2.1 Biogas production

Biogas is produced when organic materials are degraded by microorganisms in an anaerobic environment. Biogas mainly consists of methane (CH_4) (50-75 %) and carbon dioxide (CO_2) (25-50 %) (Wellinger et al., 2013). Other components of biogas are water (H_2O), oxygen (O_2), sulphur (S_2) and hydrogen sulphide (H_2S). The digestion takes place in four different stages; hydrolysis, acidogenesis, acetogenesis and methanogenesis (Sarker et al., 2019). To maintain a stable anaerobic process, these four stages should all be present at the same time. The energy carrier in biogas is methane and it is produced during the methanogenesis stage (Wellinger et al., 2013). In Figure 1, a simplified overview of a biogas production system is shown.

Figure 1. A schematic overview of a biogas production system.

Different organic materials can be used as substrate (inputs) for the biogas production process. Common substrates are food waste from households and restaurants, industrial waste from the food processing industry and slaughterhouses, sludge from wastewater treatment plants, manure and other residues from the agriculture sector (Wellinger et al., 2013). Depending on the

composition of the substrate used, different pre-treatment technologies are needed, to prepare the substrate for digestion in the digesters at the biogas plants. Pre-treatment can include crushing or grinding to reduce the size of the material, diluting to make the substrate more volatile, and removal of unwanted material such as plastics, textile, metals or gravel (Wellinger et al., 2013).

Anaerobic digestion can be performed at different temperatures, most commonly at mesophilic (35-40°C) or thermophilic (55-60°C) temperatures. The temperature influences the degradation of the organic material as well as the stability of the process (Wellinger et al., 2013). A thermophilic process has a higher degradation rate and a shorter retention time may therefore be required. However, a higher temperature could imply a higher sensitivity to changes in temperature and pH, and thus a more sensitive process (Wellinger et al., 2013). A higher temperature may also result in a higher energy demand. However, the surrounding climate also affect the energy demand. In a warm climate, it may be necessary to cool the digester, whilst other climates involve a need to heat the digester, in order to maintain the required temperature for the process.

The produced biogas can be used as it is (raw) in a gas turbine to generate electricity, in a boiler to generate heat, or in a combined heat and power (CHP) plant to generate both heat and electricity (Scarlat et al., 2018). Biogas can also be upgraded to have the same properties as natural gas (98% methane). Upgraded biogas is usually referred to as biomethane. Biomethane can be injected into natural gas grids or used as a vehicle fuel (Scarlat et al., 2018). Biomethane can also be cooled down to a liquid state, liquefied biogas (LBG). LBG has a higher energy density than upgraded biogas and can be used for heavy road transport as well as sea transport (Benjaminsson and Nilsson, 2009). Raw biogas, biomethane and LBG can be used for different industrial applications, for example as replacements for fossil gases such as natural gas and LPG (Johansson and Söderström, 2011).

2.2 Digestate

Another product from the biogas process is the digestate. The digestate is the remaining solid material after anaerobic digestion. The digestate is rich in nutrients and can be used as a fertilizer on farmlands, thus leading to the recirculation of nutrients. The digestate has the potential to replace mineral

fertilizer, if it is of a high quality. This means that it must be free from impurities, be safe for the environment and living organisms and have a declared content of dry matter and organic dry matter, nutrients and pH (Al Seadi and Lukehurst, 2012). The substrate and the anaerobic process parameters influence the composition of the digestate (Drosg et al., 2015). The digestate is rich in nitrogen, phosphorus, potassium and sulphur, as well as other micronutrients, which enables the use of digestate as a fertilizer (Drosg et al., 2015). Digestate can improve the microbiology of the soil, and thereby increase respiration and organic carbon (Hagman and Eklund, 2016). Digestate may also contain heavy metals, making it problematic to use on farmland. The EU has announced recommended limit values for concentrations of heavy metals in soil (European Parliament 2018) and many member states have their own limit values (Al Seadi and Lukehurst, 2012). According to EU regulation 1069/2009 animal by-products must be sterilized before used for biogas production, to ensure that transmissible diseases are not spread through the digestate (European Parliament, 2009). In Sweden, regulations demand that substrates containing animal by-products are hygienized (sterilized). This can be done by heating the substrate to 70°C for one hour, or, if the process is thermophilic, by heating the substrate to at least 55°C for six hours (Swedish Board of Agriculture, 2014).

In Sweden, the Swedish Waste Management Association introduced certification for digestate as a biofertilizer in 1999. To comply with the requirements for certification, the digestate needs to meet the standard values for metals, presence of infectious agents and visible impurities (Swedish Waste Management Association, 2019). In 2018, 2.8 million tonnes of digestate were produced in Sweden, of which 86% was used as fertilizer on agricultural land (Klackenberg, 2019). The rest was used for e.g. final coverage of landfills.

2.3 Biogas outlook

According to the World Biogas Associations report *Global Potential of Biogas* (Jain et al., 2019), there were approximately 132 000 small, medium or large-scale digesters in operation in the world in 2017. Added to this, there are around 50 million micro-digesters in operation, the majority of which are found in China (Jain et al., 2019). The world's total biogas production was 370 TWh in 2017 (World Bioenergy Association, 2019). The distribution around the world can be seen in Figure 2. According to the World Biogas Association, the world's biogas

potential is 10-14 PWh (Jain et al., 2019). Included feedstocks are food waste (1 PWh), livestock (3 PWh), crop residues (3.5 PWh), energy crops (4 PWh) and sewage (0.3 PWh). Predictions about the future are difficult to make and there are many uncertainties. However, according to the World Biogas Association, only around 3% of the world's total potential for biogas production was realized in 2017.

Figure 2. Biogas production in the world 2017. Based on data from the World Bioenergy Association (2019).

More than half of the biogas produced in the world, 197 TWh, is produced in Europe. Kampman et al. (2017) have assessed the potential for biogas production in Europe beyond 2020. The assessed potential is between 335 and 470 TWh, depending on different scenarios, involving either growth or accelerated growth in feedstock deployment. The majority of the biogas produced in Europe is used for electricity production (Scarlat et al., 2018). In Europe, the total installed electric capacity of biogas plants was 10.5 GW in 2017, and the total electricity production from biogas was 65 TWh (EBA, 2018). The agriculture sector is the main contributor to the substrate used in these plants (EBA, 2018). The substrates used includes animal manure, agricultural residues and energy crops.

Upgraded biogas (biomethane) production is growing in Europe, and in 2017 there were 540 plants in 15 different countries (EBA, 2018), see Figure 3. France is

the country with the fastest growth. However, Germany has the highest number of biomethane plants with 195 plants (2017), followed by 92 plants in the UK. In total, 19 TWh of biomethane was produced in Europe in 2017 (EBA, 2018). In two years, since 2015, production has increased by 57%. The majority of the biomethane produced is injected into natural gas grids (Scarlat et al., 2018).

Figure 3. Number of plants producing biomethane in Europe. Data from EBA (2018)

In Sweden, there were 280 biogas plants in 2018 producing 2 TWh of biogas. Of the biogas produced 63% was upgraded to biomethane and 20% was used for heat generation (Klackenberg, 2019). Smaller amounts are used for industrial application and electricity generation, and 10 % was flared (Klackenberg, 2019). Biomethane can be injected into gas grids, compressed or liquefied into LBG. In Sweden, biomethane is primarily used for vehicle fuel (87%) with the rest being used in industry or for heat and electricity production in connection with a gas grid. There has been an increase in the amount of biomethane imported from Denmark, in 2018 totalling approximately 1.6 TWh in 2018. Injection into the national gas grid is possible for the grids in south-west Sweden and Stockholm. The rest of the country has no grids, other than some smaller, local grids. In 2018, 544 GWh of biomethane produced in Sweden was injected into the national gas

grids, and in total 23.5% of the gas in the south-west grid was biomethane, including the imported biomethane from Denmark (Klackenberg, 2019).

The report *Proposal for National Biogas Strategy 2.0*, presented by several Swedish biogas actors, states an aim to reach biogas production of 15 TWh by 2030 (Energigas Sverige, 2018). In a report from 2008, the biogas potential – excluding the potential from forest residues and aquatic substrates – is 14 TWh, but with constraints regarding technology and economic conditions the potential is set at 11 TWh (Linné et al., 2008). In another report, from 2013, the potential for 2030 is up to 10 TWh, in a scenario featuring favourable condition (Dahlgren et al., 2013).

