Norwegian University of Life Sciences
Faculty of Environmental Sciences and
Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2018:6

Reduction of environmental impacts through optimisation of biogas value chains. Drivers, barriers and policy development

Reduksjon av miljøbelastninger gjennom optimalisering av biogass verdikjeder. Drivere, barrierer og politikkutforming

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Summary

Biogas production from anaerobic digestion of organic resources can potentially contribute to a reduction in greenhouse gas emissions in several sectors and can play a central role in both the bioeconomy and the circular economy. Several European countries have political goals to increase biogas production and to increase the amount of manure to anaerobic digestion. The treatment method is, however, known to be costly and the markets for biogas and for digestate are immature. There is a need for a better understanding of how the biogas value chains should be designed to minimise environmental impacts while at the same time achieving profitability for the actors.

In Norway the most common substrates for biogas production are sewage sludge and organic waste from households and industry. Manure is identified as the substrate with the greatest theoretical biogas potential, but there are currently few plants utilising manure. Until recently, biogas in Norway has mainly been applied to generate heat, where a large share has been utilised internally at the plant or in surrounding buildings. In the last few years, however, several new and existing plants have invested in upgrading equipment to produce biomethane for use as a fuel in the transport sector. The most common treatment of the digestate, which is a co-product from anaerobic digestion, is to dewater it and use the dry fraction as a soil improvement product, while the wet fraction is sent to waste water treatment. A few new plants do, however, deliver liquid digestate to agriculture as a biofertiliser.

The objective of this thesis has been to make a contribution towards knowledge regarding ways of optimising Norwegian biogas value chains to reduce environmental impacts, by developing models that can provide decision support. The aim is to suggest improvements to the regulatory systems and the preconditions for further development of the biogas industry in Norway. Systems theory and system analysis methodology was applied, and three different domains were assessed: environmental impacts, economy of the actors in the value chain and policies. The case studies were limited to the substrates organic waste from households (food waste) and manure from cattle and pigs. In the economic assessment, only the annual results for the biogas plants and cattle and pig farms were calculated.

Four scientific papers were developed as part of this PhD thesis. In the first paper, life cycle assessment methodology and generic results were presented for the BioValueChain model. The model was developed to be able to evaluate the environmental impacts of different options for biogas value chains. In the second paper, environmental assessment was combined with economic assessment of large scale biogas plants for four different value chain configurations. In addition, the most profitable option was used as a reference to calculate the incentives necessary to make the most preferable option in terms of reduction of environmental impacts as profitable as the reference.

A comparative assessment of biogas value chains in Norway and Denmark was carried out in Paper 3. Denmark has implemented an end-use support of biogas through a feed-in tariff, while Norway provides investment support and support for farmers per tonne manure delivered to a biogas plant. The objective was to evaluate the effect of different regulatory systems. This was achieved by defining a Norwegian and a Danish biogas value chain, and calculating the costs and income. In addition, the economic results were calculated for the Norwegian value chain when assuming Danish conditions, and vice versa.

In paper 4 the methodology of an optimisation model for the use of manure resources for anaerobic digestion in one region was described, and the model was employed to perform a case study on 50 farms in one region in Norway. The model calculated the economic profit for farmers and the

greenhouse gas emissions for three options: no biogas production, farm scale biogas production and centralised biogas production.

The results in this PhD work showed that the amount of organic waste and manure used for anaerobic digestion should be increased to reduce environmental impacts. The most preferable option for the use of biogas is as a fuel for transport to substitute diesel, and the best use of the digestate is as a fertiliser in agriculture as a substitute for mineral fertiliser, which requires a high level of sector integration in the value chain. To obtain a maximal reduction of greenhouse gas emissions, efforts should be made to avoiding diffuse emissions and reducing emissions from the storage of digestate.

The economic calculations showed that large-scale biogas plants in general lack economic incentives to include the agricultural sector in the value chain. Inclusion of the transport sector is the most profitable option for use of biogas only for the largest scale biogas plants and for those who are able to sell biomethane for a high price.

The most profitable option regarding the management of manure for cattle and pig farms was the supply of manure to a centralised biogas plant and the return of the digestate as biofertiliser. This was, however, dependent on the agreement between the farm and the biogas plant. As a result of the newly introduced support per tonne manure sent to biogas production, investment in a small scale biogas plant can also be profitable for most cattle and pig farms, all though the majority of farms in Norway would struggle to find a good use for the biogas on the farm. This indicates that the current barriers to increased use of manure resources for biogas production are not principally economic.

The current support system has contributed to an increase in biogas production. Based on the assessments performed as part of this thesis, however, some recommendations were made to improve the framework conditions of an optimised biogas production in Norway, to reduce environmental impacts and achieve the political objectives. While the exemption from CO_2 tax and road fee has contributed to an increased use of biogas in the transport sector, an increase in the taxes for fossil fuels could contribute to making upgrading of the gas the most profitable option for most large-scale biogas plants. Raising the importance of the environmental aspects in public procurements would enhance the role of biogas in achieving the political objectives of obtaining fossil free public transport and in the reduction of environmental impacts from waste treatment. In addition, it is important to consider measures that motivate large scale plants to use manure as a substrate and deliver digestate to agriculture.

An increase in the knowledge regarding the economy of farm scale biogas production in a Norwegian context would make the results from the economic assessment more robust and reduce the risk for farmers in making the investment. These include knowledge with regard to the start-up and operation of small scale plants to avoid unforeseen costs. Political instruments that encourage the development of technology for cheaper small scale upgrading solutions could further reduce the greenhouse gas emissions, as would the use of raw biogas in tractors and other agricultural equipment currently using fossil fuels. In some regions, this could also be achieved by implementing regional development plans for farm scale production with piping infrastructure and centralised upgrading. These measures could promote an increase in the amount of manure for biogas production

The work carried out as part of this thesis has shown that models combining environmental life cycle assessment and economic cost assessments can serve as decision support and can make a valuable contribution to policy development. The results are, however, highly dependent on the quality of the data used and the level of detail in the models. In order to increase the robustness of the results, there is a need for more research into the quantification of emissions from the storage and spreading of digestate, and ways in which they can be reduced. In addition, there is a need for a greater understanding of the properties of digestate as a fertiliser, such as the fertilising effect, carbon storage and other contributions to soil quality. More research should also be carried out on the emissions from dewatering and composting of digestate, and its use as a substitute for peat. Furthermore, the cost assessments could be expanded to also to include the economy of the actors in the transport sector and the farmers receiving digestate.

Sammendrag

Biogassproduksjon fra anaerob utråtning av organiske ressurser kan potensielt bidra til reduksjon av klimagasser i flere sektorer og kan spille en viktig rolle i både bioøkonomien og sirkulærøkonomien. Flere europeiske land har politiske målsetninger om å øke biogassproduksjon og øke mengden gjødsel til anaerob behandling. Behandlingsmetoden er derimot kjent for å være kostbar, og markedene for biogass og biorest er umodne. Det er behov for en bedre forståelse av hvordan verdikjedene bør utformes for å minimere miljøbelastningene samtidig som man oppnår lønnsomhet for aktørene.

I Norge er de vanligste substratene for biogassproduksjon kloakkslam og organisk avfall fra husholdninger og industri. Gjødsel er identifisert som substratet med det høyeste teoretiske biogasspotensialet, men det er foreløpig få biogassanlegg som bruker gjødsel som råvare. Inntil nylig har biogass i hovedsak blitt brukt til å generere varme, hvor en stor andel har blitt brukt internt i anleggene eller til å varme opp bygninger i nærheten. I løpet av de siste årene har derimot flere nye og eksisterende anlegg investert i oppgradering og produserer biometan til bruk i transportsektoren. Den vanligste behandlingen av bioresten, som er et biprodukt fra den anaerobe behandlingen, er å avvanne den og bruke den tørre fraksjonen som et jordforbedringsprodukt og sende vannfasen til renseanlegg. Noen få nye anlegg leverer derimot den flytende biorest til lanbruket som biogjødsel.

Hensikten med denne avhandlingen har vært å bidra til økt kunnskap om hvordan norske biogass verdikjeder bør optimaliseres for å redusere miljøbelastninger ved å utvikle modeller som kan gi beslutningsstøtte. Målet er å foreslå forbedringer av virkemiddelapparatet og forutsetningene for videre utvikling av biogassindustrien i Norge. Systemteori og systemanalyse-metodikk ble brukt, og tre ulike aspekter ble analysert: miljøpåvirkninger, økonomien til aktører i verdikjeden og politikk. Casestudiene er begrenset til substratene organisk avfall fra husholdninger (matavfall) og gjødsel fra storfe og gris. I økonomianalysene ble kun det årlige resultatet til biogassanlegg og storfe- og grisegårder analysert.

Fire vitenskapelige artikler ble utviklet som en del av avhandlingen. I den første artikkelen ble livsløpssmetodikk og generelle resultater for BioValueChain-modellen presentert. Modellen ble utviklet for å muliggjøre evaluering av miljøpåvirkninger fra ulike alternativer for biogass verdikjeder. I den andre artikkelen ble miljøanalyser kombinert med økonomiberegninger for storskala biogassanlegg for fire ulike verdikjede-konfigurasjoner. I tillegg ble det mest lønnsomme alternativet brukt som referanse til å beregne hvilke insentiver som er nødvendig for at den mest gunstige løsningen med tanke på reduksjon miljøbelastninger, blir like lønnsom som referansen.

En komparativ analyse av biogass verdikjeder i Norge og Danmark ble gjennomført i Paper 3. Danmark har implementert støtteordninger for sluttbruk av biogass gjennom en feed-in tariff, mens Norge tilbyr investeringsstøtte og støtte til gårder per tonn gjødsel levert til biogassanlegg. Hensikten var å undersøke effekten av ulike virkemiddelsystemer. Dette ble utført ved å definere en norsk og en dansk biogass verdikjede og beregne kostnadene og inntektene. I tillegg ble de økonomiske resultatene beregnet for den norske verdikjeden under danske forutsetninger, og vice versa.

I Paper 4 ble metodikken til en optimaliseringsmodell for bruk av gjødselressurser i en region til biogassproduksjon beskrevet, og modellen ble brukt til å gjennomføre en casestudie på 50 gårder i en region i Norge. Modellen beregnet årlig økonomisk resultat for gårdene i regionen og utslipp av klimagasser for tre alternativer: ingen biogassproduksjon, biogassproduksjon på gårdsanlegg og sentralisert biogassproduksjon.

Resultatene i PhD-arbeidet har vist at organisk avfall og gjødsel i større grad bør benyttes til biogassproduksjon for å redusere miljøbelastninger. Den beste løsningen for bruk av biogassen er som

drivstoff slik at biogassen kan erstatter diesel, og den beste løsningen for bruk av biorest er som biogjødsel i landbruket til å erstatte mineralgjødsel, noe som krever et høyt nivå av sektorintegrering i verdikjeden. For å oppnå maksimal reduksjon av klimagassutslipp, bør det fokuseres på å redusere diffuse utslipp og å redusere utslipp fra lagring av biorest.

Økonomiberegningene vise at storskala biogassanlegg mangler generelt økonomiske insentiver for å inkludere landbrukssektoren i verdikjeden. Inkludering av transportsektoren er kun det mest lønnsomme alternativet for anlegg over en viss skala eller for anlegg som får en høy pris for den oppgraderte gassen.

For storfe og grisegårder er det mest lønnsomme alternativet med tanke på gjødselhåndtering å levere gjødsel til et sentralt biogassanlegg, og å få bioresten i retur. Denne konklusjonen er svært avhengig av avtalen mellom gården og biogassanlegget. Takket være den nylig introduserte støtten per tonn gjødsel til biogassanlegg, kan investering i et gårdsanlegg også gi økonomisk overskudd for bonden, til tross for vanskeligheter med å finne et godt bruksområde for gassen. Dette gir en indikasjon på at barrierene for å øke mengden gjødsel til biogassproduksjon på det nåværende tidspunkt ikke i hovedsak er økonomiske.

Det eksisterende virkemiddelapparatet har bidratt til en økning i biogassproduksjonen. Basert på analysene som er utført i denne avhandlingen kan det likevel gis noen anbefalinger til forbedringer i rammevilkårene for en optimalisert biogassproduksjon i Norge, for å redusere miljøpåvirkningene og for å oppnå de politiske målsetningene. Unntak fra CO_2-avgift og veiavgift har sannsynligvis bidratt til en økning i bruk av biogass i transportsektoren. En ytterligere økning i avgiftene for fossile drivstoff vil sannsynligvis medføre at oppgradering blir den mest lønnsomme løsningen for de fleste storskala biogassanlegg. Et økt fokus på viktigheten av miljøaspekter ved offentlige innkjøp kan bidra til å oppnå de politiske målsetningene for fossilfri kollektivtransport og reduksjoner av miljøbelastninger fra avfallshåndtering. I tillegg er det viktig å vurdere virkemidler som kan motivere storskalaanlegg til å bruke gjødsel som substrat og levere biorest til landbruket.

En økt forståelse for økonomien til gårdsanlegg under norske forhold vil gjøre resultatene fra de økonomiske beregningene mer robuste og redusere risikoen for bønder som ønsker å investere. Dette inkluderer kunnskap om oppstart og drift av småskalaanlegg for å unngå uforutsette utgifter. Politiske virkemidler som legger til rette for utvikling av teknologi for billigere småskala-oppgradering kan redusere klimagassutslippene ytterligere. Det samme kan bruk av rågass i traktorer og annet landbruksutstyr, som på det nåværende tidspunkt bruker fossilt drivstoff. I noen regioner kan det være aktuelt å lage en regional plan for biogassproduksjon med rørnett og sentralisert oppgradering. Disse tiltakene vil kunne bidra til å øke mengden gjødsel til biogassproduksjon.

Arbeidet som er gjennomført i forbindelse med denne avhandlingen har vist at modeller som kombinerer livsløpsanalyser og økonomiberegninger kan bidra med beslutningsstøtte og kan gi verdifulle innspill til politikkutforming. Det er likevel viktig å være oppmerksom på at resultatene er svært avhengig av kvaliteten på datagrunnlaget og detaljnivået til modellene. For å øke robustheten til resultatene er det behov for mer forskning på kvantifisering av utslipp fra lagring og spredning av biorest, og reduksjon av disse utslippene. Det er i tillegg behov for en bedre forståelse av egenskapene til biorest som et gjødselprodukt, slik som gjødseleffekt og karbonlagringseffekt og andre bidrag til jordkvalitet. Det er også behov for mer kunnskap om utslipp fra avvanning og kompostering av biorest og på erstatning av torv. Videre kan kostnadsberegningene med fordel utvides til å inkludere aktørene i transportsektoren og gårder som mottar biorest.

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To my children, Kaja and Lars: I do not expect you to read this any time soon. You deserve a bright future, and I will do my best to make sure that your generation inherits a liveable world. This is just a tiny contribution.

My last thanks go to Torjus. This would not have been possible without your support and our team work. I am sorry that you had to discuss biogas on Saturday afternoons and Sunday mornings. I realise it may not be other people's favourite topic. But I am afraid it will not end any time soon…

Contents

List of supporting papers

Paper 1

Kari-Anne Lyng, Ingunn Saur Modahl, Hanne Møller, John Morken, Tormod Briseid and Ole Jørgen Hanssen (2015): The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. *International Journal of Life Cycle Assessment* (2015) 20: 90.

Paper 2

Kari-Anne Lyng, Aina Elstad Stensgård, Ole Jørgen Hanssen and Ingunn Saur Modahl (2017): Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains. A case study on different levels of sector integration. Submitted to *Journal of Cleaner Production*.

Paper 3

Kari-Anne Lyng, Lise Skovsgaard Nielsen, Henrik Klinge Jacobsen and Ole Jørgen Hanssen (2017): The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark. Submitted to *Energy Policy.*

Paper 4

Kari-Anne Lyng, Ole Jørgen Hanssen, Aina Elstad Stensgård, Pieter Callewaert and Mia Bjerkestrand (2017): Optimising anaerobic digestion of manure resources on a regional level. Submitted to *Sustainability*.

1 Introduction

While solid materials such as plastic and metals may be recycled into the same product, the recycling of organic waste is less straightforward. As an example, food waste cannot be used as food once it has been discarded and stored at normal air temperature, as it will start to degrade and will no longer have the same properties. Despite this, organic waste is a valuable resource, both because it can contribute to the production of renewable energy and as it contains a significant number of limited resources: essential nutrients for crops, such as nitrogen, phosphorous, potassium and a wide range of micronutrients. While the best environmental solution is to avoid unnecessary waste, a certain amount of waste is inevitable. Organic waste from households and industry represent a resource that should be managed in the best way possible.

Livestock manure is normally not considered to be waste, but can be regarded as a co-product or a side stream from the production of meat and milk. It plays an important role as a fertiliser by providing nutrients in food production. At the same time, misplacement, storage or over use of manure can be a source of local pollution and emissions of greenhouse gases. Correct management of manure resources is thus of major importance.

The use of anaerobic digestion to produce biogas and digestate represents a means of recycling the organic resources. Several European countries have ambitions to increase biogas production, and Norway is no exception. The primary motivation varies between countries and can be either to reduce greenhouse gases, to improve recycling rates of food waste, to produce renewable energy or to better distribute the phosphorous resources in manure.

For this reason, it is interesting to explore the many aspects of the biogas value chains. What are the environmental benefits, and should the value chains be organised in a certain way to maximise the reduction of harm to the environment? Do the actors have the economic incentives necessary, or should the regulatory system be changed in order to lead development in the right direction? Can countries learn from one another when it comes to organising the value chains and to improving the regulatory systems?

2 Background

2.1 Environmental challenges and the attempts to reduce them

2.1.1 Climate change

Emissions of greenhouse gases cause increased temperatures in the earth's atmosphere, which can have fatal consequences. These include the melting of the polar ice, rising sea levels and extreme weather. The increased concentration of carbon in the atmosphere is caused by human activity that interferes with the natural carbon cycle. Through the extraction of fossil resources, carbon that was intended to be stored in the seabed for up to thousands of years is introduced into the atmosphere.

According to the intergovernmental panel on climate change (IPCC), it is extremely likely that a considerable share of the observed increase in global average surface is anthropogenic (caused by human activity) (IPCC, 2014). As shown in Figure 1, carbon dioxide is the most important greenhouse gas, followed by methane and dinitrogen monoxide. The two latter are highly relevant when studying organic resources, as they can potentially be emitted during the breakdown of organic matter.

