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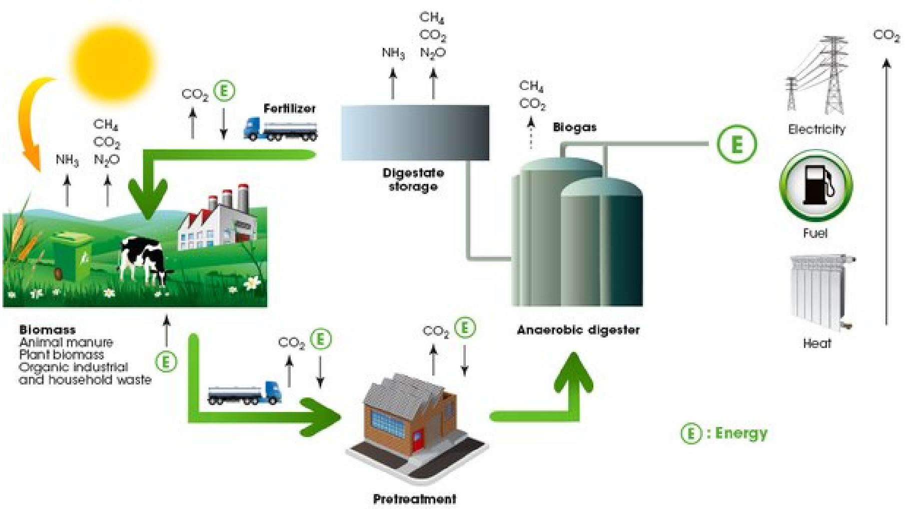
PH.D. THESIS

BIOGAS VALUE CHAIN – MICROECONOMIC INCENTIVES AND POLICY REGULATION

LISE SKOVSGAARD NIELSEN



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PREFACE

This thesis has been submitted to the Department of Management Engineering at the Technical university of Denmark (DTU), in partial fulfilment of the requirement for acquiring the PhD degree. The work has been supervised by Henrik Klinge Jacobsen (DTU) and Nina Juul (DTU). The PhD study has been funded by the Danish Council of Strategic research as part of the interdisciplinary research project BioChain and was conducted from August 2013 to March 2018. The thesis consists of two parts. The first part introduces the thesis background and motivation. It gives an overview and discussion of the theory and methods applied, followed by a summary and discussion of the achieved results. The second part is a collection of the five research papers that have been written during the PhD study.

Lise Skovsgaard Nielsen

March, 2018

ENGLISH SUMMARY

Recently, climate change issues have gained more importance on the international agenda, increasing the willingness to decrease GreenHouse Gas (GHG)-emissions. The European Union (EU) targets GHG-emissions with country goals for CO_2-emissions, Renewable Energy production, and Energy savings. Denmark is far ahead with development of renewable energy production primarily through wind power, which is an inflexible type of power production. Biogas is a renewable fuel that could function as regulating power, and when based on manure, it potentially has a reducing effect on GHG-emissions.

Biogas has been produced and developed in Denmark since the 1970's; however, the development has been rather slow until 2012, when regulation was changed, thereby increasing profitability for biogas producers. The focus for this dissertation has been to evaluate the private economic consequences for the biogas value chain under this new regulation.

This dissertation will examine the private economic challenges regarding value chains, the feasibility depends on economic support. The game theoretic implications are analysed, when support in one part of the value chain is contingent on actions in other parts of the chain. It is also examined how regulatory restrictions such as monopoly regulation can affect choices made in other parts of the value chain. It is shown that regulation affects the value chain decision in several ways regarding input types, the level of output, and final applications of the output.

The overall research question for this thesis concerns the private economic profitability in the biogas value chain with focus on regulation, risk and ownership structures. The questions are treated in four journal papers based on a combination of microeconomics and policy analyses. A socio-economic analysis regarding the value of biogas in the energy system is performed through energy systems modelling in a fifth journal paper.

Most new biogas plants and several old plants chose to upgrade biogas, even though model results imply that direct use in a Combined Heat- and Power plant (CHP) might be at least as profitable as upgrading. Cooperative game theory is applied together with private economic modelling and policy

analyses in order to explain this development.

Both quantitative and qualitative analyses are applied, based on microeconomic theory, to extract the main risk factors facing the biogas value chain and to explain the private economic incentives behind the choices made by investors regarding inputs, scale and output.

This dissertation has contributed several results regarding the interaction between public regulation, private incentives, and profitability of the value chain. Specific contributions are analyses considering the interaction of flexible regulation with regard to biogas inputs, and risk for producers with suggestions for policy design. In addition, the potential value of biogas in the energy system is analysed in comparison to CO_2-damage cost. A contribution is furthermore, the application of cooperative game theory on the value chain, illustrating how choices made regarding value chain design and participation can be explained by strategic behaviour and possible profit allocation.

DANISH SUMMARY

I de senere år er klimaforandringer blevet mere nærværende på den internationale dagsorden, og viljen til at reducere drivhusgasemissionerne er steget. EU har adresseret drivhusgasemissionerne med landemål for CO_2-reduktionskrav, produktionsmål for vedvarende energi og energibesparelser. Danmark er langt i udviklingen af vedvarende energi, primært gennem den ufleksible vindkraftproduktion. Biogas er vedvarende, kan potentielt fungere som reguleringskraft, og baseret på gylle kan biogas potentielt have en reducerende effekt på drivhusgasemissionerne.

Biogas er produceret og udviklet i Danmark siden 1970'erne. Udviklingen har dog været langsom indtil 2012, hvor reguleringen blev ændret, hvormed rentabiliteten blev øget for biogasproducenterne. Fokus for denne afhandling har været at evaluere de privatøkonomiske konsekvenser for biogasværdikæden i henhold til denne nye regulering.

Gennem denne afhandling undersøges privatøkonomiske udfordringer vedrørende værdikæder, som er afhængige af økonomisk støtte. Spilteoretiske implikationer analyseres, når støtte i en del af værdikæden er betinget af handlinger i andre dele af kæden. Det undersøges også, hvordan lovgivningsmæssige begrænsninger, såsom monopolregulering, kan påvirke valg i andre dele af værdikæden. Det er påvist, at regulering påvirker værdikædens udformning på flere områder: vedrørende inputtyper, produktudbyttet og de endelige anvendelser af produktet.

Det overordnede forskningsspørgsmål for denne afhandling handler om den privatøkonomiske rentabilitet af biogasværdikæden med fokus på regulering, risiko og ejerskabsstrukturer. Spørgsmålene behandles i fire artikler baseret på en kombination af mikroøkonomi og politikanalyse. En socioøkonomisk analyse af værdien af biogas i energisystemet udføres gennem energisystemmodellering i en femte artikel.

De fleste nye biogasanlæg og flere gamle anlæg har valgt at opgradere biogas, selvom modelresultater indikerer, at direkte anvendelse i et kraftvarmeanlæg kan være mindst lige så rentabelt som at opgradere. Kooperativ spilteori anvendes sammen med privat økonomisk modellering og politisk analyse for at forklare denne udvikling.

Både kvantitative og kvalitative analyser anvendes på baggrund af mikroøkonomisk teori for at forklare de privatøkonomiske incitamenter bag investorernes valg vedrørende input, skala og output samt udpege de vigtigste risikofaktorer, som biogasværdikæden står overfor. Denne afhandling har bidraget med resultater vedrørende samspillet mellem offentlig regulering, private incitamenter og rentabilitet af værdikæden. Specifikke bidrag er forslag til politisk design og analyser af samspillet mellem fleksibel regulering med hensyn til biogas input og risiko for producenterne. Desuden analyseres den potentielle værdi af biogas i energisystemet i sammenligning med CO_2-udledningsskadesomkostninger. Et yderligere bidrag er anvendelsen af kooperativ spilteori i forhold til værdikæden, der illustrerer, hvordan valg vedrørende værdikæde design og deltagelse kan forklares af forhandlingsstyrke og mulig fortjeneste.

ACKNOWLEDGMENT

This thesis concludes a four-year period during which, I have been blessed with an extensive level of new knowledge and challenges; while at the same time I felt that I was on the right track. For this, I can thank both my colleagues and my family.

I would like to thank my main supervisor professor Henrik Klinge Jacobsen, for always telling me, that everything was all right, and I did not need to worry. I would also like to thank Henrik for asking the right and sometimes annoying questions regarding results or, when I had a brilliant idea; and I also thank him for watching my back, so I did not start too many other time consuming projects next to the thesis. I would also like to thank him for our supervisor meetings which always ran late, as we also had to work around our lives in general and an interesting, perhaps not so thesis-related, theoretical discussion.

Thanks to Nina, my co-supervisor for converting a post-doc position into a PhD, for introducing "work and writing focus"-tools into my work; and for leaving her plans for the day in order to help me out breaking the code to a puzzle in an assignment.

Of course, thanks also to Ida Græsted Jensen, my roommate and colleague on the BioChain project. Thank you for good collaboration, moral support and fun at the office; without you, my office and work would have been much lonelier. I have been blessed with many good colleagues, who have provided me with both academic support as well as interesting conversations and cake; thank you for that.

Of my colleagues I would in particular like to thank Marie Münster as a partner in the Biochain project and also for her academic as well as moral support; besides enrolling me into the Future gas project. In general, I would like to thank all my project partners in the Biochain project for good company during our project meetings, and for help with data. In particular, I would like to thank Lone Abildgaard for all the data provided to us.

I also would like to thank all my co-authors of whom in particular I would like to mention Kari-Anne Lyng, who agreed on a fast paper during the summer holiday, and of course, Ida Græsted, Henrik Klinge as well as Alessio Boldrin and Jin Mi Triolo.

I thank all the helpfull employees at the governmental agencies in general, who were always willing to help and provide me with as much data as possible. In particular, I would like to thank the Biogas task force that have provided me with data that was highly relevant for my work, and finally, thanks to Søren Tafdrup.

Furthermore, I would like to thank all my good colleagues at the Future Gas project, giving me something to look forward to, in particular Professor Poul-Erik Morthorst and Tara Sabbagh Amirkhizi.

Finally, I would also like to thank my family, in particular thanks to my wonderful daughters, Maja and Cecilie for reminding me that there are other things to life than biogas, and for demanding my attention, when a problem bothered me. And last, but not least, thanks to my husband Jens Kromann, for supporting me throughout my thesis, for his patience, and for giving me extra flexibility when needed; for pushing me and for telling me to calm down when needed. I also thank him for helping me with technical insight, at skewed hours.

List of publications

Articles included in the thesis

Paper A: A. Boldrin, K.R. Baral, T. Fitamo, A.H. Vazifehkhoran, I.G. Jensen, I. Kjærgaard, K.-A. Lyng, Q. van Nguyen, L.S. Nielsen, and J.M. Triolo. "Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting". In: *Energy* 112 (2016). ISSN: 03605442. DOI: 10.1016/j.energy.2016.06.068

Paper B: Lise Skovsgaard and Henrik Klinge Jacobsen. "Economies of scale in biogas production and the significance of flexible regulation". In: *Energy Policy* 101 (Feb. 2017), pp. 77–89. ISSN: 03014215. DOI: 10.1016/j.enpol.2016.11.021. URL: http://linkinghub.elsevier.com/retrieve/pii/S0301421516306176

Paper C: Kari-Anne Lyng, Lise Skovsgaard, Henrik Klinge Jacobsen, and Ole Jørgen Hanssen. "The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark". 2018, *ready for submission*

Paper D : Ida Græsted Jensen and Lise Skovsgaard. "The impact of CO2 -costs on biogas usage". In: *Energy* 134 (2017), pp. 289–300. ISSN: 03605442. DOI: 10.1016/j.energy.2017.06.019. URL: http://www.sciencedirect.com/science/article/pii/S0360544217310113%7B%5C%%7D5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0360544217310113

Paper E: Lise Skovsgaard and Ida Græsted Jensen. "Recent trends in biogas value chains explained using cooperative game theory". 2018, *re-submitted to Energy Economics*

Other relevant work throughout my thesis

Conference paper: Lise Skovsgaard and Henrik Klinge Jacobsen. "Economies of scale in biogas production and supporting regulation". In: *IAEE Energy Forum*. Antalya Special Issue. 2015. DOI: 10.1016/j.enpol.2016.11.021

Conference presentation: Lise Skovsgaard. *RERC Conference 2014 June 16-18: The combined effect of regulation and support in agriculture and energy, related to biogas production*. 2014

Report: Lise Skovsgaard, Tara Sabbagh Amirkhizi, Poul Erik Morthorst, Christian Rutherford, and Alexander Kousgaard Sejbjerg. *Markets and regulation: overview over Danish and EU tariffs*. Tech. rep. 2017, pp. 1–51

Contents

Abbreviations and word explanations

BIOGAS	Biological gas produced through anaerobic digestion
BIOMETHANE	Upgraded biogas, meaning biogas, where CO_2 have either been removed or H_2 have been added and thereby converted the excess supply of CO_2 to CH_4
CAC	Command and Control regulation
CAPEX	Capital expenditures
CHP	Heat- and power plant
CH_4	Methane
Digestate	Degassed substrate after biogas production, often a mix of manure and a co-substrate
EU-ETS	The EU Emissions Trading System
EQ	Equation
GHG	Green house gas
HHV	Higher Heating Value or Upper heating value relates to the maximum of energy produced during combustion. HHV includes the energy produced when the water vapour from combustion is condensed. LHV (Lower Heating Value) does not include energy from the condensed water vapour. In Denmark are fuels mostly traded after HHV but regulated (meaning taxed or subsidised) following LHV
HRT	Hydraulic Retention Time, which is the average time period in which the biogas substrate is digested in the digester, retention time is typically lower in thermophilic– compared to mesophilic digestion

IR	Individual rationality
IncReg	Incentive regulation
K	Potassium, K is derived from Neo-latin: Kalium
Linepack	Linepack is the storage gained in the gas grid through pressure
Mesophilic	Is a lower temperature area in biogas production in the area of 20-45°C
NG	Natural gas
N_2O	Laughing gas or Nitrous oxide
N	Nitrogen
NPV	Net Present Value
OW	Organic waste, defined as source separated food waste from households and solid organic waste from the industry and service sector
OPEX	Operational expenditures
RES	Renewable Energy Sources
P	Phosphorus
s.t.	Subject to, commonly applied in optimisation problems, max y s.t. x and z
PTG	Power To Gas, electricity is converted into H_2 through electrolysis
Thermophilic	Is a higher temperature area in biogas production in the area of 41-122°C
Vertical Integration	When different parts of a value chain are integrated, e.g. if a shoe factory buys a leather production plant, instead of just buying the leather from the plant

Part I

Economic implications of Danish biogas regulation

CHAPTER 1

INTRODUCTION

Climate change has in recent years gained in importance on the international agenda, and actual changes in the climate have become more and more evident for most people. Large investments have been made in sustainable energy production as replacements for fossil energy usage, and new technologies are developed along with political targets for greenhouse gasses (GHG)-reduction and renewable energy production. Biogas production has the advantage of turning waste products with large GHG-emissions (from N_2O and CH_4) into a renewable fuel, and thereby replace CO_2-emissions from fossil fuels *and* reduce GHG-emissions, when laughing gas and methane is converted into CO_2.

With the Energy Agreement in 2012 [27], biogas was one of the renewable fuels that was targeted even more than before; and a biogas taskforce was initiated in order to kick-start a higher production of biogas and identify the more important challenges for biogas production. The taskforce should then consider whether further initiatives are necessary, to achieve the decided goals. The focus of this thesis is similar; however, the approach is with a more theoretical viewpoint.

The aim of this thesis is to get a better understanding of the private economic challenges facing the biogas value chain with a microeconomic focus regarding regulation, scale, risk and profit allocation. The approach is with regulatory glasses to investigate and evaluate the options (as well as the challenges) faced by either the biogas plant or the value chain.

1.1 Research focus

There is a long tradition for biogas production in Denmark, mostly connected to the extensive agricultural sector, where manure have been degassed. However, biogas production is expensive, and it has not proven feasible to produce biogas in Denmark without a high level of support.

The objective of this PhD study is to evaluate current regulation surrounding the biogas value chain[1], to identify economic challenges for the biogas producer, and potentially suggest possible solutions taking overall political goals into consideration. Attention is given to the entire value chain; however, the focus will be on micro-economic incentive and policy regulation. In particular where regulation can interfere with economic efficiency related to e.g. economy of scale, input- and output options, or profit allocation. The following questions are addressed in the PhD:

1. Both the energy- and agricultural sector are highly regulated — nationally as well as internationally. How does existing regulation affect the biogas production and can a more efficient production be achieved by changing regulation, while still keeping biogas production profitable?
2. The biogas value chain encompasses a great variety of ownership structures, input- and output markets; some with perfect competition, some with monopoly. How does this mix of market- and ownership structures influence the biogas value chain?
3. Risk is a recurring issue in relation to biogas production in terms of risk on input cost and availability, output demand variation and price, and particularly on changes in regulation. Which risk factors are most influential on the biogas value chain, and how may this be addressed?

Biogas production contributes with several positive externalities in the form of reduced smell, improved usage of the nutrients from manure and CO_2-reduction; furthermore, biogas production can solve waste treatment challenges and deliver renewable energy to the energy systems. I have *not* tried to estimate a value of these externalities; instead I have focused on the private economic profit optimisation for the biogas plant or value chain, in order to explain some of the mechanisms and decisions we see in Danish biogas production. Finally, I have studied how biogas would be applied in the socio-economic best way in the energy system, given estimates on CO_2-reduction from biogas and CO_2-damage costs found in the literature.

The microeconomic analyses regarding biogas regulation is concentrated on the effect of a given regulation and an assessment of the tools related to targets: *more than an attempt to design the optimal regulation*. The biogas value chain is complicated and involves many stakeholders [81]; and, private economic

[1]The value chain concept applied in this study can be understood as a supply chain or more generally be described as a set of activities; performed by a group of production entities in order to deliver a product or service for the market, for a further description see section 3.1

analyses are focused on the understanding of current developments for Danish biogas value chains, *rather than to find the optimal value chain design*.

1.2 Research context

Biogas production has developed significantly in Denmark since the start of biogas production in the late 1970s [81]. The development in biogas production was slow until a significant change in biogas regulation was agreed upon with the Energy Agreement in 2012 [27]. The Energy Agreement [27] focused in general on the fulfilment of the European 2020-goals, and the movement of Danish energy consumption towards fossil independence by 2050. Regarding biogas production, a biogas taskforce was established in order to aid the development of Danish biogas production. Greater support was agreed upon, and probably most importantly, biogas support was directed towards applications, such as direct use in industry and biogas upgrading, in addition to the existing support of biogas for direct use in local heat and power production (CHP). Poeschl, Ward, and Owende [103] identified Biomethane for utilisation in the transport sector as the most promising application of biogas in the future Germany. Similar conclusion have been made by the Biogas Taskforce [37]; an earlier analysis from the Biogas Taskforce in february 2014 [20] concludes that upgrading is most feasible from a private economic viewpoint, while direct consumption in a local CHP is most feasible from a socio-economic viewpoint at least in the short run. Since the Energy Agreement was ratified by EU in 2014 [46] biogas production has increased significantly and the projection is that it will increase even further–maybe even exceed the most optimistic projection presented in figure 1.1 of 20 PJ by 2020. From the figure, it is clear that most of the additional biogas is upgraded to biomethane and transported through the natural gas grid.