According to Kampman et al. (2017), policy instrument are the main driver for the development of biogas production. In the EU member states, different economic policy instruments have been established for biogas. The most common support system in Europe is the feed-in tariff, which provides payment to those supplying the grid with renewable energy for a specified time period, often long-term period (Deremince et al., 2017). This has been established in Germany, for example, where there is no subsidy for methane production, only for the electricity generated at CHPs, from biogas (Pfau et al., 2017). In Denmark, as another example, biogas production is subsidised if the biogas is either used to generate electricity or upgraded and delivered to a natural gas grid (Danish Energy Agency, 2019).

In Sweden, there are several direct or indirect economic policy instruments directed towards biogas. One example is the *manure-gas support* (SFS, 2014). To qualify for this support, a biogas producer must be included in the project for gas from manure. The project started in 2014 and ends in 2023 (Jordbruksverket, 2015). Economic support is only allocated for the share of biogas production that originates from manure. There is also support for local climate investments, linked to the entire biogas process. This support is awarded for measures that contribute to the local fulfilment of strategies, plans or programmes for climate and energy, or for measures that contribute to the national targets for greenhouse gas emissions, a fossil free transport sector by 2030 or the vision of a resource-efficient energy supply by 2050 (SFS, 2015). Since 1995, taxes have been levied on fuels and electricity generation in Sweden. Energy and CO₂ taxes are levied on fuels. Biogas used as fuel for heating is exempt from energy and CO₂ taxation, while taxes on biogas used as a transportation fuel are deductible (SFS, 1995).

Food industry

3

The world's population increased by one billion during 2005-2016 (FAO, 2018). This rise in population places great demand on the world's food supplies. The food supply chain can be divided into four different levels: production, processing, retail and consumers (Storup et al., 2016). Organic waste (or by-products) can occur at all levels. According to Gustavsson et al. (2011), around one third of the food produced is lost or wasted. In developing countries, more than 40% of the losses occur during the post-harvesting and processing levels, whilst in industrialized countries more than 40% of losses are allocated to the consumer and retail levels of the value chain (Gustavsson et al., 2011). In 2012, the total amount of food waste in the EU was estimated at 88 million tonnes (Stenmarck et al., 2016). Within the EU, the food and drink industry is the largest manufacturing sector in terms of employment, value added and turnover (FoodDrinkEurope, 2018). EU is the largest exporter and the second largest importer of food and drink products in the world (FoodDrinkEurope, 2018). According to Pazera et al. (2015), more and more biogas plants in Europe use waste from the food industry as a substrate for biogas production, even though there is untapped potential in many countries.

In Sweden, the food industry is the fourth largest industrial sectors in terms of employment and the most widely spread geographically (Swedish Food Federation, 2020). In 2017, the energy demand from the food industry in Sweden was 4.8 TWh (Swedish Energy Agency, 2019). This corresponds to 1% of the total energy use in Sweden, see Figure 4. Fossil fuels represent 1.5 TWh of energy use and biofuels 0.6 TWh, with the remainder being accounted for by electricity, district heating and other fuels (Swedish Energy Agency, 2019). The sector is dominated by small companies, and only around 14% of companies have more than ten employees (Swedish Food Federation, 2019). As mentioned above, food

is lost or wasted throughout the whole food supply chain. In 2005, landfilling of organic waste was prohibited in Sweden, resulting in increased amounts of waste being treated either biologically or by incineration (Swedish Waste Management Association, 2018).

Figure 4. The energy use in different sectors in Sweden in 2017. Data from the Swedish Energy Agency (2019).

Carlsson and Uldal (2009) present eight different sectors of the food industry: slaughterhouses, egg producers, fisheries, bakeries, dairy factories, ethanol and starch production, vegetable and fruit processing, and sugar manufacturers. These generate e.g. fish waste, fruit and vegetable waste, yeast, dairy waste and slaughterhouse waste that could be used for biogas production. Different waste streams consist of different nutrients and have different levels of methane potential. In 2018, 11% of the total amount of substrates used for biogas production in Sweden derived from food industry waste, including slaughterhouse waste (Klackenberg, 2019). There are six industrially located biogas plants in operation in Sweden, producing a total of 143 GWh of biogas (2018) (Klackenberg, 2019). The industries with industrially located biogas plants are (number of plants): pulp and paper (2), brewery (2), dairy production (1) and sugar manufacturing (1). The biogas produced is used for heating or industrial processes or is flared (Klackenberg, 2019).

Some of the key concepts in this thesis will be presented in this chapter, together with earlier research within each concept, connected to biogas production systems. Systems analysis are performed in all studies referred to in this chapter and the key concepts presented in this chapter are closely connected to each other. Studies referred to in this chapter including only one of the key concepts; environmental assessment, energy analysis or economic evaluation, are found in subchapters with the same name. Studies including two of the concepts environmental assessment, energy analysis or economic evaluation are found in subchapter 4.1. Subchapter 4.5 includes studies involving all the three concepts related to resource efficiency in this thesis: environmental assessment, energy analysis and economic evaluation. More detailed information about the approaches used in the appended papers can be found in chapter 6.

4.1 Systems analysis

According to Churchman (1968), a system can be defined as a collection of components, connected to each other and working together towards an overall system objective. The components are isolated from the surrounding environment by a system boundary. The system does not control the surrounding environment, but the surrounding environment influences the system.

A system can be analysed from different perspectives and with different objectives, and a systems analysis is often the foundation for environmental, energy and economic assessments. When performing a systems analysis, it is important to clarify which components (processes) are included in the system, as well as how they are connected to each other. It is also essential to clearly define

the system boundary and possible processes outside the boundary that affect the system (Churchman, 1968).

Systems analysis is the foundation for many analyses of energy, environment and/or economy in connection with biogas production systems. For example, Rajendran and Murthy (2019) conducted a review of lifecycle assessments (LCAs) and techno-economic studies connected to biogas production. In their review, the system boundaries of the studies are declared, as well as the goals and the scopes. The review showed that between 2007 and 2016, there were five times as many scientific papers connected to LCAs (520 papers) than to economy (101 papers). Khoo et al. (2010) compared biogas production from food waste with incineration and composting, and found that biogas reduced GHG emissions and had a lower energy demand. Martínez-Ruano et al. (2018) carried out a systems analysis on biogas production from banana peel. The analysis was focused on economy and energy and included two scenarios: stand-alone biogas production and a biorefinery concept. Korres et al. (2010) performed an LCA to determine whether biomethane produced from grass could be a sustainable transport fuel. The study included a greenhouse gas balance and an energy analysis.

4.2 Environmental assessment

Environmental assessment of biogas production systems often includes an LCA. For example, Hijazi et al. (2016) reviewed LCAs for biogas production systems in Europe. According to Hijazi et al. (2016), the process of performing an LCA can be divided into four steps: definition of aim and scope, compilation and quantification of all inputs and outputs, impact assessment and interpretation of the results. An LCA can have different system boundaries, e.g. field to wheel, cradle to grave, or gate to gate. Systems expansions can also be applied, to include emissions of the products replaced by the studied systems (Börjesson, 2008). In this way, the indirect environmental benefits of the system are included in the assessment.

Environmental assessments connected to biogas have been carried out to compare different substrates, different utilization options for the biogas produced and different systems, for example. Börjesson and Berglund (2006) and Timonen et al. (2019) compared the environmental effects of different substrates. Pérez-Camacho et al. (2019) performed an LCA, comparing three different

utilization options for biogas: combined heat and power (CHP), vehicle fuel and injection to gas grid. Woon et al. (2016) also compared three different utilization options for biogas: vehicle fuel, CHP and city gas. Oldfield et al. (2016) carried out an environmental assessment of five different options for treating food waste, including biogas production. Naroznova et al. (2016) studied the global warming potential of biogas production compared to incineration. Börjesson and Berglund (2007) compared different substrates and included alternative systems.