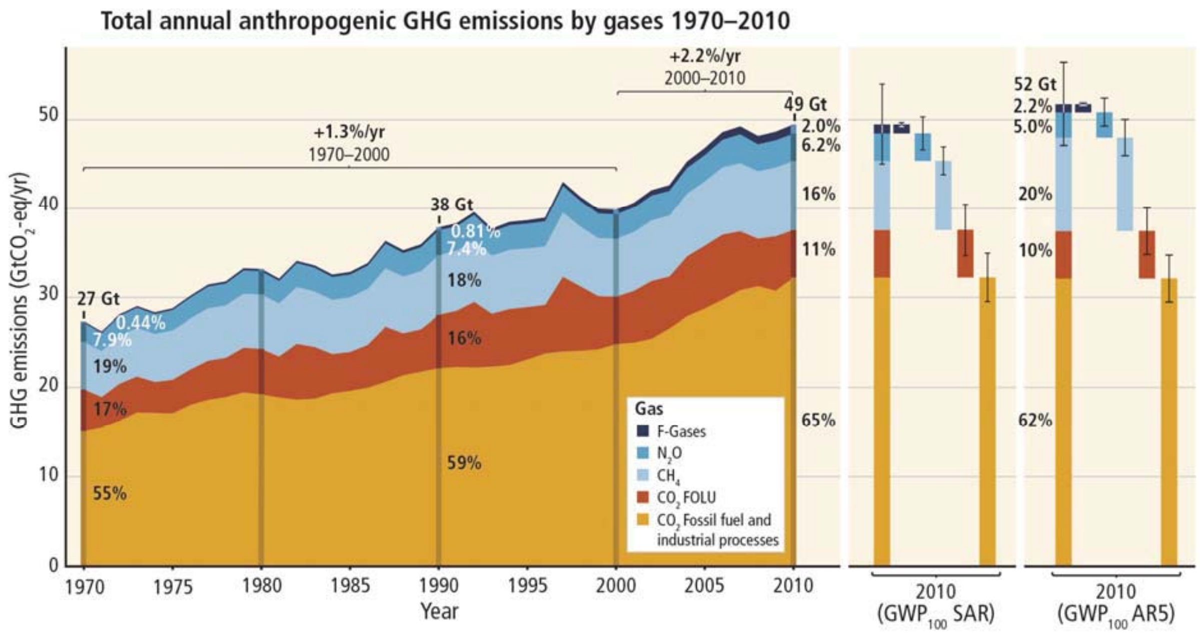

Figure 1 Total annual anthropogenic GHG emissions by gases (IPCC, 2014)

As climate change is an international challenge, collaboration is necessary between nations to reduce emissions. The first major milestone for a common battle against climate change was the Kyoto protocol, adopted in 1997, and enforced in 2005, with internationally binding emission reduction targets for each nation (UNFCCC, 2017).

In 2016, the Paris agreement was achieved. The participating countries committed to maintaining a global temperature rise in this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. The agreement requires the signatory nations to implement programmes containing measures to mitigate climate change. These include policies, incentive schemes and investment programmes which address all sectors, including energy generation and use, transport, buildings, industry, agriculture, forestry and other land use, and waste management (UNFCCC, 2017).

Although Norway is not a member of the EU, The Norwegian government has committed to EU targets of reducing the emissions of greenhouse gases by at least 40% in 2030 compared with levels in 1990.

This implies a significant reduction of greenhouse gases in all sectors (Norwegian Environment Agency, 2015).

Figure 2 shows the emissions of greenhouse gases per sector in Norway in 2015. The sectors that contribute to the largest emissions are transport, petroleum, industry and agriculture. The sectors most relevant for the biogas value chain are waste, agriculture, energy supply and transport.

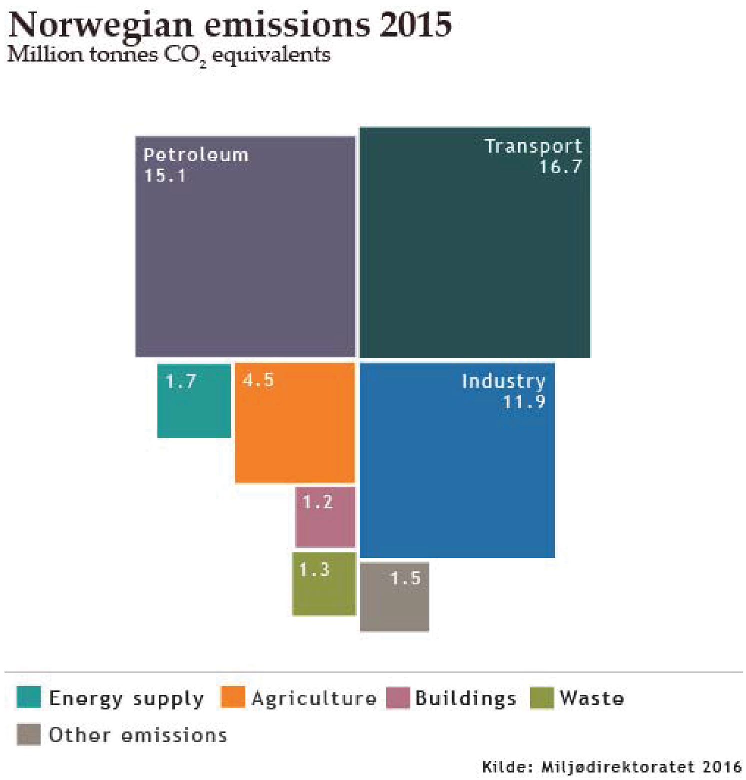

Figure 2 Greenhouse gas emissions in 2015 (Norwegian Environment Agency, 2017a)

As shown in Figure 2, transport is the sector with the highest emissions: 16.7 million tonnes CO2-equivalents in 2015 (Norwegian Environment Agency, 2017a). The emissions from transport must be reduced to almost zero by 2050 to achieve the "*well below 2 degree*" goal (Norwegian Environment Agency, 2015). While the proportion of renewables in the gross final consumption of energy in Norway was 69.2% in 2015, that of renewable fuels for transport was only 8.9 % (Eurostat, 2017).

Agriculture accounts for 8.5% of Norwegian greenhouse gas emissions. Manure management plays an important part in the emissions from agriculture, which makes up about 0.8 per cent of the Norwegian emissions of GHGs in 2005 (Norwegian Environment Agency, 2017b). According to Gundersen and Heldal (2015) the agricultural sector is responsible for 73% of the emissions of dinitrogen monoxide (N_2O) and 53% of methane (CH_4) in Norway. The Norwegian Environment Agency, (2014a) identified agriculture as the sector with the highest remaining emissions in a low emission society in 2050.

2.1.2 Acidification

Emissions of ammonia (NH_3) can contribute to increased acidification, which is one of the greatest environmental challenges in Norway, and which resulted in a reduction in biodiversity in rivers and lakes in the 1970s (Norwegian Environment Agency, 2014b). Agriculture and the management of manure from livestock plays a key role in reducing the emissions, as 92% of the ammonia emissions in Norway are from agriculture, where 89% of this is loss of ammonia to air from manure (Gundersen and Heldal, 2015).

2.1.3 Resource management

Rockström et al. (2009) defined and identified nine global boundaries with threshold values within which humanity can operate safely. They estimated that, in addition to climate change, the *nitrogen cycle* was one of three boundaries that were already exceeded. This shows that sustainable management of organic resources containing nitrogen and other nutrients is of major importance.

Waste policies and regulations in Norway and the EU are based on the principle of the waste hierarchy, describing general priorities concerning the treatment of waste: firstly prevention, then re-use, material recycling, energy recovery and lastly, disposal (European Commission, 2008). The priorities of the waste hierarchy are not always valid, which is the reason that life cycle assessment has been recommended as a more holistic approach, taking into consideration several environmental challenges as well as local conditions and geographical variations.

In 2012 Europe's bioeconomy strategy was launched and adopted in order to address the production of renewable biological resources and their conversion to vital products and bio-energy (European Commission, 2012). The bioeconomy comprises those parts of the economy that use renewable biological resources from land and sea – such as crops, forests, fish, animals and micro-organisms – to produce food, materials and energy (European Commission, 2017). A Norwegian bioeconomy strategy was published in 2017, where one of the measures proposed was to stimulate increased use of life cycle assessment within relevant areas (Norwegian Government, 2017).

The focus on waste as being a potential resource instead of a problem that needs to be handled, was reinforced in December 2015, when the EU adopted a Circular economy package to stimulate a transition to a more circular economy. The aim is to contribute to "closing the loop" of product- and material life cycles through increased re-use and recycling. The package introduced a common EU target for recycling 65% of municipal waste by 2030 (European Commission, 2015). Consequently, incineration of organic waste must be reduced, increasing interest in using anaerobic digestion as a waste treatment method.

2.2 Biogas value chains

2.2.1 What is biogas?

Biogas is produced from organic material through *anaerobic digestion* (AD) which is a process whereby microorganisms break down biodegradable materials in the absence of oxygen. *Raw biogas* consists of about 60% methane (CH_4). The rest is mainly carbon dioxide (CO_2), but the gas may also contain small amounts of hydrogen sulfide (H_2S), moisture and siloxanes. Raw biogas can be used to produce heat or electricity. If the gas is sent through an upgrading process, which removes the other gases to obtain a methane share of over 97%, this gas is known as *biomethane*. Biomethane has the same properties as natural gas and can be fed into a natural gas grid or used as a fuel for transport in gas vehicles.

The organic material, such as food waste and manure, that is fed into the digester is referred to as *substrate*. Mixing several substrates (*co-digestion*) may have an advantage, as the properties of the different substrates can complement one another. AD plants can be found in different sizes, from large industrial scale to small scale farm plants.

In the anaerobic digestion process, *digestate* is formed in addition to biogas. Digestate is an organic material (slurry) consisting of a number of valuable nutrients such as nitrogen, potassium and phosphorous. It can be applied to soils directly in a liquid state to be used as a *biofertiliser*, or it can be separated into a dry and a liquid fraction through a dewatering process. The dry fraction can be composted and used as a soil improvement product. The wet fraction is normally rich in nitrogen and is most commonly sent to a waste water treatment plant.

2.2.2 Biogas in the EU

In 2015, biogas production in the European Union (EU) corresponded to 174 TWh, which is 7.6% of all primary renewable energy production. Germany is by far the largest producer of biogas, representing about 50% of the total production, followed by Italy and the United Kingdom. 9% of the biogas in the EU is produced from sewage sludge, 18% from landfills (landfill gas) and 72% of the biogas was produced from other substrates (organic waste from agriculture, households and industry) (Kampman et al., 2016). The development of biogas plants has recently slowed down in Germany and Italy, as a result of changes in support schemes, while the United Kingdom has almost doubled the number of agricultural and waste based plants in recent years (Torrijos, 2016).

Most of the biogas produced in Europe is used for electricity production (62%) followed by heat (27%). Biomethane used as a fuel for transport constitutes about 11% of the generated energy from biogas. The countries with the highest use of biomethane as a fuel are Germany, Sweden and the Netherlands (Kampman et al., 2016). According to EurObserv'ER (2014) the production of biomethane is increasing in the EU, primarily because it enables countries to reduce their reliance on natural gas imports.

In some countries biogas represents a significant share of the total production of renewable energy in agriculture (Luxembourg, Germany, Slovenia, Denmark, Netherlands, Austria and Czech Republic) (Eurostat, 2013).

2.2.3 Biogas in Norway

In Norway, biogas production has emerged primarily as a waste treatment method for sewage sludge and organic waste from households and industry. Raadal et al. (2008) estimated the national theoretical biogas potential to be 6 TWh. The realistic biogas potential in Norway in 2020 has been estimated to be 2,3 TWh (Norwegian Environment Agency, 2013).

In 2008 the national production of biogas was 180 GWh, where 19% was flared, 53% was used for heat purposes and only 2% of the gas was used for transport purposes (Raadal et al., 2008). Nedland and Ohr (2010) did a survey on behalf of the trade association Waste Management Norway, that showed that about 63% of the energy produced by biogas plants was used to cover internal heat demand in 2010. A significant share of biogas was flared and on average only about two thirds of the capacity of the biogas plants was exploited. This poor utilisation can be explained by low energy prices as well as few incentives to produce green electricity because of a large share of hydropower in the electricity mix. Electricity is the primary energy carrier for heat in Norwegian households and industry (Statistics Norway, 2016, 2015). Although Norway is a major producer of natural gas, the domestic use is very small, and the gas pipe infrastructure is limited.

Previously there have been no official statistics regarding the development of biogas in Norway. In 2015, however, information on the production and use of biogas was collected from biogas plants as part of the national energy balance. In the national energy balance for 2015, Statistics Norway (2016) reports that the total consumption of biogas constituted nearly 3% of national bioenergy use, and that the amount of biogas used was 361 GWh. According to Waste Management Norway, however, the estimated production capacity of biogas will be close to 600 GWh by 2018 (Måge, 2015). This was confirmed by the compilation of data from various sources on the production of biogas (Enova, 2014; Lånke et al., 2016; Norwegian Environment Agency, 2013).

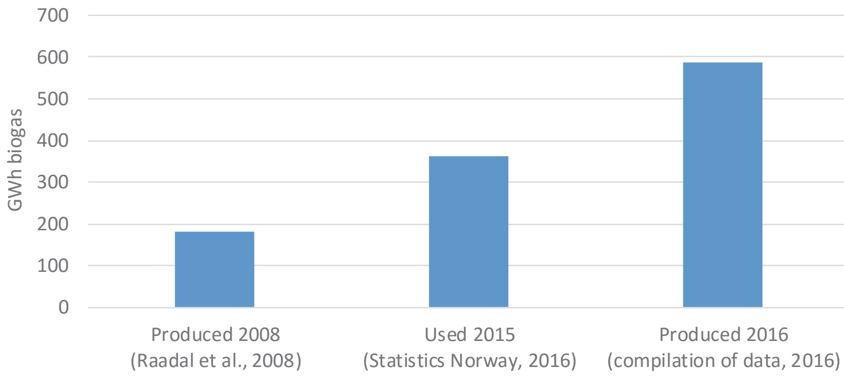

Figure 3 Data on biogas produced and used in Norway in 2008 and 2016

Figure 3 shows that there are significant deviations between the biogas used in 2015 and the biogas produced in 2016. Several large-scale plants have recently been built and were in a start-up phase during this period. Many plants run at reduced capacity and have a higher level of flaring during the first years. It is most likely that the deviation shows that there is still a large amount of flaring and that the capacity is not fully utilised in many plants.

In Figure 4 the compilation of data from several sources was combined with Google searches for the building year of each plant and the year of investment in upgrading facilities for some of the plants. There are substantial limitations regarding the accuracy of the background data of the graph, as there may be variations in production from year to year and because many of the plants did not run at full capacity during the first year(s). It does, however, illustrate that there has been a sizeable increase in the capacity for biogas production and that the number of plants upgrading from biogas to biomethane has recently expanded rapidly.

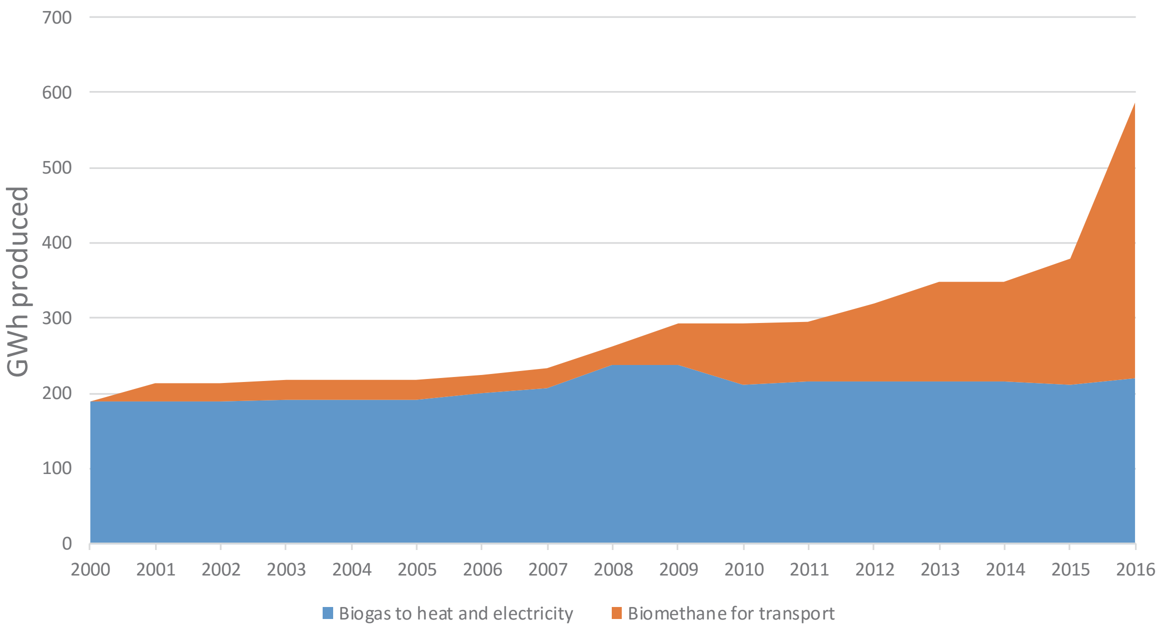

Figure 4 A rough estimation of biogas production in Norway from 2000 to 2016

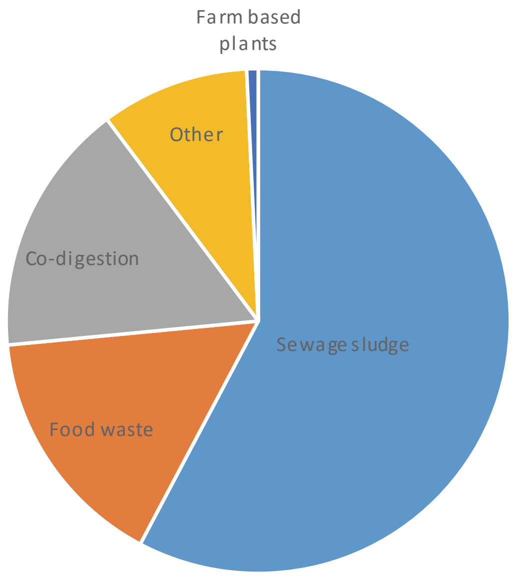

Figure 5 Type of biogas plants based on substrates used per GWh biogas produced

In Figure 5, the biogas plants were classified into type of input, based on the compilation of data from several sources. This shows that most of the biogas plants in Norway treat sewage sludge and food waste. The co-digestion plants treat either a combination of food waste and sewage sludge or a combination of food waste and manure.

Access to substrate is important for the biogas plants. According to the national waste statistics, about 48% of the organic waste from all sources went to biogas production in 2015 (Statistics Norway, 2017a). About 94,000 tonnes was sent from households to biogas production in 2015 (Statistics Norway, 2017b) and approximately 68% of households have source separation of organic waste (Raadal et al., 2016). In recent years some organic waste has been exported to Danish and Swedish biogas plants because of competitive prices relating to the treatment of organic waste. According to Mepex (2012) this export comprised about 70,000 tonnes in 2010.