Danish biogas has been examined both socio-economically[65, 83, 32, 34, 66, 67, 20, 97, 36, 124] as well as from a private economic perspective [101, 17, 81, 66, 20]. The positive externalities have also been highlighted, see e.g. [59, 69, 80]. The analysis concern economic feasibility, biogas applications and e.g. compare upgrading to direct application in a CHP private economically and socio-economically see e.g. [20, 67]. citetJacobsen2014 further find that GHG-emission reductions are relatively cheap through biogas production compared to carbon reductions through biogas in Germany.

Other countries such as Germany, Austria and Sweden are also far in their development of biogas production [59]; and some of those do also upgrade biogas for the gas grid, such as e.g. the Netherlands [57], Italy [43] and Germany. Anaerobic biogas production is characterised by a vast diversity in *potential* inputs and applications; and even though there are parallels between substrate inputs, applications and regulation in Denmark and other European countries,

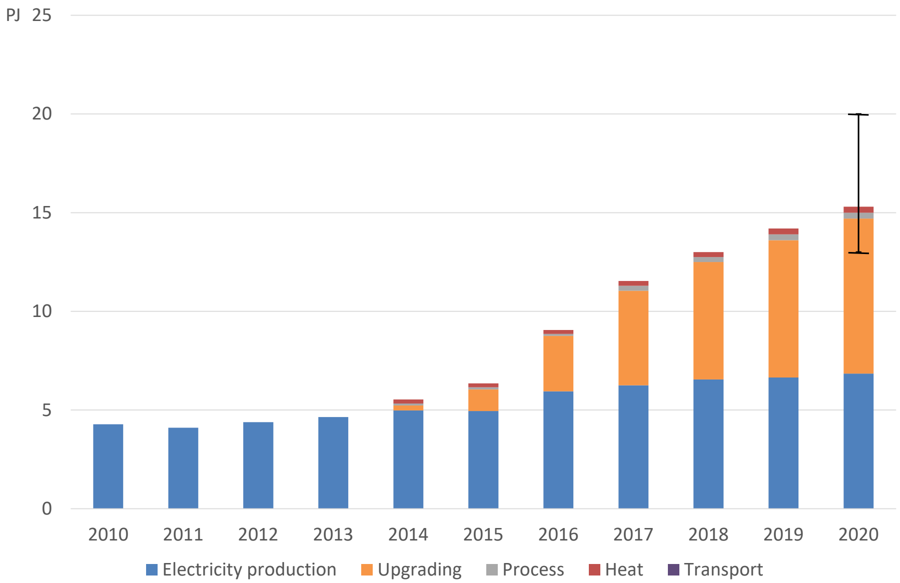

Figure 1.1: Development in Danish biogas production and consumption, data are actual data until 2016 and then projected data on the basis of planned investments in biogas plants and upgrading facilities; Source:[55]

the complexity of the value chains will typically entail a degree of country specifics, which can complicate cross-country comparisons.

1.3 Contributions and outline

The papers presented below deal with the research questions in various ways. They include plant- or energy system modelling together with costs of biogas and the role of biogas with regard to CO_2-reduction in various ways.

Paper A: "Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting". Nine cases are compared in this paper, with regard to the effects on private economic profit, GHG-emissions and the energy account. The cases include three plant sizes and three input variations over the mix of pig slurry and sugar beet. The overall conclusion was that economic feasibility is negatively correlated with sugar beet input, while the energy account and GHG reduction is positively correlated with sugar beet input.

Paper B: "Economies of scale in biogas production and the significance of flexible regulation". In this paper, the results from paper A were investigated

	Paper A	Paper B	Paper C	Paper D	Paper E
Economic incentives and value chain design		x	x		x
Energy- and environmental regulation		x	x	(x)	x
Risk		x			x
Plant- and energy system modelling		x		x	x
Cost of biogas	x	x		x	
GHG-emissions	x		x	x	

Table 1.1: Overall themes of the papers

further, now with focus on private economy, regulation and risk. The primary result confirm results from the literature, finding that there *is* economy of scale in biogas in Denmark. Even though transport cost can have a significant influence on the result, it does not seem to outweigh the positive scale effects from capital expenditures. The most significant factor is cost related to the co-substrate, sugar beet, compared to the biogas yield generated from applying this co-substrate.

Paper C: "The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark". In this paper, structural conditions, political goals and policies are compared between Norway and Denmark, and the primary result is that the viability of a value chain is highly dependent on structural conditions and the regulation applied directly on and around the biogas plant.

Paper D: "The impact of CO_2-costs on biogas usage". In this paper, we apply the energy system model, Balmorel, in order to investigate how the socio-economic optimal biogas use changes, when estimates for the socio-economic damage costs from CO_2-emissions are changed. The overall conclusion is that the socio-economic damage costs should be significantly higher than the current CO_2-quota price in the European ETS-system if biogas should be socio-economically feasible to use in the energy system; assuming that CO_2-reduction is the most valuable positive externality from biogas.

Paper E: "Recent trends in biogas value chains explained using cooperative game theory". In paper E, two optimal value chain designs are found using a plant level optimization model, and three profit allocation mechanisms are applied on these value chains. The results from the profit allocation and plant level optimization indicate several explanations as to why it can be difficult to get livestock farmers involved with biogas production if they do not invest in the plant themselves, and why so many biogas plants choose to upgrade to biomethane even when the optimal choice of value chain design seem to be local CHP production.

The remainder of this thesis is divided into two parts. Part I contains a background chapter, where relevant background information is briefly presented; a chapter on the theory and afterwards the methods applied in this thesis; a chapter on results and discussions; and, finally, concluding remarks and outlook. Part II contains the five papers briefly presented above.

CHAPTER 2

BACKGROUND

In the following sections, I expand my presentation of the context within which Danish biogas is consumed and producers operate.

2.1 Basics about biogas

Biogas is the term for renewable gas produced from an organic feed-stock, including both degassed manure, waste or waste water through *anaerobic digestion* or *gasification* of an organic material such as e.g. wood. It may even include *hydrogen from electrolysis* based on renewable electricity. All are renewable gasses with a number of properties. Throughout this thesis I primarily apply two terms:

- **Biogas**; defined as biogas produced through *anaerobic digestion*, mainly on wet substrates such as manure, waste water and other organic co-substrates. **Biogas** consists of approximately 65% methane and the rest is CO_2 plus a bit of H_2S and H_2; this gives a higher heating value (HHV) of approximately 25.9MJ/NM3
- **Biomethane**; defined as upgraded biogas cleaned from H_2S and where most CO_2 is either removed; or H_2 is added through methanation converting the CO_2 and H_2 into CH_4 and O_2. **Biomethane** in this sense consists of approximately 98% methane and the rest is typically CO_2 together with a bit of H_2; the higher heating value of biomethane is approximately 39MJ/NM3, which is somewhat lower than the average higher heating value for natural gas in the Danish gas system of approximately 43.8MJ/NM3

Biogas produced through *anaerobic digestion* can be produced on the basis of any organic material if you are patient enough. However, commercial productions prefer wet material and may add water in the pre-treatment process depending on the input substrates. *Anaerobic digestion* can operate within mesophilic temperatures around 35 °C and thermophilic temperatures around 55°C , where optimal retention time is both dependent on the input mix and production temperature. The exact specifications rely on *efficiency demands*; for example, if production should be within a given time frame and somewhat consistent; *economic feasibility*, e.g. for capacity, output prices and transport distances for feedstock; and *regulation*; examples are input- and output restrictions, support or taxation.

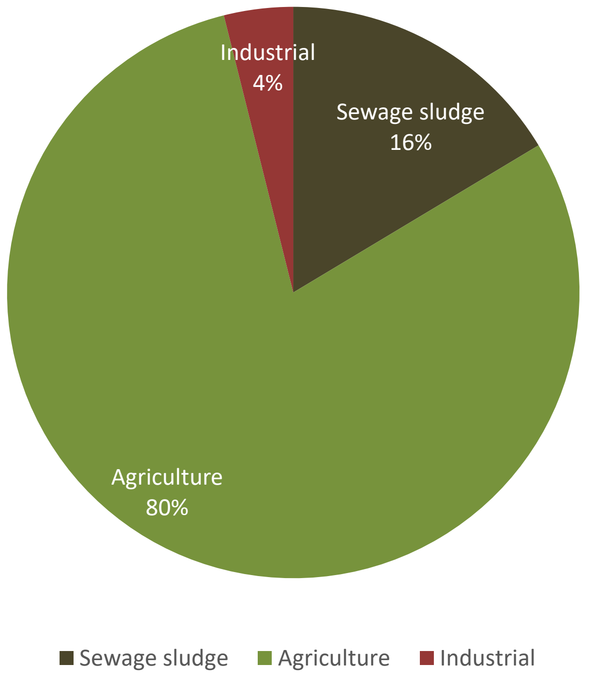

Figure 2.1: Primary feedstocks in Danish biogas production *Source:* [22]

Biogas production also yields a residual digestate containing a mix of the digested inputs. Depending on the input this digestate can be de-watered and composted, deposited as waste; or, if the inputs are sufficiently unpolluted, it can be reused as an improved fertiliser on agricultural soil. The advantage of the latter is that nutrients are recycled and the digestate serves as a valuable commodity instead of a waste product.

The biogas yield can vary over the year due to changes in input and the quality of the inputs; however, it is complicated to change the yield over a short time period. First of all, digestion lasts for a longer time (up to two months), if you want to change output in a week, the output depends on what you entered into the digester yesterday. Secondly, due to the delicacy of the anaerobic core bacteria in the digester, the bacteria risk dying with too much change in the input mix. Finally, there still is a lack of knowledge concerning *when* a given yield is gained from a given substrate[1].

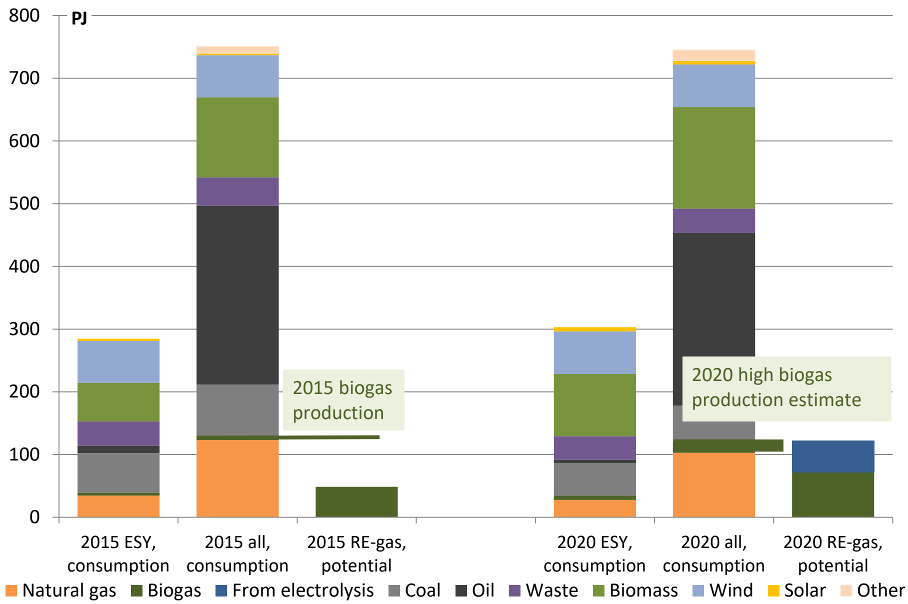

Figure 2.2: Danish biogas in relation to energy consumption and potential *Sources:* Fuel consumption estimates [18], Biogas production estimates[55], Biogas potentials ([35, 7] p. 49 and p. 4)

Biogas is expensive to store locally; therefore, most biogas plants only have storages that can contain less than or up to one day of production. Consequently, biogas is produced steadily and should also be consumed steadily. Biogas is therefore perfect for a constant producing industrial consumer or for upgrading, where the natural gas system can serve as an almost infinite storage. When it comes to CHP-production, biogas is more suitable as a baseload fuel and less relevant for seasonal determined production or temporal fluctuations.

[1] a model have been developed through the *Biochain project*, which specifically address this issue see e.g. [56].

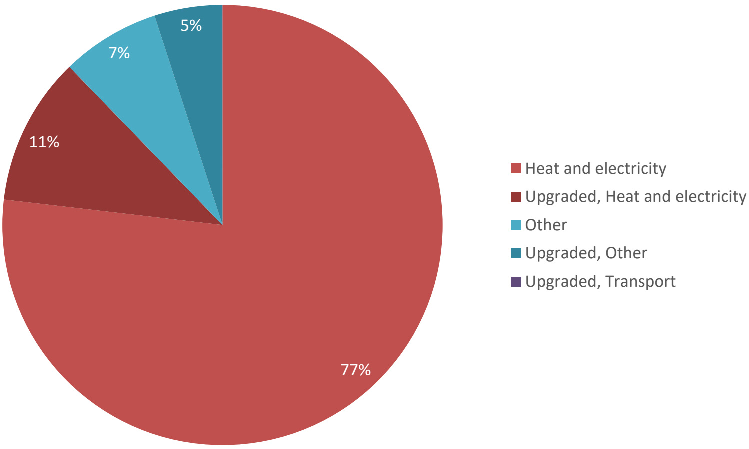

Figure 2.3: Primary application of Biogas in Denmark by 2015. Not all applications are clearly acunted for; also, *other* can in principle both include transport and flaring [18].

In figure 2.2 I present the Danish biogas production for 2015 together with expected production for 2020[55]. When this production is compared to Danish fuel consumption for the total gross energy consumption (all consumption, [18]) or even just the heat- and power sector (ESY,[18]) it becomes clear that biogas plays a very insignificant role in Danish energy consumption. Biogas could potentially play a larger role if the total potential was exploited (RE-gas potential[35, 7]). In fact, if all biogas was produced and upgraded with the addition of H_2 from electrolysis, biomethane could in principle replace the natural gas consumption in 2020. Recent unpublicised data imply that Danish biogas production may exceed 20PJ by 2020; however, we will not be even *close* to the expected natural gas consumption.

Data indicate that the Danish Energy Authority does not expect all biogas to be applied in the heat- and power sector by 2020, even though this is how biogas and biomethane predominantly have been applied, see figure 2.3. Overall I conclude that biogas and biomethane can function as a *supplement* in the future energy system, and maybe even substitute current natural gas consumption.

2.2 Energy– and agricultural markets

Biogas producers operate between several sectors, both with regard to inputs and output. In figure 2.4, the relevant sectors are presented and how they relate in the Danish biogas setting. In this section, I will present Danish agriculture and which markets the agricultural sector operates on, as most biogas in

Denmark is produced on the basis of agricultural residues, and the agricultural sector receives most of the digestate after digestion (see also figure 2.1). I will also present the electricity–, the heat– and the natural gas markets as heat- and power producers consume most of the biogas, while the natural gas price and market affect the biogas price and opportunities.

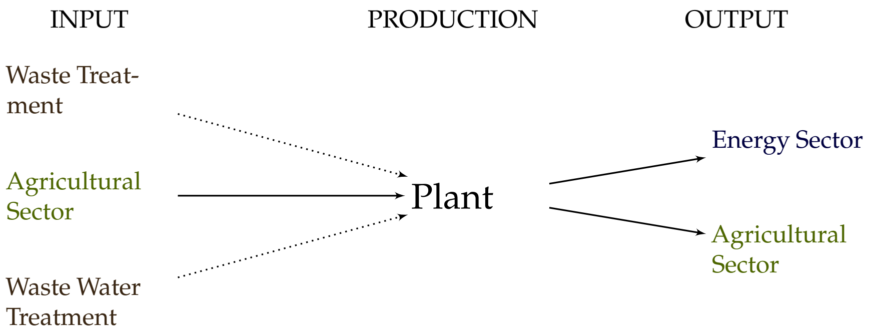

Figure 2.4: Sectors contributing to the biogas value chain

Danish agriculture

Danish agricultural production has a significant share of Danish commodity production, and includes a large variety of livestock farmers where pig- and dairy farmers comprising the largest part. The production is efficient, capital intensive and exceeds the Danish consumption substantially. Agricultural producers operate on international markets with a high level of competition and price volatility. These conditions can have several implications for the biogas production.

The agricultural production **is capital intensive**, due to high prices on agricultural soils and a highly industrialised production. This means a significant debt which can complicate investments in a biogas plant through a decreased willingness to risk on capital; even though it may seem profitable and the best way to obtain a reasonable profit from the biogas value chain, as presented in paper E. **Mineral fertilizers are currently rather cheap** compared to other cost factors in agricultural production, and even though digestate seems to have a positive effect on production compared to manure, this may be marginal compared to the alternative cost for mineral fertilizers. **Organic farmers** do not use mineral fertilizer as conventional farmers do, so to them, digestate represents an extra value. However, even though organic farming is increasing, it still represents a small share compared to conventional farming. **Quality and reputation of quality** is important, maybe in particular when you operate on international markets. Actors in the agricultural sector are therefore careful with regard to risking their reputation. Specifically, the Danish dairy sector has been reluctant to allow fodder produced on soil where digestate was spread, if this digestate contained organic waste from household separation[112].

Danish energy markets

The Danish energy system is founded in combined heat- and power production (CHP); central plants mostly fuelled by coal and wast together with decentral plants mostly fuelled by natural gas. Danish energy production as well as consumption is rapidly developing towards more renewable energy, with a large wind power capacity supplying more than 35% of Danish **electricity consumption**[23]. The increasing proportion of renewable **electricity production** through wind– and solar power increases the price volatility of electricity compared to earlier, when the primary electricity supplier were power plants that could ramp up and down, following the demand. Electricity prices are varying significantly through the day and year; even though the Danish energy system is well connected to neighbouring countries through inter-connectors; in particular Norwegian hydro power can help moderate the price peaks.