4.3 Energy analysis

Energy analysis of biogas production systems can be performed in different ways. Havukainen et al. (2014) evaluated methods for examining the energy performance of biogas production systems. Three different methods were reviewed and 16 different studies evaluating the energy efficiency of biogas production systems were included. They concluded that a comparison of the studies was difficult, due to the use of different system boundaries and different approaches. Berglund and Börjesson (2006) performed an energy balance for the lifecycle of biogas production, including the collection, transportation and spreading of digestate. The results were shown on an aggregated level for the biogas plants studied. Pöschl et al. (2010) evaluated the energy efficiency of biogas production systems using different substrates and different utilization options. Primary energy was used for all energy flows in the studied system. Prade et al. (2012) performed an energy balance for four different scenarios for the utilization of hemp.

4.4 Economic evaluation

Economic evaluations are necessary in order to be able to study the economic performance of biogas production systems. Lantz (2012) made an economic evaluation with focus on CHP using biogas produced from manure. The conclusion was that scale affects the profitability of the biogas plant, and it could be more profitable to produce biogas from manure at larger plants. Sgroi et al. (2015) analysed the economic performance of biogas production from manure and giant reed silage. Gebrezgabher et al. (2010) performed an economic optimization focusing on feedstocks and utilization options for digestate. Skovsgaard and Jacobsen (2017) studied the total net income of biogas

production systems. Upgrading and injection to gas grids were compared to CHP as well as the effects of increasing the scale of biogas plants compared to increased transportation distances.

4.5 Resource efficiency

The concept of circular economy is increasingly related to biogas production systems. A circular economy aims to replace waste with the reuse of material and products (Ellen MacArthur Foundation, 2013). There are many studies of biogas production systems and circular economy, e.g. Fagerström et al. (2018), Yazan et al. (2018), Donia et al. (2018) and Abad et al. (2019). However, this thesis will not deal with the concept of circular economy, examining instead the closely related concept of resource efficiency.

According to the European Commission (2011) resource efficiency means making more from less and minimizing waste. Biogas production from waste could be a resource-efficient alternative; however, it is difficult to assess its resource efficiency. To enable such an assessment to be made, resource efficiency is connected in this thesis to energy, environment and economy, as defined by Ersson (2014).

Wu et al. (2016) carried out a comparison of three different utilization possibilities for biogas: CHP, biomethane and fuel cell. Three different perspectives were used: environment, energy and economy. Uusitalo et al. (2013) compared three different utilization options: raw gas to CHP, biomethane to CHP and biomethane as a vehicle fuel. The electricity produced at the CHP was assumed to be used for electric cars. Thomsen et al. (2018) analysed different options for producing biogas from food waste instead of incineration. Their analysis included an environmental and economic assessment, as well as an energy efficiency analysis. Feiz and Ammenberg (2017) performed a multicriteria analysis on feedstocks for biogas production, including energy, environment and economy, as well as other factors.

SYSTEMS STUDIED

5

In this thesis, biogas production systems have been studied with different system boundaries, each boundary surrounding the others, creating a higher system level. The levels are: European level, regional level, company level and biogas plant level. In Figure 5, a biogas production system is shown together with the four system boundaries applied in the studies in the appended papers.

Figure 5. A schematic picture of a biogas production system, with the different system levels for the studies performed in the appended papers.

Figure 5 shows different sources for the substrate used for biogas production. These are aquatic substrates such as fish and algae, substrates from households, the industry sector and farms and substrates from the forest. The biogas produced can be used in the industry sector, as vehicle fuel or utilized for heat and electricity production. The figure also shows that the digestate resulting from the biogas production can be used on farms as fertilizer.

5.1 European level

In Paper I, biogas production in different countries in Europe was studied, and especially the classifications of different kinds of biogas production systems. Classifications of biogas production systems were retrieved from eleven countries in Europe namely: Austria, Denmark, Finland, France, Germany, Ireland, the Netherlands, Norway, Sweden, Switzerland and the UK. Of these, four countries provided classifications with an underlying description of the classification: Denmark, Sweden, Switzerland and the United Kingdom. These countries were used to illustrate that there are different classifications of biogas plants used in different countries. To enable this, an attempt was made to insert ten biogas plants in Sweden into the country-specific classifications, to see how many plants fitted into each of them.

A framework for categorization of biogas plants was developed, which addresses all parts of the biogas production system shown in Figure 5, from substrate used to utilization of the produced biogas and digestate. The ten Swedish biogas plants were used to test the framework.

5.2 Regional level

The regional level presented in Figure 5 is addressed in papers II and IV. By region, a larger geographical area is meant, not necessarily in accordance with official geographical regions in Sweden or as defined in other countries. The analysis at regional level includes different treatment methods for organic waste from the food industry and different utilization options for biogas. The produced biogas could be used for heat and electricity, industrial applications or as vehicle fuel and the digestate could be used as fertilizer on farmland. Paper II highlights the importance of system definition and system boundaries. In Figure 6, a generic

overview of a system treating organic by-products is shown. The system is a simplification of the reality, and only the processes that are of interest for the scope of the study should be included. The basis of the system is industrial organic by-products. The by-products could either be used for biogas production (right part of the figure) or treated in other ways (left side of the figure). All treatment methods for the organic by-products generate some end products. All end-products are also assumed to be able to be produced in alternative ways (alternative production methods). This means that for example End-product I can either be produced by Treatment method I or by Alternative production method I. The demands for the end-products are assumed to be constant in the system. Hence, the end-products must be produced in some way. If the organic by-products are treated by Treatment method I, End-product I is produced, and hence, Alternative production method I is inactivated. However, all other end-products in the system must be produced, and therefore, Alternative production methods II-VIII are active. Since all these processes are inside the system boundary, all affect the results for the system.

Figure 6. A generic overview of a system treating organic by-products. The dotted line indicates the system boundary.

In paper IV, five different regions with food companies were studied. In order to choose interesting regions to study, all food producing companies in Sweden with 50 or more employees were mapped. From this map, five regions were identified as interesting to study, i.e. regions with many food companies and little or no biogas production. In these regions all food companies with more than 20 employees were identified and contacted. However, many food companies

have few employees, and the reason for the limitation in numbers of employees was that the number of employees was assumed to have some correlation with the scale of the production and hence, the amount of available organic by-products. The scope was to study which alternative of the treatment methods for organic by-products are most resource efficient from a systems perspective. Three different scenarios were developed to reach the scope of paper IV, according to the proposed research design in paper II. Information about the scenarios can be found in Table 2.

Table 2. Information about the different scenarios.

	Description
Scenario BAU	The organic by-products are used for production of animal fodder, heat and electricity or fertilizer
Scenario CHP (Biogas scenario)	The organic by-products are used for production of biogas and digestate (fertilizer). The biogas is used for heat and electricity.
Scenario Vehicle (Biogas scenario)	The organic by-products are used for production of biogas and digestate (fertilizer). The biogas is upgraded and used for vehicle fuel.

The scenario Business as Usual (BAU), see Figure 7, describes the real situation in the regions where the organic by-products are either used for animal fodder production, incinerated to generate heat and electricity or composted to be used as fertilizer. The other two scenarios are fabricated biogas scenarios where the organic by-product is instead assumed to be used for biogas production. In the scenario Combined Heat and Power (CHP), see Figure 8, the biogas produced is used to generate heat and power. In the scenario Vehicle, Figure 9, the biogas produced is used as vehicle fuel.

Figure 7. The scenario BAU

Figure 8. The scenario CHP

Figure 9. The scenario Vehicle

Four different end-products were identified in the systems studied in paper IV: animal feed, heat and electricity, vehicle fuel and fertilizer. The same total demands for the end-products are assumed in the system, no matter the scenarios. For example, there is a need for a certain amount of animal fodder in the system, regardless of the treatment of the organic by-products. The scenario with the highest production of the end-products is assumed to determine the level of the total demand for all scenarios. The scenarios determining the total demand for the different end-products are shown in Table 3.

Table 3. The scenarios determining the total system demand for the different end-products in the systems studied.