Although Raadal et al. (2008) estimated manure to comprise 42% of the total theoretical national biogas potential, only about 1% is currently exploited. There are at present seven biogas plants that treat manure: one large scale industrial plant and six small scale farm plants (Pettersen et al., 2017). By contrast, Sweden has 31 farm scale biogas plants (Ahlberg-Eliasson et al., 2017).

Because of the large proportion of biogas plants treating sewage sludge, most of the digestate is dewatered and sent to composting. This is due to legal restrictions on the use of digestate as a fertiliser when the heavy metal content exceeds a certain limit (FOR-2003-07-04-951, 2003). A few food waste plants supply liquid digestate as biofertiliser to agriculture.

3 Thesis statement and research questions

3.1 Objective of this thesis

The objective of the research has been to contribute to enhancing the understanding regarding ways of optimising Norwegian biogas value chains to reduce environmental impacts. This was done by developing models that can provide decision support and can contribute to improving the regulatory systems and the preconditions for further development of the biogas industry in Norway.

3.2 Thesis statement

The thesis statement in this PhD project was defined as follows:

Increased and optimised biogas production will reduce environmental impacts,

but specific policy instruments are necessary

to motivate the actors to choose the environmentally preferred solutions.

3.3 Research questions

Based on the research statement, four research questions were expressed:

RQ1: *What are the most significant environmental impacts from Norwegian biogas value chains?*

RQ2: *What are the economic drivers and barriers in design of biogas value chain designs, and how do they influence environmental impacts?*

RQ3: *How can policies and regulatory measures influence the decisions of the actors, and how does this in turn affect the environmental impacts?*

RQ4: *Under which conditions should livestock manure be used for biogas production in Norway, when should farmers invest in farm scale biogas plants and when should manure go to centralised biogas production?*

Four scientific papers have been developed as part of the PhD thesis.

Paper 1: The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains.

Paper 2: Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains. A case study on different levels of sector integration.

Paper 3: The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark.

Paper 4: Optimising anaerobic digestion of manure resources on a regional level.

In addition, a small survey among actors in the biogas value chain in Norway was carried out.

3.4 Scope and limitations

The assessments in this PhD project are made in a Norwegian context. This has had implications for the data collected, the design and structure of the scenarios and, in turn, the results and conclusions. Other countries have different organic resources available with different geographical distribution, other markets for energy and transport fuels, other markets for digestate, different price levels for products and services, different laws, political targets and incentives. While one of the strengths of the methods used in this study (system engineering, life cycle assessment and economic assessment) is its specificity, it is also a limitation because it cannot automatically be generalised. The models developed in this project may, however, be adapted to fit conditions in other countries. The approaches developed of combining an environmental and economic assessment of the actors in order to evaluate the effect of political measures, can give input to other studies with similar objectives. Even though there are major differences in biogas value chains, some of the results will be valid in other countries because some of the challenges are likely to be universal.

In the case studies, the substrates included are limited to organic waste from households (food waste) and manure from cattle and pig. Other substrates may lead to different conclusions, while some of the results will be relevant for other substrates.

In some countries energy crops are used for biogas production. As energy crops can occupy land that could have been used for food production, this poses some ethical issues. As this thesis is limited to waste resources, these issues are avoided and will not be discussed further.

There are many different environmental challenges that could potentially have been addressed in more detail. In this thesis, the main emphasis has been on global warming as well as the resource management perspective. Other environmental impacts have, however, been included when possible or discussed qualitatively.

This work only covers two of the three pillars of sustainability (environment, economy and society), as the social aspects have not been assessed separately. Indirectly, however, the assessments touch upon the social dimension, as human welfare is dependent on the economy and the environment.

The work on this PhD thesis has involved a large number of academic disciplines such as environmental science (which includes chemistry, biology, engineering) economics and political science. The cross-disciplinary nature of this project can be regarded both as a strength and a weakness. Maintaining the wider perspective and at the same time attempting to make detailed assessments within several disciplines (environment, economy and policies) is demanding. To resolve the climate crisis, however, cross-disciplinarity is likely to be a necessity. Although this thesis makes only a small contribution, it demonstrates that a holistic approach is both useful and possible.

4 Theory and methodology

4.1 Systems theory and model development

The work carried out on this thesis is based on the approaches of systems theory and system engineering. System engineering is an interdisciplinary research field with the intention of enabling the realisation of successful systems (Haskins, 2006). It is a holistic approach where one strives to include the entire life cycle of the system through a system analysis. System analysis is the method of breaking a system into its component parts for the purpose of studying how well they work and interact in accomplishing their purpose (Bentley, 2007). System thinking involves the development of knowledge regarding the way in which a system relates to other systems, how systems behave and how they should be managed (Haskins, 2006).

The *system* in this case is the combined product system of biogas and digestate, which includes all the related activities, substrates, materials and energy flows required to produce and use the products. The biogas value chain is defined as the chain of activities performed on the organic resources to increase value and to utilise the resource.

The system has been described through the development of *models*. The models are simplifications of the reality, where system boundaries are drawn between the system under study and surrounding systems. Modelling requires quantification of the relevant flows (such as energy, material and money) between different parts of the value chain and between the system and the surrounding systems. In systems engineering complexity may represent a major issue (Haskins, 2006). A very complex model is likely to give a more accurate representation of the reality, but requires a sizeable set of data and assumptions and is time consuming to develop. Development of simpler models is less challenging, but involves greater uncertainties. The challenge is to find a good balance.

Once the models were developed, different value chain alternatives were assessed in *case studies* by changing parameter values in the models to fit defined scenarios.

In order to be able to address the research questions, three different domains were explored:

- Environmental impact of biogas value chains
- Economic incentives and barriers (economy of the actors in the value chain)
- Policies (including political instruments and general framework conditions)

In the following section, the connection between the three domains and the methodology used to assess the biogas value chains within each of the domains will be described.

4.2 Assessing environmental impacts, economic sustainability and political measures in parallel

To assess environmental impacts, economic incentives and political instruments in parallel, it was necessary develop an understanding of the dynamics between the three domains. Figure 5 shows how the biogas value chain affects the environment, and how the biogas value chain is affected by policies and the economy of the actors.

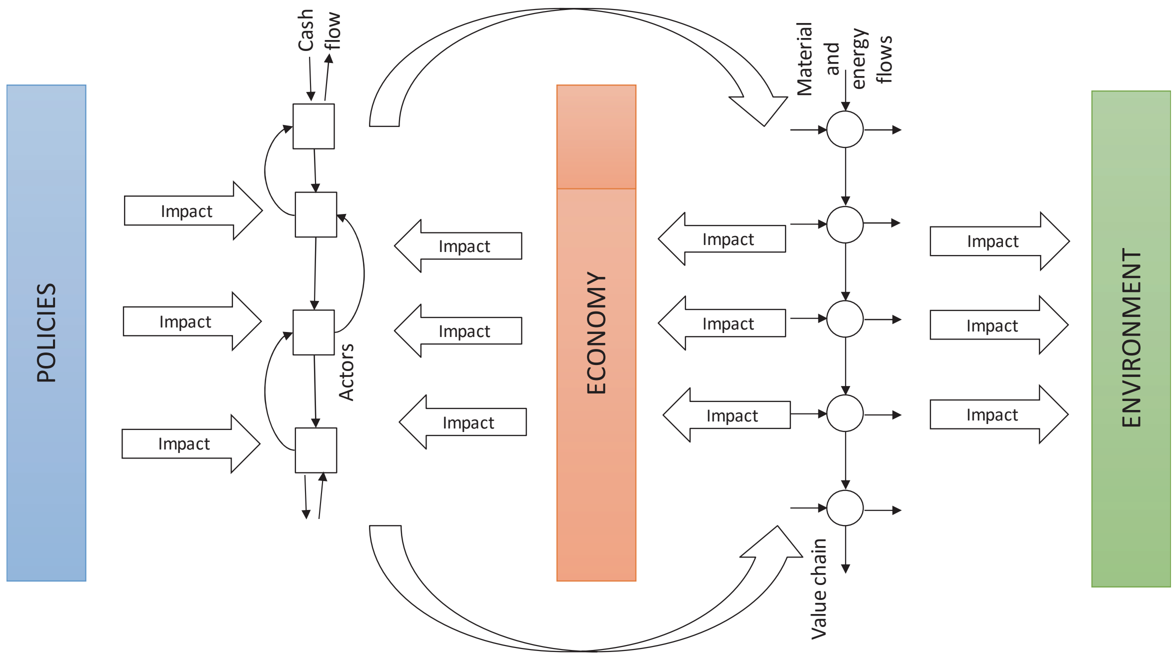

Figure 6 Illustration of connection between the environmental impact, the economic barriers and incentives and the environmental policies

The *environmental impacts* are affected by the *material and energy flow* of the organic resources, including the energy use, treatment processes and activities performed on the material, in addition to emissions to air, water and soil.

The *actors* in the value chain affect how the value chain is designed, and thus impact where the energy and material flows go and how they are treated. The actors are defined as the humans or the institutions involved in the activities and processes in the value chain. The physical flows (input of material and energy, and output of products) affect *the economy* of the actors, as the income and costs are related to the quantities of product and services purchased from and sold to the market.

The *policies* have a direct impact on the economy of the actors through economic instruments. In addition, policies can indirectly affect decision making by the actors through, for example, instruments that affect the markets of the products or through the imposition of regulatory and administrative restrictions.

4.3 Life cycle assessment methodology for biogas value chains

In order to assess the environmental impacts of biogas value chains, life cycle assessment (LCA) methodology was applied. LCA is a commonly used methodology in quantifying the environmental impacts of a product or a service throughout the entire value chain, from material use and production, to transport, production processes, use and end of life of the product. The methodology is based on the ISO 14044 standard (ISO, 2006) and the European commission has developed a guideline for performing LCA (European Commission JRC, 2010). The principal steps in an LCA project are shown in Figure 7. The assessments start with goal and scope definition. An inventory analysis is then performed on the system defined in the previous steps, where all relevant flows of material and energy are systemised. The inventory data is then converted into environmental impacts in the impact assessment step. Finally, the results are interpreted and conclusions are drawn. The steps of an LCA are iterative, meaning that although the steps are normally performed in the described order, it is common to go back to previous steps and carry out modifications and improvements throughout the whole process.

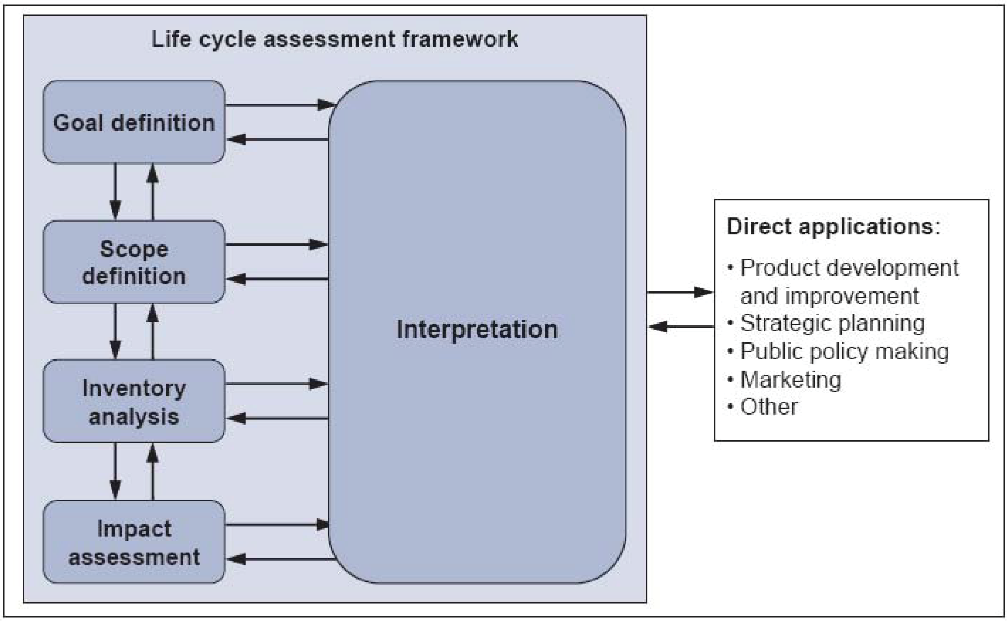

Figure 7 Framework for life cycle assessment (European Commission JRC, 2010, modified from ISO 14040:2006)

According to Ekvall et al. (2007) one of the strengths of using LCA to evaluate waste management systems is that it helps in expanding the perspective beyond the waste treatment itself, by including the most important surrounding systems in the assessment. Performing LCA of a waste management system involves a different approach when defining the system boundaries, compared with that taken in LCA of a conventional product system. While conventional product-oriented systems often start with the extraction of raw material, waste systems use waste resources as their raw material. Whereas the purpose of LCA of a conventional product (such as an apple) is to quantify the environmental impacts relating to the function of the product (e.g. to feed a person), the purpose of LCA of a waste management system is typically to determine which treatment option and utilisation of the resource is the best for a certain amount of waste with a certain composition. The raw material extraction in a waste system can be considered as the collection of the waste, as shown in Figure 8. The production and use of the material before it became waste is therefore not included as a part of the system because the stakeholders dealing with the waste management do not have an impact on what happens before the material becomes waste. This is defined as the *Zero burden* approach (Gentil et al., 2010).

The European Commission has published a specific guideline for LCA of waste management systems (European Commission JRC, 2011). Laurent et al. (2014a) summarised the *lessons learned and perspectives* from a review on LCA studies on solid waste management systems and presented a *methodological guideline for a better practice* (Laurent et al., 2014b).

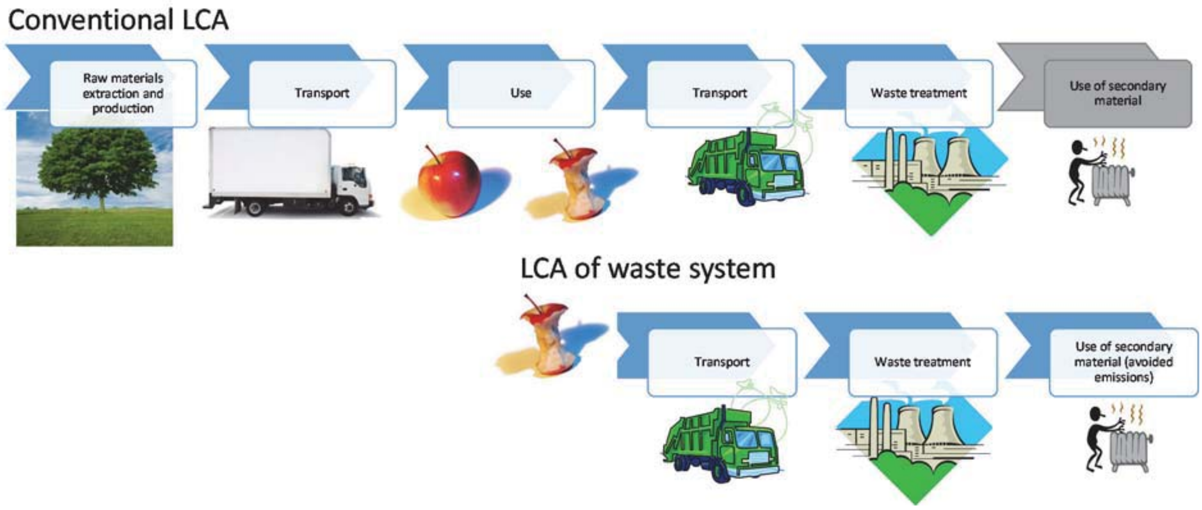

Figure 8 System boundaries of life cycle assessment of an apple and the waste treatment service of an apple (Lyng, 2014)

In order to be able to assess the environmental impacts of different value chain designs, the BioValueChain-model was developed. This is an LCA model specifically designed for biogas value chains. The model was built in the LCA software tool SimaPro (PRé, 2017) by defining a set of parameters with basis values that can be changed to specific values when performing case studies. Examples of parameters are biogas yield, transport distances, energy use and energy carriers during anaerobic digestion, methane loss and substitution of alternative energy carriers by biogas and fertiliser or soil improvement products by digestate. The methodology and data are described in Paper 1 and appendices. The model was continuously updated and improved throughout the project. Updates in background data and the preconditions for the models are described by Modahl et al. (2016).

A few papers describing similar LCA models for waste management were found in the literature. Winkler and Bilitewski (2007) compared six different LCA models for evaluation of solid waste management by applying the models to specific cases. The comparison showed high variation and contradictory conclusions. They concluded that each model has advantages and disadvantages, and that the choice of model should be based on the goal and scope of the study. According to Gentil et al. (2010) most waste management models tend to be developed to fit the conditions in their respective countries, and are thus most suitable to be applied in the country where they have been developed. The Swedish ORWARE model (Dalemo, 1999; Eriksson et al., 2002) and the Danish EaseWaste model (Kirkeby et al., 2006), which has been further developed and renamed EaseTech (Clavreul et al., 2014) both contain separate modules for the biological treatment of organic waste (Boldrin et al., 2011; Dalemo et al., 1997; Sonesson et al., 1997). There were no examples found in the literature of LCA models used to assess farm scale biogas production or co-digestion of food waste and manure from cattle and pig.

4.3.1 Purpose of the study and type of decision

The purpose of the environmental assessment in this thesis is to evaluate the environmental impact of current biogas value chains, as well as to look at the development of new and existing biogas value chains so as to achieve existing political objectives.

In the *General guide for LCA*, the European Commission JRC (2010) defines three different categories of LCAs, each relating to the type of decision into which the LCA study will give input (see Figure 9). The type of decision will have an impact on the system boundaries and the use of data, which will in turn affect the result of the study.