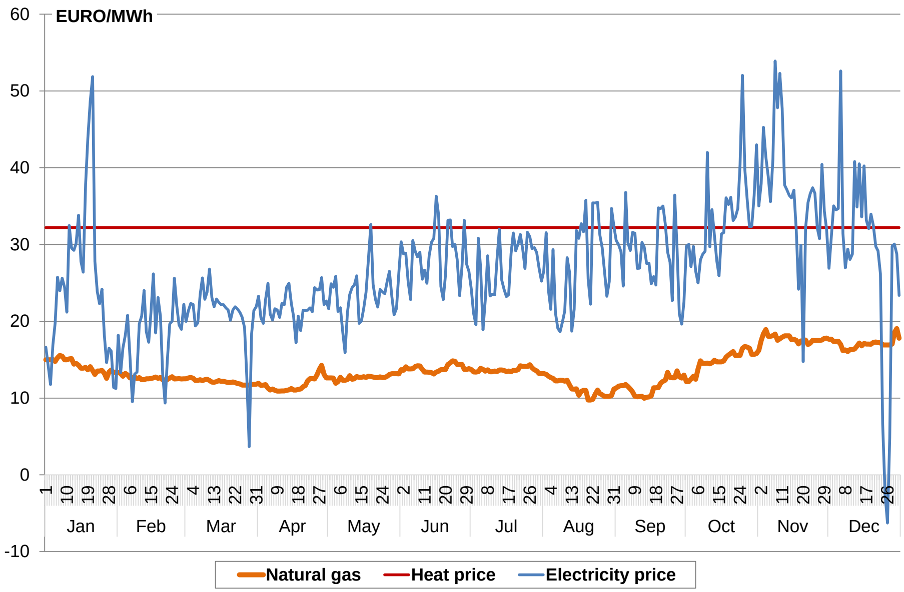

Figure 2.5: Danish gas and electricity prices for 2016 together with Vinderup heat price

Figure 2.5 depicts the day to day price variation for respectively electricity, heat and natural gas. The heat price, is the yearly regulated heat price for Vinderup district heating area, which is situated close to the applied geographical position of the model biogas plant used in most of my papers. District heating areas are natural monopolies and regulated as such following the cost of service regulation (*hvile-i-sig-selv in Danish*). The heat price usually does not vary within the year; however, as also indicated by figure 3 in paper E it can vary significantly over years and from area to area. In 2016, heat prices in Denmark varied from 20-171€/MWh [41] between heated areas.

The Danish gas grid is large and can supply major areas of Denmark; it is furthermore well connected to Germany and Sweden. Nowadays, the gas market is developing towards a more liquid market with increasing intra-day trading[40, 39]. Gas has traditionally mostly been traded through longer contracts, and price variations are typically yearly or seasonal. One reason for the low intra-day price variations is the nature of the gas system. Gas is directly storable and the gas grid function is a temporary storage through the line pack, where the available capacity is determined by volume and the controlled pressure in the grid. Therefore, gas , in contrast to electricity, has to be consumed almost instantly after it is injected into the grid. Gas consumption is currently decreasing, among other things, due to a decrease in the CHP-consumption as the consequence of looser CHP-regulation. Lower electricity prices have reduced the profitability of local CHP production, putting a pressure on regulators to loosen co-production requirements (for heat– and power) and allow for heat-only production from electric heat pumps and heat boilers or the currently very popular biomass-based heat boilers.

For biogas producers the potential consequence of the described development in the energy markets is that *district heat producers are more reluctant to use biogas* in heat- and power production due to the potentially higher heat costs. Furthermore, the less volatile gas market and "grid storage" through line pack can seem to be a better fit for the almost constant biogas production.

The current decrease in gas consumption may in time increase transport costs in the gas grids, as they are also a monopoly following the cost of service regulation. So, with a system where capital expenditures are a considerable part of total costs, a volume decrease will, all else being equal, tend to increase cost per Nm3.

2.3 Danish and European energy– and environmental policy

Both European and Danish energy– and environmental policy is extensive and complicated, based on targets for GHG-reduction goals in general, and specifically, with regard to the energy–, transport– and agricultural sectors. Furthermore, there are targets for renewable energy production and sustainability at the EU– as well as at the national level. On top of this, other EU regulations exist which try to restrict national countries from favouring own products compared to products from other European countries.

Below I will present the overall regulation, with regard to GHG-emissions, and renewable energy together with waste and waste water, which all affect biogas production.

Danish and European environmental policy

Danish regulation with regard to **water environment** is based on the European Water Directive [48] and the agricultural policy known as the European fertilizer decree [47]; both operate together with by overall principle that most potable water in Denmark should be untreated ground water pumped up from the subsoil. This means hard restrictions on water released into the environment, water from agricultural fields. And therefore also fertilizers dispersed on the fields. In Denmark, the water environment is regulated through nutrition accounts based on the bulletin on livestock [30] and water area plans (Vandområdeplaner (2015-2021)[29]).

Biogas production is not directly connected to water environment regulation; however, when manure is digested through biogas production, nitrogen is sometimes more easily absorbed by plants, and potentially less nitrogen is released into the water environment[80]. Furthermore, the phosphorus release differs from one manure type to another, so in areas with harsh restrictions on phosphorus discharge, can central biogas plants, mixing the manure, be a way to allow for more animals per hectare than would otherwise be allowed. With the Green Growth agreement in 2009, harder restrictions were set on nitrogen discharge, and a target was set that 50% of all manure should be digested through biogas production by 2020[26]. However, later versions of the agreement have decreased the restrictions on nitrogen discharge[16], reducing the value of biogas digestion from the livestock farmers point of view, and the 50% target is no longer official policy.

In Denmark, there is a long tradition for waste incineration in CHP-plants. Separation of organic waste and waste residues in private households is relatively recent in Denmark; however, it is increasing, and with the latest resource strategy [28] a target has been set at 50% **waste recycling** by 2022. This is a development that will probably be expanded with the European Circular economy package [44], and with the increase in source separation the usage of organic household waste may also increase in biogas production. Currently, organic household waste only accounts for approximately 1% of total biomass input, but this may change with new regulation underway. The bulletin regarding sludge [88] is under revision to ease the usage of organic household waste while still assuring that soil pollution will not increase at the same time.

GHG-emission is one of the larger environmental challenges, dealt with at the global, European and national level. At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The EU-countries have together committed the European Union to reduce GHG-emissions by at least 40%, compared to 1990 emissions. The common European commitment originates from an already initiated common European goal on GHG-emission reduction as a part of the 2020 goals from 2010, on a 20% reduction in GHG-emissions, a 20% renewable energy share of final energy consumption and a 20% increase in energy efficiency [45].

Each country within the EU contribute to the GHG-emission reduction with a sub-target that depends on the ability of each country to reduce emissions, both in terms of natural– and economic resources. EU policy with regard to GHG-emission reduction is comprised of two parts: one part that is covered by the European CO_2-quota system also known as EU-ETS, and another part that is covered by separate national goals targeting specific emitters that will not naturally form a part of EU-ETS. Emitters participating in the EU-ETS are large energy– and industrial producers. The agricultural– and transport sectors have historically been targeted in various ways outside the EU-ETS; however, as industry and energy production have become increasingly more efficient in GHG-emission reduction, do these sectors stand out to be targeted more efficiently.

Danish and European energy policy

European Energy policy is largely coloured by the GHG-reduction agenda combined with an urge to increase the security of energy supply, as many European countries are dependent on energy from outside their own boarders and outside Europe (more specifically Russia and the middle east); this does, also, to some extent apply to Denmark. Therefore the 2020-goals are targeting CO_2-reduction, renewable energy production and energy savings.

In Denmark there is no natural access to hydro-power production and as hours of direct sun are limited compared to countries in the southern part of Europe has solar power only just started to become profitable with the large reduction in production costs. Wind on the other hand is a large natural resource in Denmark, and wind power has been supported and expanded for a long time. Before the expansion of wind energy, Denmark was highly dependent on fuel based heat and power production. In 1978 a significant supply of oil and gas was found in the North Sea, and in 1979 the decision was made to put down a large and widespread natural gas grid [96]; in order to take advantage of the new gas supply. During the 1980's a focus on energy savings pushed forward a development of heat- and power production with both central and decentral plants. Central plants were to a high degree supplied with coal and waste for waste incineration, while decentral plants were mostly based on natural gas [96]. This means that Denmark today has a highly developed natural gas grid and a large supply of local heat distribution grids.

When biogas production started in approximately the same period as decentral heat– and power plants were built, it was natural that biogas would be used in local heat and power production; in particular, as biogas has also been applied for fuelling power production[58] in other European countries.

Danish heat– and power production has historically been heavily regulated by a co-production requirement for heat– and power, fuel constraints conditioned on geography, and cost-of-service regulation on heat production. Furthermore, fossil fuels, used for heat production, are highly taxed, along with CO_2-taxes; however, fuels used to run electricity production are untaxed. In return, electricity is highly taxed depending on how it is consumed; this has an impact on the efficiency of electricity consumption, hereunder for heat-pumps or electrolysis for upgrading of biogas to biomethane[2]. Heat production is a monopoly following the cost-of-service regulation with a focus on keeping heat prices down.

As the share of wind power production has increased, electricity based on co-production has become less profitable. This has been solved by a temporary support fee for CHP produced electricity (treleds-tariffen), and a loosening of the co-production requirement and fuel constraints, which have helped the current energy system to adjust to a new reality. It has; however, also allowed for a new investment wave in biomass-based heat production, which may not be sustainable in the long run, and, in the meantime, has reduced the competitiveness of biogas as a fuel in heat- and power production.

Biogas regulation

There are large varieties in the European biogas value chains. In Denmark, Germany, and the Netherlands, most of the input substrates for biogas are found in the agricultural sector [63]. In Norway, Sweden and Finland, most biogas is based on organic waste and sewage sludge [62, 98]; while in UK, Italy, Spain and France, most biogas originates from landfills [43]. In some countries, biogas production is driven by investment support and direct– or indirect support on the input; for example, Norway and to some extent Sweden. These countries together with Finland, do nevertheless also support the usage of biogas for transport. Most countries support biogas one way or another as output for transport, electricity production or other applications [76, 43, 66, 12].

In Denmark, biogas is primarily supported through feed-in tariffs or – premiums, sometimes assisted by temporary investment funds. The last investment fund was set up with the Energy Agreement in 2012 [27]. A

[2]Regulation regarding methanation as in: "upgrading of biogas by adding hydrogen from electrolysis" is further presented in appendix A in paper E

2016	Direct use			Udgraded
	CHP	Heat	Industry & transport	All uses
Unit	€/MWh	€/GJ	€/GJ	€/GJ
Feed-in tariff	108.6			
Feed-in premium	59.6		5.23	10.86
NG price dependent	45.0	4.5	4.5	4.5
Temporary	10.7	1.07	1.07	1.07
Total	**164.3**	**5.58**	**10.8**	**16.43**
Tax on gas for heating	0	0	0	9.6

Table 2.1: Direct– and indirect support for biogas in 2016, *sources:*[21, 115]

fundamental requirement for Danish biogas support is that the production is sustainable. This basically means that biogas should be based on waste substrates. Specifically, there is a limit on how much energy crops (e.g. maize and sugar beet) can be added as co-substrate. By 2018 the limit will be a maximum of 12% energy crops as co–substrate; prior to this, was 25% [19].

Until 2012, the Danish regulation followed some of the same principles as used elsewhere in Europe, with a feed-in tariff or –premium for produced electricity [43, 76, 12]. Since the Energy reform in 2012 [27], regulation has changed so that biogas upgraded to biomethane and sold on the gas market (through the gas grid) is put on the same regulatory footing as biogas used locally for heat and power production, while biogas used directly for industry, transport or heat production receive a lower support. One advantage of the Danish regulation is that support does not decrease with scale as it has done, for example, in Germany and Austria [33, 126]. There are no taxes on biogas used for heat production in contrast to biomethane, which is taxed the same way as natural gas.

The support tariffs for 2016 can be seen in table 2.1. The support has been approved by the EU and will last until 2023, when new regulations should be decided, and then approved by the EU. A part of the support will be phased out from 2016 to 2020 (the temporary fee) and another part of the support depends negatively on the natural gas price, which thereby reduces the risk of price variations for natural gas.

Summmary

Biogas can be produced from almost any type of waste preferably wet substrates. The technology is in principle simple and low-tech, on the other hand, delicate where a few wrong steps can break the whole process down. Biogas should be consumed constantly following production, and change in production takes time. In Denmark; if biogas is upgraded to biomethane it can be injected to the large natural gas grid and be stored infinitely.

This thesis is written in a transition period where both the energy system and the application of biogas is changing. The classic application of biogas is for heat- and/or power production. It could be argued that biogas is too valuable for this application as biomass, and that wind is in fact a cheaper substitute for respectively heat and power production. Biogas or biomethane may instead be utilised in industry and the transport sector, where cheap renewable substitutes are less easy to find. Such a transition to biogas consumption may need incentives for industry to change, and it would also demand a significant increase in gas fuelled vehicles, as they were almost non-existent in Denmark just a few years back.

I focus on the choice between direct consumption in a local CHP and upgrading. How upgraded biogas (biomethane) is applied is not a fundamental theme of this thesis. Currently, it seems that biomethane is applied in heat- and power production, this; however, may change, and I hope my work will contribute to the understanding of how changes in regulation can affect past, present and future developments.

Biogas is connecting several sectors; in particular, the agricultural, waste and energy sectors. These sectors all affect the environment concerning water quality and regarding carbon emissions, and are therefore also regulated in this respect. Biogas can have a positive effect on water quality and reduce carbon emissions; currently, this is acknowledged; unfortunately, only to a small degree encouraged. Instead most incentives are focused on the renewable energy production in the form of large subsidies for renewable power production such as Wind and solar power.

Together, with many other EU countries Denmark has traditionally focused the biogas support on biogas based electricity, whereas Danish regulation, in contrast to in other countries, has been supplemented with a sustainability demand, meaning that only a smaller share of the input substrates could be energy crops if the biogas should be supported. Since 2014 has upgraded biogas also been supported significantly, aiding the biogas production and consumption into its own transition period.

CHAPTER 3

THEORETICAL FRAMEWORK

The theoretical framework for this thesis is based on micro-economic theory with specific focus on industrial– and environmental economics. The standard assumptions from micro-economic theory of perfect information, perfect foresight and perfect markets do not hold when examining real world markets such as biogas. Therefore as the work in this dissertation focusses on applied theory, the theoretical topics circles around imperfect markets, lack of foresight, imperfect– and asymmetric information.

In this chapter a group of key concepts are defined, compared and discussed. The concepts and their implications are taken into consideration throughout the papers, some as background knowledge while others are investigated empirically through economic models or the following analyses.

3.1 Definition of key concepts

It can be difficult to make a clear definition of *a market* [122], so I will apply a broad definition stating that *a market is where goods and close substitutes are traded among more than two parties*[1] *within a geographical area, where the geographical expansion depends on transport options and –costs*.

The biogas value chain is affected by markets with varying degrees of competition [2] and monopolies. In the following pages I will difine how I will use the value chain concept in this thesis. This is followed by a short

[1]Meaning it is not a bilateral trade.

[2]Such as some agricultural markets, the electricity market and straw market.

introduction to a group of key concepts regarding the perfect market, economy of scale, market failures and ways of internalising these failures.

Value chain

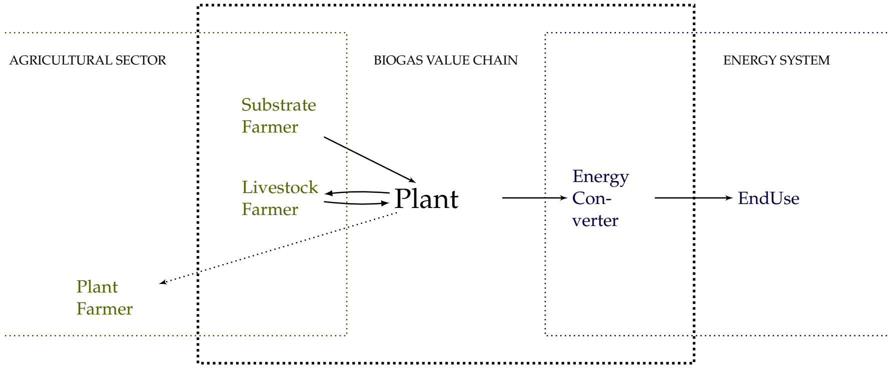

Figure 3.1: The biogas value chain

Figure 3.1 illustrates the primary parts of the biogas value chain within this thesis. The potential owners within the closed dotted square are those necessary to include in order to receive support for Danish Biogas.

The **value chain** can more generally be described as a set of activities performed by a group of production entities in order to deliver a product or service for the market. The concept applied in this thesis focusses on the value added from each production entity, where the value added is defined as additional measurable economic value of i products, while Q is quantity, C are costs and P is the price. Prices are not always easily defined in the value chain, but in principle the exchange from one entity to the next in the chain will be associated with a price.

$$ValueAdded = \sum_{i \in \mathcal{I}} P_i Q_i - \sum_{i \in \mathcal{I}} C_i \qquad \forall i \in \mathcal{I} \tag{3.1}$$

Each entity is considered autonomous and can produce one or more products. The focus in my thesis is on private economy: sometimes calculated for one entity, sometimes calculated or optimised for a chain of entities; these will be more specifically defined in each paper.

The **value chain** concept can also be considered as a decision support tool within a firm as described by Porter [104]; or even more widely in the form of Global Value Chains (GVC)[31, 50, 11], where, for example environmental, poverty and gender issues can be taken into consideration [11]. This thesis uses only the narrow economic definition described above and does not consider any of the broader concepts from Porter or on Global Value Chains.

Perfect markets

A market with **perfect competition** entails several prerequisites.

- It involves a large number of buyers and sellers that are each so small compared to the market that they are considered as *price takers*
- *Perfect information*, where all market participants knows all production and demand functions
- *perfect foresight*
- none, or at least negligible *transport and transactions costs*

Very few, or more correctly, no markets fulfil this completely: some agricultural markets, the stock market, and electricity markets are often considered as markets with close to perfect competition [122].

Most markets are more or less affected by **market failures**, so price and quantity are typically not perfectly optimal. Below, I present three types of market failures affecting the biogas value chain.

- *externalities* can be defined as non-priced goods or bads, whose effect on the social costs function is excluded from the optimisation of a given action (e.g. production of a good). Externalities can be exemplified as pollution or as reduction of pollution, an externality from degassed manure is the conversion of GHG-emissions (from N_2O and CH_4) into the less potent CO_2-emissions. This positive externality constitutes at the same time (as many other externalities) another market failure, as it is a *public goods*[3][84, 54, 122].
- *asymmetric– and lack of information* means that production– and consumption choices are made on the basis of incomplete information, and thereby risk is included in the calculation which essentially increases transaction costs. This is included in the thesis as the rationale behind public regulation, but the definition or correct internalisation of these externalities is not the main focus of the thesis.
- *market power* is when one or a few market players can affect the price(s) in the market, and they therefore are not price takers.