	Animal feed	Heat and electricity	Vehicle fuel	Fertilizer
Scenario	BAU	CHP	Vehicle	Biogas scenarios

The total demand for animal feed is determined by the scenario BAU, since this is the only scenario where animal feed is produced from the organic by-products from the food companies. Animal feed is assumed to be replaced with either soya or grain, depending on the composition of the organic by-products. The same assumption was applied by Tufvesson et al. (2013). The total demand for vehicle fuel is, likewise, determined by the scenario Vehicle. Vehicle fuel is assumed to be replaced with diesel as an alternative, in accordance with Korres et al. (2010)

and Woon et al. (2016). For heat and electricity, the total demand for the system is regulated by the scenario CHP, since the potential production of heat and electricity in this scenario is larger than the production of heat and electricity in the scenario BAU. The total demand for fertilizer is, likewise, regulated by the biogas scenarios. The same potential amount of fertilizer is assumed in the two biogas scenarios, since it is the utilization of the produced biogas that differs between them. Digestate is assumed to be replaced with mineral fertilizer, in accordance with Tufvesson et al. (2013), Fagerström et al. (2018), Naroznova et al. (2016) and Timonen et al. (2019). The total demand for the different end-products is the same in all three scenarios. However, since the total amount of organic by-products available in the five different systems studied (regions) differs, the total demand for the different end-products differ between the systems studied.

Two different system boundaries were set for the studies in paper IV. The economic system boundary includes the active treatment methods of the organic by-products, whilst the energy and environmental system boundary includes the alternative treatment methods as well. The economic evaluation was chosen to be focused on a company perspective, with direct costs and revenues, whilst the environmental assessment and energy analysis were chosen to be focused on a societal perspective. The economic evaluation could be performed from a societal perspective as well, but input data of the economic performance of the alternative treatment methods is required, and hence a more complex analysis is necessary. Further, investments are made by companies, and hence, it was considered more relevant to perform the economic evaluation from this perspective.

5.3 Company level

The company level in Figure 5 includes substrates from industry and farms as well as utilization of biogas and digestate. The difference between this level and the regional level is that on the company level, one food company is in focus, in contrast to the regional level where several companies are included. In paper V, Sweden's largest manufacturer of mayonnaise-based salads, particularly with beet crops, was studied. The company's energy demand is met by oil and electricity, and the possibility of replacing some of the oil with internally produced biogas was examined. The organic waste from the company is currently sent to an external biogas plant and to a wastewater treatment plant

(WWTP), and a small fraction is retrieved by local farmers to be used as animal feed. Excess heat is available at the production site, from boiling and blanching of potatoes, and the possibility of using the excess heat to cover the heat demand associated with biogas production was also studied. The waste is transported with trucks, running on diesel, from the food company, and the cost of this transportation is borne by the food company.

A farm is located close to the food company. The farm breeds pigs and the possibility of using the liquid manure as substrate for the biogas production at the food company is studied as well. The digestate is assumed to be returned to the farm, without costs or revenues for the food company. It is also assumed that the digestate can replace the manure as fertilizer at the farm. Two different systems are studied, a baseline system and a modified system which represent the alternative involving a biogas plant at the food company. Figure 10 shows the systems studied.

The boxes and flows in red represent the baseline system and the boxes and flows in blue represent the modified system, besides the boxes and flows in black that are included in both systems studied. In the modified system the organic waste from the food company is treated at the internal biogas plant, which could be heated with excess heat from the food industry or by burning a small part of the produced biogas. The digestate is assumed to be used on the fields of the pig farm as fertilizer and the produced biogas is used at the food company to produce steam, and thereby decrease the demand for oil at the company. It is assumed that less biogas will be produced at the external biogas plant and at the WWTP due to the decrease of substrates, and hence, other fuels are needed for vehicles and in the district heating system. Gasoline is assumed to replace the biogas in the transport system, since the main users of biogas in this geographical region are private cars and taxis. In the district heating system, wood is assumed to replace biogas, since wood is the most common fuel in this system.

As can be seen in Figure 10, two different system boundaries have been applied. For the economic evaluation and energy analysis, direct effects of the shift in treatment of the organic waste for the company were chosen. However, for the environmental assessment the indirect effects of the shift were considered as well.

Figure 10. The figure illustrates the two different systems studied in paper V. Boxes and flows in red are included in the baseline system and boxes and flows in blue are included in the modified system, besides the boxes and flows in black that are included in both systems studied. The system boundaries are marked with crosshatched and dotted lines. The crosshatched line indicates the system boundary for the greenhouse gas emissions and the dotted line indicates the system boundary for the economic evaluation and energy analysis.

5.4 Biogas plant level

The biogas plant level in Figure 5 only includes the biogas plant. Of course, indirectly, the substrates are included, but mainly as input to the system and are not in focus on this level. A methodology for analysing energy demand at biogas production systems on a detailed level was developed in paper III. As part of that, definition of the system to be studied was necessary. In Figure 11, the sub-processes identified are shown, together with the defined system boundaries. Two different levels of system boundaries are applied in the methodology. Level 1 includes the sub-processes: reception of substrate, pre-treatment, hygienization, anaerobic digestion and digestate storage. Level 2 is the larger system level and

includes all sub-processes in level 1 as well as gas cleaning, upgrading and compression of upgraded gas. The reason for having two different system levels is to increase the ability to compare biogas plants with each other. If a biogas plant does not upgrade the produced biogas, it can still be compared to a biogas plant with an upgrading unit, using system level 1 for both plants. The processes outside of the system boundaries are not included in the proposed methodology but are inputs to and outputs from the system.

Figure 11. The system studied in paper III.

The goal for the methodology proposed in paper III was that it should be robust and consistent. To test this, the energy demand at two different biogas production systems was analysed. The two plants differ in composition and

input. Plant A is the larger of the two plants and the substrate used consists mainly of industrial organic waste from food manufacturers in the area. The digestion process is mesophilic, and gas is collected in both the digesters and in the digestate storage. Plant B mainly treats organic household waste. The process is thermophilic and the hygienization of the main share of the substrate is performed in the digester. A batch process is used, and an additional, separate, hygienization tank is available, to be able to feed the digester with hygienized substrate when the gas production from the digester drops.

METHODS

6

The methods used in the different papers are briefly described below. For more detailed information about the methods, please see the appended papers. Table 4 sets out the connections between the different methods used and the papers. The methods have been divided into data collection and systems analysis. Data collection includes literature studies, measurements, workshop and interviews, whilst systems analysis includes the methods of energy analysis, environmental assessment and economic evaluation.

Table 4. Methods used in the papers

		Paper I	Paper II	Paper III	Paper IV	Paper V
Data collection	Literature studies	X	X	X	X	X
	Interviews				X	X
	Workshop	X				
	Measurements			X		
Systems analysis	Energy analysis			X	X	X
	Environmental assessment				X	X
	Economic evaluation				X	X

6.1 Data collection

Data collection has been used in all the papers appended to this thesis. The different methods used for data collection are literature studies, interviews, workshop and measurements.

6.1.1 Literature studies

Literature studies have been the basis for the data collection to some extent in all papers. Here, literature studies means the collection of information from written sources of various kinds. All types of literature, from scientific literature to company specific invoices, have been studied. The literature studies have been used as a complement to other data collection methods in the appended papers.

In paper I, two literature studies were performed to retrieve information on country-specific classifications of biogas plants in Europe, as well as information on the Swedish biogas plants studied. Different reports, e.g. country reports of biogas production and environmental reports, were studied along with homepages of companies operating biogas plants.

Scientific literature and reports have been the basis for the research design presented in paper II. In paper IV, the data collection was carried out after the regions of interest had been established. Company-specific numbers were used for amounts of organic by-products available. These were collected through interviews. All other necessary numbers for the calculations were retrieved from scientific literature and different reports.

Data about the two biogas plants studied in paper III, was collected through invoices, process statistics, technical documents and process monitoring systems, provided by personnel at the two biogas plants.

In paper V, data was partly retrieved from statistical information on amounts of waste in an Excel file provided by the food company, but also from the energy logging system and invoices of different kinds. An existing energy audit report was also used together with a report on a recycling solution for the boiler. Data was collected over one year.

6.1.2 Interviews

Interviews are used to retrieve information and to create knowledge of a studied subject, through an interaction between the interviewer and the interviewee (Kvale and Brinkmann, 2009). Interviews can be done in three different ways: structured, semi-structured and open-ended. Structured interviews include closed-ended questions which give consistency when performing multiple interviews (Yin, 2015). Semi-structured interviews include the ability for the interviewer to be more flexible, and additional questions can be added during the interview (Corbin and Strauss, 2014). However, during these kinds of interviews there should be an overall plan for the interview. Lastly, the open-ended interview is a non-structured interview with open-ended questions (Yin, 2015).