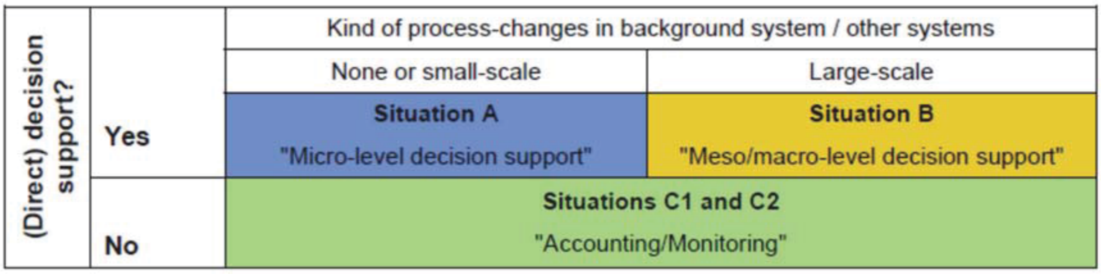

Figure 9 Different type of goals for LCA (European Commission JRC 2010)

LCA of waste management systems is handled in a separate guideline, where the three decision support situations have been described in more detail (European Commission JRC 2011):

- **Situation A, micro-level decision support**: *Refers to decisions supporting direct changes (optimisation) in the waste management system at a local, regional or plant-specific level.* This includes selection of a treatment route from among several alternatives for a specific waste stream, selection of a specific waste stream for treating or optimising existing treatment routes. The decision resulting from this type of LCA will only have small-scale consequences for the systems (no large additional demand for recycling facilities or change in the national market price for secondary materials).
- **Situation B, meso/macro-level decision support**: *Typically involves decision support for strategies with large-scale consequences on the background system or other systems.* In this case, the effects of the target decision are significant enough to cause structural changes to the installed capacity of at least one process outside the foreground system. Examples of this would be large scale policy development and policy information.
- **Situation C, accounting/monitoring**: *Typically concerns decision-perspective/retrospective accounting/documentation of what has happened (or will happen based on extrapolation forecasting) without accounting for any consequences that the target system may have on the background system or other systems.* Examples would be annual accounting of national waste management sector environmental impacts and environmental reporting.

A distinction is often made between attributional and consequential LCA. While attributional LCA is based on an accounting principle, where one attempts to model the system as it is, consequential modelling strives to include the impact that the system under study has on the background system and/or other systems (European Commission JRC, 2011).

European Commission JRC (2011) describes *attributional* life cycle inventory modelling as "accounting", "book-keeping", "retrospective", or "descriptive". This includes the use of historical, fact-based, measurable data, and includes all the processes that are identified as relevantly contributing to the system being studied.

Consequential life cycle inventory modelling is sometimes also known as "change-oriented," "effect-oriented," "decision-based" or "market-based". The aim is not to reflect the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain, taking into account market-mechanisms, and potentially including political interactions and consumer behaviour changes (European Commission JRC, 2011).

European Commission JRC (2010) recommends attributional modelling to situation A and C, while situation B requires a consequential approach. Ekvall et al. (2016), however, argue that the *General guide for LCA* is internally inconsistent when making recommendations about ways of choosing between attributional and consequential modelling, and concludes that a consequential approach should be employed for situation A and B with the ILCD handbook's current definition. The BioValue

Chain model presented in Paper 1 has primarily been employed to assess situation A and C decision types.

4.3.2 Functional unit and system expansion

An important aspect of the LCA methodology is that it deals with the comparison of product systems, and not of the products as such (Klöppfer and Grahl, 2014). This means that the environmental impacts of a product or a service are quantified in relation to the function that the product or service provides to the user. This enables the comparison of completely different products that provide the same service. An example would be a comparison of transport systems (1 person kilometre) instead of simply making comparisons within the product providing the service (1 bus). The former makes it possible to compare bus and train travel providing the same function. The quantified performance of a product system is referred to as the functional unit (ISO, 2006).

A biogas value chain can provide several functions:

- Treatment of food waste and manure
- Generation of heat, electricity and/or upgraded gas for natural gas grid or as a fuel for transport
- Production of biofertiliser or soil improvement product.

As described in chapter 2.2.3, anaerobic digestion has in Norway traditionally been regarded as a technology for the treatment of sewage sludge and organic waste from household and industry. Unlike some other countries (such as Denmark and Germany) the principal driver for treating manure through anaerobic digestion is not primarily to produce renewable energy or biofertiliser, all though these are valuable products. The national political objective of increasing the amount of manure for biogas production indicates that the primary objective is to treat manure through anaerobic digestion, and as a consequence, reduce the environmental impacts.

Based on this, the *primary function* of the biogas value chain is assumed to be the treatment of a specific amount of waste and manure. This is common practice in waste management LCAs and LCA models for waste (Laurent et al., 2014, European Commission JRC, 2011, Gentil et al., 2010). Biogas and digestate can thus be regarded as *secondary products* or *extra functions* generated by the waste treatment service, and their environmental impacts can be included by utilising system expansion.

System expansion involves expansion of the system boundaries and the functional unit to include the additional functions offered by the secondary products. This is achieved by including the avoided emissions of the products or services substituted on the market by the biogas or digestate. System expansion is a common approach applied in about 75% of the waste management LCA studies reviewed by Laurent et al. (2014a). The disadvantage of applying system expansion is that it requires a prediction as to what will happen as a consequence of providing a product within a market (Heijungs and Guinée, 2007). The advantage of applying system expansion is that one avoids allocating the environmental impacts between co-products. According to the general standard of LCA one should endeavour to avoid allocation between co-products where possible (ISO, 2006).

The functional unit in the model was thus defined as: *Treatment of a specific amount of dry matter (tonnes of DM per year) of organic substrates of a given mix (of organic waste and/or manure) in a specific region, including avoided emissions caused by the generated products when substituting materials and energy carriers*.

The identification of substituted products when applying system expansion is dependent on the location and time perspective, and reliant on the purpose of the study. The assumption must be made for every case study, and sensitivity assessments to assess the robustness of conclusions are important. Table 1 shows the two secondary products: biogas and digestate, their current applications and examples of products on the market that the secondary products can be assumed to substitute.

Table 1 Applications of the secondary products from treatment of organic resources in the LCA model

Treatment	Secondary product	Application	Substituted products
Anaerobic digestion	Biogas	Heat	District heating mix Heat from oil Heat from wood pellets
		Electricity	Electricity
		Fuel for transport (if upgraded)	Diesel
		Gas grid (if upgraded)	Natural gas
	Digestate	Biofertiliser	Mineral fertiliser
		Soil improvement/ compost	Peat

If a biogas plant with an upgrading facility is built, and the biogas plant supplies the biomethane to the transport sector, and vehicles running on diesel are replaced by gas vehicles running on biomethane, one can make a valid assumption that the biomethane substitutes diesel. If liquid digestate is supplied to a farm as biofertiliser and this results in the farmer buying less mineral fertiliser, the digestate will substitute mineral fertiliser.

While the situations described above are easy to relate to and are more or less straightforward, other assumptions will be dependent on the methodology applied (attributional or consequential) and are continuously being debated in the LCA community. Substitution of heat and electricity are examples of those.

The *General guide for life cycle assessment* recommends the use of the average market mix in situations A and C (European Commission JRC, 2010). In situation C it is recommended using the expected mix of the long-term marginal processes, as long as the process is identified as being affected *by "big" large-scale changes as a consequence of the analysed decision*. (Laurent et al., 2014b) found that an approximately equal number of studies use national grid mix and marginal energy supply when crediting electricity or heat sold.

The advantage of the BioValueChain and other such models, is that scenario assessment and varying assumptions can be tested in order to evaluate the robustness of the results, including testing the results for different energy carriers (market mix or marginal technologies).

4.3.3 System boundaries and life cycle phases

In the BioValueChain model, presented in Paper 1 of this thesis, the biogas value chain was divided into life cycle phases, as shown in Figure 10. The life cycle phases include storage of manure on the farm, collection of food waste, transport, pre-treatment of food waste (where unwanted objects are removed), the anaerobic digestion process, upgrading of biogas (if relevant), substitution of a relevant product, and further treatment and use of the biogas and digestate.

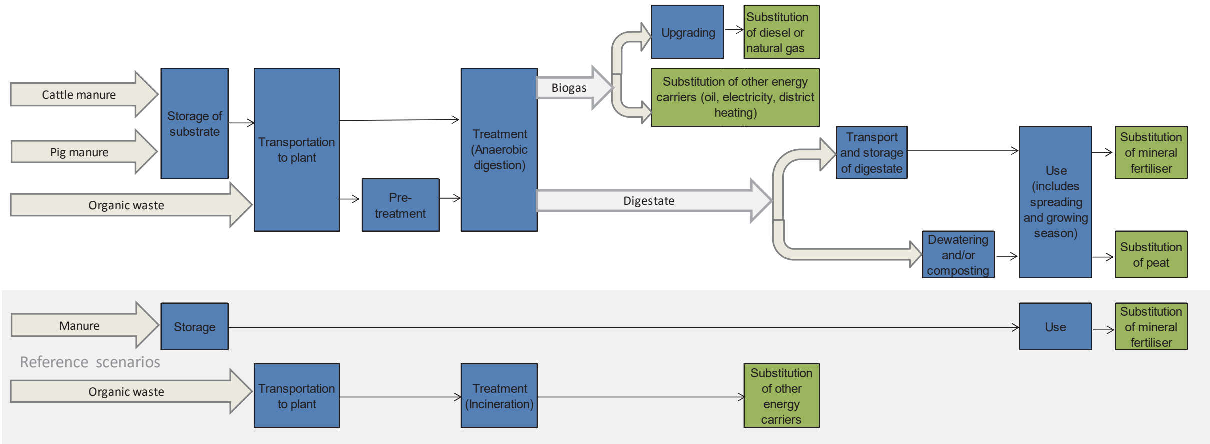

Figure 10 The life cycle phases defined in the LCA model (Paper 1)

Parameter values for the energy use, waste and emissions for each of the life cycle phases were defined and given basis values. The basis values were intended to reflect Norwegian conditions and typical/average Norwegian conditions for biogas value chains, as described in Paper 1. In the case studies performed in Paper 2 and 4, the parameter values were changed to fit the defined scenarios and the purpose of the study.

As shown in Figure 10, reference scenarios were defined: incineration together with residual waste for organic waste from households, and direct use of manure as fertiliser for untreated manure on farms.

4.3.4 Environmental impact assessment

The model will enable the assessment of any environmental indicator, as long as the relevant emissions are included in the inventory. The environmental indicator categories included in Paper 1 were: global warming potential (GWP), potential abiotic depletion of fossil fuels and acidification potential.

Papers 2 and 3 only included assessment of the potential effect on global warming. The impact assessment methods used when assessing global warming were IPCC (2013) characterisation factors as implemented in SimaPro 8, with corrections suggested by Muñoz and Schmidt (2016). The factor for biogenic CO_2 was defined as 0. This is because the organic substrates analysed do not contribute to an increase in the concentration of carbon in the atmosphere. The emitted carbon was “recently” removed from the atmosphere through biological processes and is likely to be released to the atmosphere within a short time independent of the treatment method. The factor for biogenic methane was defined as 2.75 kg CO_2 lower per kg methane when compared with fossil methane. For the other environmental indicators the CML-IA-method v.3.01 was applied (Leiden University, 2013).

4.4 Economy of biogas value chains

In order to evaluate the economic drivers and barriers relating to biogas value chains and to analyse how political and economic instruments influence the economy of the actors, the annual economic results were assessed for central actors in the value chain.

According to economic theory, the actors in the value chain are profit maximisers. This implies that the actors are more likely to choose alternatives that generate high profit over those that generate less profit. It is further assumed that it is unlikely that an actor will choose an option if, in the long term, the costs exceed the income. There is, however, reason to believe that other factors than economic short-term profit will have importance for the actors in this type of value chain. This was shown by Karlsson et al. (2017) who evaluated the success factors in agricultural biogas production in Sweden, and found that the actors accepted that as long as the biogas production and distribution broke even, lower financial returns were tolerated. Their business strategy accepted the likelihood of short term economic losses and accepted a balance between economy, environmental and social benefit. The annual economic profit gives, nevertheless a good indication on how likely it is for the actor to choose one option over another and provides a reliable pointer as to economic drivers and barriers. For this reason, the economic assessments included private but not social costs and income.

Biogas production (anaerobic digestion) has earlier been identified as an expensive greenhouse gas mitigation measure and a technology with low or no profit for the actors (Norwegian Environment Agency, 2015). The Norwegian Environment Agency (2013) calculated the private economic profit to be around zero (0.0002 Euro/kWh or 0.002 NOK/kWh) for food waste to biogas production, and negative profit (net costs) of 0.14 Euro/kWh (1.27 NOK/kWh) for manure to biogas production.

Møller and Martinsen (2013) found that in Denmark, biogas production generally was financially profitable for the agricultural sector and local CHP facilities, but unprofitable for the biogas plants and the state. Yngvesson and Tamm (2017) addressed the challenge of achieving profitability in Swedish biogas value chains. This was done by benchmarking the costs of 12 biogas plants treating organic waste from households and industry in Norway and Sweden. The production chain was divided into functions, which showed that pre-treatment and the treatment of reject contributed to 40% of the costs, while 37% of the costs were from hygienisation, digestion and further treatment of the digestate. The remaining costs were those relating to upgrading of the gas (20%) and odour reduction (3%).

Jansson (2014) found that several Swedish farm scale biogas plants were not economically profitable. This was due to low biogas production and difficulties in finding a profitable application for the biogas, principally as a result of low energy prices. The size of the plant was shown to have a positive impact on the investment costs and labour costs per produced amount of biogas, but Jansson did not find evidence that larger farm scale plants were more profitable than those on a smaller scale.

The existing literature shows a need for enhanced understanding regarding means of developing profitable biogas value chains, identifying the economic barriers and, most importantly, how these barriers can be overcome.

4.4.1 Assessing costs in combination with environmental life cycle assessment

When assessing environmental and economic factors in parallel, one should be aware of the methodological differences between LCA and economic analyses. While LCA does not consider a specific time perspective (when the environmental impact occurs), this is an essential aspect in economic investment analyses. Figure 11 shows that actors in the value chain are responsible for different parts of the life cycle. LCA studies do not usually consider which actor contributes what, while in cost assessment this is normally an important element of the study (Norris, 2001).

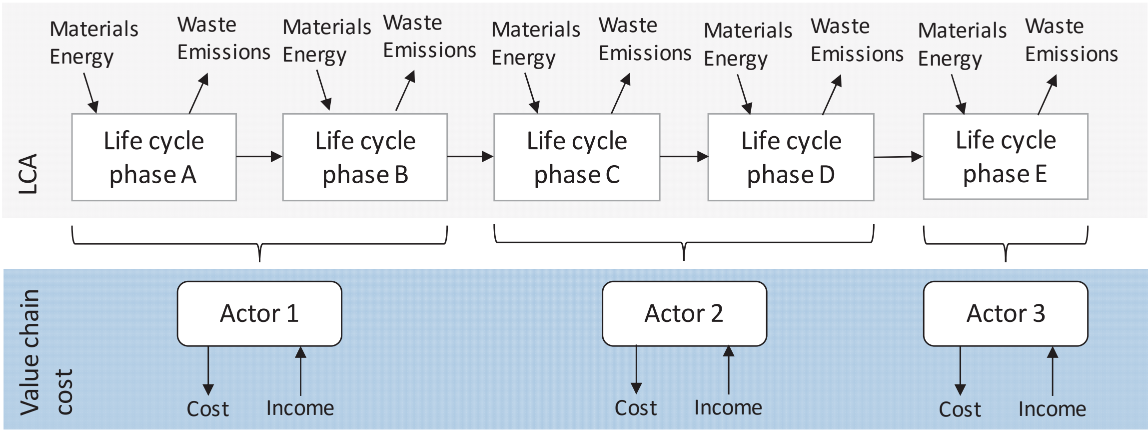

Figure 11 Illustration of connections between life cycle phases and actors

Life cycle costing (LCC) is considered to be an appropriate approach to combine with LCA, as there are similarities in the methodology. LCC and LCA can supplement each other and give valuable background information for decision makers (Reich, 2005). While LCA is an internationally standardised methodology independent of sectors (ISO, 2006), this is not the case for LCC methodology. There exist, however, sector oriented standards for LCC, for example ISO 15686-5 for buildings and constructions (ISO, 2017) and ISO 15663 for petroleum and natural gas industries (ISO, 2000). There are also several guidelines for performing environmental LCCs (Heijungs et al., 2012, Swarr et al., 2011, Hunkeler et al., 2008). These standards and guidelines, however, chiefly consider product-oriented life cycle studies and do not include specific guidelines for waste treatment processes. There are, nonetheless, a number of studies found in the literature that combine LCA and assessment of costs for anaerobic digestion and waste management systems.

Reich (2005)presented an assessment of a municipal waste management system that combined LCA and Life cycle costing (LCC). LCC was defined as an assessment of all the costs incurred by the waste management system, as if the LCA system was a single economic actor. All costs (such as investment costs, operative costs, decommissioning costs and sales revenues as negative costs) were discounted to present value and then summarised.

Similarly, Martinez-Sanchez et al. (2015) presented a life cycle costing methodology based on a bottom-up calculation approach. This study distinguished between conventional, environmental and social LCC, and it compared incineration with biogas production from organic household waste. According to Martinez-Sanchez et al. (2015) the economic assessment of waste management systems and technologies involves three context-specific challenges: 1) which type of costs should be assessed (private or social) 2) for whom should these costs be assessed and 3) which cost calculation principles should be applied.

Franchetti (2013) compared four different configurations of the anaerobic digestion of organic waste with combustion (incl. energy recovery). The comparison considered economy, energy and emissions, using LCA to assess environmental impacts. It also looked at the internal rate of return (IRR) and payback time in order to assess which technology would be the most favourable investment in the specific case. The results were related to an annual amount of food waste in North West Ohio, USA. Uusitalo et al. (2013) compared different ways of using the biogas produced at a Finnish plant, applying LCA and cost estimations from the natural gas grid owners' perspective. The aim was to investigate ways in which biogas should be used in order to gain the highest reduction in greenhouse gas emissions with the lowest costs. The results showed that from an economic perspective it would be most profitable to use biogas as transportation fuel in gas-operated cars. The greatest reduction of GHG emissions was obtained if biogas was used as transportation fuel or as an electricity source for electric cars.

Certain parts of the LCC methodology are defined differently in the literature. For example, while some claim that all parts of the value chain must be included in an LCC, others argue that it is sufficient to include the economy of one actor in the value chain. The rationale is that if the price of the materials and energy put into the product is included, then all upstream costs are included, and if income from sales of the end product is included, then the downstream costs are included. Some LCCs only include costs, while some define income as negative costs, and includes both costs and income. According to Martinez-Sanchez et al. (2015), the system boundaries of an LCC should be depend on the study in question and should correspond closely with those of the LCA.

While there are various studies in the literature combining cost assessment and LCA for biogas value chains, there is a need for economic assessments relating to Norwegian conditions. This need arises out of the significant differences in biogas value chains between countries and differences in cost levels.

4.4.2 Economy of the actors in the biogas value chain

The approach taken in assessing the economic barriers and the effect of political economic instruments in this thesis, was that of calculating the *annual economic results* for different actors and of various value chain configurations. This was achieved by subtracting the annual capital expenditures (Capex) and the annual operational expenditures (Opex) from the yearly income (see equation (1)). Where the annual income is greater than the costs, the activity represents a net profit for the actor.

$$\textit{Annual economic result} = \textit{Income} - (\textit{Capex} + \textit{Opex}) \qquad (1)$$

The capital investments were annualised on the basis of an interest rate and a payment period. The annual costs (Opex) and income were assumed to change at the same rate as inflation. All economic values were converted to Euros, with an exchange rate of 8.953 NOK/Euro which was the annual average of daily figures in 2015 (Central Bank of Norway, 2015).