Imperfect markets

A **monopoly** is the extreme case of market power with only one supplier for the market. The monopolist is not a price taker, and optimises price or quantity so *Marginal Revenue equals Marginal Costs*, which result in higher prices than in the competitive market. **Oligopoly** is the intermediate between perfect

[3]Public goods are characterised as goods that are non-rivalrous and non-excludable.

competition and monopoly and price setting can be explained by Bertrand (oligopolistic price competition) or Cournot (oligopolistic quantity competition) where the result is a function of the number of suppliers to the market N. $n = 1$ gives the monopoly price, while $n \to \infty$ approaches the perfect competitive price see e.g. Mas-Colell, Whinston, and Green [84] chapter 12 or [122].

A high degree of market power for one or few suppliers/consumers can be the result of several things such as e.g. high transport costs, limited access to resources, lack of transparency or *increasing return to scale*.

Bilateral monopolies[4] can also occur; for example, in value chains where two parts of the value chain are specialised in order to serve each other, and in those cases it can be difficult to find efficient prices. The Myerson-Satterhwaite theorem states that it is impossible to achieve ex. post efficiency in bilateral trade in cases of private information [92]. Private information is often an issue in biogas, as e.g. a CHP cannot control the cost characteristics of the biogas plant, and the biogas plant cannot monitor and verify the probable demand for CHP outputs. Blair, Kaserman, and Romano [8] find disagreement in the literature with regard to finding an optimal solution for the quantity and price between bilateral monopolies. They end up concluding that the social optimal solution can be found only with joint profit optimisation, and that the price between the parties is a way to share the maximized profit. **Vertical integration**[5] can be a way to ensure joint profit optimisation and this will be discussed further below.

Another type of monopoly occurs when the long-run average costs curve continue to decline when the entire market is covered: these are called **natural monopolies** and appear when the production function involves an **increasing return to scale**. Infrastructural investments such as railways, roads and energy transmission are often natural monopolies. This type of infrastructure is often publicly owned and/or monopoly regulated in order to reduce rent seeking behaviour with excessive prices. The challenge is that the regulator does not know the *true* production costs, and is therefore challenged to discern the product price. A common monopoly regulation form for utilities in Denmark is "cost-of-service"-regulation in Danish "hvile-i-sig-selv" and the principle is that the utility should get the costs covered and nothing else. These utilities are usually consumer owned, owned by the municipality, the state or something similar in order to discourage the desire for rent seeking. The utilities are often monitored by the competition authorities [6] through benchmarking and similar monitoring. Other regulatory forms are e.g. Cost-plus (costs covered plus a little profit) or Yardstick regulation (a maximum price set from benchmarks).

[4] E.g. when a producer has a sole supplier, who only serve this producer.

[5] When parts of a value chain are merged, in the biogas value chain this could be a vertical integration between the biogas plant and energy converter: basically meaning that they get the same owner

[6] (In the Danish energy case by DERA (Danish Energy Regulatory Authority).

None of the regulation forms are optimal due to asymmetric information, it is; however, out of scope for this thesis to discuss any further.

Return to scale

Return to scale refers to how production costs change as the production is scaled up and down. *Constant return to scale* follows the assumption, that production can be scaled up and down in size without affecting production costs. A common production function applied in micro-economics is the Cobb-Douglas function and an example of this is presented in equation 3.2. Here would $\alpha + \beta = 1$ would result in *constant return to scale*.

$$Q = AK^{\alpha}L^{\beta} \qquad \forall \alpha, \beta \geq 0 \tag{3.2}$$

Q is quantity, A, α and β are constants, K is capital input and L is labour input. *Decreasing return to scale* would be when $\alpha + \beta < 1$, while $\alpha + \beta > 1$ results in *increasing return to scale* also referred to as ***economy of scale***, see [84] chapter 5.

Economy of scale often appears when there is a high degree of fixed costs; for example, in cases including large infrastructural investments such as in the case of district heating, where capital expenditures (capex) are a significant part of the cost function. There are plenty of examples for economy of scale e.g. when gas pipes are laid down, the highest costs concern the immersion of the pipes, while the diameter of the pipes is less cost-determinant, it is therefore easy to double production (in this case capacity through the diameter) without doubling investment costs. There is in general a tendency towards large investments that have lower cost per capacity units than smaller investment; this also counts for biogas investments.

Environmental economics

Several issues are described and discussed within **environmental economics**, and many of these overlap with industrial economics since both theoretical areas are founded in micro-economics. Here I will focus on **estimation of externalities** and **internalisation of externalities**.

To **estimate the economic value of an externality** is complicated as externalities in nature are unpriced goods and bads. *It has not been the scope of this thesis to perform any estimations on environmental benefits*, therefore apart from this short text below, I will not go into any further details on the estimation of the economic value of externalities. The purpose of estimating the economic value can be seen for example in the*socio economic analysis* of biogas: to determine the environmental value of a biogas plant, the production of biogas, and treatment of manure see e.g. [66, 124, 34]. To estimate the economic value of an externality can also be a tool for **internalising** this externality.

Estimates relate to the costs of restoration after an environmental damage (if possible), adaptation costs or Social Costs of damage. An approach, often applied in socio economic analysis and other comparative studies, is to use an already existing alternative price for a given action. A common example of this is an approximation of CO_2-externality costs to be the CO_2-quota price from the EU-ETS market. The basic assumption behind this is either that the amount of CO_2-quotas have been decided on the basis of the CO_2-damage costs or that an alternative to a given project on CO_2-reduction could be to buy CO_2-quotas. In paper D we apply external source estimates of GHG/damage costs. The cost estimations rely on, respectively, SCC-estimation methods (Social Costs of Carbon) and projections for CO_2-quota prices.

A significant part of environmental economics focusses on **the internalisation of externalities**, where an overall principle is that *the regulatory tool should be placed as close to the source as possible*. Environmental regulation theory distinguishes between two types of regulation: *Incentive Regulation* and *Command And Control regulation, (CAC)*. *Command and control* regulation is characterised as permissions, standards, injunctions or prohibitions; examples within agriculture are limits for fertilisation and number of livestock per hectare. Within the energy sector, examples include fuel restrictions in the heat– and power sector combined with co-generation demands or standards for filters on smokestacks, for example, for heat and power plants. Non-tradable quotas or emission permissions for e.g. for NO_x is also CAC-regulation. *Command and control* regulation is an effective tool to remove specific types of pollution, such as when Danish CHPs were prohibited to emit sulphur dioxide. It is also efficient to ensure a given technological level within a sector, and is for example abundantly applied within energy saving.

It can, however, due to asymmetric information, be difficult for a regulator to figure out, where it would be *very* costly to reduce emissions, and where emissions could be reduced rather easily. In these cases *incentive regulation* can prove to be more efficient.

Incentive regulation entails both taxes and tradable qoutas with regard to pollution reduction — both tools are currently applied to reduce carbon emissions. The advantage of *incentive regulation* is that the polluter is incentivised to reveal her actual abatement costs under the assumption that she chooses the cheapest option between abatement (reduce emissions) or to pay the carbon tax/buy a quota (pollution). There is a large and exciting literature on this issue, for example, see [84, 53] for a nice introduction and Hanley, Shogren, and White [54] and Baumol and Oates [4], Baumol and Oates [5] and Sandmo [113] will provide a more in depth presentation; hereunder, an introduction to the concept of *the double dividend*[7]. For this thesis are taxes and qoutas taken as given, and the fact that the EU-ETS suffers from oversupply of

[7] The notion that internalisation of externalities through green taxes can give two dividends, first the externality is internalised, second, other taxes with high deadweight losses can be removed, creating another dividend.

CO_2-quotas is applied as background knowledge.

Another way of reducing pollution is to promote alternatives to pollution. With regard to GHG-reduction this can be to incentivise production of renewable energy or degassing of manure (manure treatment). Also in this case *incentive regulation* can include price mechanisms and quantitative tools. Green certificates in Sweden and Norway on the electricity system is an example of the application of a quantitative tool[3]. Green certificates can also be applied as a price mechanism[2]; green certificates are for example also released for upgraded biogas in Denmark; however, this certificate only serves as a potential extra income, as a small feed-in tariff. Danish biogas in general focuses on price mechanisms in the form of feed-in tariffs and feed-in premiums.

Risk and uncertainty

The perfect market is characterised by perfect *information* and perfect *foresight*, meaning that all market participants have all the necessary information regarding cost and benefits for a given product at present time and in the future. Risk is not an issue under these conditions, since everything is known to all parties; however, these are not realistic conditions. The relevant consideration is therefore *what* and *how much* is unknown or put differently *where* the risk and *how severe* it is.

Theory on **expected profit** presented by e.g. Mas-Colell [84] p. 207, considers risk by comparing different profit outcomes combined with the likelihood of reaching each of the potential profit outcomes. **Expected profit** then is the sum of potential profits times the likelihood that this outcome will occur. A simple version of this is presented in eq 3.3 below:

$$\pi^{expected} = \alpha \cdot \pi^{low} + (1 - \alpha) \cdot \pi^{high} \quad \forall \, \alpha \in [0; 1] \tag{3.3}$$

Where α represents the risk that the set of parameters will result in low profits π^{low} with a given investment, $1 - \alpha$ represents the chance of π^{high}. The preferences for risk can also be added to the equation in the form of $\rho \in [0; 1]$. The *risk neutral* stakeholder would weigh each possible outcome equally, which in this case would mean that $\rho = 0.5$ was multiplied with each possible outcome. *Risk averse* investors would weigh the bad outcome higher than the positive outcome; and thereby understand the expected profit of investments with high risk lower in the profit calculation.

When risk relates to future outcomes, risk can be reduced by reclaiming investment costs as fast as possible. This can be done by applying a short *depreciation period* and/ or to add a *risk premium* to the interest rate. It is often assumed that private investors are risk averse, while public investors such as municipalities, the state and somewhat publicly owned utilities are assumed to be more risk neutral. *Socio-economic* investment calculations therefore tend to have longer depreciation rates than *private economic* calculations. Similarly, interests rates are typically higher in *private economic* calculations compared to for *socio economic* calculations. Both have significant importance for calculating whether an investment seems profitable or not, in particularly when risk is included in the calculation.

Risk does not always relate to the future, it can also relate to **asymmetric information** between market participants. Two standard terms within micro-economics are *Moral Hazard*, that relates to how market participants ensure that their counterparts act in everyone's best interest [84]. Examples of this could in the biogas value chain relate to how the biogas plant secures enough dry matter content in the manure delivered by the livestock farmers. The other standard term is *adverse selection* and relates to which "type" the counterparts are. Within this thesis *adverse selection* is particularly interesting in relation to profit allocation. For example, when production costs form part in the profit allocation mechanism, and knowledge of good alternatives for the participants increases bargaining power.

Game theory

Game theory is applied within several areas of micro-economic theory hereunder *industrial* and *environmental* economics as well as *cost-and-profit allocation* theory. Game theory can be applied to explain and predict *strategic behaviour* and through this to avoid inefficient outcomes.

Game theory was first presented by Von Neumann and Morgenstern [125] considering zero-sum games between two and more than two players: their work developed into **non-cooperative game theory** and **cooperative game theory**. **Non-cooperative game theory** is founded on the hypotheses of the rational and self interested agent that optimises for himself, assuming that his counterparts are just as self interested as himself. John Nash [94] extended the zero-sum games into non-constant sum games and developed the theory within **non-cooperative game theory** by introducing dominant strategies in order to single out the expected outcome of a given game. A classic example of a non-cooperative game is *the prisoners dilemma* formalised by Alfred Tucker[8], where the socially optimal solution (seen from the prisoners viewpoint) would appeared to be that if nobody talked to the police, both would receive a small punishment. But the *dominant* strategy for both parties is to talk to the police which results in a *Nash Equlibrium (NE)* where both criminals are incarcerated for a long time [84, 51]. There is abundant evidence for the *prisoners dilemma*; however, criminals do not always tell, and a game theoretic explanation for

[8]Two criminals are being interrogated separately, knowing that the other criminal is also interrogated. If he tells the police, the criminal in question will suffer a harsh punishment. If nobody talks to the police, both will get a small punishment. If the criminal in question tell about the other criminal, the first go free, unless the other criminal also talked to the police, then both will be punished with a discount see e.q. [51, 122]

this is that criminals often work together again and again, which makes the situation a **repeated game**.

According to the theory on **repeated games**, a dominant strategy in a one-shot game can be transformed into a socially better strategy for all players, if the game is *repeated*. This requires that players are informed on 1) which strategy to choose and 2) that other players will retaliate against deviating players in the following rounds. This line of thought has to a great extent been applied in theory on *collusion strategies* between officially competing firms that collude to keep prices up in the market. Empirical data show several cases where collusion agreements have been kept *only on oral agreements*: all founded in the risk of retaliation from other collusion members.

Several types of games are applied within game theory, and there is a clear distinction between static (one stage games), such as the prisoners dilemma, and sequential (multi stage) games. In static games, choices are made by the players simultaneously, while choices are made stepwise in sequential games such as the *ultimatum* game[9]. Non-cooperative game theory follows the hypothesis that in an "ultimatum"-game with multiple rounds and perfect information *one* Nash Equilibrium can be found in the first round by the use of *backward induction*, meaning that the results from potential future rounds are included in the suggestions made in the first round.

Empirical studies, however, find that untrained players will not naturally apply backward induction but tend to concentrate on the first round and respond independently of the options in the following rounds [64]. Another assumption in non-cooperative game theory is that players are *perfectly rational*, meaning that they will not reject an offer which is better or as good as what they would alternatively achieve by rejecting, even if the offer is a zero share of the pie. J. Johnson [64] and other empirical studies [86] find that this assumption can be difficult to back up, as players tend to retaliate by rejecting the offer, if they are offered less than what they perceive as *fair*; even if this result in an even lower gain. J. Johnson [64] also find that players can be taught to apply backward induction and that these players tend to adapt their strategy depending on which type of players they are playing against (perfect rational or retaliating players). *Backward induction* is one of the strategic tools we apply in paper E as part of the decision making for the best choice of value chain design.

Cooperative game theory is also known as *Coalitional game theory* and was also first described by Von Neumann and Morgenstern [125], when they investigated a zero-sum game with more than two players. Von Neumann and Morgenstern [125] found that a coalition between two or more players could

[9]A game where two agents split for example an amount of money or a pie, the first agent decides the division of the pie and the other agent decide whether to reject or accept; this game can also be extended, so that if the second agent rejects, she can suggest a new division and so forth.

result in a better outcome than if they played by themselves; and that a coalition would be stable if this additional gain was distributed among all members in such way that all members would gain more from staying in the coalition than by leaving it. Lemaire [77] argues that to find this distribution is the same as to solve the **cost allocation problem**; he further points out that terms like *the core*[10] and *the nucleolus* [11] had already been described long before Von Neumann and Morgenstern. Tijs [121] points out the advantage of applying game theory within cost-and-profit allocation theory as a mean to include the strategic aspects into the considerations, they further stress that theoretical studies are unable to determine what is the best allocation form, as this in the end depend on preferences.

Nash [95] define a cooperative game as *a game where individuals are able to agree on a joint plan of action and that this plan is enforceable*. An overall challenge for cooperative games is that it is difficult to find one unique solution to a game and that it often is pointless to set up a strict set of rules for the game set-up or as Nash [95] puts it:

"*Rather than solve the two-person cooperative game by analysing the bargaining process, one can attack the problem axiomatically by stating general properties that "any reasonable solution" should possess. By specifying enough such properties one excludes all but one solution*." — John Nash

This approach is very similar to the *evaluation criteria* applied within cost-and-profit allocation theory [9, 60]. Within cost-and-profit allocation theory are applied axioms in line with the axioms presented within classic cooperative game theory (for an example, see [95]); and also social criteria such as degrees of equality or fairness [60], notions which are also connected to cooperative game theory in recent years [85]. In paper E we focus on the fairness criteria *Equality* and *Individual Rationality*, this is explained further in section 3.3.

Ownership structures in the value chain and vertical integration

The economic worth of each step in the value chain is not always clear to estimate. Some intermediate products may be priced in a transparent market, others may be priced bilaterally between the partners in the value chain. A solution to difficult price estimation can be **vertical integration**, where parts of the value chain are merged, which thereby potentially decreases the need for pricing in the value chain.

Vertical integration can be considered as a problem if it limits competition and leads to deadweight losses through power abuse; literature on these problems are extensive (see e.g. [122, 78, 105, 106]), and large parts of the European energy markets are therefore regulated in order to reduce existing

[10] *Allocations within the core are stable, as the core only contain those allocations where no set of players in the coalition are all better off if they break the coalition to form another coalition.*

[11] Is an allocation mechanism that per definition is within the core.

vertical integration [74]. It is however, also argued that vertical integration can increase efficiency in value chains by avoiding sub-optimisation (see e.g. [119, 13]).

Biogas value chains in Denmark and Norway are in paper C compared with regard to regulation and structural conditions. The degree of vertical integration in the paper, disregarded with the assumption that the exact ownership structure is irrelevant for that analysis.

The level of integration can, however, play a role in the design of the value chain, and it may not always be possible to integrate each entity of the value chain vertically. There is in Denmark a large variation in the ownership structures of the biogas value chains. This can be due to lack of capital, so for example farmers who wanted to build a biogas plant were unable to invest in the entire value chain; or for example a CHP, was not allowed to invest in a biogas plant due to monopoly regulation.

The main theme of paper E is to understand some of the potential effects on the value chain when there is an underlying interdependence between owners in order to receive support. Vertical integration could be an option to avoid conflicts on profit allocation; however, as mentioned above, this would not clarify the challenges when vertical integration is not an option. The approach in paper E is to consider an optimal value chain design assuming joint profit maximisation, then consider a number of profit allocation mechanisms for a potential cooperative. When potential profits and profit allocations are found, are these results evaluated, taking strategic considerations into account, to find the likely effects on the value chain design.

Horizontal integration - cooperatives - cost and profit allocation

Horizontal integration can be an option, as an alternative for two firms to compete. A merger can bring scale advantages, and if the merged firm is adequately large, it can become a price setter instead of a price taker. The economy is full of horizontal integration, and in order to avoid too large firms with monopoly behaviour, countries and regions such as the EU often have limitations on mergers. The United States has historically had a particularly harsh regulation in this field.

An alternative to mergers are cooperatives, where a group of smaller producers cooperate on parts of the value chain. Danish agriculture has a long tradition for this with slaughterhouse and dairy production; cooperatives owned by the farmers delivering livestock and milk for processing and sale as a unified vendor [9]. Such cooperatives often include various producer types and with asymmetric information can it be challenging to find the optimal cost-and-profit allocation that ensures optimal production and still keeps the relevant producers in the cooperative. Cooperative game theory and in particular cost-and-profit allocation theory deals with these challenges. This will be presented further in section 3.3.