Structured interviews were used to retrieve information on the amounts of organic by-products from the food manufacturing companies in paper IV. Structured interviews were chosen, since multiple interviews were performed, and consistency in the questions was strived for. All companies in the studied regions were contacted by email and telephone and asked about their amounts of organic by-products, and the current treatment methods for these by-products. From this, eight different categories of food waste from the food industry were identified: fish waste, fruit and vegetable waste, yeast, dairy waste, flour/bread, potato waste, slaughterhouse waste and sugar.

In paper V, data was collected through semi-structured interviews with employees at the food company, at the biogas plants receiving the organic waste and at the transportation company, which transports the waste from the food company. Semi-structured interviews were chosen, to enable flexibility during the interviews, both for the interviewer and the interviewee. Some questions were pre-defined, and others were added during the interviews, depending on the answers given by the interviewee.

6.1.3 Workshop

During the work on paper I, a workshop was conducted to identify possible categories to describe biogas production systems. According to Ørngreen and Levinsen (2017), the group participating in the workshop should be kept small, to allow all participants to be heard. Eight academic experts on biogas systems participated in the workshop conducted for paper I. Their fields of expertise

range from digestion, systems analysis, and energy to environmental issues regarding biogas production. Brainstorming was the main method used at the workshop, to be open to multiple solutions (Prathibha Varkey et al., 2009). The problem formulated for the participants was to identify possible categories for characterizing biogas plants. The European classifications found during the literature study were not shown for the participants until afterwards, to avoid preconceptions. In accordance with Summers and White (1976), the participants first wrote on note paper, before a joint discussion. After some categories had been identified, the participants were asked to prioritize between the categories. According to Ørngreen and Levinsen (2017), one of the major weaknesses of workshops is the risk that some of the participants become passive. To overcome this during the conducted workshop, each participant was given the opportunity to mark the five categories that they found most essential in describing a biogas system. The categories with the most marks composed the framework for categorization, which was used further on in the study. For a more detailed description of the workshop, please see paper I.

6.1.4 Measurements

In paper III, some measurements were necessary to complement the data retrieved from the literature studies performed. Installed meters were used, as well as instantaneous and logging measurements of electricity use. Speed drivers were used to determine the power of the devices. The data collection was performed over the course of one and two months respectively at the two biogas plants.

6.2 Systems Analysis

According to Churchman (1968), systems analysis can give a more complete picture of the effects on a system, in contrast to studying the components of the system one by one. Systems analysis is the basis for the analyses performed in the appended papers. One part of the aim of this thesis is to assess the resource efficiency of different treatment methods for organic waste from the food industry. To be able to achieve this, the analysis has been divided into three perspectives, relating to resource efficiency: energy, environment and economy. In this subchapter the methods used for the analysis in the appended papers are described. However, for a full description, please see each paper.

6.2.1 Energy analysis

Energy analysis has been performed on different system levels in papers III, IV and V, and paper II describes the methodology for the energy analysis applied in paper IV. The methodology includes energy balances for the studied systems, and input and output to all included processes in the studied systems are considered. The energy balance includes all energy going into the system and includes usable energy as well as losses. To be able to compare different kinds of energy carriers (electricity, diesel, heat), all energy flows are converted to primary energy. Primary energy is energy that has not been transformed in any way, for example wind energy or coal. Primary energy factors (PEF) used in paper IV are found in Table 5. The PEF is set at zero for energy/fuel that is to be considered as a rest, e.g. no new raw materials need to be added (Gode et al., 2011). This is valid for wind energy and organic by-products. However, there is an energy demand for conversion of the energy/fuel to electricity and hence, the conversion factor in Table 5 is not zero. For the other primary energy sources (e.g. coal and biomass), the PEF is set at one and the rest of the factor in Table 5 is composed of the energy demand for conversion (Gode et al., 2011). For example, coal condensing power has a PEF of three, which means that to deliver one unit of electricity, three units of energy (coal) are needed.

Table 5. Primary energy factors

Type	Primary Energy Factor	Reference
Coal condensing power	3.0	(Persson, 2008)
Wind power	0.05	(Gode et al., 2011)
Biomass (wood chips)	1.06	(Gode et al., 2011)
Diesel (with 5% RME)	1.09	(Öman et al., 2011)
Incineration of organic by-products	0.04	(Gode et al., 2011)

The PEF is multiplied by the energy use of an activity, to get the primary energy use of that activity, see Eq. 1. Activities are, for example, upgrading of raw gas, animal fodder production, electricity production and production of diesel.

$$\text{Primary energy use}_{\text{activity } x} = \text{Energy use}_{\text{activity } x} * \text{PEF}_{\text{activity } x} \quad (1)$$

In paper IV, two different electricity mixes are considered due to the large differences in primary energy factors and environmental performance between different kinds of electricity. For example, the primary energy factor for wind power is 0.05 and the factor for coal condensing power is 3. Since two different mixes of electricity were used, two sets of results were presented, one set for each electricity mix.

Biogas potential in the available substrates has been calculated in papers IV and V, using specific methane yields, derived from literature, and available amounts of substrates, derived from interviews or documents from the companies. The amounts of substrates were multiplied by the corresponding methane yields to get the biogas potential for that substrate.

In paper V, the available amount of excess heat from the food company was estimated using energy logging data from the company. The possibility of using this heat for the heating demand in the internal biogas plant was evaluated. For detailed information about the calculations, see paper V. The demand for oil at the company and diesel for transporting the waste to the external biogas plants was also analysed. If an internal biogas plant was to be built at the food company, the oil demand would be decreased, and the transportation to the external biogas plants would stop. However, the production at the external biogas plants is assumed to decrease and as a result, the output of vehicle fuel and district heating respectively would decrease. Biogas for vehicle fuel is assumed to be replaced with diesel and wood replaces biogas for district heating, and the amounts needed are based on the methane potential in the substrates.

In paper III, a methodology for analysing the energy demand at biogas plants is presented. The methodology is inspired by the methodology for energy audits for manufacturing industry, developed by Rosenqvist et al. (2012). The methodology described by Rosenqvist et al. (2012) includes instructions on how to allocate energy use into unit processes. According to Rosenqvist et al. (2012), and Söderström (1996), unit processes are the smallest parts of an industrial

energy system. The unit processes can be divided into support processes and production processes. Support processes are processes needed to support the production, e.g. administration, lighting, ventilation and steam, and production processes are processes needed for the production, e.g. mixing, moulding, drying and packing. However, processes at biogas plants are often described in terms of sub-processes, such as pre-treatment, anaerobic digestion and upgrading. Therefore, the methodology for analysing energy demand at biogas plants includes both of these approaches and also a combination of the two.

6.2.2 Environmental assessment

When performing an environmental assessment, several impact categories could be considered. According to Hijazi et al. (2016), the greatest environmental benefit of biogas systems, compared to fossil systems, is in global warming potential (GWP), and according to Cherubini and Strømman (2011), it is the most common impact category used in scientific studies. Other impact categories that could be used includes acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential or toxicity potential (Cherubini and Strømman, 2011).

Environmental assessments have been performed in papers IV and V. In paper V, the environmental assessment is represented by GWP. To give a wider understanding of the environmental performance of the studied systems, GWP, AP and EP are studied in paper IV. The emissions from the systems studied are translated to CO₂-eq (GWP), SO₂-eq (AP) and PO₄³⁻-eq (EP) respectively, with the conversion factors presented in Table 6.

Table 6. Conversion factors for GWP (Solomon et al., 2007), AP and EP (Guinée, 2002).