The annual economic results were assessed from three different perspectives in three thesis papers, as shown in Table 2: that of large scale biogas plants in Paper 2, that of the value chain as a whole in Paper 3 and that of the farmers in Paper 3.

Table 2 Assessment of annual economic results in the three papers of this thesis

	Paper 2	Paper 3	Paper 4
Annual results calculated for	Large scale biogas plant	Value chain	Farmer
Data sources	Application data	Data mainly from Danish publications	Data from Norwegian small scale and centralised plants

In paper 2 the costs and income of the biogas plants were calculated in an economy model for large scale biogas plants developed in Excel, based on data from 12 Norwegian biogas plants. The data was obtained from the granted applications for investment support funding through the Enova programme in 2012-2015 and was provided by Enova through a confidentiality agreement (Enova, 2014). The Enova programme offered up to 30% investment funding in this period for plants with a planned production of more than 1 GWh per year. The relevant information from the applications was analysed and aggregated.

The Capex and Opex for large scale plants are related to the pre-treatment of the organic waste, the anaerobic digestion process and further treatment of the digestate as well as the upgrading of the biogas where relevant, as shown in Figure 12. The income is from payment for the treatment of organic waste and from sales of the upgraded biogas or the heat/electricity.

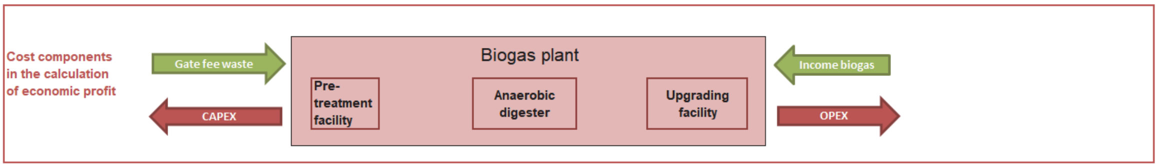

Figure 12 Calculation of annual results for Norwegian large-scale biogas plants (Paper 2)

The minimum, maximum and median income from biogas and from treatment of source separated organic household waste was estimated on the basis of economic data from the investment support applications, as shown in Table 3 and 4.

Table 3 Income from biogas at Norwegian large-scale biogas plants (Paper 2, Appendix A)

	Median (€/kWh)	Min (€/kWh)	Max (€/kWh)
Biogas used for energy	0.03	0.02	0.04
Upgraded biogas	0.04	0.03	0.08

The median values were used as a basis for the assumptions, while the minimum and maximum values were employed in the sensitivity assessments.

Table 4 Income per tonne of treated waste at Norwegian large-scale biogas plants (Paper 2, Appendix A)

	Median (€/tonne)	Min (€/tonne)	Max (€/tonne)
Source separated organic waste from households	69.81	55.85	106.11

Regression lines with the best fit were developed for Capex and Opex for large scale plants based on the economic data from the investment support applications, as shown in Figure 13. The costs were defined as a function of the annual production of biogas (in GWh). Two different functions were developed: 1) cost function for plants without an upgrading facility, and 2) cost function for plants with an upgrading facility. It was not possible to develop regression lines that differentiated between the costs of different use of the digestate, as there was a lack of detailed information in the applications.

The differences in operational costs were thus based on information collected directly from biogas plants.

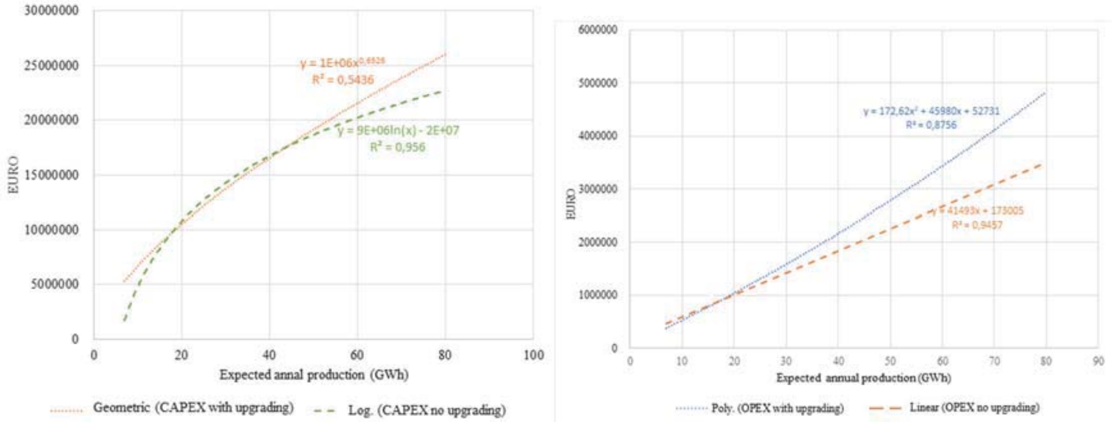

Figure 13 Capital and operational expenditures for Norwegian large scale plants as a function of GWh biogas produced (Paper 2, Appendix A)

The R^2 value indicates how well the line fits the data, where R^2=1 means a perfectly fitted line and R^2=0 no linear correlation. The R^2 value for the CAPEX lines are 0,96 and 0,54, and for the OPEX lines the R^2 values are 0,88 and 0,95, indicating a good fit between the data and the model.

4.4.3 Optimisation modelling methodology

Agriculture in Norway is dominated by relatively small farms in scattered locations. In order to obtain a greater understanding regarding ways of achieving the political goal of increasing the amount of manure for biogas production, it was necessary to look at two possibly contradictory objectives in parallel: that of choosing the most profitable solution for the farmers and that of minimising the emissions of greenhouse gases. The objective was to establish when manure should be used for biogas production, under which circumstances manure should be transported to a centralised biogas plant and which type of farms ought to invest in a farm scale biogas plant.

Existing studies confirm the usefulness of developing optimisation models. Willeghems et al. (2016) developed a model that facilitated the economic and environmental assessment of the spatial distribution of livestock in order to reduce manure pressure in livestock intensive regions. Another optimisation model evaluated the size and location of biogas plants in Portugal by applying an objective function that minimises investment, operational and maintenance costs; transport costs and social rejection (Silva et al., 2017). Jones and Salter (2013) developed a whole-farm optimisation tool in the UK to assess the viability of farm based anaerobic digestion using a holistic approach. They did not take into consideration centralised biogas production or greenhouse gas emissions.

A binary integer linear optimisation model was developed and run in Excel Solver (Microsoft, 2017). The model was inspired by a waste handling optimisation model developed by Stensgård (2014) and based on the model developed by Bjerkestrand (2017), with some improvements in data quality and functionality. The model calculates both economic profit for the farmer and the greenhouse gas emissions from three manure management alternatives, based on information relating to the amount of manure, estimation of the energy use on each farm and the distance to a centralised biogas plant. The three alternatives for each farm were: 1) no biogas production, 2) farm-scale production, and 3) centralised biogas production. The optimisation model contains three objective functions: 1) maximising the revenue for the farmers, 2) minimising the emissions of greenhouse gases, and 3) overall optimisation by maximising profit when the potential impact on global warming is considered to be a cost. The model was tested by performing a case study on 50 farms in Vestfold

County in Norway. The objective functions, methodology for calculating the environmental impacts, and the costs and the data used are described in detail in Paper 4.

4.5 Assessment of policies affecting the biogas value chains

The effect of the regulatory system and political instruments on biogas value chains was addressed in three of the papers:

- Paper 2 assessed the economic incentives necessary for large scale plants to choose the best scenario concerning the reduction of greenhouse gases.
- Paper 3 presented a comparative assessment of the economic instruments and the regulatory systems in Norway and Denmark and the ways in which they affect the biogas value chains.
- Paper 4 assessed the effect of existing political economic instruments from the perspective of the farmers.

In addition, a survey was carried out among the actors in the Norwegian biogas industry concerning drivers, barriers and potential political instruments relating to increased biogas production.

As illustrated in Figure 6, the environmental policies do not have a direct influence on the environmental impact of a product system: it is when policies affect the decisions of the actors (through restrictions on possible solutions or through instruments that steer the decisions of the actors in certain directions) and then in turn affect the physical flows, that they have an environmental effect.

4.5.1 The regulatory system and political incentives in Norway

In order to be able to assess the effect of existing and future political instruments, it was necessary to obtain an overview of the current regulatory framework and economic incentives.

In 2014 a national biogas strategy was published that promoted the goal of increasing biogas production (Norwegian Ministry of Climate and Environment, 2014). The strategy document declares that there is a considerable potential for increased biogas production by 2020, and that economic costs have represented the greatest barrier so far. A white paper from 2009 stated a national goal of 30% of manure to biogas production by 2020 (The Norwegian Department of Agriculture and food, 2009). This goal has, however, not been confirmed in following white papers. The biogas industry has stated that its vision is to produce 10 TWh, which constitutes 20% of the domestic use of fuel for transport (Måge, 2015).

Table 5 The regulatory system and economic incentives affecting biogas value chains (Paper 3)

		Regulatory framework	Economic incentives
Input	**Access to substrates**	=>Public procurement of municipal organic waste. =>For certain substrates hygienisation is required.	Support per tonne manure to biogas (to the farmer)
Plant	**Anaerobic digestion plant**	Cost of service regulation for municipal organic waste affects income.	=>Investment support =>Plants that co-digest substrates can apply for funding to become national pilot
Output	**Biogas to Heat/CHP**		
	Biogas for upgrade		
	Biogas for transport	Public procurement for public transport (buses) and waste collection vehicles	Exempt from road fee and CO_2 tax compared with other transport fuels
	Digestate in agriculture	=>Restriction on spreading areas for waste water residues => Logistics: Cleaning of vehicles to avoid infections	

As shown in Table 5, there are three key economic political instruments affecting the production of biogas value chains:

- **Investment support**: Industrial scale biogas plants can apply for investment support through the Enova programme. Applications are evaluated on the basis of criteria relating to cost and energy efficiency. Farm scale plants can apply for investment support through Innovation Norway.
- **Support per tonne manure**: Recently a form of economic support was introduced for farmers who supply manure to a centralised biogas plant or to their own farm scale biogas plant. The support is calculated on the basis of the dry matter content of the manure to biogas production (FOR-2014-12-19-1815, 2015).
- **Exemption from road fee and CO_2-tax**: Users of fossil fuels must pay a road fee and a CO_2-tax. As users of biomethane as a transport fuel do not have to pay these taxes, biogas as a fuel has an advantage on the market.

In the value chains that include food waste, the decision of the actors is affected by the cost of service regulation ("the self-cost principle") in the national waste regulations (FOR-2004-06-01-930, 2004). The income from treatment of municipal waste must cover the costs of treating that waste and cannot pay for, or be financed by, other substrates in the plant. This is because the waste fees paid by residents to cover the treatment of their waste must reflect the actual price of the service. Both organic waste from households and biogas used in public transport are purchased through public procurement. The regional goals for reduction of greenhouse gases and the pre-defined criteria and weighting of the environmental aspects in the calls for tenders can affect the decision of the actors in the biogas value chain.

There is no economic support targeting the use of digestate. The value chain is affected by the by-product regulation regarding the requirements for the sterilisation of substrates (FOR-2016-09-14-1064, 2016) and the fertiliser ordinance regulating the use of digestate as fertiliser (FOR-2003-07-04-951, 2003).

4.5.2 Comparative assessment

European countries provide different economic instruments relating to the increase and improvement of biogas production. Figure 14 shows an overview of support schemes for biogas and biomethane. When studying the effect of different political instruments, it is useful to look at countries with varying sets of regulatory systems and see how they have affected biogas production. A comparative assessment between Norway and Denmark was thus carried out in Paper 3.

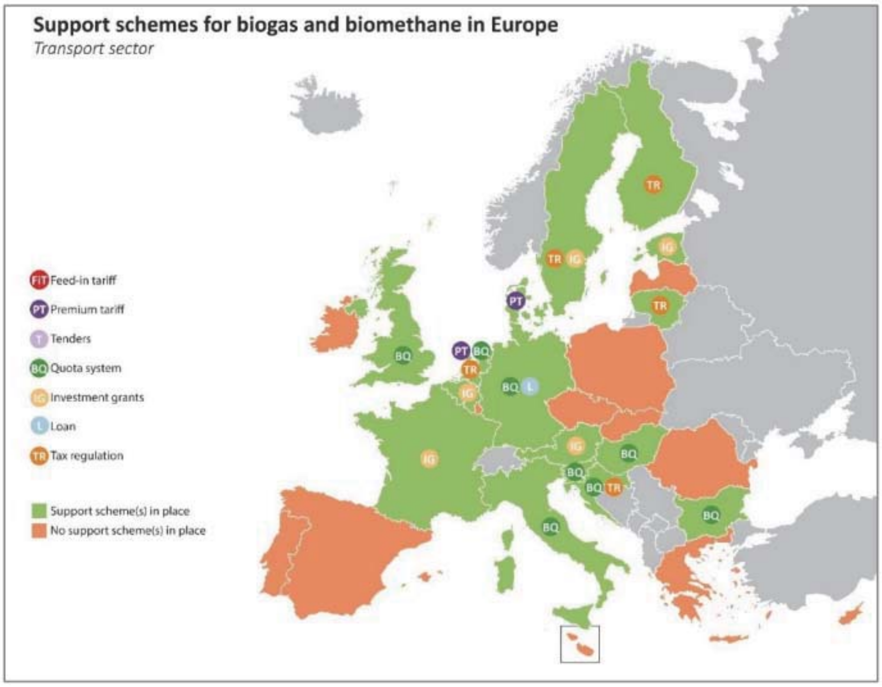

Figure 14 Support schemes for biogas and biomethane in Europe (Kampman et al., 2016)

While Denmark currently provides end-use support through a feed-in tariff for electrical power and gas delivered to the grid, Norway offers investments support for plants and economic support to farmers sending manure to biogas production for treatment. In Paper 3, the effects of those political instruments were assessed by analysing the economic effects of political goals and the regulatory system. A Norwegian and a Danish value chain was defined and described, and the costs and income of the value chains were estimated. The effect of the instruments was assessed by analysing ways in which the Danish instruments would affect the Norwegian value chain, and vice versa. The costs and income were categorised into input, conversion, output and transport of manure and digestate.

4.5.3 Survey among actors in the biogas value chain

In addition to the environmental and economic case studies, a simple survey was carried out among actors in the biogas industry in Norway. The survey was done during a national seminar in 2015 on organic waste treatment, organised by Waste Management Norway. The participants had 15 minutes to respond to the survey which concerned drivers, barriers and potential political instruments relating to increased biogas production. 27 people participated. Although the size of the biogas industry in Norway is limited, the sample is too small to make any statistically significant conclusions. The responses were, nevertheless, used as an indication of the views of the actors, as a supplement to the assessments that were made in the four scientific papers.

As shown in Figure 15, most of the respondents represented biogas plants, but other parts of the value chain such as waste possessors, agriculture, trade organisations and researchers/consultants were also represented.

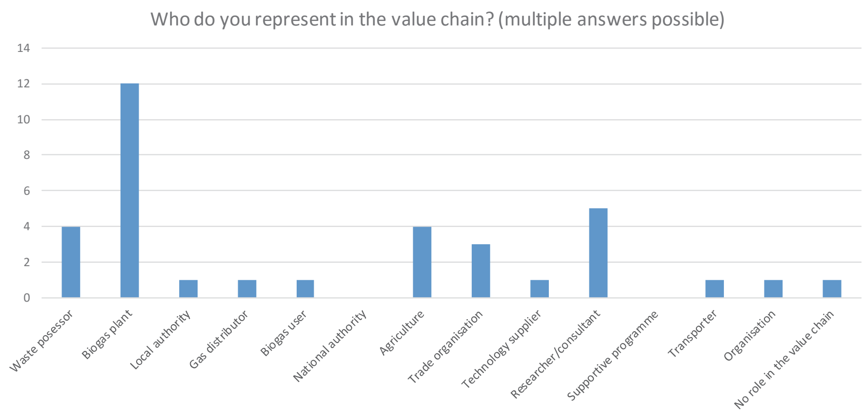

Figure 15 The respondents

Figure 16 shows that most of the respondents have many years of experience in the biogas industry.

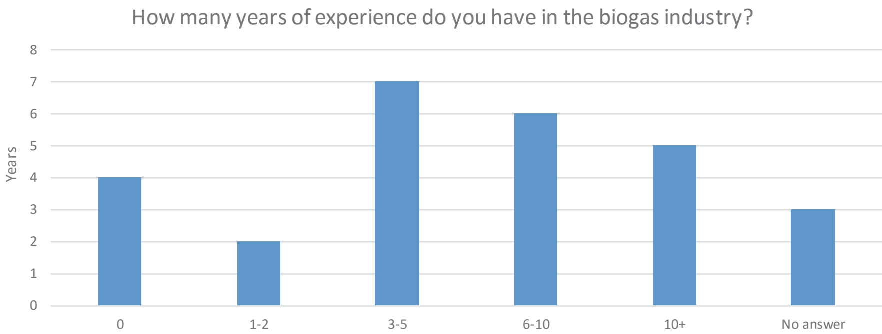

Figure 16 Years of experience among the respondents

The respondents were asked to rate the importance of different barriers, drivers and political instruments as being unimportant, slightly important, quite important, very important, extremely important or don’t know. The results from the survey are shown in section 5.5.

5 Results

5.1 Summary of the key findings in Paper 1

Paper 1 described the methodology and generic results of the BioValueChain model, an LCA model specifically developed for biogas value chains. The model was further used to assess the environmental impacts of various biogas alternatives in Papers 2 and 4. It consists of a large number of parameters that can be changed in order to perform assessments for specific plants or specific regions.

In Paper 1, results from the model were presented on the basis of the general parameter values, representing typical or average Norwegian values. The results cannot be used to make decisions in specific cases, but indicate where the hotspots are, and where there is a significant need for specific data when performing case studies. They also reveal where there are data gaps, where there is a need for further research and where it is acceptable to use average or generic data if specific data is not available. The results were presented per tonne of dry matter for source separated household waste (food waste) and manure from cattle and pig. The scenarios assessed in Paper 1 are shown in Table 6.

Table 6 Scenarios assessed in Paper 1

Reference			**Treatment**	**Avoided product (heat)**	**Avoided product manure**
0	Organic waste		Energy recovery	District heating mix (NO)	
0	Manure		Used as fertiliser		Mineral fertiliser
Scenario			**Treatment**	**Avoided product biogas**	**Avoided product digestate**
A	Organic waste	Manure	Biogas production	District heating mix (NO)	Mineral fertiliser
B				Heat from oil	
C				Electricity (Nordel)	
D				Diesel	
E					Compost (dewatered digestate)

5.1.1 Potential impact on global warming

The net results (emissions and avoided emissions from all life cycle phases) from Paper 1 are shown in Figure 17. A net positive result signifies that the emissions throughout the value chain are larger than the avoided emissions due to substituted products (biogas and digestate), while negative results imply that the avoided emissions are greater than the emissions.