3.2 Internalisation of externalities

A focus in environmental economics regarding energy is on the extensive usage of fossil fuels with the well known externality of GHG-emissions increasing world wide climate change. Several policy instruments have been investigated and applied in order to reduce the use of fossil fuels and to increase the use of alternative fuels. Fossil fuels are e.g. taxed or large fossil fuel consumers have imposed quotas on CO_2-emissions. Furthermore, renewable energy sources (RES) are supported through support schemes with incentives for the targeted producers. My work regarding biogas policy is founded in environmental economic theory presented by for example [113, 10, 120, 54, 4, 5] and applied environmental– and energy economics [130, 73, 72, 99, 75, 38, 3, 3] on the one hand and biogas specific literature on the other. A literature study on biogas regulation has been performed in paper C; here I only mention a few examples. Raven and Gregersen [109] made a comparative assessment between biogas development in the Netherlands and Denmark, pinpointing among other things the importance of long-term support and the following reduced risk for investors; Lantz, Svensson, Björnsson, and Börjesson [76] analyse the regulatory landscape for biogas in Sweden and acknowledge the complexity of biogas production, which complicates the regulatory analysis. Others apply existing regulation in the analyses and assess the results from a private economic perspective such as e.g. Delzeit and Kellner [33] or from a socio-economic perspective such as e.g. Jacobsen, Laugesen, and Dubgaard [66].

Biogas production is to a high degree affected by regulation directly pointed towards the biogas production itself as well as regulation directed towards the adjacent sectors or sectors that are part of the biogas value chain. *The focus in this thesis has been to obtain a better understanding of the policy effect on profitability in the value chain and which policy instruments are best to reach a policy target*. For this the economics of biogas regulation and risk have been addressed throughout the papers in this dissertation, following the same approaches as briefly presented above.

Support schemes and risk

Danish biogas regulation consists of both **feed-in tariffs** and **feed-in premiums**. The **feed-in tariff** is a subsidy for a given product instead of a price; in the case of biogas CHP's can entirely be fuelled by biogas (directly fed into the CHP) choose freely between a feed-in tariff or –premium. The advantage of the feed-in tariff is that it eliminates risk, as the producer knows exactly what income she receives for each kWh produced. Instead, the regulator takes the risk of price changes by receiving the electricity (or any other commodity), to sell on the market. The **feed-in premium** consists of an additional subsidy added to the market price: the feed-in premium is applied in the case of CHP's producing on both biogas and natural gas and when gas is upgraded. In the case of feed-in premiums, the producers are carrying the risk of price changes, and the advantage of this is that those (the producers), who *can react* on price changes, will be those who *have the advantage of reacting*. The amount of produced biogas can only be changed slowly (over weeks) and local storage is expensive. Therefore, when electricity is produced entirely on the basis of biogas it can be difficult to respond to any price signals from the fast changing electricity market. It would therefore make little sense to incentivise the price responses from CHP's fuelled entirely on biogas; hence, the feed-in tariff[12]. Gas prices are not as volatile as the electricity prices (see 2.5); historically gas prices have varied with the seasons, a pattern that is less significant now, but it will overall be easier to predict price changes in gas and react accordingly. This could be an argument for the use of feed-in premiums for biomethane, however, biogas producers are usually aiming for total usage of all capacity, both due to high investment costs and production efficiency. Therefore, they may not react to price signals from the market. Instead, they may agree on a fixed price for the biomethane with a gas shipper in order to reduce risk.

An argument for the use of feed-in tariffs compared to feed-in premiums is that the regulator can, to a higher degree, be considered as risk neutral, where biogas producers more often could be expected to be risk averse, and thereby set higher value on secure investments compared to risk neutral agents, as described in section 3.1. Kitzing and Weber [73] show that in the case of wind power, where production is volatile and difficult to control, support via feed-in premiums will have to be higher than total support given in the form of feed-in tariffs (tariff cost minus electricity income) to reach the same result. This is due to the additional risk imposed on the wind power producer in the case of feed-in premiums.

Though gas prices are less volatile from hour to hour, prices still vary over years. Figure 3 in paper E presents a significant price span, where average prices were approximately 31 Euro/MWh in 2013 and 15 Euro/MWh in 2016. The Danish biogas feed-in tariff is to some extent taking this into consideration as some of the feed-in tariff is determined by the natural gas price from the year before.

[12]CHP's fuelled on both natural gas and biogas will to a larger degree be able to react on price signals, as natural gas can supplement production during price peaks or extra heat demand: these production plants only receive a feed-in premium.

3.3 Allocation theory applied on the value chain

The Danish biogas value chain is characterised by that one part of the value chain receives support; contingent on that a set of restrictions should have been obeyed in other parts of the value chain. This can become a challenge, if different agents own parts of the value chain.

As an outsider, trying to understand the significance of the biogas regulation, it can be challenging to deduce all aspects, when the allocation of profits are unknown and data on the internal prices within the value chain are scarce. The approach has predominantly been to consider a larger part of the value chain as one corporate entity and let the profit allocation within the value chain be an unknown factor.

In paper E we decided to take a step deeper into the considerations made within the value chain. In this case we divided the owners into two subgroups containing a) the necessary owners to obtain support and b) the unnecessary owners, as presented in figure 3.1.

Several consideration were made in the preparation of the analysis made in paper E. One option was to investigate *vertical integration* as a theme, however, a challenge with this approach was that the ownership structures in current biogas value chains vary significantly and the exact structure is affected by issues such as capital constraints and monopoly regulation. This means that *Vertical integration* might not even be an option in some value chains, while it already has happened in other chains. Finally, this kind of analysis may not say much about strategies within the chain – only try to eliminate sub-optimisation.

Another path could be to consider the challenges between bilateral monopolies, this was indirectly included in the analyses. The cornerstones of the analysis became profit allocation theory and strategic measures from gamethory; in particularly cooperative game theory became relevant for the analysis.

Profit allocation schemes without initial integration

Cost- and profit allocation theory can be considered as an alternative to *horizontal integration* and includes both strategic considerations as formalised in cooperative game theory [95, 60] and more pragmatic considerations as e.g. formulated by Bogetoft and Olesen [9]. Unique optimums are not in focus within this theory, instead are allocations mechanisms designed to satisfy a set of axioms [95] or *fairness criteria* [9, 60] obeying general criteria for a typical cooperative such as e.g. *equality*[60] and more pragmatic/specific criteria referring to specific cooperatives [9]. Bogetoft and Olesen [9] presents a long list of potentially relevant criteria depending on the type of cooperative hereunder including how to avoid the risk of defection from some owners; others present the fairness criteria at a more general level see e.g. [121, 60].

Two fairness criteria; equality and individual rationality, are considered in most cooperative game theoretic literature related to (cost) allocation see e.g. [121, 9, 49, 114, 87, 60], and the allocation mechanisms applied in paper E are in particular evaluated according to these fairness criteria.

Equality can be interpreted in many ways. Denmark has a long tradition for cooperative movements in the agricultural sector, and "one man—one vote" was a general principle in these cooperatives. Non-cooperative game theory follows the hypothesis that the rational agent in a one shot *ultimatum* game (see also section 3.1) would offer the other agent a zero share of the pie, which the rational agent would accept. Several empirical studies show that most people does *not* take the entire cake, and if they do the other part would retaliate and not accept the offer. McCain [86] presents this as an argument for including social norms and reciprocity motives into the cooperative game theory and thereby get closer to the empirical findings. Hougaard [60] argues that equality in some form, e.g. direct equality or maximin equality, can be found in most large religions and thereby social norms.

Another important element of *homo economicus* is *individual rationality*: "Does it make sense to join in? Or is there a better alternative?". The vague version of this is that the individual gain for each owner of a given allocation mechanism should at least not be negative. This is formulated in eq 3.4

$$\pi_o^{alloc} \geq 0 \quad \forall o \in \mathcal{O} \tag{3.4}$$

Where π_o^{alloc} refer to the profit for owner o, with a given allocation mechanism. It may however not be enough to comply with eq 3.4 in order to ensure stable collaboration. Truett and Truett [123] argues that one specific price between two parties can be found and the bargaining power between the two parties contribute in determining this price. The bargaining power can depend on the level of information between the parties in the value chain [107] or a maybe more important factor is *how dependent* each participant is on the collaboration. This dependency can be approximated from the best alternative for each participant.

The best alternative (often referred to as the stand-alone profit) is highly relevant with regard to profit allocation. Due to *Individual Rationality* is an allocation mechanism unstable if the profit allocated to a coalition part is below her stand-alone profit. Furthermore, a profit allocation is stable if it is *within the core*, where the core *is the set of allocations where profits are more beneficial for all group members compared to stand-alone profits or profits in another coalition*[9].

Fairness criteria can be applied to rank the allocation mechanisms. Some fairness criteria can be considered as *must haves*, while others may be considered as *nice to have*. Allocation mechanisms that includes most of the important criteria in the best matter can be ranked as better than other mechanisms. The importance of each criteria is subjective and depend on the allocation problem.

The purpose of using the payment schemes and the fairness criteria in paper E is to understand the current development in biogas production, by considering potential profit allocations and through the best alternatives to get a pictures of the potential bargaining power of the actors in the value chain.

Payment schemes

Within the allocation– and cooperative game theoretic literature are several (cost) allocation mechanisms presented and tested both theoretically, e.g. [121, 114, 87, 86, 60] and empirically [85, 49, 79, 93] The *proportional allocation* mechanism is an example of an allocation where profits are allocated in accordance with cost [60]; this could be in proportion to total costs, capital costs or other. Other payment schemes focus more directly on the egalitarian principle such as the egalitarian method, where profit is divided equally between all parties in the cooperative [121, 77, 85]. The *Shapley rule* is designed from the cooperative gains, that each part has contributed with [77, 85, 49]. While the *nucleolus payment scheme* includes Incentive Rationality (IR) in the profit allocation, as it depend on the alternative profit of the marginal participant [85, 114, 49].

Most of these allocation mechanisms are designed as alternatives for *horizontal integration* of homogeneous producer types with slightly different properties and where each co-owner to a large extent is replaceable. Examples of this *outside* the biogas value chain could be a cooperation of wood suppliers [49] or a collaboration among liquefied natural gas suppliers [85]. Within the biogas value chain it could be the cooperative between the Madsen brothers[13] [82] or a suppliers association between the livestock farmers, which would be considered as one part of the value chain but would in itself be a cooperation of farmers. In such a cooperative the producers would be homogeneous with slightly different properties, such as distance from the plant, type of manure and content of dry matter in the manure. A good allocation scheme for such cooperatives would probably include incentives to deliver a high dry matter content.

The value chain presented in figure 3.1 represent rather heterogeneous parties: Livestock farmers as one group, the plant and the energy converter and the closest alternative to cooperation is *vertical integration*. This means that the allocation mechanisms described above may not be applied in the same way, as the effect from defection is another for the value chain. This became a challenge in paper E, when it should be decided which allocation mechanisms to be select. It *is* possible to apply well known allocation mechanisms including an element of equality, however if IR should be taken into account such as

[13]Three brothers each own a farm, and together they own a biogas plant and an upgrading facility

it is in the nucleolus, it became necessary to alter the allocation mechanism significantly.

Applied mechanisms and discussion

The three allocation mechanisms presented below *are not expected to be the exact allocation mechanisms applied in real world value chains*, however, it is considered as likely that chosen allocation mechanisms will include an element of equality (each owner is important), proportionality (if you risk much, you should gain much) and an element of individual rationality (if your alternatives are good, you have better bargaining power). The application of all three allocation mechanisms therefore give a sample space within which real world allocations are likely to be. The allocation results were therefore not applied as final results but made a sample space of potential profit gains for each owner in the chain formed part of an initial conclusion together with expectations to bargaining power. This together provided an opening for a discussion and understanding of the current development in the Danish biogas sector.

The **Full Equality** method can also be referred to as direct equality or e.g. the egalitarian method. Profits with this profit allocation method will be shared equally between the owners; irrespective of their contribution to the profit. The constraint for the full equality allocation is represented below:

$$\pi_o^{Eg} = \frac{1}{\mid \mathcal{O} \mid} \sum_{o' \in \mathcal{O}} \pi_{o'}^{Eg} \quad \forall o \in \mathcal{O} \tag{3.5}$$

Here the profit π_o^{Eg} of each owner o, will be a an equal share of the total profit for all owners $\sum \pi_{o'}^{Eg}$.

Advantages of this allocation method are that it is easy to calculate and comprehend, while the need for input data is rather limited; moreover it will be formulated the same way independently of whether the owners are homogeneous in the sense as a cooperative of livestock farmers or heterogeneous as a cooperative of different value chain actors.

The disadvantages of this method could be, that it does not take the fairness criteria *Individual Rationality* into the calculation and even though the need of data is limited, there will be a risk of over reporting of costs (adverse selection). Furthermore, it is not self-evident that the fairness criteria *equality* is fulfilled. If all owners in the value chain share the same cost-level this mechanism could be considered fairly equal. However, if one owner is the primary cost bearer, she would also bear the highest risk using this mechanism, which may not be considered fair.

The **proportionality** mechanism is not as simple as *full equality*; instead it takes the cost burden into consideration by allocating the profits according to each of the owners costs, e.g. total costs, CAPEX or OPEX. Which costs, profits are allocated according to, could be determined by the dominating cost factor, risk or something else.

The proportionality allocation is presented below:

$$\pi_o^{Prop} = \alpha C_o^* \quad \forall o \in \mathcal{O} \tag{3.6}$$

Where α is the percentage of the cost C_o^* that can be covered for each of the non-substrate owners.

The advantage of the proportionality mechanism is that it is rather simple to calculate, and the data need is not substantially higher, than in the case of full Equality. A disadvantage of the mechanism is that it suffers somewhat from adverse selection, since owners have an incentive to boost their own costs in order the achieve a higher share of total profits. Another advantage of the method is that it does take the risk of costs into consideration; this at the same time means, that the method does not reflect, when all parts of the value chain are *necessary* to gain support. Furthermore, incentive rationality is not represented in the allocation mechanism.

The **Individual rationality** mechanism is inspired by the nucleolus allocation mechanism. In the traditional nucleolus all combinations of participating owners and their alternative profits are utilised in the allocation, and profit for each owner is found by maximising the distance, λ from the obtained profit, π_o^{Nu} to the alternative profit, π_o^{ALT} for all relevant *subsets*, $\mathcal{S}$ of the participating owners, o, see [9]. This is represented in equation 3.7:

$$\sum_{o \in \mathcal{S}} \pi_o^{Nu} - \sum_{o \in \mathcal{S}} \pi_o^{ALT} \geq \lambda \quad \forall \mathcal{S} \subset \mathcal{O} \setminus \emptyset \tag{3.7}$$

The owners in the traditional nucleolus are of the same type, see e.g. [49], and the operability of the collaboration would therefore not be relying on each owner individually. The **Individual rationality** mechanism is a simplification of the nucleolus and is applied for a group of owners under the assumption that the group of owners, cannot be reduced, and if one owner opt out, the remaining owners will form a smaller cooperation.

For the individual rationality mechanism the distance is maximised from the *obtained profit* to the *alternative profit* the owner would get by not participating. All subsets of the chain is left out of the calculation; giving the constraint for the individual rationality cost allocation:

$$\pi_o^{IR} - \pi_o^{ALT} \geq \lambda \quad \forall o \in \mathcal{O} \tag{3.8}$$

The advantage of this allocation mechanism is that the obtained solution will be within the core, meaning that all owners are better of when they are participating in the value chain, compared to be by themselves. The principle can seem more fair as it is likely to yield a more equal allocation than the proportional principle. On the downside however, costs are not taken into consideration and the risk of adverse selection is even higher than for the proportional mechanism, since the need of data is high and the allocation mechanism gives incentives for dishonest reporting on the best alternative.

The purpose of the analysis was to understand the strategic considerations related to profit allocation and the following choices made by the owners, before (ex ante) and after (ex post) investments are made in the value chain. In paper E we find the best alternatives for the important parties in the value chain — both before investments and ex post. The potential profits from different value chain designs, profit allocations together with ex ante- and ex post considerations are then compared. Conclusions on probable strategic choices are then drawn through the application of backward induction[14].

[14] A method from game theory, where a player in time t takes possible outcomes in time t+1 into consideration for her choices in time t

CHAPTER 4

RESEARCH METHODS

Methods applied in this thesis, have been used in order to get a better understanding of the economic incentives affecting the optimising agents surrounding and at the biogas plant. For this, I have both used sheer case based calculations as well as optimisation models.

Perspectives	Methods	**Paper A**	**Paper B**	**Paper C**	**Paper D**	**Paper E**
Quantitative models	Excel simulations	x	x	x		
	Optimisation				x	x
	Sensitivity		x		x	x
Policy instru-ments	Quantitative implementation	x	x	x		x
	Qualitative assessment		x	x		x
	Comparative analyses	x	x	x		
Value Chain extent	Plant level	x	x		x	
	Value chain			x		x
	Profit allocation					x

Table 4.1: Methods and perspectives applied in the papers

As presented in table 4.1 quantitative models are applied as a basis for analyses in all papers, often combined with sensitivity analyses for the most critical parameters. A large part of my work has been to analyse the effect of *current regulation* implemented in my models; and compare results with the reality in order to suggest policy changes.

In the sections below, I present my approach regarding the quantitative models and the inclusion of the surrounding regulation. Some regulation is included as cost, income or a restriction for the model; other regulation will have to be considered specifically throughout the analyses.

4.1 Quantitative models

Most of the papers in this thesis are based on the theory of microeconomic optimisation, some analyses have been case-based excel simulations, while others were based on an investment- and production optimising model presented below. In paper D, a socio-economic analysis is performed with an energy systems model.

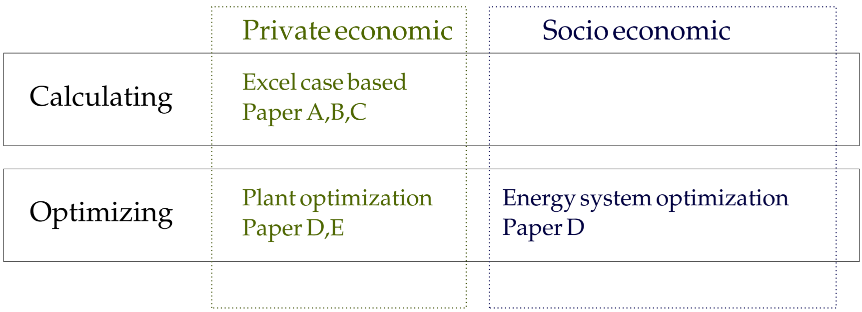

Figure 4.1: Quantitative models

One year is considered in all quantitative models, where investments are distributed along the expected lifetime of the investment following an annuity, using the equation 4.1.

$$C_x^{Capex} = P = \frac{r * PV}{1 - (1 + r)^{-n}} \tag{4.1}$$

Where P corresponds to the periodic payment, which in our models are considered as the yearly payment also described as CAPEX. PV represent the present value of the investment, at the beginning of the period, while r is the yearly interest rate and n corresponds to the number of payment periods, in this case the expected technical lifetime of the investment. The private economic analyses are all calculated for an average year in line with e.g. [100, 131, 52, 33], while the socio-economic analysis performed in the energy systems model Balmorel is calculated for the year 2025. The argument for using 2025, is that we wanted to investigate the nearer future, and still include new investments in the modelling.