Compound	GWP [g CO ₂ -eq/g]	AP [g SO ₂ -eq/g]	EP [g PO ₄ ³⁻ -eq/g]
CO ₂	1	0	0
CH ₄	25	0	0
N ₂ O	298	0	0
PO ₄ ³⁻	0	0	1
NO ₃ ⁻	0	0	0.1
NH ₃	0	1.88	0.35
NO _x	0	0.7	0.13
SO ₂	0	1	0

Specific emission factors, i.e. the amounts of emissions generated by a specific activity, were retrieved from literature, for all the activities included in the systems studied. Examples of activities are upgrading of raw gas, production of diesel, electricity and animal feed. The factors were then multiplied by the relevant conversion factor. The total GWP, AP and EP were then calculated by summing the emissions for all activities in the systems, see Eq. 2-4. The results were used to compare the different scenarios with each other, and to compare the results for the different electricity mixes.

$$Total\ GWP = \sum GWP_{activities} \quad (2)$$

$$Total\ AP = \sum AP_{activities} \quad (3)$$

$$Total\ EP = \sum EP_{activities} \quad (4)$$

6.2.3 Economic evaluation

According to Rehl and Müller (2011), the most important consideration when choosing a treatment option for organic waste is profitability. In this thesis, two different means of economic evaluation have been used. The first one is investment opportunity (IO), which was used in paper V. The IO is calculated on an annual basis and offers a way to estimate how high the cost of a system change can be, for the investment to be profitable. IO can therefore be used even if the investment costs for some reason are unknown. The IO is calculated by comparing costs associated with an existing system to costs associated with a modified system. The IO is an annual savings potential and depending on the pay-back requirements of the company being studied, give an indication of how much the investment can cost to be profitable. In paper V, the annual cost of the different systems was calculated, and the differences between the annual costs gave the investment opportunities for building a biogas plant and a heat recovery system. The annual costs include transportation costs and purchase of oil. The IO must cover both the investment and associated costs, such as costs for maintenance and operation. The IO in paper V was calculated according to Eq. 5.

$$IO = C_{existing\ system} - C_{modified\ system} \quad (5)$$

where $C_{existing\ system}$ is the annual system cost for the existing system and $C_{modified\ system}$ is the annual cost for the system after the change.

Paper II presents the methodology applied in paper IV. The net profit for the studied systems is calculated. This includes all revenues and costs, including investment costs for new treatment methods, in the systems studied. Revenues in the systems are connected to sales of the end-products and costs are connected to the different treatment methods. The calculations were made according to Eq. 6. Investment costs for existing treatment methods are not included.

$$Net\ profit = \sum Revenues_{system\ x} - \sum Costs_{system\ x} \quad (6)$$

The numbers used for the economic evaluation are derived from literature and hence, there are substantial uncertainties concerning the costs and revenues of the systems. However, the economic evaluation is not meant to give exact numbers on the economic performance of the different systems, but to give an indication of the performance and to enable comparison between the different scenarios.

RESULTS AND ANALYSIS 7

This thesis is based on five papers and in this chapter a selection of the results from the papers are presented. An overview of the relation between the papers and the research questions is found in Table 1 in the first chapter of this thesis. For more information about the specific results, see each appended paper.

7.1 Research question 1

The first research question is:

How can comparison and analyses of biogas production systems be realized at different system levels?

In papers I, II and III, different approaches for studying biogas production systems have been presented. The ability to compare the performance of different biogas plants is vital, and therefore, a common, international, categorization is needed. In paper I, existing classifications of biogas plants in four European countries were analysed, using ten different Swedish biogas plants. For detailed information about the biogas plants, see paper I. Table 7 shows the results from that analysis. As can be seen, the ability to include the plants in the classifications differ a great deal. In the Danish classification, only two plants fit, whilst in the classifications used in Sweden and the UK, all the plants could be included. However, in the classification from the UK, no plants are classified as agricultural, while two plants are found in the agriculture class of the Swiss classification. Thus, even though the classifications could include classes that have similar names, the implication of the class may differ.

Table 7. The biogas plants studied in paper I inserted into the European classifications analysed in paper I.

Denmark	Sweden	Switzerland	United Kingdom
Farm	Farm-scale	Agriculture	Agricultural
⑤⑥	⑤	⑤⑥	
Centralized	Co-digestion	Commercial/Industrial	Community
	①③④⑥⑨	④	①②③④⑤⑥⑦⑨
	Industrial	Industrial WW	Industrial
	⑦⑩	⑦⑩	⑦⑩
	Landfill	Landfill	Water industry AD
	②	②	⑧
	WWTP	WWTP	
	⑦⑧⑩	⑧	

①Bjuv ②Helsingborg ③Laholm ④Linköping ⑤Luleå ⑥Malmö ⑦Umeå ⑧Uppsala
⑨Västerås ⑩Örnsköldsvik

In paper I, a categorization for biogas plants is developed. The result from that paper is a Framework for Categorization. The Framework consists of eight categories: Substrate, Organization, Biogas Use, Digestion Technology, Localization, Digestate and Capacity. Within each category, a number of subcategories are found. The Complemented Framework for Categorization is the Framework, with subcategories included, see Table 8.

When studying biogas plants, the subcategories can differ, depending on the characteristics of the biogas plants studied. The aim with the subcategories is that the biogas plants should be represented in at least one subcategory within each category. If no biogas plants in a specific study are included in a specific subcategory, that subcategory should be removed from the framework. Hence, the Complemented Framework may include different subcategories, depending on the biogas plants being studied in a specific study. The framework is supposed to facilitate comparisons between different plants and enable the identification of similarities and differences between the plants. The framework can be used as a foundation towards a common (European) classification for biogas plants. A common classification could facilitate knowledge sharing between and within countries.

Table 8. The Complemented Framework for Categorization from paper I. The headings of the columns are equal to the categorises, and the subcategories are found in each column.

Substrate	Organization	Biogas Use	Digestion Technology	Localization		Digestate	Capacity
Manure	Municipality	Vehicle Fuel	Mesophilic (15-45 °C)	Main Substrate On-site	Upgrading On-site	Certified Fertilizer	Small (< 1,000 m³)
Industrial Waste	Commercial	Electricity	Thermophilic (40-65 °C)	Substrate Pumped	Gas Transported by Vehicle	Soil Improvement	Medium (1,000-10,000 m³)
Wastewater Sludge	Substrate Owner	Heat		Substrate Transported by Vehicle	Local Gas Grid	Uncertified Fertilizer	Large (> 10,000 m³)
MSW	Shared Ownership	National Gas Grid			National Gas Grid		
Fat		Internal Use			Internal Use		
Crops					Energy Conversion for External Use		

Paper II presents a research design for assessing the resource efficiency of organic waste from the food industry. The design involves the steps shown in Figure 12. Detailed information about the different steps is found in the appended paper.

Figure 12. The research design presented in paper II.

The research design is outlined to include economic evaluation, energy analysis and environmental assessment, to assess the resource efficiency of different treatment methods for organic waste. The steps of system development and evaluation perspectives are iterative and depending on the evaluation perspective chosen, the systems may need to be adjusted, hence the dotted arrow

in Figure 12. The design includes a systematic approach to evaluating biogas production systems and includes the three aspects of resource efficiency highlighted in this thesis: energy, environment and economy. The proposed research design makes it possible to perform assessments of resource efficiency of biogas production systems. The research design was applied to five different regions, and the results can be found in chapter 7.2, and in paper IV.

Instead of focusing on higher system levels, as with the two approaches described, another way to study biogas production systems is to focus on the production site. In paper III, a methodology for analysing energy demand on a detail level for biogas production systems was developed. The methodology in paper III was inspired by the method for energy audits in the manufacturing industry presented in Rosenqvist et al. (2012). The focus in the methodology is on allocation and analysis of energy data on a detailed level. The biogas production system was divided into sub-processes, see Figure 13. The processes in green are included in system level 1 and the processes in green and blue are included in system level 2. These system levels complement the system levels described earlier in the thesis. The processes outside the system boundary are excluded from the system studied.

Figure 13. The biogas system presented in paper III.

A taxonomy of unit processes was also presented in paper III, see Table 9. The unit processes are divided into production processes and support processes. Production processes are directly connected to the production of biogas and digestate, e.g. mixing of the substrate in the pre-treatment, whilst support processes are processes supporting the production but not directly connected to the production, e.g. lighting or ventilation.

Table 9. Unit processes presented in paper III.

Category	Unit process	Examples of applications
Production processes	Disintegrating	Crushing, grinding and tearing of substrate in pre-treatment
	Mixing	Mixing of substrate in reception, pre-treatment and digester
	Heating	Heating of substrate in hygienization and digester
	Cooling	Cooling of digester, cooling of substrate from hygienization
	Concentrating	Concentrating substrate and digestate by removing water e.g. centrifuging
	Diluting	Diluting substrate by adding fresh water or process water
	Packing	Compressing gas into gas cylinders
	Administration	Control systems, computers
Support processes	Cooling	Cooling of equipment and space cooling
	Lighting	
	Compressed air	Production of compressed air for the biogas production process
	Ventilation	Ventilation of production area
	Pumping	Pumping of substrate, water, biogas, etc.
	Tap water heating	
	Internal transport	Vehicles and conveyors (screw, scraper, conveyor belt, elevator)
	Space heating	
	Steam	Production of steam for the biogas production process

Two different biogas plants were used to validate the methodology. The results from the analysis were presented in three different ways: energy allocated to sub-processes, energy allocated to unit processes and a combination of the first two. An example of how the two approaches can be combined is shown in Figure 14. The figure shows the sub-process anaerobic digestion for the two plants studied. The boxes in grey show the connection to other sub-processes. The circles at the top show the unit processes included in the two different plants. As can be seen, the unit processes differ between the two plants. For detailed information about the other sub-processes at the plants, see the appended paper.