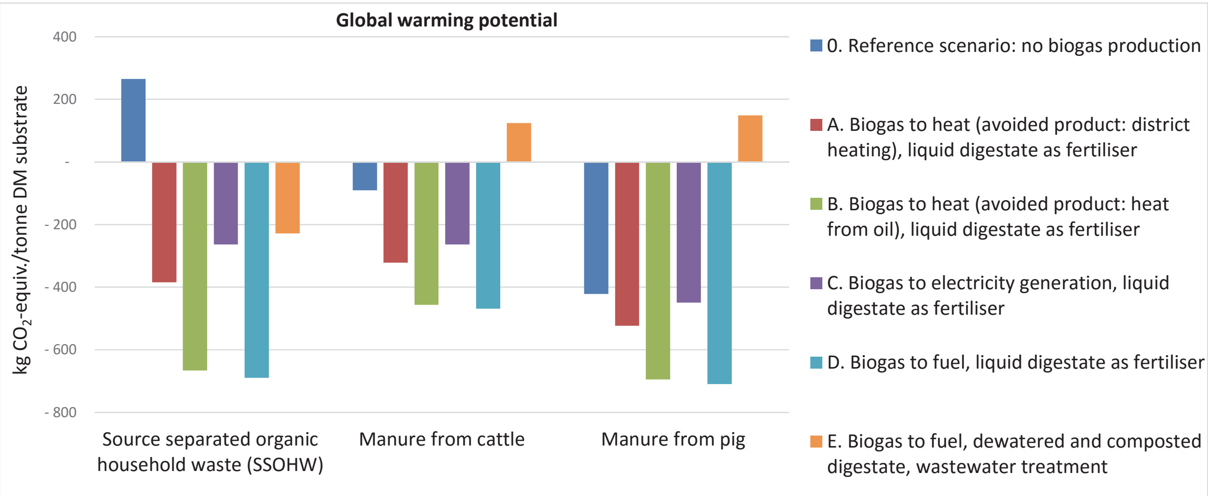

Figure 17 Global warming potential per tonne dry matter of each substrate (Paper 1)

Most of the biogas production scenarios included in the assessment resulted in a higher net benefit in terms of global warming compared with the reference scenarios for all the substrates (organic waste from households and manure from cattle and pig). The exception was the scenario with the dewatering of the digestate for the manure substrates (Scenario E). The most desirable option for all substrates is Scenario D: upgrading of biogas for transport purposes (diesel is substituted) together with the use of liquid digestate as fertiliser (mineral fertiliser is substituted).

Figure 18 shows the results categorised into the life cycle phases for the reference and the best and the worst biogas scenario (D and E) for each of the substrates. The most important life cycle phases are the avoided burdens from the use of biogas and digestate. This shows that the purpose to which the biogas and the digestate is put is of major importance for the overall results.

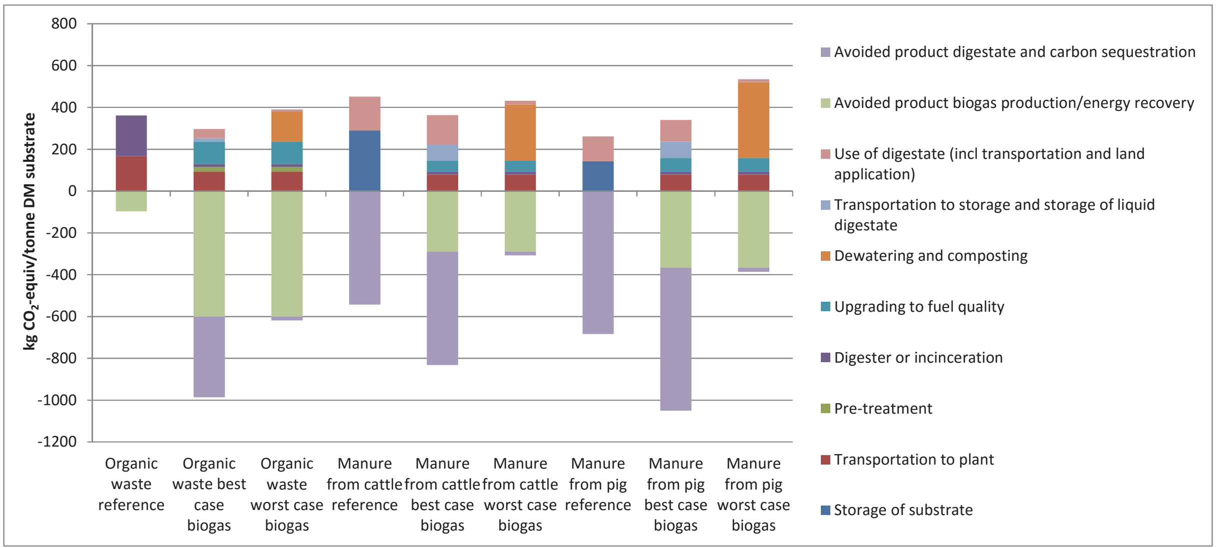

Figure 18 Results for the reference and the best and worst biogas scenario (Paper 1)

Upgrading the biogas to biomethane results in higher emissions during the upgrading process, due to methane loss. The benefits of substituting diesel, however, override the disadvantages of the additional emissions. Dewatering and composting of the digestate is less beneficial than producing liquid digestate to be used as fertiliser, mainly because of potentially large emissions of N_2O during the dewatering process and because substituting peat (by compost) is of less benefit than substituting mineral fertiliser (by liquid digestate).

The sensitivity assessment underlined a need for the use of specific data referring to transport distances, biogas potential and plant efficiency. Because all direct emissions from the biomass have considerable impact, research regarding the quantification of emissions from storage of manure and digestate, and of diffuse emissions, as well as developing measures to reduce them, should be prioritised.

As the use of biogas and digestate is of such importance, the assumptions made regarding quantification of loss of nitrogen, the amount of plant available nitrogen and the carbon content in the digestate will have a considerable impact on the results. This is also the case for quantifications of the carbon content and share of storage stable carbon.

5.1.2 Other environmental impacts

Two other environmental impact categories were assessed. These were *abiotic depletion potential* and *acidification potential*. Abiotic depletion is an indicator for the use of non-renewable fossil resources. The results showed that biogas production from organic waste from households resulted in a reduced net use of fossil fuel resources when compared with incineration with energy recovery. In the case of the manure substrates, however, some biogas alternatives resulted in an increased use of fossil fuels when compared with the reference scenario (using untreated manure as fertiliser). This is partly because the reference scenario for manure includes little use of fossil fuels and partly because manure has a low biogas yield compared with organic waste from households, resulting in lower substitution rates for biogas. The preferred scenario in terms of the potential impact on climate change (Scenario D) does, nevertheless, also represent the most favourable scenario for abiotic depletion of fossil resources.

Biogas production resulted in a reduction or no change in the acidification potential for manure when compared with the reference scenario. In the case of the organic waste from households, however, the biogas production led to increased acidification in some of the biogas scenarios when compared with incineration. For the most desirable scenario in terms of global warming, the difference between the reference and the biogas scenario is marginal.

The sensitivity assessments showed that the results for the other environmental indicators are less robust than those relating to climate change.

5.2 Summary of the key findings in Paper 2

In paper 2, the potential effect on global warming was assessed together with the annual economic results for four different value chain configurations of a large-scale biogas plant in Norway. The four scenarios represent different levels of sector integration, as shown in Figure 19. In Level 1, which represents a conventional biogas plant in Norway built before 2010, the value chain primarily only involves the waste sector, while in Level 2 the biogas plant supplies biomethane to the transport sector. In Level 3, the agricultural sector is included as a receiver of liquid digestate as fertiliser, while in Level 4 the agricultural sector is fully integrated, both as a supplier of manure to the plant and as a receiver of digestate.

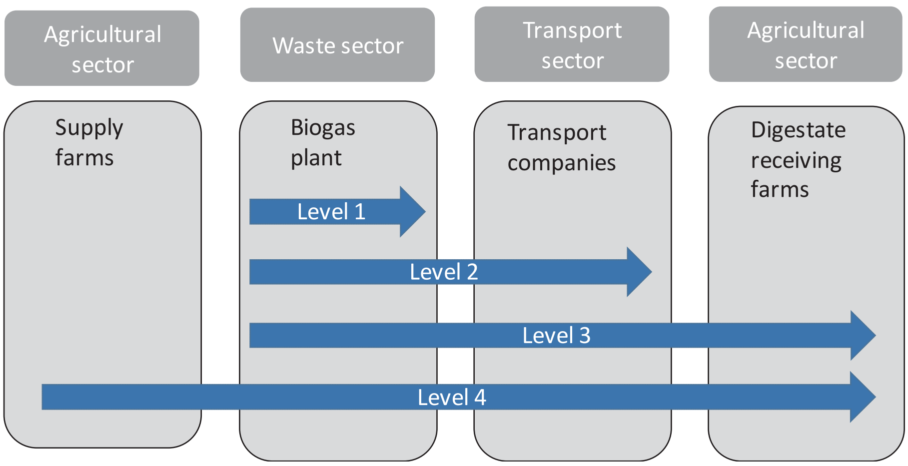

Figure 19 Sector integration in the four scenarios assessed in Paper 2

The results from the environmental assessment showed that Level 4 resulted in the most significant reduction of greenhouse gases, while Level 1 resulted in the highest emissions. The economic assessments showed that the most advantageous solution concerning the reduction of greenhouse gases was the least profitable option for the large-scale biogas plant (Figure 20). This was due to transport costs, and costs for storage of manure and liquid digestate.

Figure 20 Environmental and economic results for large scale biogas plants (Paper 2)

The conclusion was that a high level of sector integration in the value chain is desirable in terms of the reduction of environmental impacts, but is less favourable in terms of economic profit for the centralised biogas plant. A sensitivity assessment of the economic results was performed by entering minimum and maximum values for the cost and income factors. This showed that the ranking of the results remained the same for most of the input values, with three exceptions: income from sales of biogas and potential income from sales of dry digestate, as well as the cost of wastewater treatment. These are largely dependent on the local market situation for biogas and digestate.

In the case of plants over a certain size or when assuming high income from sales of biomethane, investment in upgrading facilities and in supplying biomethane to the transport sector appeared to be more profitable than producing heat from biogas. This may indicate that only small additional incentives are necessary to overcome the barriers to a better utilisation of biogas in Norway. It would seem, however that much more attractive incentives are required to overcome the economic barriers to the inclusion of the agricultural sector in large-scale biogas production in Norway.

In order to achieve the same economic profit in Level 3 as in Level 1, an increase of 21% in the gate fee for the organic waste, or an incentive of about 8 Euros per tonne digestate was necessary. To obtain the same economic profit in Level 4 as in Level 1, an increase of 24% in the gate fee or 7 Euros per digestate was required. These numbers are dependent on the size and type of farms in the plant's surrounding area, the transport distances and the agreement between the farmer and the biogas plant. They are also dependent on the alternative cost of waste water treatment and costs/income relating to dry digestate/compost.

5.3 Summary of the key findings in Paper 3

In paper 3, a comparison was done of the economy of biogas value chains in two different countries who have implemented different sets of political instruments. While Denmark provides end-use support through a feed-in tariff for electrical power and gas delivered to the grid, investment support for biogas plants and support to farmers sending manure to biogas production are offered in Norway. The regulations in the two countries reflect the overall political goals in the two countries: an increase in the share of renewable energy in Denmark and sustainable management of organic resources in Norway.

A Norwegian and a Danish value chain were defined, and the cost and income of each value chain was calculated. To evaluate the political instruments, it was necessary to gain a general understanding of the differences in the design of biogas value chains and the overall political objectives. As shown in

Figure 21, there are significant fundamental differences in the annual production of biogas, which substrates are used and the utilisation of biogas in the two countries. While the Norwegian biogas industry generally belongs to the waste sector, biogas production in Denmark is primarily found in the agricultural sector. The biogas produced has previously been poorly utilised and is now increasingly used in the transport sector. Denmark's biogas production is chiefly used for heating and electricity.

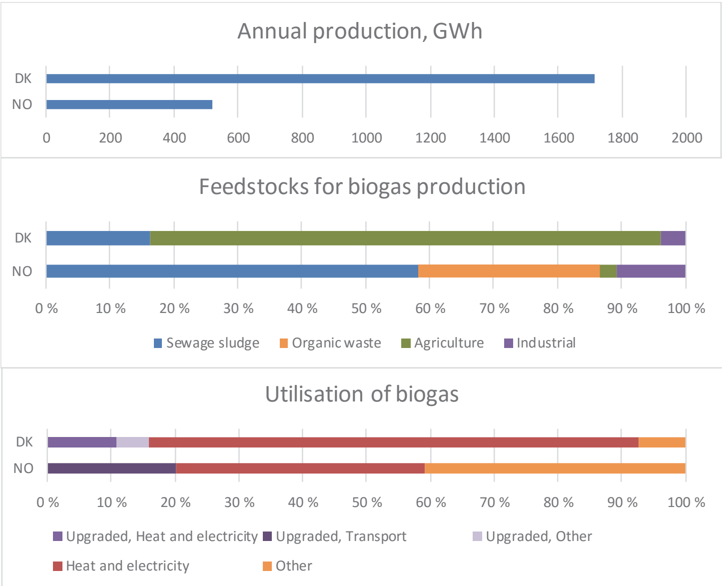

Figure 21 Biogas production in Denmark and Norway (Paper 3)

The Norwegian value chain assessed in this paper corresponds to the Level 4 scenario in Paper 2: A large scale biogas plant co-digesting food waste and manure from surrounding farms, that upgrades the biogas to biomethane for use in transport and returns the liquid digestate as biofertiliser in agriculture. The Danish biogas value chain was assumed to produce heat and electricity based on manure and deep litter, and to return the liquid digestate back to the farms.

The economic calculations of the Danish and the Norwegian biogas value chain showed that the total costs can be assumed to be higher in Norway because the treatment of organic waste from household and industry requires pre-treatment. The estimated cost of transport was approximately 100% higher in Norway than in Denmark, but these costs did not have a significant effect on the results.

The assessment showed that the main difference in the profitability of biogas value chains in Denmark and Norway is found in the organisation of the economic incentives. More than 60% of the total revenues in the Norwegian case originated from the input side (income from waste- and manure treatment). The investment support contributed with a reduction in capital expenditures. In Denmark, however, most of the income was from sales of energy with feed-in tariffs or a premium.

In both the countries, the regulatory systems have resulted in more plants and thus increased biogas production. When the Danish instruments were introduced to the Norwegian value chain and vice versa, the economic result for the value chain became negative. This is because the Norwegian value chain is designed to rely on high incomes from the input, while the Danish biogas plant is designed on the basis of an expected income from the sales of the biogas. This reveals that the viability of a value chain is highly dependent on structural conditions and the regulatory system.

The output based support in Denmark incentivises the use of high-yield inputs, and avoidance of biogas losses. Introducing input based support that is complementary to output based support could contribute to even more of an increase in the amount of manure used for biogas production, and potentially reduce the search for high yield substrates. It could also potentially lead to an increase in manure treatment in areas with a lower farm density. As the economic instruments in Denmark are solely targeting the output, they do not promote the use of organic waste from households and industry other than indirectly through a potential increase in biogas yield. The current system does not encourage the use of biogas in transport.

The input based support in Norway is likely to have contributed to an increase in source separation of organic waste from households, less focus on the biogas yield, more flaring and use of heat from biogas internally at the plant and in surrounding buildings. The use of biogas in the transport sector has increased, aided by the indirect support provided by an exemption from road fees and a CO_2-tax on fossil alternatives. This development is likely to contribute to less flaring and better use of the production capacity in the plants. The Norwegian support for the use of biogas in transport is less than the average support in Denmark, but the input support for manure, gate fee and investment support compensates for this. The development in Norway shows that, with the right incentives, biogas can and will be used in the transport sector.

The input of organic waste from households in Norway comes at a high cost due to the need for pre-treatment and requirements for documenting the quality and content of the digestate. The user's acceptance of the digestate can be a challenge when the origin of the substrate is from the waste sector. This issue is also seen in Denmark, where the diary sector has shown reluctance towards the use of digestate produced from organic household waste.

In both countries, the political objectives are directed towards greenhouse gas reduction, although the emissions sources are from different sectors: In Denmark the main emphasis is on the energy sector, while in Norway the goals are targeting increased biogas production in general and its production from manure from the agricultural sector specifically. It seems, however, that the national goals in the two countries are converging, presumably aided by common EU regulation.

It is not possible to conclude that one support system is superior to the other, as they are designed to achieve different political objectives and to fit different structural conditions. It may, however, be possible to increase regulatory efficiency if the countries can take inspiration from each other.

5.4 Summary of the key findings in Paper 4

In paper 4 the optimisation model described in Section 4.4.3 was applied to find the optimal solution for anaerobic digestion of manure resources from 50 cattle and pig farms in Vestfold. Sensitivity assessments were carried out to be able to discuss the results at a national level. The three alternatives in the model are shown in Figure 22: no biogas production, farm scale biogas production and centralised biogas production.

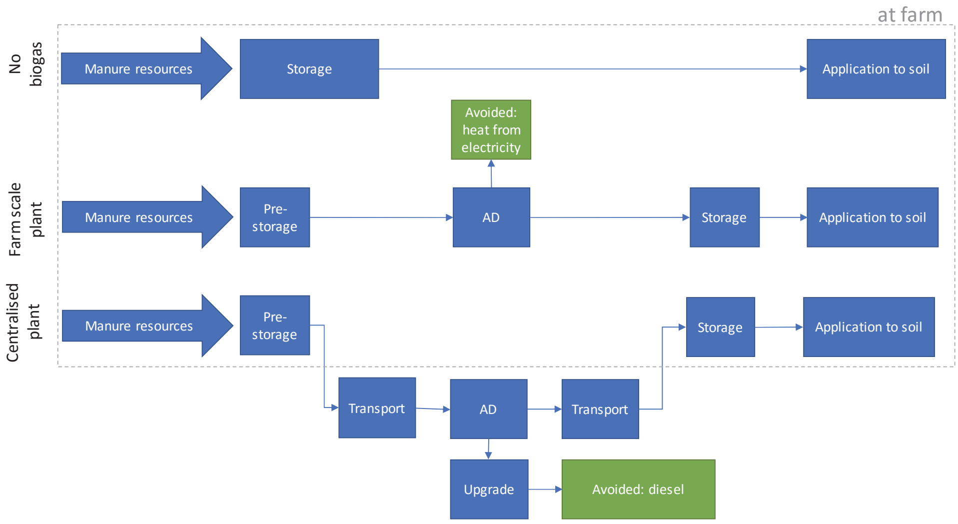

Figure 22 The three different manure management options assessed in Paper 4

When the objective function was applied, of minimising the greenhouse gas emissions in the region (without taking into consideration economic costs and income), the *centralised plant* alternative was suggested for all 50 of the farms. This may be explained by the environmental benefit of upgrading the biogas to biomethane to substitute diesel as a fuel for transport. In the case of the *farm scale plant* alternative, the biogas is used to meet the demand for heat on the farm, which gave a lower benefit in terms of greenhouse gas emissions. Even if the heat generated from biogas on the farm substituted oil combustion, the centralised plant alternative was more beneficial because a significant proportion of the heat generated in the farm scale plant alternative was assumed to be used for running the plant. In regions where centralised plants are not an option, however, the farm scale alternative is a viable option in terms of reducing greenhouse gases, even if the gas is not used to phase out fossil alternatives. This is due to reduced emissions from storage and spreading.