For both the private economic– and socio-economic analyses we have used the national recommendations for socio-economic analyses [24] with regard to the interest rate. Biogas production is fairly capital intensive, so results are quite influenced by assumptions regarding interest rate and lifetime. There are good arguments for using higher or lower interest rates and shorter lifetime, however, actual feasibility has been of less focus in this thesis, instead, I have mostly considered comparative feasibility, and for this prevails the argument of consistency by using the national recommendations.

Case simulations of profit in excel

In the papers A, B and C analyses are performed with a comparative focus, where few things are changed and everything else is being equal. Profits are not maximised, however, transport costs are minimised given scale and input mix in all models. In paper A and B, nine cases are compared, only with variations in size and input mix, where the objective of the model in these papers is to analyse the effects from these variations in inputmix and scale. The economic model is basically presented by the equations 4.2, 4.3 and 4.4.

$$\pi_{plant} = INC_{plant} - C_{plant} \tag{4.2}$$

Where π is the profit, INC is the income and C are costs. Income is described by:

$$INC_{plant} = \sum_{i \in \mathcal{I}} \sum_{k \in \mathcal{K}} inc_{i,k} \qquad \forall i \in \mathcal{I}, k \in \mathcal{K} \tag{4.3}$$

Where $\mathcal{I}$ = output = gas, digestate and $\mathcal{K}$ = types of income = commodity price, subsidy, certificate price..... Costs are described by:

$$C_{plant} = \sum_{j \in \mathcal{J}} \sum_{l \in \mathcal{L}} c_{j,l} + \sum_{i \in \mathcal{I}} \sum_{l \in \mathcal{L}} c_{i,l} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, l \in \mathcal{L} \tag{4.4}$$

Where $\mathcal{J}$ = input = manure, co-substrates, $\mathcal{I}$ = output = gas, digestate and $\mathcal{L}$ = types of costs = transport, OPEX and Capex for pre-treatment, plant, storages, after-treatment and so on.

In paper C two biogas value chains are compared for both Norway and Denmark. Here, the unified profit of the most relevant parties in the biogas value chains are compared, in order to include the most relevant regulation and still keep the story clear. This basically changes e.g. 4.2 to eg. 4.5.

$$\pi_{value\,chain} = INC_{value\,chain} - C_{value\,chain} \tag{4.5}$$

In this case scale, costs and input mix are kept almost constant, while regulation and structural conditions vary.

Optimisation models

Two optimisation models are applied in this thesis, the plant level model presented in [68] using integer programming and the energy systems model Balmorel [110] using linear programming.

Plant level model

The plant level model is a biogas plant optimisation model that optimises the profit of the biogas plant or a pre-defined part of the biogas value chain.

$$\text{Max} \quad \pi = INC - C \tag{4.6}$$

$$\text{S.t.} \quad \text{Cost and Income} \tag{4.7}$$

The plant level model optimises profits for the entire value chain. This includes transport costs, storage, pretreatment, temporary storages, the biogas plant, after storages, after treatment in the form of cleaning as well as end uses in what is referred to as energy conversion in the papers. Energy conversion refer to upgrading (hereunder several technologies), Heat- and power production (CHP) or heat production. I contributed among other things to decisions regarding which relevant energy converters to include, regulatory constraints, taxes and subsidies. The time resolution in the model divided in such way that the input side is weekly while the output side is hourly.

The development of the plant level model was initiated in the beginning of the *Biochain project*, where data was collected while main inputs- and outputs were decided. The foundation for the economic model applied in the plant level model was the economic model which I prepared for the excel-model applied in paper A and B, and the initial data set was also the same as for the excel-model. Based on the results from paper A and B it was decided that the plant level model should include economy of scale, this was included through the application of integer programming.

The plant level model is applied in paper E, where a pre-defined part of the value chain is optimised using cost prices between each part of the value chain. Profits are then allocated through various methods presented in section 3.3, by using a profit allocation add-on developed for the plant level model. The plant level model is also applied in paper D in order to find a representative biogas cost to use as input in Balmorel.

Balmorel

The energy system model, Balmorel [110, 129] is applied in paper D. Here the objective is to analyse the socio-economic optimal use of raw biogas and biomethane in the Danish energy system, given the calculated biogas cost and climate gas emissions in CO_2-equivalents, estimated in [128, 127]. Balmorel is a technology rich, bottom-up, partial equilibrium model in which one can analyse the effect of various changes in the energy system and choose to optimise investments, given assumptions on future energy demand. Balmorel is adoptable to any choice of geography, however, it is mostly applied in the Nordic and Baltic countries. An advantage of the model is that the existing capacities are well represented on a detailed level; furthermore the model is flexible and can be extended with several add-ons. For this paper the model was operated in investment mode (BB2)and the model was given the possibility to utilise different fuels in one conversion technology with the add-on called combtech. This was relevant in relation to paper D, as upgraded biogas could then be applied in natural gas turbines reflecting the real energy system. In the version of Balmorel that we applied are profits not maximised, instead *total system costs are minimised given the exogenous final energy demand, fuel availability, emissions*[1] *and a lot of other restrictions*.

TIMES-DK and EnergyPLAN are some of the immediate alternatives to Balmorel. Some of the overall characteristics of the three models are presented in table 4.2. The table is taken from [15] table 3-5 and combined with updated knowledge, and for the TIMES-DK has the general properties from TIMES/MARKAL been fitted the properties for TIMES-DK.

One significant difference between Balmorel and EnergyPLAN is the lack of investment optimisation in the EnergyPLAN model, this was a clear disadvantage for our analysis in paper D where we specifically wanted to go forward in time to allow the model to take new investments into consideration in the optimisation.

TIMES-DK *would* have been applicable to perform an analysis with both investment and operational optimisation. A potential *disadvantage* of the model would be the 32 time-slices which are currently designed for TIMES-DK that follows a specific profile matching analysis for the Danish electricity system. These specific time-slices could be less applicable for the investigation of short term storage and thereby the potential flexibility advantages from gas fired CHP's. This flexibility advantage could be relevant to capture in relation to biomethane in a future system with even more inflexible wind- and solar power compared to today. We were furthermore under the impression that biogas would be better represented in Balmorel compared to TIMES-DK at the point in time, where this paper was initiated. TIMES-DK on the other hand would

[1] If emission costs are associated or an emission cap has been defined

Type		Balmorel	EnergyPLAN	TIMES/MARKAL
Type	Simulation	Yes	Yes	Yes
	Scenario	Yes	Yes	Yes
	Bottom-up	Yes	Yes	Yes
	Operations opt.	Yes	Yes	Yes
	Investment opt.	Yes	-	Yes
Types of analysis	Timeframe	Max 50 years	1 year	Max 50 years
	Time-step	hourly	hourly	Using time slices
Energy sectors considered	Electricity	Yes	Yes	Yes
	Heat	Yes	Yes	Yes
	Transport	-	Yes	Yes

Table 4.2: Model comparison

probably give a better representation of the industry and transport sectors which are relevant with regard to gas consumption - in particularly within green transport.

A determining argument for applying Balmorel were the available add-ons. In our case the already described combtech add-on, which fitted well with our wish to analyse how natural gas consumption could be replaced with Biomethane under the right circumstances. There is furthermore a large degree of flexibility in programming of the model, it was for example possible to tailor the code for our analyses by creating a combined target for biogas and Biomethane.

Socio-economics in Balmorel

Balmorel performs an economic optimisation with a simplistic representation of a socio-economic analysis. The socio-economic optimisation is a cost-based analysis, where national taxes and subsidies are omitted. Costs used in the model are mainly expected market prices (excluding taxes and subsidies). In the recommendations for socio-economic analyses in Denmark, these market prices are usually increased with the net-tax factor and additional public spending are increased even further with a tax deadweight loss factor. The basic idea behind the net-tax factor is that resources used in the given project could alternatively have been used on other projects, where the costs on average would have been taxed by the net-tax factor. If the given projects end up with a public net deficit, this deficit should be weighed with costs of increasing a tax somewhere else in the public economy - corresponding to the tax deadweight loss factor [24]. The basic assumption for Balmorel is that the entire system optimises as if it was owned by one benevolent system manager, with the purpose of minimising total system costs under a given set of restrictions.

A private economic analysis in Balmorel includes taxes and support schemes providing the model with the actual prices that each technology faces and thereby actual costs for the varying producers competing in the system. Balmorel still entail the total system optimisation approach and will therefore not capture any sub optimisations from the real world - however it will give a picture of how well technologies compete among each other. A private economic analysis is e.g. relevant if you want to investigate the impact of a given regulation in relation to a specific technology. The focus in paper D was however to consider the externality of reduced CO_2-emission, which was why we applied the socio-economic version of the model.

Model discussions in a broader sense

The *benefit* of **optimisation models** is the received assistance from the model to find the best available solution for the optimising agent. This is in particular practical, when there are many variables to combine in a range of ways. A *challenge* with single objective optimising models such as e.g. linear–optimisation models, is that the model usually find *one* optimal (corner point) solution, which may be highly sensitive to few changes in the input data; this was e.g. shown in paper E. Models do not have to be linear, however, each time the linearity is abandoned, the complexity of the model increases, which again increases calculation time. An example is the plant level model, where integer programming is introduced in order to implement economy of scale for plant investments, but most of the model is kept linear, in order to keep calculation time down. A method to test the robustness of the results is to perform proper sensitivity analyses around the solution.

Optimisation models are relevant for a great variety of analyses: to find the best choice out of many options, and through sensitivity analyses to analyse the effect of parameter changes; however, with this kind of models you have to perform additional analyses, if you want test the robustness of your results as this will only appear if you change your inputs or restrict your model. If on the other hand you are interested in a group of specific cases it can be just as effective with a far less complicated **case-based simulation model**, which has been the case in the papers A, B and C. The Danish case in paper C was, however, chosen based on an optimised input mix found in the plant model.

In the choice between **a plant level model** and **an energy system model** it has been considered, which analyses should be made. The energy system models can incorporate a high degree of opportunities for the energy usage, but, when biogas only counts for a small part of the entire energy system, it becomes difficult to see the effect on output if input changes. Furthermore, it becomes necessary to simplify the input options in order not to drown in additional calculations and data needs. For most of the papers in this dissertation, focus has been on the biogas plant as the center of the value chain and with this focus only few analyses seemed to fit an energy system model. One example could be an analysis of the advantage of upgrading, where biomethane produced in one part of the country, can be consumed in the other part of the country. This would be difficult to capture in a plant level model.

The choice between **static** and **dynamic** models is another consideration, where a **dynamic** model in this case is defined as containing the possibility to include a *rolling horizon*. The models applied in this thesis have primarily been in a static form. The advantage of a dynamic model at plant level could be the option of allowing for new investments in e.g. pretreatment capacity, adapting to price changes on inputs. Calculation time is an issue which modellers always consider when the model is designed; and calculation time tend to increase significantly when the model goes from static to dynamic. In our case it was concluded that the benefits from a dynamic model could not outperform the lower calculation time from the static model —supplied with sensitivity analysis. Similar conclusions were made in the considerations on including **stochastics** on electricity– and natural gas prices in the plant level model. In this case a risk analysis convinced us not to include *stochastics*, as gas– and electricity prices comprise a relatively small part of the biogas income due to the high level of support.

It is possible to apply the energy systems model Balmorel in a dynamic form with rolling horizon, it has not been deemed relevant though. The dynamic part of the model can show *when* a given investment will be most profitable, given variable input prices and demands throughout a set of years. This was not the main focus in paper D, which is why the dynamic functionality was not applied. In general it has not been considered relevant to apply more dynamics in the analyses performed for this thesis.

4.2 Data: challenges and choices

Emphasis has been on finding data that reflect the actual cases worked on for illustrative reasons, and data that are within the range of what is found elsewhere in the literature.

In Denmark there are data from official sources[2] on energy demand and prices on electricity, natural gas and other fuels. Even heat prices are officially presented through public statistics to make up for the lack of an actual heat market [41]. Furthermore, there are data for a large variety of technologies with regard to investment cost and operational expenditures as well as data on sizes

[2]Official sources are here defined as open public sources such as Danish Energy Agency, Danish Energy Regulatory Authority, Energinet, SKAT, Environmental Protection Agency and similar

Data type		Sources	Uncertainty	Decision
Energy prices	Electricity (h)[a]	Nord Pool spot	low (DK)[b]	
	Heat (y)	DERA	low(lo)	Focus on actual data sources when available
Fuel prices	Gas (d)	Gaspoint nordic and DEA	low(DK)	
	Other fuels (biomass, coal etc.)	DEA	low to medium(DK)	With no direct source we apply a common applied source for consistency with other scientific work
Biomass input	manure, straw etc.	Seges	high(lo)	Best available data, see also in text
Investment and production costs	Energy converter[c]	Technology catalogue[25]	medium(int)	This source is considered as fairly secure and updated; it is applied for all available technologies
	Biogas plant	Biogas taskforce[d]	medium high (DK)	By applying almost the same data as the Biogas taskforce we ensured consistency with other work
	Pre-treatment	Seges	high (lo)	Best available data, see also in text
Carbon, current and projections	EU-ETS prices	DEA	medium(int) to high	DEA has access to actual spot-prices and provide consistency nationally and internationally in their prognosis
	Cost estimates	Bergh and Botzen [6]	high(int)	Review paper applied by climate scientists gave a large spectrum of possible costs, we applied the highest and one of the lower estimates to provide a range

[a](h) means hourly data, (d) means daily, (y) means yearly and so forth
[b] (int) means international data, (DK) means Danish or national, (lo) means local
[c]such as upgrading technologies, CHP, Heatboiler...
[d] see also the section on investment and operational costs

Table 4.3: Data sources, degree of uncertainty and decision

and efficiencies. All these data have been applied in various ways throughout this thesis, and when available have these sources been preferred. These data have typically also applied by other scientists which increases transparency and the opportunities to compare data.

In table 4.3 I present most of the general data, I have applied in my papers together with the primary source, how uncertain I perceive the data and my primary argument for applying this source. More exhaustive presentations are provided in the papers; here I focus on three overall data types and three types of data sources. These are data from applicants applying for investment grants for biogas plants, Biochain project partners and Danish reports and statistics.

It is not as easy to find standardised data on biogas production, in particular are prices and availability of inputs highly depended on local conditions, therefore are most data related to biogas production found within Danish literature and even with focus on specific areas. Data in the papers both rely on raw data from the Biogas Taskforce, their reports and our own calculations on the basis of reports and papers. These data have been compared to data from other sources, when possible.

Investment and operational costs

Data from official sources have in general been preferred to data from specific stakeholders, in order to make our results as comparable as possible. Furthermore, when possible we have tried to apply several sources and compare data.

Plant production costs are based on OPEX and CAPEX reported by plants that applied for funds from the temporarily earmarked investment fund; set up for biogas plant investments as a part of the Danish Energy Agreement in 2012 [27]. Data was treated and compared to the calculations made by the Biogas Taskforce report on biogas usage in the heat and power sector[35]. To linearise data we have applied the same break points as in [68]. These data may be biased by the applicants, however the utilised data only include data from plants who actually received support, and thereby are considered as realistic by the evaluation board. An advantage of the data is that they have been applied by the biogas Tastforce and other scientists as eq. [67]. This increases the consistency in results between us, and others.

For the value chain calculations we have furthermore included **production costs for biomass input**, for this it was not possible to obtain data from official sources. Instead we relied on our partner in the Biochain project: *SEGES* which is an agricultural consultancy also working with biogas production. SEGES developed a model to calculate biomass production costs together with pre-treatment costs. These data were collected and treated by people with experience within this area which increases the validity of the data.

Data on **output production costs and efficiencies** could to some extent be found in the official technology catalogue [25], in other cases we had to find other sources for specific data, this is further described in the relevant papers. The exact usage of data has varied a bit through the papers I therefore refer to them for further explanations.

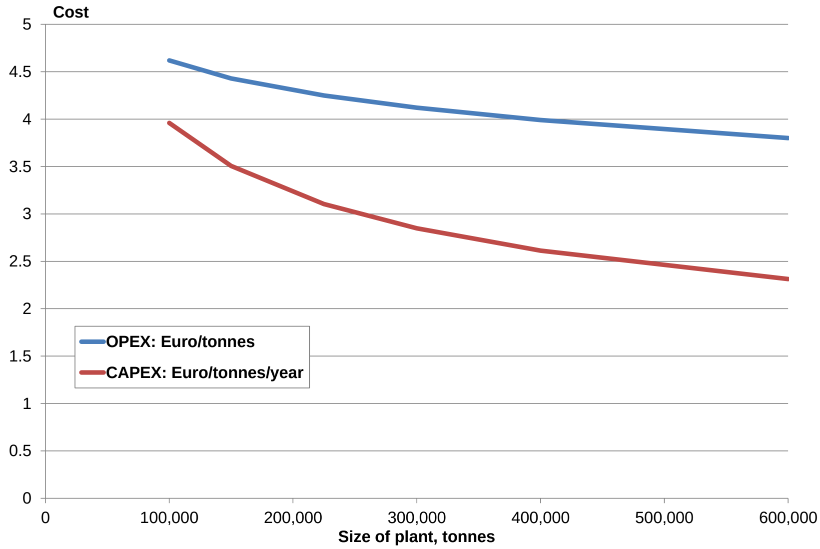

Figure 4.2: OPEX and CAPEX for the biogas plant is based on a fitted trendline.

Prices on goods with no official market

Another data challenge throughout this thesis concern prices on **inputs and some outputs** due to the lack of official markets for many of the inputs. **Manure** which is the primary input in *agricultural biogas production* contains a low value compared to the volume. This limits the distance from where it can be obtained to approximately 15-20 kilometres, which often gives the plant and farmers an almost monopolistic relationship between each other. Usually farmers are receiving the **digestate** afterwards. This has a somewhat additional value to the farmers as it smells less, it is easier to bring to the fields and the plants may have a better uptake of the nutrients from the digestate [80]. The actual additional value is difficult to estimate. And in order to add as few unknowns as possible we chose not to add more potential value than from the nutrients, this value was estimated following the suggested prices and average fertiliser content presented in [7], the value found was similar to other estimates found see e.g. [102].