Figure 14. An example of how a combination of the two allocation approaches for energy demand can be illustrated. From paper III.

7.1.1 Analysis RQ 1

To be able to increase the biogas production in the world, and to promote new innovations within the biogas sector, knowledge sharing and comparison between different biogas solutions is vital. There are different approaches that can be used to perform an analysis of biogas production systems at different system levels, in order to be able to compare biogas production systems and improve the possibilities for knowledge sharing. The approaches presented in this thesis are:

- Categorization
- Resource efficiency analysis
- Energy demand analysis

The approaches could be applied to different system levels of the biogas production system. The connection between the system levels shown in Figure 5, in chapter 5 (Systems studied) and the approaches presented in this thesis are found in Table 10.

As can be seen in Table 7, there are large differences in the classifications of biogas plants in European countries, both in the different classes included in the classifications, but also how the plants are classified (the definitions behind the different classes in the classifications as indicated in the text). On a European level, the categorization can give information about the biogas development in different countries. For example, the most common substrate or utilization of the produced biogas can be shown in the categorization. However, categorization of biogas plants could be interesting at all system levels for finding plants that are similar, or different, and for sharing knowledge and experience. On a regional level, a categorization could increase knowledge sharing, and hence the development of biogas solutions, within a region as well as between regions. On a company level, categorization can be used by, for example, food companies interested in starting to produce biogas. The categorization begins from the biogas plant levels, since the plants are the foundation of the categorization. A single biogas plant could use the categorization to find similar, or different, plants, in order to share knowledge and experience of processes and implementations of new technology, for example.

Table 10. The connection between the system levels and approaches for analysing biogas production systems. The cross indicates the level at which the approach has been applied, and the arrows the levels at which it could be applied. The grey arrow indicates that the energy demand analysis could be used as input for systems analyses at higher system levels.

	Categorization	Resource efficiency analysis	Energy demand analysis
Level 1 (European level)	x	↑	
Level 2 (Regional level)		x	↑
Level 3 (Company level)		x	
Level 4 (Biogas plant level)	↓	↓	x

Resource efficiency analysis could be implemented at all different system levels, but, the scope of the analysis may differ, depending on the level. At the lower levels, the perspective may be more related to one plant and/or company. Resource efficiency analysis could be used at these levels to, for example, assess the best utilization option for the produced biogas, or whether the digestate should be dewatered or not. At the higher levels (level 3 and 4), the scope may instead be to see the substitution effects from a larger perspective, and the effects on the surrounding system.

The energy demand analysis can be conducted in order to understand the energy performance of the plant, or to find processes where energy efficiency measures can be implemented. The approach can also be used to compare the energy performance of two or more biogas plants. The energy demand analysis could be used as a basis for systems analysis at higher system levels and could for example be used as input to a resource efficiency analysis.

7.2 Research question 2

The second research question is:

How can organic waste from the food industry be treated in a resource efficient way?

This has been addressed in papers II, IV and V. Paper II presented a research design on how to assess the resource efficiency of biogas production from organic waste. The steps included in the design are shown in Figure 12. The research design presented in paper II is then applied in paper IV. Five different systems of regions with food companies in Sweden were studied, referred to as system A-E. Resource efficiency was analysed from an economic, energy and environmental perspective. The environmental perspective was divided into GWP, AP and EP. Three different scenarios were analysed, see Table 2 in chapter 5.2.

A compilation of the results of the analysis is found in Table 11. The table shows the most preferable scenario from the different perspectives in the respective systems. Note that this does not mean the shown scenario is the only preferable one. In several of the systems more than one scenario had good results for the different perspectives studied. However, the results showed that one of the two biogas scenarios studied was the most preferred scenario in the systems from almost all perspectives. With an electricity system based on wind power, scenario Vehicle had an advantage from the perspectives of GWP and AP. With an electricity system based on coal condensing power, scenario CHP had an advantage in the perspectives in terms of energy, GWP and AP. The reasons for this are partly a higher electricity demand in the scenario Vehicle, and partly large differences in specific emissions connected to wind power and coal condensing power. Scenario Vehicle has a higher electricity demand due to the upgrading step of the raw biogas, whilst in scenario CHP electricity is instead produced. Scenario Vehicle is the most preferred scenario from an economic perspective in four of the five systems studied. A reason for this is the relatively low electricity price in Sweden. From a eutrophication perspective, scenario Vehicle is the most preferred one in all system, regardless of the electricity system.

Table 11. The results from paper IV. The most preferable scenario is shown for each perspective in the different systems studied. Note that this does not mean the shown scenario is the only preferable one. In several of the systems more than one scenario had good results for the different perspectives studied.

Information about the different scenarios can be found in Table 2 in chapter 5.2

	Economy	Energy		Environment					
				GWP		AP		EP	
		Coal	Wind	Coal	Wind	Coal	Wind	Coal	Wind
System A	Vehicle	CHP	BAU	CHP	Vehicle	CHP	Vehicle	Vehicle	Vehicle
System B	Vehicle	CHP	BAU	CHP	Vehicle	CHP	Vehicle	Vehicle	Vehicle
System C	BAU	CHP	BAU	CHP	CHP	CHP	Vehicle	Vehicle	Vehicle
System D	Vehicle	CHP	BAU/Vehicle	CHP	Vehicle	CHP	Vehicle	Vehicle	Vehicle
System E	Vehicle	CHP	Vehicle	CHP	Vehicle	CHP	Vehicle	Vehicle	Vehicle

In paper V, the aim was to study the change from biogas production at an external biogas plant to production at the food company's own integrated biogas plant. The possibility of recovering excess heat from the food company was studied as well. The analysis was performed from an environmental (GWP), energy and economic perspective. The energy analysis showed that the available excess heat could cover the potential heat demand for a digester and that around 29 MWh could be saved per year due to less transportation. The economic results of the assessment are shown in Figure 15. The results are presented for two alternatives: (1) excess heat is used for heating of the biogas digester and (2) biogas is used for heating the digester. The investment opportunity is larger with excess heat utilization. In Figure 15, the processes influencing the investment opportunity are also shown. The largest saving corresponds to a decrease in the oil demand at the company.

Figure 15. The investment opportunity (IO) for the food company in paper V. The bar to the left shows the IO when excess heat is used for heating of the digester and the bar to the right shows the IO when biogas is used for heating of the digester.

The environmental assessment showed that the integration of a biogas plant with the food company leads to a decrease of in total greenhouse gas emissions, see Figure 16. When the emission factor for biomass was set at zero, the decrease was the largest. Utilization of excess heat leads to higher reductions in greenhouse gas emissions, compared to utilization of biogas to heat the digester, no matter the emission factor for biomass. The process that contributes most to the results is the reduction of oil use in the boiler at the company. However, when emissions from biomass are considered, emissions from using biogas in the boiler instead of oil also lead to new emissions, and hence the smaller change in the two left bars. Other processes influencing the results are the need for more gasoline in the transport system, as well as an increase in wood fuel for the district heating system, when biogas is produced at the food company and used for industrial processes instead. Emissions connected to manure decrease when the manure is digested, instead of being spread on farmland directly. For more detailed results, please see paper V.

Figure 16. The results of the environmental assessment in paper V. The diagram shows the changes in GWP between the two systems studied.