When applying the objective function of maximising the economic profit for the farms in the region (without taking into consideration environmental impacts), the *centralised plant alternative* was suggested for 40 of the farms, while the *farm scale alternative* was suggested for 10 of the farms. The model did not choose the *no biogas* alternative for any of the farms in the region. In reality, 32 of the farms in the region currently supply manure to a centralised biogas plant, while there is only one farm scale plant. The sensitivity assessment showed that the economic results were highly dependent on the agreement between the centralised plant and the farmer.

The assessments showed that the farms are dependent on the recently introduced governmental support per tonne manure for the farm scale plant to be profitable. They also demonstrated that transport of manure is likely to be limited by economic costs before the emissions from transport compromise the positive effects of substituting diesel in the *centralised plant* option.

The results from this study indicate that the farmers' economy is currently not the primary impediment to increasing the amount of manure for biogas production in Norway. Efforts should be made to encourage the existing and planned centralised plants to include manure as a substrate, as well as decreasing the risks of building farm scale plants and increasing knowledge among relevant actors with regard to anaerobic digestion in agriculture.

To achieve an even greater greenhouse gas reduction in the farm scale alternative, priority should be placed on finding ways of substituting fossil energy carriers on the farm or in the surrounding areas. This might be achieved through technological development for cheaper small scale upgrading solutions and for the use of raw biogas in tractors and other agricultural equipment currently using fossil fuels. Regional development plans for farm scale biogas production, including a piping infrastructure and a centralised upgrading could also be an option in some regions.

5.5 Survey: opinion of the actors

The results from the survey on drivers, barriers and political instruments relating to Norwegian biogas value chains are shown in Figure 23.

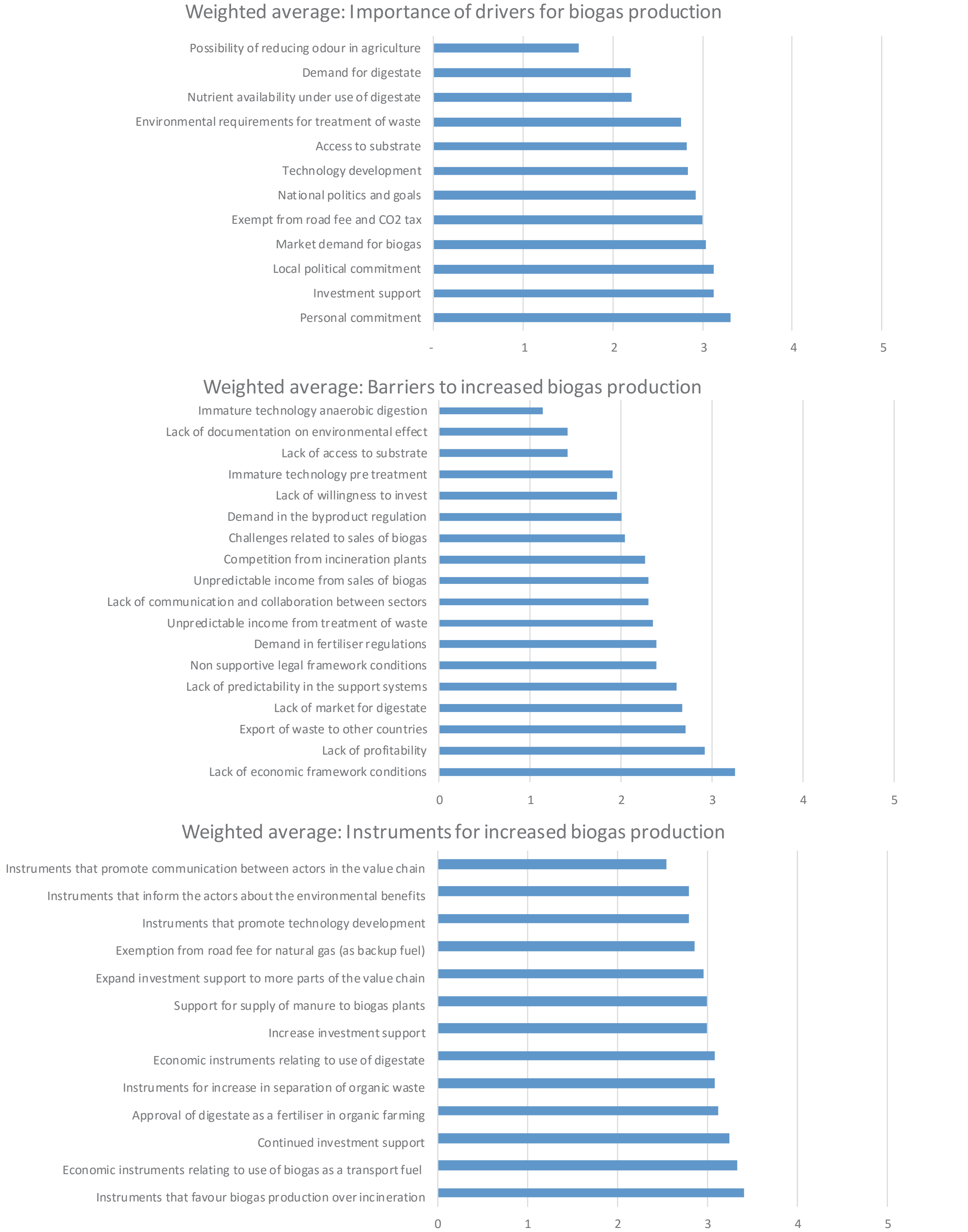

Figure 23 Survey of the actors in the biogas value chain in Norway (1=unimportant, 2=slightly important, 3=quite important, 4=very important, 5=extremely important)

Personal commitment, *investment support* and *local political commitment* were rated as the most important drivers, while *possibility of reducing odour in agriculture*, *demand for digestate* and *nutrient availability* were rated as the least important drivers.

The three most important barriers according to the actors were *lack of economic framework conditions*, *lack of profitability* and *export of waste to other countries*. *Immature technology, lack of documentation of environmental effect* and *access to substrate* were rated as the least important barriers.

Among the political instruments, there are small deviations between the answers. The three instruments that were rated as the most important were *instruments that favour biogas production over incineration*, *economic instruments relating to the use of biogas as a transport fuel* and *continuation of the investment support*.

Generally, the economic aspects seem to be rated by the actors as having high importance, while factors regarding communication between actors and the documentation of environmental effects and technological aspects seem to be rated as less important.

6 Discussion

In this PhD thesis, three domains were explored in parallel: Environmental impacts, economy of the actors and policies affecting the value chain. Below, each of the three domains are discussed, in addition to methodological implications.

6.1 The environmental impacts from biogas value chains

A review performed on LCA studies of waste management systems by Laurent et al. (2014a), found that with the exception of landfilling, there is no definite agreement among the existing studies with regard to which waste treatment technology in general performs better for any waste types. This shows that the results of the study are largely dependent on local conditions and on the methodological choices as a consequence of the purpose of the study. This is confirmed in the case of organic resources by Börjesson and Berglund (2006), who concluded that the environmental impacts from biogas production was significantly affected by the properties of the raw material digested, the energy efficiency of the production and the status of the end-use technology. There are, nevertheless, some aspects of the results from the assessment of the environmental impacts from biogas value chains under Norwegian conditions presented in Papers 1, 2 and 4, that can be generalised. These are summarised by three statements, as described below.

The amount of food waste and manure for anaerobic digestion should be increased. Anaerobic digestion resulted in reduced impacts for most biogas scenarios compared with the reference scenario (which was defined as incineration with energy recovery for organic waste and direct use as fertiliser for manure). This was also found by Börjesson and Berglund (2007), who concluded that biogas systems normally led to improvements when assessing Swedish conditions. The statement above could, however, be invalidated if there are high emissions of N_2O and CH_4 somewhere in the value chain, if there is poor or no utilisation of the biogas or the digestate, or if the reference scenario for organic waste includes energy recovery where the energy fully substitutes fossil energy carriers.

The assessment of two other environmental indicators showed that anaerobic digestion may in some cases result in increased emissions when compared with the reference scenario. Bernstad and la Cour Jansen (2011) reached similar conclusions when assessing waste management of household food waste in Sweden: anaerobic digestion resulted in net avoidance of GHG emissions, but gave a larger contribution to other environmental impact categories. The results from Paper 1 showed, however, that in a Norwegian context the optimal scenario in a global warming perspective did also represent the best scenario (or equal to reference scenario) for the other environmental impact categories assessed. This shows that efforts should be made in developing optimised biogas value chains and optimising existing ones.

***The digestate produced should be used as a fertiliser in agriculture to substitute mineral fertiliser where possible*.** This requires that there are farms with a need for fertiliser in the surrounding area and that the digestate fulfils the quality requirements described in legislation. Few studies have been done specifically on the emissions of different management methods for digestate, especially under Norwegian conditions. The literature shows large variations in emissions and that some technologies can contribute to reducing them (e.g. Rodhe et al., 2015; Vázquez-Rowe et al., 2015). There is a need for more research regarding the quantification and measures for reduction of emissions during storage and spreading of liquid digestate on the fields, and dewatering and composting of digestate. Enhanced knowledge about and the substitution rates for mineral fertiliser by liquid digestate, and the potential for substituting peat and other alternatives for dry digestate would also improve the understanding of how digestate should be utilised.

The biogas produced should be used to substitute fossil fuels. In Norway, the generated biogas should be upgraded to biomethane and used in the transport sector to achieve the most significant reduction in greenhouse gases. Using biogas to generate heat or electricity is less favourable because of the sizeable renewable share in the energy mix. In other countries with a different energy mix, the use of biogas for heat and electricity may result in larger reductions in greenhouse gas emissions, dependent on the degree to which the energy from biogas contributes to phasing out fossil alternatives. Uusitalo et al. (2013) concluded that the most favourable use of biogas in a Finnish perspective was as a fuel for transport or in combined heat and power plants with regards to reduction of greenhouse gas emissions. Bernstad and la Cour Jansen (2011) found that use of biogas for transport resulted in the largest reduction of greenhouse gases in Sweden. If, however, energy generated from raw biogas was assumed to substitute Danish coal power, energy generation was preferred over the use of biogas as a fuel in Sweden. As, however, the energy system in most European countries is undergoing a transition towards an increased share of renewables independent of biogas, use of biogas for transport will represent a better option in the future, as the change is moving at a slower pace in the transport sector.

The use of manure from cattle and pig for anaerobic digestion will reduce emissions of greenhouse gases regardless of the use of the biogas, under the condition that a reduction in storage time reduces emissions of N_2O and CH_4. This necessitates that the current use of manure, as a fertiliser on the fields, is substituted by the digestate and provides the same (or improved) functionality. If, however, manure is used for biogas production without returning the digestate back to the farm, biogas production is not preferable.

The results showed that large-scale biogas production is generally more beneficial than small-scale in the reduction of greenhouse gases in Norway, because it can be assumed that small scale biogas plants use the biogas internally to a greater extent and because there are difficulties in finding a useful application for the biogas on the farms. This conclusion is dependent on the large-scale plant being within reasonable distance. It also requires upgrading the biogas to biomethane and returning liquid digestate as biofertiliser to agriculture.

Small scale biogas plants for manure can also be a viable option in an environmental perspective if a centralised biogas plant is not available. All biogas plants should pay extra attention to avoiding diffuse emissions from the production facility and prioritise measures to reduce emissions from storage of the digestate.

Achieving optimised biogas value chains requires a high level of sector integration: integration of the waste sector as a raw material provider and converter of waste resources into products, and the transport sector as a user of biogas and agriculture, both as a provider of manure as a raw material and user of the digestate.

The environmental assessments include collection of a large amount of data, such as energy use, the theoretical and practical biogas yield of the different substrates, conversion losses in the different parts of the value chain and emissions from the organic material in the different life cycle phases. The quantification of the different parameters requires making assumptions that introduces uncertainties to the results. Sensitivity assessments were performed in Paper 1 to assess the robustness of the conclusions and decrease the uncertainties. These assessments revealed some areas where more research is recommended to strengthen the conclusions in this thesis.

The quantification of emissions from organic materials is challenging as there are large variations in the physical properties of the organic matter and because the emissions depend on many different factors. For example, the composition of source separated household waste is dependent on the food habits of the households in the specific region and can vary throughout the year. The composition of waste can have large impacts on the results, as underlined by Slagstad and Brattebø (2013). Emissions from storage of manure and digestate is dependent on properties of the organic material, air temperature, size of storage and how much of the material is in contact with air.

In addition, there is limited access to data on the operation of Norwegian biogas plants (such as the use of heat and electricity, amount of reject in pre-treatment and actual biogas yield). Most of the data is thus based on literature and design data. Collection of data from Norwegian plants over several years would give a better basis for estimating the environmental impacts from future biogas plants.

As the emphasis in this study was on the biogas value chain, only one reference scenario was included per substrate, representing the most common alternative. To be able to assess the organic resources in a valorisation perspective other treatment routes of the organic resources, such as for example the use of food waste as animal feed, should be included in further developments of the LCA model.

6.2 The economy of the actors in biogas value chains

Anaerobic digestion has been identified as a technology that generates little or no economic profit for the actors in the value chain (Norwegian Environment Agency, 2015, 2013). In the survey among the actors in the biogas industry in Norway, investment support was identified as one of the most important drivers, while lack of profitability and lack of economic framework conditions were among the three most important barriers. This demonstrates that the economic framework conditions are seen by the actors to be challenging.

The economic calculations performed as part of this thesis did, however, show economic profit for most biogas value chains. The sensitivity assessment carried out in Paper 2 showed that positive economic profit of the large-scale biogas plant was dependent on the price in sales of biogas, the gate fee prices for waste and the interest rate for loan. The cost estimations did not include unforeseen costs and start-up costs, which might explain why the survey and the assessments show contradictory results.

The key findings in the assessment of the economy of actors in the value chain in Paper 2, 3 and 4, can be summarised by four statements, as described below.

Upgrading of biogas for use in the transport sector is the most profitable option only under certain conditions. Upgrading of biogas to biomethane was only profitable for plants above a certain scale, or for plants with high income from sales of biomethane. This shows that the exemption from CO_2 tax and road fee may be an important driver for the most preferable use of biogas in terms of reduction of greenhouse gases, which is also concluded by Larsson et al. (2016) from a Swedish perspective. Jacobsen et al. (2013) showed that in Denmark the upgrading of biogas was only preferable if the sales prices of heat were very low.

Most large-scale plants in Norway treat sewage sludge and organic waste from household and industry. For those plants, payment for the treatment of waste (gate fee) is the most important income. As stated by Lantz et al. (2007) higher gate fee for anaerobic digestion compared with incineration can represent a barrier for increased biogas production.

On a general level, large-scale biogas plants lack the economic incentives to include the agricultural sector in the value chain. This is due to high costs relating to the transport and storage of manure and liquid digestate. This conclusion is dependent on transport costs (distances), agreement between plant and farmers and the alternative costs of the dewatering and processing of dry digestate or compost (costs for dewatering and costs/income from dry digestate/compost).

Supply of manure to a centralised biogas plant is likely to be the most profitable option for cattle and pig farms. When compared with investing in a farm-scale biogas plant or no biogas production, centralised biogas production was identified as the most profitable option for most cattle and pig farms included in the assessments. This does also represent the option with the lowest risk. This conclusion is, however, highly dependent on the agreement between the farm and the centralised plant.

Small scale biogas plants can be profitable for most cattle and pig farms **and** ***the barriers to an increase in farm scale biogas production are not principally economic.*** The support per tonne manure produced has recently been introduced and has improved the preconditions for manure to biogas. Although the avoided costs of heat at the farm are small, the economic assessment showed that farm scale biogas production was profitable for most of the farms under the current economic support system. These results were somewhat surprising, given the low number of existing farm scale biogas plants in Norway. The support per tonne manure for biogas production is crucial to obtain profitability, as the sensitivity assessments in Paper 4 showed that investment support alone was not sufficient to make it profitable for the farms to make an investment. Jones and Salter (2013) found that anaerobic digestion could be economically viable on medium and large arable farms in the UK. According to Ahlberg-Eliasson et al (2017) Swedish farm scale biogas plants are experiencing harsh economic conditions, confirmed by Jansson (2014), who found that several Swedish farm scale biogas plants were not economically profitable. Karlsson et al. (2017) concluded that several farmers in a successful biogas value chain in Sweden took a considerable personal financial risk and were defined as *influential enthusiasts*. Karlsson et al. (2017) further point out that the biogas industry cannot rely on such enthusiasts alone.

As the support per tonne manure in Norway is recently introduced, the effect of this political instrument may not be visible yet, and can potentially have a positive impact on increasing the amount of manure for biogas in the future. This is, however, difficult to predict, as there are few data available on the costs of small scale plants, including information concerning the economic risks and the costs of start-up and technical problems. Ahlberg-Eliasson et al. (2017) suggested a detailed long-term evaluation programme on the production efficiency of farm scale biogas production in Sweden. Increased knowledge with regard to these topics would reduce risk and improve the understanding of necessary measures for increasing the amount of manure to biogas production even more.

6.3 Policy development for increased and improved biogas production

Policies have played an important role in the development of the biogas industry. Kampman et al. (2016) found that the existence, stability and reliability of the policy framework and support schemes appear to be the number one driver in all the countries across the EU, independent of whether they already have a mature biogas market in place or not.

Biogas production embraces a number of sectors including waste treatment, agriculture, energy and transport. As concluded by Huttunen et al. (2014a) policies relating to one domain also have the supporting effects of meeting the goals of another domain. This should be taken into consideration when developing and implementing new policies.