Biogas production is to some extent a by-product of other production based on the waste products from agriculture and industry. Earlier, waste products from particularly the agricultural industry was easy to obtain for the biogas plants and plants were even paid to receive the waste. Today, with more biogas plants wanting to receive the waste, it seems that biogas plants pay to receive the substrates [81]; biogas plants are reluctant to reveal the actual

Data type		Sources	Uncertainty	Decision
Specific input data	Biogas Yield	Various sources hereunder project partners	high	The sources varies and are specified in the papers, yields were often cross checked with other sources, and sensitivity analysis were made in cases of additional uncertainty
	Transport costs	SEGES[a]	medium	Costs were calculated from one specific location which was emphasised in all papers
	Fertiliser value	Birkmose, Hjort-Gregersen, and Stefanek [7] p.52	high	One specific value was applied in most analysis to provide consistency and calculated with focus on best alternative costs for mineral fertilisers. Positive externalities were not included
Values from biogas	Carbon reduction	Wenzel and Hamelin [127][b]	high	The newest and to our knowledge the most thorough analysis made on this estimate
	Biogas price	Plant model and [101]	high	Best available data, see also in text
	Biogas certificate	PlanEnergi [101]	high	Best available data, see also in text combined with the certificate price
Regulation	Taxes and subsidies	Skat.dk, DEA and Energinet	low	Most data could be found on the relevant homepages
	CAC	DEA,DERA and other ministerial home-pages	medium	Focus on actual data sometimes found with help from relevant actors in the specific area

[a] Transport costs were calculated from one specific location for a biogas plant (Maabjerg Biogas) who was involved with the Biochain project and provided us with updated data on biomasses and manure types within a radius from Maabjerg biogas in 10 kilometres steps. We then calculated transport costs following a principle of average distance from the biogas plant and to the suppliers. This is further described in the supplementary material for A

[b] Data from [127, 128] were combined with own calculations in order to find one specific estimate for carbon emission reductions as a consequence of biogas production

Table 4.4: Specific estimates, data sources, degree of uncertainty and decision

prices though, so we have had to rely on data from other sources such as the Biogas Taskforce that was initiated along with the Energy Agreement in 2012 [27]. A conversation with an agricultural contractor for example proved to me how cost and value on straw vary significantly depending on quality, time constraints, geography and field size. As a consequence of this we have tried to focus on production costs using estimates from SEGES combined with qualitative considerations, more specifically explained in the individual papers.

Similar considerations have been made with regard to the **biogas price**. We have assumed that biomethane would receive a value of the natural gas price plus a green certificate price; total costs should then be covered by this income besides support and potential digestate income. As there is no open market for *green certificates* has the best estimate been the EU-ETS price, as this is what the green certificate in principle could be traded for, see also paper B. It is even harder to get a clear estimate on a price for *biogas applied directly*. I could have dug deeper into various sources such as the biogas applications or by sending out questionnaires to biogas producers; this would have led my work in another direction, and would not necessarily have given me better answers to my research questions. Instead I decided in most cases to focus on cost prices found by applying the plant level model (presented in Jensen, Münster, and Pisinger [68]) and the incentives and options for a larger part of the value chain. The exact choices made regarding price– and cost estimates have varied from paper to paper, depending on the case set-up. These choices are presented separately in the papers.

Specific estimates

Throughout all papers the search for data have been a time consuming task. Some data could be reused through the papers, while others were needed specifically for the given paper. The overall approach have been to look for data in open source statistics and reports form e.g. the Biogas Taskforce. I have furthermore contacted specialists within the Biochain project [3] and from outside the project [4]. I have then interviewed them regarding the data, I needed to get an overall picture of the investigated area. Knowledge from this have in most cases been backed-up by written data sources that I have referred to in the papers. This approach have proven to be very efficient to get into new areas, however, it does not *ensure* that all elements have been covered for a given issue. This uncertainty have been dealt with by double-checks and sensitivity analysis for determining parameters.

[3]e.g. Lone Abildgaard, Michael Støckler or Jin Mi Trioli

[4]e.g. Søren Tafdrup (DEA), Bruno Sander (Biogasbranchen) and governmental agencies within tax and environment

Sensitivity analyses

As data are hard to find or can be hard to predict it has proven useful to apply sensitivity analyses with regard to those parameters, identified as most critical.

In paper B on economy of scale, a case study was employed to form a general picture on the potential for scale effects in biogas production. It is always difficult to generalize on the basis of a case study as some factors and assumptions will be case specific and subject to insecurity. This was taken into consideration throughout the qualitative analyses. Furthermore, a sensitivity analysis was performed, in order to get a picture of the importance of specific factors such as yield and transport costs. The method chosen for the sensitivity analyses was a constant symmetric variation to compare the significance of risk regarding the investigated factors. The sensitivity analysis was conducted with regard to the profit where the factors in question were halved and increased by 50%. The 50% was chosen from the perspective of achieving substantial alterations in the results; and in the same time sustain symmetry. We were aware that the probability of variation would vary depending of the factors, this was then assessed qualitatively afterwards.

Another kind of sensitivity analysis was also performed in paper B, where it was investigated whether variations in the yield would have different effect on the profit for a plant that upgrades biogas compared to a plant that delivers biogas directly to a CHP plant. This analysis was performed to investigate the effect of two different support schemes for biogas.

In paper D sensitivity analyses are performed on the CO_2-cost in order to evaluate the socio economic value of biogas with varying CO_2-costs. These analyses were also utilised to see under which CO_2-costs it would be socio economically beneficial to use biogas.

In E the value of sensitivity analyses became clear as the optimal solution changed significantly with only few modifications of the input prices. It was then chosen to do some extra sensitivity analyses, where only one parameter changed; and where gas-, electricity- and heat prices was from the same year (2013, 2015 and 2016)- simulating three different possible realities for a plant. The following analysis was based on two potential value chains with two potential realities, in order to generalise the results and get a clearer picture of which risks the biogas value chain faces.

4.3 Inclusion of regulation in the analyses

Both *direct* and *indirect* regulation can have a significant influence on the economics for the biogas value chain, and as presented in section 3.1 and 2.3 are both command and control– (CAC) as well as incentive regulation (IncReg) applied. Policy instruments are therefore when I found it relevant

implemented quantitatively in the applied models if possible; and **assessed qualitatively** in the paper analyses when necessary. In table 4.5 most of the regulatory instruments considered in this thesis are listed. The instruments have been categorised with regards to type (IncReg or CAC), (direct or indirect), which part of the value chain they affect (green for agriculture, black for plant and blue for energy sector,) and whether they have been implemented in the quantitative models (**marked with bold**) or considered qualitatively (marked with regular types).

	Direct	Indirect
Incentive regulation	**Support schemes**	Tax exemptions for biomass and fuels for electricity production
	Taxation of inputs	Taxation of fossil fuels
	Green certificates	CO_2-quotas
Command and control	**Input restrictions**	Nutrient restrictions (farmers)
	Planning regulation	**Waste on fields restrictions**
	Wobbe index	**Monopoly regulation (heat)**

Table 4.5: Categorisation of regulation

Quantitative implementation of incentive based regulation

Incentive based regulation is mostly implemented **quantitatively** in the private economic models as additional income or cost; embracing the underlying assumption that biogas plants or value chains maximise profits including the support provided and applied taxes. The specific implementation of each policy instrument is described in the papers.

A common challenge for biogas value chains is that one end of the value chain can be supplied with support, while conditions for support (e.g. that biogas is based on waste products) can be addressed in another part of the value chain that may not necessarily be the same owner. As already mentioned, Danish biogas support is focused on output as biomethane or electricity based on biogas; similar regulation can be found in e.g. Germany, Italy and Austria [**Walla2008a**, 33, 100]. While in Norway indirect support is given in the beginning of the value chain, under the condition that waste is being treated see e.g. paper C. How support provided at one point in the value chain transmits into profits in the different entities of the value can be difficult to estimate. Several approaches have been applied throughout this thesis. In paper B it was assumed that approximately all support is handed over to the biogas plant combined with a qualitative discussion on how likely this assumption was. This method demands a qualified idea of how support is in fact divided, if the division of support is an important part of the analysis. An alternative approach applied in paper C is to consider the entire value chain, which may be just as relevant if focus for the analysis is directed towards the entire value chain. My final approach has been to consider the allocation of total profits, by first optimising profits for the entire value chain, and then consider various allocations of this profit, this was focus in paper E and is further described in section 3.3.

Implementation of command and control regulation

Through the papers *command and control* regulation has been implemented **quantitatively** where it was possible and relevant as e.g. input restrictions on energy crops; in other cases the regulation has been considered **qualitatively** sometimes together with sensitivity analyses.

The significance of cost-of-service regulation on heat is complicated to include quantitatively and is therefore primarily considered qualitatively. It is known from tried cases that agreed-on prices between the biogas plant and a local CHP have been judged to be reduced, with reference to the cost-of-service regulation[42]. However, there is little public information on how this affects biogas prices in general. In this dissertation, this issue has been dealt with through sensitivity analyses as an additional risk and discussed as a potential determining parameter in the qualitative analysis of the results in paper E.

Chapter 5

Results and discussion

Biogas production can potentially contribute with a large variety of positive externalities, but the production has so far not been economically viable unless it was considerably supported. The new regulation decided upon in 2012 paved the way for biogas upgrading, which increased the opportunities for biogas plants and future applications of biogas.

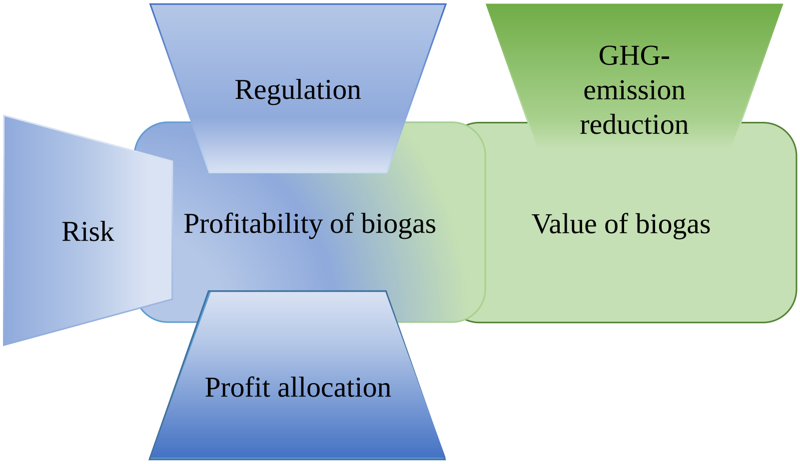

Figure 5.1: Questions to be answered

My motivation for this thesis was to get a better understanding of Danish biogas *value chains in order to identify any potentials to steer current regulation in a more efficient direction*. My approach has been to investigate how current regulation affect the value chain with regard to profits, risks, opportunities and strategic behaviour.

In chapter 1, I presented three overall research questions that I had decided to address throughout my thesis. Some of these questions have been the theme of an entire paper, some have been a part of the underlying mindset throughout my work, and maybe received less focus as I grew wiser. A common feature of the questions is that focus is on the private economic profitability of biogas production:

1. How does existing regulation affect the biogas production and can a more efficient production be achieved by changing regulation, while still keeping biogas production profitable?
2. How does this mix of market- and ownership structures influence the biogas value chain?
3. Which risk factors are most influential on the biogas value chain, and how may this be addressed?

These questions do not deal with the big elephant in the room: "Why should we support biogas production"? I do not claim to answer this question in my dissertation. However, in paper D, we investigate the socio-economic value of biogas for the energy system, when marginal damage costs of GHG-emissions are included. And by that I contribute to a part of this question.

5.1 Summarized contributions of the dissertation

With this dissertation I have contributed with several results regarding the interaction of public regulation, private incentives and profitability of the biogas value chain.

Specific contributions consist of the initial design of the economic model which is the cornerstone of the models applied in the analyses hereunder the value chain optimising plant level model described in section 4.1. These models have been developed and updated to lay the ground basis for the analyses made, considering the interaction of flexible regulation with regard to biogas inputs and risk for producers, with suggestions for *policy design*, analyses of *the potential value of biogas in the energy system in comparison to CO_2-damage cost* and the application of *cooperative game theory* on the value chain.

Contributions regarding policy design based on analyses on private economic profits in the value chain, show the *significance of flexibility in both incentive based as well as command and control regulation*; this both apply regarding inputs and outputs in the biogas value chain. The *Danish focus on biogas output* reflected in high subsidies on energy output, emphasise a value chain focus on input substrates (prices and potential yield) and incentivises a reduced biogas leakage, reduced flaring at plant level; however, also reduced own use of biogas in the production.

I identified several cases where inflexible regulation, regarding types of input, and following usage of the output can reduce the profitability of the production and thereby potentially increase the need for support. Profitability can also be reduced when biogas is consumed directly in a monopoly regulated CHP with an inflexible consumption pattern and a regulator who might push the biogas price downwards.

My **Contributions regarding profit allocation and strategic behaviour** in the biogas value chain was analysed using **cooperative game theory**. The work illustrate how strategic choices made regarding value chain design and participation can be explained by the application of game theory.

These results further revealed that regulation affects the value chain design and therefore a strategic explanation of why biogas plants choose to upgrade, while farmers can be reluctant to participate unless they are co-owners in the biogas plant.

A policy implication from this work is that policy makers should be aware of the final goal, when regulation is designed, and that sheer output support can be expected to result in more biogas. They should, however, also be aware that the amount of energy produced can be dampened by substrate restrictions and for example monopoly regulation on the energy side. Regulation, directly targeting GHG-reduction may potentially result in the same level of GHG-reduction, at a lower cost in support.

Contributions in relation to the value of biogas are found in the approach of investigating the socio-economic costs of biogas in the energy system, when GHG-emission damage costs are varied.

5.2 Results from paper A-E

Paper A: "Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting". Nine cases are compared in this paper, with regard to the effects on private economic profit, GHG-emissions and the energy account. The cases include three plant sizes and three mix of pig slurry and sugar beet. The results presented in figure 5.2 show that economic feasibility is negatively correlated with sugar beet input, as net-income only is positive when no sugar beet is added[1]. The energy account and GHG-reduction, on the other hand, is positively correlated with sugar beet input, meaning that net-energy consumption and net-carbon emissions are negative. Furthermore; we found a tendency to economy of scale, at least while sugar beet is not added. The result when sugar beet is added

[1]PSSB-0: means a substrate input of 100% manure and no sugar beet, PSSB-12.5, means 12.5% sugar beet, while PSSB-25, means 25% sugar beet.

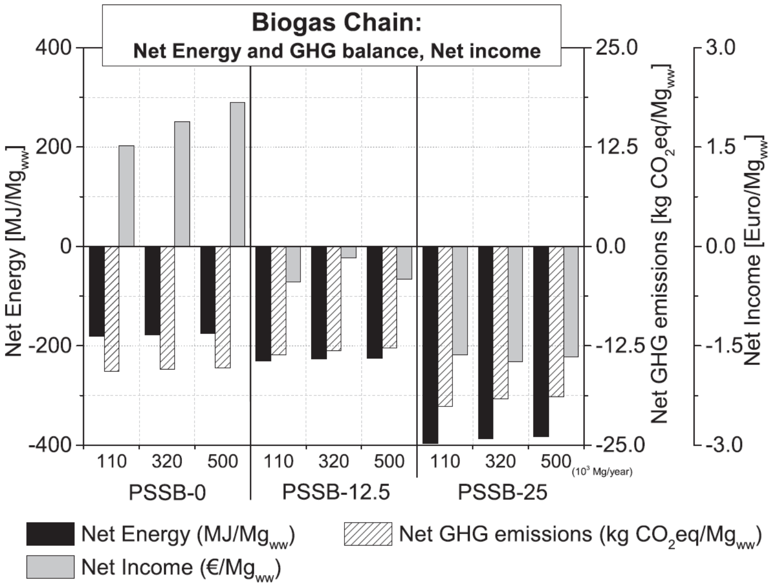

Figure 5.2: Comparative overview of net energy balance (MJ/Mg), net GHG balance (kg CO_2eq/Mg), and Net Income (V/Mg) per Mg ww of input to the biogas plant; Source: Paper A

are less conclusive. In this paper, the overall focus of the thesis is targeted regarding profitability of biogas, when scale, input and therefore also yield changes.

Paper B: "Economies of scale in biogas production and the significance of flexible regulation". In this paper, the research questions regarding risk and regulation are targeted. The nine cases from paper A are investigated further, now with focus on private economy taking scale, regulation and risk into consideration. The first result is a confirmation of similar analyses on economy of scale in biogas [33, 126]. We *can* find economy of scale in biogas in Denmark, and even though transport costs can have a significant influence on the result, they do not outweigh the positive scale effects from capex, at least when substrates are not extraordinarily far from production. The scale effect is; however, outweighed by upgrading costs and transport costs, when sugar beet is added as co-substrate; while the price of sugar beet eliminate all profits in the value chain; at least when we apply the biogas yield estimated for paper A.

An overall conclusion for this paper was that biogas yields are important for profits, and a biogas plant should have flexibility to switch co-substrates. Several sensitivity analyses were performed within the paper, concluding that the most significant factor for profits is the biogas yield; the importance of

2016		NO	NO→DK	DK	DK→NO
	Production (GWh)	**43**	**32**	**36**	**36**
Input	**Cost**	16.469	31.223	4.121	4.121
	Revenue, manure	7.756	0	0	16.154
	Revenue, Waste	80.798	0	0	0
Transport	**Cost**	10.831	3.924	8.475	21.208
Conversion	**Cost**	34.758	42.313	43.490	38.566
Output	**Cost**	9.490	2.676	13.372	29.295
	Revenue, digestate	0	6.107	8.411	0
	Revenue, biogas	39.200	69.717	81.302	24.566
Total in Euro/GWh produced		**56.207**	**-4.312**	**20.256**	**-52.471**

Table 5.1: Case results in Euro per GWh produced, the table include costs and revenue for each of the four cases, showing that the value chains only achieves a positive net-income in the home countries

substrate prices and transport costs was less influential. The risk on biogas demand was further investigated; and we found risks regarding seasonal volumes, as well as long-term structural volume risk. Furthermore; we found that risk in relation to scale and volume favour upgrading, as the risk on volume variations increase with scale, when the biogas plant becomes the sole supplier of a local CHP.

Paper C: "The implications of economic instruments on biogas value chains – a case study comparison between Norway and Denmark". In this paper, the research question regarding regulation is targeted by the comparison of structural conditions, political goals and policies between Norway and Denmark. We found that the viability of a value chain is highly dependent on structural conditions and the regulation applied directly *on* and *around* the biogas plant. Results are found by comparing an agricultural based value chain in Denmark, where support is focused on the *output* product biogas, and move this value chain to Norway, where support is focused on *inputs and investments*; and at the same time transport costs more than doubles. We find that the viable value chain becomes infeasible, when moved. A Norwegian value chain was in parallel moved to Denmark. Results from paper C and presented in table 5.1 show that even though the value chain was assumed to receive Danish biomethane support; the Norwegian value chain would not be viable in Denmark. The Norwegian value chain was based on waste and manure and producing gas for transport.