7.2.1 Analysis RQ2

The overall results show that treating organic waste from the food industry with anaerobic digestion to produce biogas could be a good option from the different aspects of resource efficiency under these circumstances. In paper IV, the results for the two biogas scenarios are positive for the energy and economic perspectives in all the systems studied. This indicates that the systems will have a net output of energy, i.e. more energy is delivered from the system than is used in the system, as well as being profitable in economic terms. For the environmental perspective the results differ somewhat. For AP and EP, both biogas scenarios have negative results for all systems, meaning that both scenarios result in a reduction in the emissions connected to acidification and eutrophication. For GWP however, the results differ between the scenarios when the electricity is produced from coal condensing power. Scenario CHP results in a decrease in greenhouse gas emissions for all systems, whilst scenario Vehicle results in an increase in emissions of greenhouse gases for all systems. The reason for these results is the high demand for electricity when upgrading biogas to vehicle fuel, and the high emissions factors for coal condensing power. In scenario Vehicle electricity with high emission factors is used, whilst in scenario CHP electricity with high emission factors is replaced. When electricity is

produced from wind energy, both biogas scenarios have negative results for GWP, i.e. resulting in a decrease in greenhouse gas emissions. This shows the influence the electricity system could have on the results, but also that the results are dependent on what is replaced in the systems studied. This is also evident in paper V, where two systems for biogas production are studied. The results show that the best option from an economic and environmental (GWP) perspective is to produce biogas locally at the studied food company. The reason for this is mainly due to the ability to decrease the consumption of oil at the food company, with the installation of a biogas plant.

CONCLUDING REMARKS 8

8.1 Discussion

There is considerable potential in the world for biogas production - according to the World Biogas Association in total only around 3 % of the global potential for biogas production was realized in 2017 (Jain et al., 2019). However, the true realisable potential is difficult to assess, and depends on many different aspects, including availability of substrates, regulations and market incentives (Martin, 2015). Biogas is mainly produced in Europe, where Germany dominates production. To increase production on a global scale, the benefits of biogas systems need to be promoted, and methods for analysing and comparing biogas production systems can be an important part of this. An increase in biogas production can create new jobs and new industry sectors as well as local and regional development.

This thesis studies biogas production systems, and different approaches to performing analysis of such systems. The approaches can be used for different system levels. For the biogas plant level, categorization as discussed in Paper I could be interesting for finding other plants that are similar to yours and sharing knowledge and experience with other biogas plants. At the lower system levels the user of the categorization could be a biogas plant, or maybe a food manufacturing company, interested in starting a biogas project. In that case, the categorization can serve as input concerning, for example, what kind of process is used by plants with similar substrate. The categorization could also give information on localization of a biogas plants, and what similar plants have done, e.g. which substrates are pumped, and which are transported by truck. In a report from the International Energy Agency, a common classification was presented together with information about biogas production in 15 countries

around the world (Fagerström and Murphy, 2018). However, there were at least six more classifications in the report, which shows the complexity of creating a classification that can be used in many countries. The Framework for Categorization presented in this thesis could be a starting point for work on finding an international classification for biogas production plants.

Resource efficiency is a complex concept. It could include material resources, human resources and even knowledge. In this thesis the concept has been limited to energy, environmental and economic aspects of the concept. Many system analyses of biogas production systems include environmental assessment, but not many include all three aspects. When including environmental assessment, energy analysis and economic evaluation in the systems analysis the results from the application show the complexity of assessing resource efficiency. For example, the results in the study by Wu et al. (2016) showed that the most preferable of the different options for biogas utilization depended on the perspective: energy, environment or economy. This is in line with the results from paper IV. However, the results of the environmental assessment in Wu et al. (2016) were based on nine impact categories but transformed to a “*green degree*”, instead of showing the results for each of the impact categories. Thomsen et al. (2018) concluded that to use organic waste for biogas production instead of incineration is more beneficial from a resource efficiency perspective.

The results from paper IV showed that the two biogas scenarios were the preferred scenarios in all systems from the environmental perspective. This is strengthened by the conclusions of other system studies where biogas production systems are compared to alternative systems. For example, Pérez-Camacho et al. (2019) performed an environmental assessment including three scenarios for utilization of biogas: CHP, gas grid and vehicle fuel. The results showed that all scenarios were better than the alternative systems with fossil fuels, and producing vehicle fuel from biogas was best from a GWP perspective. Oldfield et al. (2016) made an environmental assessment of BAU and four waste management options for food waste in Ireland. The four options were waste minimization, composting, anaerobic digestion and incineration, and the environmental assessment included GWP, AP and EP. The results showed that waste minimization was the best alternative, followed by anaerobic digestion. Prade et al. (2012) performed energy balances for four different scenarios of utilization options for hemp. The hemp was utilized for: bales for CHP,

briquettes for heating and ensilage for biogas, which in turn was used for CHP or vehicle fuel. The results showed that the first two utilization options had the best net energy yields. The biogas alternatives had higher energy demands but resulted in high quality products such as electricity and vehicle fuel. In the research presented in paper II, the use of primary energy is suggested, to enable comparison of high-quality energy with low-quality energy.

Assumptions have been made in all the papers appended to this thesis, and hence, there are some uncertainties. For example, the methane yields used are retrieved from literature, and not through laboratory examination of the actual substrates. Further, the biogas potentials have been calculated for each substrate individually, even though the substrates are assumed to be co-digested at the biogas plants. To handle this, and other uncertainties connected to the studies, the results have not been presented in real numbers, but instead the focus has been on comparison between studied systems and scenarios.

The studies in paper IV and V are performed at different system levels, and with different focuses. In paper IV, the focus is on sending organic waste from several food companies to a centralized treatment facility, whilst in paper V, the focus is on the shift from centralized biogas plants to a plant at the food company. According to Lantz (2012), scale affects the profitability of biogas production systems, and it could be more profitable from an economic perspective to go for larger biogas plants. However, it also depends on local settings and conditions (Lantz, 2012). The studies in paper IV and paper V have not been performed in the same geographical region, and the economic perspective varies between them. For the study in paper V, the economic interest of the food company is in focus, and in paper IV, the economic focus is on the different treatment options. However, the focus has not in any of the studies been to evaluate which scale of biogas plant is the most preferable.

Havukainen et al. (2014) concluded that to be able to compare the energy efficiency of different biogas production systems, a consistent way of calculating energy performance is necessary. Compared to other energy analysis for biogas plants, our methodology presented in paper III analyses energy data on a higher detailed level. The methodology is flexible and hence enables energy analyses of energy demand for different kinds of biogas production systems.

8.2 Conclusion

This thesis is based upon the results from five papers, which are appended. The aims of this thesis are to perform systems analysis of biogas production systems with focus on environment, energy and economy and to explore how to analyse and compare biogas production system. The aims of the thesis are achieved by answering two research questions, found in the headings of the subsequent two subchapters.

8.2.1 How can comparison and analyses of biogas production systems be realized at different system levels?

In this thesis, three different approaches for analysing biogas production systems are presented: categorization, resource efficiency analysis and energy demand analysis. The approaches can be applied at different systems levels of the biogas production system, depending on the scope and aim of the systems analyses performed. These approaches all contribute to the understanding of biogas systems and can contribute, in different ways, towards increasing global knowledge of biogas systems. If knowledge of different biogas systems can be easily spread, more of the unused potential of biogas production may be realized, and hence more fossil fuels in the energy system can be replaced. Studying biogas production systems from different system levels, as well as from different approaches, is beneficial because it results in deeper knowledge of biogas systems and greater opportunities to identify synergies.

8.2.2 How to treat organic waste from the food industry in a resource efficient way?

Biogas production has been shown to be a resource efficient way to treat waste from the food industry, based on the conditions of the performed systems analyses. However, systems analysis is necessary, and the effects of a treatment method on the surrounding system should be included in the analysis. The results from the appended papers show that depending on the perspective in focus, the outcome for most preferable scenarios may differ. The results have also highlighted that resource efficiency is dependent on the alternative production. It is important to understand that the resource efficiency of a system always stands in relation to the system substituted.

8.3 Further work

During the work on this thesis and the appended papers, several ideas for additional studies have emerged. A continuation of the work on the Framework for Categorization would be interesting. If more biogas production plants could be included in the framework, there might be a possibility of getting closer to a common international classification for biogas production systems.

In the systems studies performed in paper IV, three scenarios were evaluated. An idea could be to instead perform an optimization of a region, including different kinds of substrate. The purpose of this would be to see which of the different treatment alternatives for organic by-products are optimal from the three different perspectives: energy, environment and economy.

Another interesting issue to study is whether it is better to have centralized large plants, or smaller ones, from different perspectives. This issue could also be studied at different system levels, to conclude whether the results differ depending on the system perspective.

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PART 2

APPENDED PAPERS

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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