In the comparative assessment in Paper 3, it became apparent that a distinction can be made between waste sector based and agricultural sector based biogas value chains. Most of the biogas value chains in Norway are waste sector based. There is, however, a political objective of increasing the amount of manure to biogas, which requires either agricultural sector based biogas production, or a connection between agriculture and the waste sector (or other relevant sectors).

In the survey among the actors, continuation of investment support was rated as the most important factor. The investment support system in Norway has been of major importance and has led to an increase in biogas plants. The advantages of the investment support system are that it reduces the capital costs when building new plants and as it is received during start-up of the plant, one avoids the risk that concerns regarding changes in the regulatory system affect the decision of the actors.

A disadvantage in the investment support system, revealed in Paper 3, is that while it does encourage increased biogas production, it does not directly encourage the avoidance of losses, or the best use of biogas and digestate. This could potentially lead to value chains with little or no reductions in greenhouse gases. To resolve this, one could consider a revision of the criteria for investment support so that the most beneficial applications of biogas and digestate are encouraged.

The use of organic waste resources for the production of bioenergy and biofertiliser/soil products is likely to play an important role in the bioeconomy in the future. Bugge et al. (2016) categorised the bioeconomy into three main visions, and Scordato et al. (2017) found that among those three visions, the bio-resource vision was predominant among actors contributing to a public hearing on the development of a bioeconomy strategy in Norway.

As it can be assumed that increased biogas production from organic waste is likely to lead to reduced emissions of greenhouse gases, access to organic waste resources suitable for biogas production is important. Availability of cheap feedstock in sufficient quantity was also identified by Budzianowski and Chasiak (2011) as one of the central challenges in biogas production in Germany. The public procurement of waste services can play an important role, both by providing predictable access to the organic resources and by developing purchasing criteria that emphasise the environmental aspects. The latter requires that the environmental impacts relating to different treatment options are well documented, through, for example, environmental declarations.

As biomethane is used primarily in public transportation (buses and waste collection trucks) in Norway, regional political goals of phasing out fossil fuels in public transport can play an important role in creating an increased and stable demand for biogas and other renewable fuels, thus complementing the effect of the tax exemptions. The public procurement of transport services also has major importance, with regards to the manner in which environmental requirements are emphasised in the criteria for selection.

Although the renewable share is changing at a slower pace in transport than in the energy sector, there are several relevant political objectives in the transport sector. In the EU at least 10% of the energy used in the transportation sector should be renewable by 2020 (European Parliament, 2009). The Norwegian parliament has asked the government to make sure that public transport as a general rule will be using low or no emissions technology or climate neutral fuels by 2025 (Norwegian Parliament, 2014). There are, however, no specific political objectives regarding the use of biogas for transport.

Economic instruments relating to biogas as a transport fuel were rated as the second most important political instrument in the survey among the actors. The CO_2-tax and road fees on the fossil alternatives have probably had a positive effect on biogas as a renewable fuel. This has led to a significant increase in the share of biogas used as a fuel. Results from Paper 2 showed that if the difference between taxes for fossil and renewable fuels were slightly increased, it is likely that upgrading of biogas would become profitable for all biogas plants in Norway, providing that there are no limitations on expansion of the market for biomethane.

In the countries where biogas production is mainly waste sector based, a common challenge in the past has been poor utilisation of the gas. A transition is, however, possible. According to Olsson and

Fallde (2014), biogas was previously considered in Sweden to be a by-product from waste and sewage sludge treatment. Sweden is now one of the countries that have the highest number of upgrading plants (EurObserv'ER, 2014). Larsson et al. (2016) concluded that tax exemption is likely to have been one of the most important instruments in increasing the amount of biogas for transport purposes in Sweden. In Germany too, the largest producer of biogas in Europe, upgrading of biogas for utilisation in the transport sector has been identified as the most promising option for the use of biogas in the future (Poeschl et al., 2010).

The economy of the actors in the transport sector have not been directly targeted as part of this research. According to Rydberg et al. (2010) investments in vehicle and filling stations were higher for biogas than for the relevant alternatives in Sweden. According to Sund et al. (2017) the barriers to increased use of biogas in the transport sector in Norway is lack of knowledge, and concerns regarding the long term price and availability of biogas as a fuel. There is a need for a greater understanding and communication regarding the environmental and economic aspects of biogas as a transport fuel when compared with other fuels, and the effect of the drivers and barriers on the transport companies.

The agricultural sector can have two important roles in the biogas value chain: as a supplier of manure and as a receiver of digestate. The environmental assessment carried out in Papers 1, 2 and 4 revealed that the use of digestate is just as important as the use of biogas for the reduction of greenhouse gases. Despite this, there are currently no specific political measures supporting a move towards an optimal use of digestate in Norway.

Huttunen et al. (2014b) identified the end use of digestate as one of the most critical points for biogas value chains in Finland. The authors found that although plants aimed at utilising the digestate as fertiliser in agriculture, they had difficulties in realising the potential. Even if the digestate was processed into biofertiliser, the plants struggled to find farmers who would accept the product. The authors pointed out two possible explanations. One was the increased effort involved compared with using mineral fertiliser, because the digestate does not have an identical effect, and the other was the additional storage costs incurred. Raven and Gregersen (2007) underlined the importance of social networks in achieving success for Danish biogas value chains, while Karlsson et al. (2017) identified well-functioning co-operation between actors (both private and public) as crucial to the successful biogas networks in Sweden.

Although the recently introduced governmental support for farmers per tonne manure to anaerobic digestion in Norway can contribute to increased communication between the waste and the agricultural sector, measures should also be considered that increase both incentives for the use of digestate in agriculture and understanding concerning its use. In addition, exertions should be made to encourage the existing and planned centralised plants to include manure as a substrate.

According to Budzianowski and Chasiak (2011) there are two basic models for the implementation of agriculture-based biogas plants in the EU member states: distributed farm-scale biogas power plants featuring co-digestion of animal manure and bioenergy crops, and centralised large-scale plants which typically co-digest manure collected from several farms together with organic residues from industry and households. Karlsson et al. (2017) identified the following success factors for agricultural biogas production in Sweden: 1) long term perspective, 2) business strategy, 3) influential enthusiasts, 4) co-operation, 5) entrepreneurial skills and experience and 6) a secure market.

For most farmers, the governmental support per tonne manure appeared to be crucial to profitability for the investment in a farm scale biogas plant, and is likely to lead to an increased level of manure to biogas production, as demonstrated in Paper 4. This support can potentially lead to an increase in the number of both farm scale and centralised biogas plants.

Paper 4 concluded that for farm scale biogas production from manure from cattle and pig, it would appear that there may be other barriers than the purely economic. There seems to be a high risk involved for farmers in investing in biogas plant. This is due to there being little information available regarding the actual costs of farm scale biogas production, such as start-up costs and the costs of unforeseen incidents. Running a biogas plant requires the acquisition of new knowledge in a subject that is far from the ordinary operation of the farm. In order to reduce risks there seems to be a need for more research on the cost of farm scale biogas production under Norwegian conditions, and training programmes on ways of avoiding unforeseen costs during start-up and normal operation.

Norwegian farms will have difficulties finding a good use for the biogas, as upgrading technologies are too expensive for small scale production and the energy used on the farm is most probably already renewable and cheap. Consequently, priority should be placed on finding new ways of substituting fossil energy carriers on the farm or in the surrounding areas. Examples are instruments that encourage the development of technology for cheaper small scale upgrading solutions and the use of raw biogas in tractors and other agricultural equipment currently using fossil fuels. Regional development plans for farm scale production, including a piping infrastructure and centralised upgrading could also contribute to finding a good use for the biogas in some regions.

6.4 Methodological implications

The development of models raises some dilemmas when it comes to level of details. A detailed model requires a large set of data, and sometimes the required data does not exist or is not completely fitted to, for example, the geographical scope or the technology in use. The application of data that is incomplete or has large uncertainties is not ideal, but it is in most cases acceptable compared with the option of avoiding the quantification of the aspects that are uncertain or setting those values to zero. Performing sensitivity assessments, as done both for the environmental and economic analysis in this thesis, does, however, show whether the conclusions are robust or not if other values are used. The development of models should thus not be avoided due to lack of data, but should be regarded as a tool to reveal where there is a need for more research. In the same manner, a model is never completely finalised, as one should aim to continuously improve the background data and functionality as knowledge evolves.

Methodological choices when performing environmental life cycle assessment and economic calculations have an impact on the results, and sometimes differences in approaches may lead to contradictory conclusions.

This study was performed with a resource conservation perspective, which was reflected in the definition of the functional unit in the LCA model and the economic calculations. The basis for all the case studies was the amount of organic resources available within a region or available for a biogas plant (organic waste and/or manure) and the treatment of those resources.

With a different perspective, for example a focus on the end-products biogas and digestate, the system boundaries and the functional unit(s) would have been defined differently. The results would then have been relating to the properties of the end-product. As both biogas and digestate have several possible end-uses (heat/electricity/fuel and fertiliser/soil improvement product), it is challenging to find one functional unit for each that can cover all application areas.

The use of system expansion and assessing the function of treating the organic resources, as done as part of this thesis, is especially useful from the perspective of the possessor of the resources, the biogas plant (in the waste or agricultural sector) and for policy developers. Assessing the environmental impacts relating to functional units that quantifies the performance of the end products are useful for the actors that make the decision on whether or not to buy the product, or which product on the market to buy. As this work has shown that the use of biogas and digestate is of large importance, assessments of the functional and environmental performance of the end use of the products could be a useful continuation of the research. This should be combined with assessment of the economic incentives and barriers of transport companies and farmers with a need for fertiliser products.

Another methodological choice with large impact on the results is the use of marginal or average data for electricity and heat and the substitution of products on the market. Advantages of using a parametrised model is that it enables performing several assessments with different assumptions to test the robustness of the results.

A model with a consequential methodology would subtract the reference scenario (avoided emissions of alternative treatment of the organic resource) from the main scenario. In the environmental assessment of this thesis, a scenario based approach was chosen instead, meaning that the reference scenario is assessed separately, and conclusions are drawn on the basis of the difference between the scenarios assessed. The difference between the two systems assessed equals the subtraction of the second system from the first system, as illustrated by Finnveden (1999).

The work carried out as part of this thesis has shown that parametrised models combining environmental life cycle assessment and economic cost assessments can serve as decision support due to their ability to show the consequences of different value chain designs and political instruments. This can be a valuable contribution to policy development. The results in the case studied showed a clear relation between the existing political instruments and profitability of the actors. This implies that the type and magnitude of the instruments are of large importance to obtain viable value chains and to lead the development in the right direction to obtain the political objectives.

7 Conclusions

Based on the results and the discussion, the conclusion for each research question of this thesis is presented below.

What are the most significant environmental impacts from Norwegian biogas value chains? (RQ1)

The most significant environmental impacts from Norwegian biogas value chains relate to the use of the biogas and digestate, principally due to the potential substitution of fossil energy carriers and mineral fertiliser. The most advantageous use of the biogas is as a transport fuel and the most favourable use of digestate is as fertiliser. This requires a high level of sector integration (waste, transport and agriculture).

In biogas value chains with large diffuse emissions or large emissions from storage of the digestate, these emissions may represent a substantial contribution to the overall environmental impacts.

It should also be noted that waste should not be generated for the purpose of producing biogas, as avoiding waste always is a better option in an environmental perspective.

***What are the economic drivers and barriers in design of biogas value chain designs, and how do they influence environmental impacts?* (RQ2)**

The actors and the literature describes challenging economic conditions for biogas production in Norway. The economic assessment carried out as part of this thesis did, however, show a net profit for most biogas value chains. Some of the important drivers, such as the price for treatment of organic waste (gate fee) and income/avoided costs from the sales of energy generated and sales of biomethane can vary largely and are often negotiated prices that are normally not available to the public. In addition, there is a lack of knowledge regarding start-up costs and unforeseen costs during operation of biogas plants in Norway. In the case of large scale biogas plants, the most important income is from treatment of the waste, while for the farm scale plant, the most larges income origins from the newly introduced support per tonne manure for biogas production. These are important drivers for increased biogas production, but they do not directly affect how the biogas and the digestate are used.

Even though use of biogas as a transport fuel is the most beneficial option in terms of reduction of environmental impacts, upgrading of the biogas to fuel quality is only economically profitable under certain conditions: for the largest scale plants or plants who can obtain a high price when selling the biomethane. It appears, however, that only a small additional incentive is necessary to make this option the most profitable for most plants.

With regards to inclusions of the agricultural sector into the value chain, however, the transport and storage costs of manure and digestate represent a barrier, and larger incentives are necessary to make this option as profitable as the alternative for the large-scale plant.

To achieve increased use of manure for biogas production, supply of manure to centralised biogas production appeared to be the most profitable option for cattle and pig farms, depending on the agreement between the centralised plant and the farmer. Farm-scale biogas production can also be a profitable option, as a result of the governmental support per tonne manure for biogas. An increase in the knowledge regarding the economy of farm scale biogas production would make the results from the economic assessment more robust and reduce the economic risk.

***How can policies and regulatory measures influence the decisions of the actors, and how does this in turn affect the environmental impacts?* (RQ3)**

The work done in this thesis shows that the existence and design of biogas value chains in Norway are largely affected by the structural conditions and the regulatory system.

Investment support has contributed to an increase in the number of biogas plants in Norway. While this can lead to the fulfilment of the political objectives of increasing biogas production, it does not contribute to incentivising the most environmentally advantageous use of biogas and digestate.

The exemption from CO_2 tax and road fees for biogas as a transport fuel do contribute as an incentive to the most environmentally favourable solution for biogas. There are, however, no political instruments specifically targeting the most beneficial use of digestate, although the support per tonne manure for biogas production will facilitate a connection between the waste and agriculture sectors.

The effect of the support per tonne manure is not visible yet, as it has been introduced recently. The economic calculations showed that this measure potentially can lead to an increase of biogas produced from manure in the future.

Under which conditions should livestock manure be used for biogas production in Norway, when should farmers invest in farm scale biogas plants and when should manure go to centralised biogas production? (RQ4)

Manure should be used in centralised anaerobic digestion where biogas is sold as a fuel for transport and the digestate is returned to agriculture in the regions where this is a viable option. This is because it is likely that the transport distances will be restricted by costs before the emissions from transport cancel out the environmental benefit of using biogas in the transport sector. If centralised biogas production is not possible, small scale biogas production is a viable option, but efforts should be made to improve the efficiency of farm scale biogas plants and avoid diffuse emissions as well as those from storage.

The conclusions drawn from the responses to the research questions confirm the thesis statement:

Increased and optimised biogas production will reduce environmental impacts, but specific policy instruments are necessary to motivate the actors to choose the environmentally preferred solutions.

It can be concluded that using organic waste and manure resources to produce fuel for transport and fertiliser products is under most circumstances a desirable option in terms of the reduction of environmental impacts in Norway. The existing political measures represent important drivers, but some improvements in the regulatory system can be done to improve existing and future biogas value chains. The results and discussion in this PhD thesis leads to the following recommendations for policies to reduce environmental impacts and achieve the political objectives:

- *Current support system should be maintained and strengthened.*
- *Public procurement should be used as a driver to increase anaerobic digestion of waste resources and to increase demand for biogas as a fuel for transport.*
- *An increase in the taxes for fossil fuels should be considered.*
- *Incentives should be developed for the use of digestate in agriculture and for existing and planned centralised plants to include manure as a substrate.*
- *The economic risks for farm scale biogas production should be minimised.*
- *Technology development should be promoted to find a better use of the biogas at the farm and develop affordable systems for centralised upgrading.*

The goal for the future should be the creation of sustainable markets that are not dependent on subsidies.

The results showed a clear relation between the profitability of the actors in the value chain and the existing political instruments. This shows the importance of knowledge about the environmental and economic effect of different types of instruments when developing policies to obtain the political objectives. The application of the models developed as part of this thesis has shown that models combining environmental life cycle assessment and economic cost assessments can be useful for decision support and can make a valuable contribution to policy development.

8 Future research

The model developed as part of this thesis can be improved, for example with regards to better data, the addition of more substrates and options for treatment and use, as well as improved functionality. Some of the knowledge gaps and potential advances are described below.

There appears to be a need for better documentation on the environmental impacts from biogas as a fuel compared with other transport fuels. In addition, more research is required into the quantification of emissions from the storage and spreading of digestate, and on ways of reducing them. These emissions are of major importance when looking at the overall environmental impacts of the value chain. Moreover, there is a need for a greater understanding regarding the properties of digestate as a fertiliser, such as the fertilising effect, carbon storage and other contributions to soil quality. Increased efforts should be made concerning reduction of the costs of handling digestate and the technological development of customised fertiliser products to meet the market needs. Additional research should also be carried out on the emissions from dewatering and composting of digestate, and the extent to which dry digestate can be a substitute for peat.

Practical experience and actual data for operation and costs of Norwegian biogas plants are not freely available. Collection of data from Norwegian plants over several years should be considered, to give a better basis for estimating the environmental impacts from future biogas plants and as a measure to share knowledge and experience between the actors in the biogas industry.

In order to obtain a better understanding of the barriers to increasing the amount of manure to biogas production, there is a need for greater knowledge regarding costs and other barriers for farm scale plants. More research and development is required to find a good use for the biogas on the farm and to develop less costly solutions for the transport of raw gas for central upgrading.

The economic assessments could in the future be expanded to include the economy of actors in the transport sectors and of farmers receiving digestate. In addition, the environmental performance of biogas as a fuel and digestate as a biofertiliser compared to other products on the market should be documented, to provide decision support for those actors.

Last, but not least, the models developed as part of this PhD thesis should be applied and updated continuously to reflect the latest knowledge and to maintain their relevance as decision support tools. As the emphasis in this study was on the biogas value chain, only one reference scenario was included per substrate, representing the most common alternative. To be able to assess the organic resources in a valorisation perspective, other treatment routes of the organic resources, such as for example the use of food waste as animal feed, should be included in further developments of the models.

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10 Appendices

Paper 1 Lyng, K.-A., Modahl, I.S., Møller, H., Morken, J., Briseid, T. & Hanssen, O.J. 2015. The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. - International Journal of Life Cycle Assessment 20: 490-502. DOI: 10.1007/s11367-015-0851-5
Paper 2 Lyng, K.-A., Stensgård, A.E., Hanssen, O.J. & Modahl, I.S. Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains. A case study on different levels of sector integration - Journal of Cleaner Production. (Submitted)
Paper 3 Lyng, K.-A., Nielsen, L.S., Jacobsen, H.K. & Hanssen, O.J. The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark. - Energy Policy. (Submitted)
Paper 4 Lyng, K.-A., Hanssen, O.J., Stensgård, A.E., Callewaert, P. & Bjerkestrand, M. Optimising anaerobic digestion of manure resources on a regional level. - Sustainability. (Submitted)

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