We further found that both countries have policy goals regarding GHG-emission reduction and usage of manure in biogas production; however, the goals are not completely aligned with regulation. While Norway seems to focus regulation on primarily input and production; is Danish biogas regulation targeting GHG-emission reductions through the substitution of fossil fuels in the energy sector. This variation in focus is probably caused by differences in the energy systems. Policy implications from the paper were that the countries might learn from each other. Norway may want to support usage of biogas more directly, while Denmark may want to support GHG-mitigation from manure. Both countries could improve regulation and awareness of the potentials of using organic household waste (OW) as input substrate and *still* find ways to apply the digestate on agricultural soil.

Scenario	CO_2-cost	Natural gas	Biomethane	Biogas
High CO_2-quota price	23.1	8.0	11.8	9.7
Low CO_2-damage cost estimate, Dice	30.3	8.4	11.3	9.2
High CO_2-damage cost estimate, Bergh	99.2	12.4	6.0	3.8

Table 5.2: CO_2-costs for the high CO_2-cost scenarios, €2015/ton; source: paper D

Paper D: "The impact of CO_2-costs on biogas usage". In this paper, we address the socio-economic value of biogas with regard to GHG-emissions. We apply the energy system model, Balmorel, in order to investigate how the socio-economically optimal demand for biogas changes, when estimates for the socio-economic damage costs from CO_2-emissions are changed. The overall conclusion is that, for biogas to be socio-economic feasible to employ in the energy system, should socio-economic damage costs be significantly higher than current and expected future CO_2-quota prices in the European ETS-system. This conclusion rely on the assumption that CO_2-reduction is the most valuable positive externality from biogas. The applied quota-prices and damage cost estimates are presented in table 5.2.

Modelling results from working with the paper are 1) the additional feature added to Balmorel, which allows for a joint target for fuel usage and 2) an update of the combtech-application that allows one technology to apply different fuels (in this case biomethane and natural gas). Other results are for example that direct use of biogas in CHP's was preferred to biomethane due to lower production costs; however, biogas and biomethane consumption increased so much in the case of very high CO_2-damage costs that biogas and biomethane was used for both baseload and regulating power[2]. This is difficult

[2]*Regulating power* is a term for electricity production, which can be regulated up and down following the system demand; gas fuelled power production can for example be applied as regulating power.

to do with direct use of biogas due to storage restrictions, which was why we had to limit investments for this type of fuel consumption. Furthermore, total fuel consumption grew in the case of high CO_2-costs as shown in figure 7 in paper D; at the same time electricity exports increased, indicating that biomethane could also be used for regulating power or even baseload in neighboring countries in the high cost case.

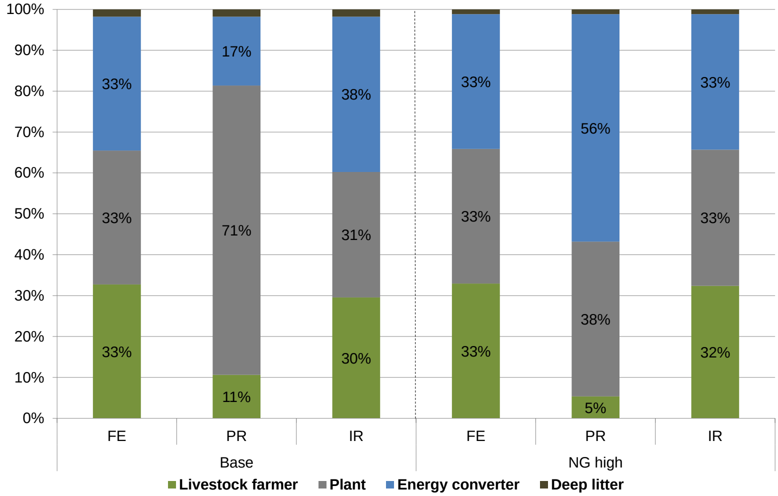

Figure 5.3: The percentage of the total profit for each owner in the base scenario and when natural gas prices are high (NG high); Source: paper E

Paper E: "Recent trends in biogas value chains explained using cooperative game theory". In paper E, all three research questions for the thesis are approached, though with a focus on ownership structures and how strategic behaviour can affect the final value chain set-up. Three profit allocation mechanisms are applied on two optimal value chain designs, found by using a plant level optimisation model. The results indicate several explanations of why it can be difficult to get livestock farmers involved with biogas production if they do not invest in the plant themselves; and why so many biogas plants choose to upgrade to biomethane, even when the optimal choice of value chain design could seem to be local CHP production. More specifically results show that upgrading would be preferred to CHP production when natural gas prices are expected to be high, while CHP is preferred, when natural gas prices are expected to be low. The optimal mix of input substrates is estimated to be approximately 70% manure and 30% deep litter.

The three tested profit allocation mechanisms are full equality (FE), where profits are distributed equally, proportionality (PR), where profits are distributed by costs, and Incentive rationality (IR), where alternative profits are taken into consideration. Results are displayed in figure 5.3, showing that livestock farmers could obtain a high share of profits with two of the allocation mechanisms. However, due to alternative incomes and the preferences of the other owners, it is likely that the chosen profit allocation would be proportional or something in that direction; leaving the farmers with a relatively small profit share.

In the paper we also find that it is likely, a plant owner would prefer upgrading; even though the profit allocation and expected profits could indicate, a plant owner preference for direct use in a CHP. This can be explained by strategic behaviour, as the plant owner, in the case of upgrading, has an improved bargaining power due to better alternatives. The disconnection of monopoly regulation from district heating, further increases the chance for her to reach the preferred profit allocation mechanism (in this case proportionality).

5.3 Discussion of results

Results in this thesis is founded in micro-economic literature within *industrial economics* regarding risk, markets and economy of scale presented in e.g. [122, 84]; *game theory* combined with allocation theory see e.g. [60, 51, 125, 95] and *environmental economics* see e.g. [54, 4, 5] all of which are further described in section 3.1. Results are based on data found in primarily Danish Biogas literature such as [55, 35, 67, 20, 97, 36] and from our partners in the Biochain project. This is further described in section 4.2

My contribution appear in analyses on the effect on Danish biogas production from current biogas regulation and the interaction with energy, GHG and agricultural regulation. How does this affect economic feasibility and risks? Which strategic actions could be expected from this interaction?

The effect of Danish biogas regulation

The application of various support mechanisms for renewable energy have previously been compared [1, 72] and assessed [75, 2, 3, 108]. Biogas regulation in other countries have also been investigated and reflected on, Lantz, Svensson, Björnsson, and Börjesson [76] for example find that the regulatory landscape for biogas in Sweden is complicated, while identifying both barriers and incentives. They concluded that the existing policy in Sweden was not enough to exploit the full potential in of biogas production. Carrosio [14] studied policies and organisational models for biogas plants in Italy. His conclusion was that the intentions of the policies are thwarted and recommended a diversification in the use of biogas and reorganisation of the political incentives. Brudermann, Mitterhuber, and Posch [12] considers biogas in Austria and emphasise the importance of favourable economic and political conditions on a long term basis. The above mentioned literature focus on biogas regulation in *one country*;

however, *comparative studies* have also been made, such as Raven and Gregersen [109] who made a comparative assessment between biogas developments in the Netherlands and Denmark. They underline the importance of formal rules; and concludes that subsidy grants and investment grants played a role in both countries. They further emphasise that long-term support mechanisms, such as in Denmark, have proved to be successful compared to the ad hoc support in the Netherlands. Another comparison has been made by Jacobsen, Laugesen, and Dubgaard [67] who compare Denmark and Germany showing that socio-economic GHG-reduction costs are significantly lower with Danish biogas policy, compared to German policy.

In paper C we compare the new Danish support system, with the fundamentally different Norwegian system. The approach is to compare biogas value chains in Norway and Denmark, two countries which are similar in many aspects except in agriculture, waste treatment and energy supply. These differences were taken into consideration when typical value chains, country goals and regulation was compared. This type of analysis combined with the quantitative test of value chain exchange between the countries is to our knowledge new.

The overall conclusion in **paper C** is that *regulation affects the value chain design, input types and end products*. It also affects how biogas is applied. We find that an input focused support system opens up for more flaring and self-consumption at the plant, while output based support incentivices as little self-consumption as possible in order to receive support for all biogas. This is illustrated by the data presented in figure 3, in paper C, where more than 40% of Norwegian biogas is consumed for "other applications", which primarily is flaring and self-consumption. Differences in input substrates between the two countries was also explained by structural differences and *command and control regulation*. For example is organic household waste (OW) almost not applied in Danish biogas production due to reticence in Danish regulation on source separation combined with complicated regulation for the application of household waste on agricultural soils. While organic household waste is a primary input substrate for Norwegian biogas production.

Policy implications from **paper C** suggest that it may be possible to reduce overall biogas support and still find a viable value chain, if livestock farmers are supported when manure is used for biogas. This is; however, much dependent on the co-substrate price, potential additional income or investment support. If support is changed it may increase the value of participating for farmers and thereby their willingness to participate. This was discussed in **paper E**. On the other hand, it may reduce total biogas production, if the output support is reduced.

The upgrading of biogas to biomethane and injection into the gas grid is a relatively new application of biogas, and so is support for this technology. Not only in Denmark but also in other countries, the investigation of opportunities, strategic, environmental and energy system effects has only just been initiated. Contributions from my thesis will hopefully help to understand both the strategic aspects of this change in regulation and changes in risks for the biogas producer.

A positive feature of Danish biogas regulation compared to output focused regulation in other countries see e.g. [126, 33], is that the support in Denmark is non-discriminatory towards large scale production as support does not decrease with scale. Economy of scale for biogas production have already been studied and demonstrated for Denmark [97] and in other countries [33, 126]; focus in these papers has, however, been on biogas applied in CHP's. With the inclusion of biogas for upgrading in **paper B** I have been able to find that biogas directly used in CHP's is limited by heat demand and therefore biogas plants were *de facto* limited in scale before it became possible to upgrade biogas and still receive support. We further found that the heat demand restriction sets a stricter limit on changes in biogas yields due to e.g. seasonal variations in input. This comparison between upgrading and direct application was to our knowledge not considered previously.

The impact of risk on profitability

The impact of risk on profitability regarding support systems has been investigated thoroughly by Kitzing [70] and in [71] with comparison between feed-in tariffs and feed-in premiums. Raven and Gregersen [109] also nicely illustrated the challenges with regulatory risk in their comparison between Danish and Dutch biogas regulation. Risk is primarily discussed in **paper B**, where risks comparisons were made between biogas used directly in heat– and power production and upgrading. Three types of risks were investigated: 1) the risk of not gaining a proper biogas price due to lack of negotiating power, 2) the lack of demand during summer periods (with less heat demand) and 3) if yields are improved. When biogas is upgraded; will additional yields only demand an upgrading capacity that is large enough to handle the extra biogas, while biogas applied in a CHP's is restricted on the heat demand. This is illustrated in figure 5.4, where profits for the upgrading plant increase with scale if yields prove to be higher than anticipated (see the 150%-case). The opposite result is found in the case of direct use, as additional yields will not pay off for a large scale plant.

Risk was evaluated quantitatively through sensitivity analyses with a constant variation and qualitatively by an individual assessment of the probability of a given scenario. It was found that plant profitability can be affected significantly by the kind of co-substrate that are included in the production. The most significant effect is when yields are not as high as expected, and if substrate costs and transport distances furthermore proves to

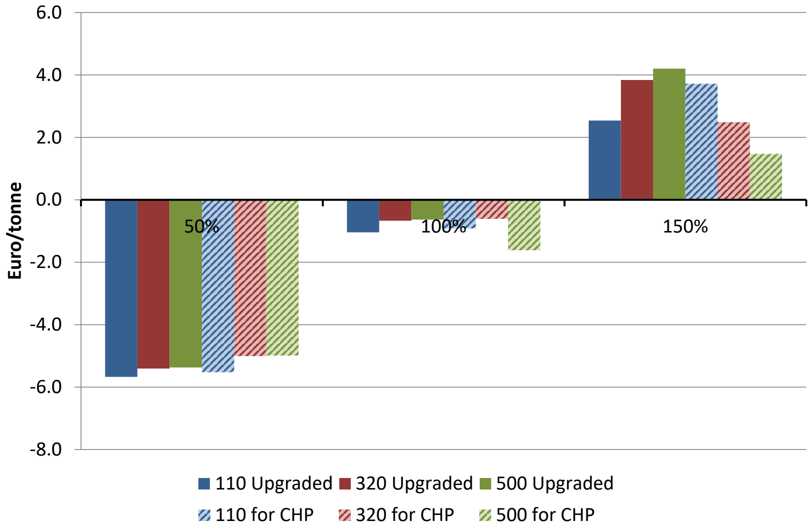

Figure 5.4: Sensitivity - net income effect with changes in biogas yield depending on the choice of direct usage in CHP or upgrading - with 85.5% manure and 12.5% Sugar beet as input; Source: Paper B

be substantial. In this case, *the sheer choice of co-substrate can define the profitability of a biogas plant*; given off course the support structure. If support is focused on the input side as in Norway, the yield is less important as presented in **paper C**, and expensive substrates would probably not be considered at all.

The conclusion in **paper B** was that *biogas producers will seek to reduce risks on input costs and quantities of co-substrates*, indicating that a flexible regulation with as few regulatory restrictions as possible would be beneficial, in order to reduce transport costs and ease flexibility in changing of input. The relevance of this was confirmed by the calculations of alternative profits in **paper E**, where the 2nd best choice of co-substrate proved to have a significant effect on profits, and if the co-substrate was changed *after* investments, profits would be reduced even further due to sunk costs and new investments for pre-treatment.

Strategic considerations on the basis of profit allocation in the value chain

Negotiating power is explored in **paper E**, where three profit allocation mechanisms, alternative incomes, and the implications on profits in the value chain are combined with potential profits for two value chains and under different price scenarios. The conclusions are, that livestock farmers are expected to gain the least share of the profit due to low bargaining power;

and that plant owners will prefer a value chain ending with an upgrading plant in order to increase own bargaining power.

We have found that this approach broaden the perspective of the strategic considerations made by the essential parties in the biogas value chain and help to understand the empirical evidence we found. To our knowledge, the approach has not yet been applied to a biogas value chain analysis; in fact, the best example we could find for an applied analysis was the study of Hubert and Ikonnikova [61], which considers the bargaining power in the Eurasian gas transit market. Hubert and Ikonnikova [61] apply allocation mechanisms as an indicator of bargaining power, whereas we consider the results as possible outcomes of a negotiation. The likelihood of these outcomes depends on the bargaining power of each participant, which is assessed through the potential alternatives before and after investments—assuming individual rationality.

Zemo and Termansen [132] apply a discrete choice experiment study of Danish farmers to examine farmers' willingness to participate in a unique, manure-based collective biogas investment. They find that farmers' participation is mainly motivated by a moderate number of partner farmers, short distance between the farm and the plant, contract options to sell biogas, *an option to cancel the partnership*, and free startup consultancy. This study goes more in depth with farmers' part of the value chain to find what motivates farmers to participate. A basis prerequisite for participation is that the farmers are co-investors. This prerequisite goes well in hand with the conclusions form paper E, where farmers risk a small share of profits if they are not co-owners of the plant.

Three issues can be discussed: 1) It could be questioned if some of these results could not have been found from a sheer risk analysis, and the answer is that it might. In fact I did investigate for example the relationship between the plant and the energy converter in **paper B**. I argue, however, that the issue with bargaining power becomes more clear when alternative profits and profit allocation mechanisms are included in the analysis. 2) An underlying assumption for the above-mentioned conclusion is that the cooperative of livestock farmers can be divided. If the livestock farmers stick together, the plant owner and energy converter would have to accept a higher profit for the livestock farmers. The considered case would probably mostly be a challenge, when some of the livestock farmers are co-owners of the plant, and therefore partly would be plant owners. To them, a higher share of profit to the plant would mean a higher share to them, and this would divide their interests from those who are not co-owners. It is probable in Danish agriculture, that some livestock farmers would be more than able to invest in a biogas plant, while others would not. 3) The discussions on the bargaining power between the plant owner and energy converter are a simplification of reality, and there are still investments in biogas plants feeding into a local CHP. There are also cooperatives that own the entire value chain and still choose to upgrade. Other issues such as heat demand in a given area, risk preparedness compared to risk aversion and expectations on future gas prices are off course also affecting the choices of the investors. *My contribution to the debate regarding upgrading versus direct consumption has been to add strategic thinking into understanding of the decisions made, given the current regulation*.

GHG-emission reductions from biogas production and usage

The reduction of GHG-emissions in comparison with renewable energy production have been treated in the literature in several ways. Amundsen and Mortensen [2] for example analyse the effect on Danish renewable electricity capacity from high carbon restriction and green certificates, they find that hard restrictions can in fact reduce renewable capacity in Denmark, Jacobsen, Laugesen, and Dubgaard [67] considers the socio-economic cost of carbon reduction through biogas production and compare it to reduction costs for biogas in Germany. The take on the analysis depend on which elements have been considered as important to investigate. Carbon reduction effects from manure treatment and the crowding out of fossil fuels in biogas production, is one of positive externalities that are typically included in the valuation of biogas. A common method to calculate net-emission from a value chain is to consider emissions from the production in a value chain and subtract the "saved" losses as when e.g. coal is replaced by biogas see e.g. [128, 127], this method can complicate comparison between cases in different studies, and an advantage of the approach in **paper A** is that the nine cases, which are compared only differs on few parameters. This makes the comparison more transparent for the drawn conclusions; which are that, the more sugar beet added to the biogas production, the higher the GHG-reduction, while negative scale effects are marginal for this result.

The approach in **paper D** is to apply the energy system model Balmorel to analyse the effect of carbon emission prices. Biogas has been applied in other analyses on systems optimisation—in particular on the issue of waste as a fuel [90, 89, 91]. Biogas is often one fuel out of many and seldom turn out to be the preferred fuel as seen in e.g. [90] and the national biomass value chain model [111]. In our analysis, we apply two main assumptions, we assume that biogas and biomethane have a negative CO_2-emission, as the only fuels in the energy system, and that the negative emissions are the same for both fuels. Furthermore; we assume that the system has access to all necessary quantities of biogas and biomethane. A potential weakness of the paper is that we do not attempt to calculate the negative emission from biogas production ourselves, and we do not distinguish between GHG-emissions from biogas and biomethane. This may reduce the strength of the results; however, we do not consider this to be very different from the other estimates used in the model.

The results still show the *direction* of conclusion namely that GHG-emission damage costs should be very high, before biogas becomes socio-economically attractive; despite of large GHG-emission reductions. The biogas potential is furthermore a challenge for the results, as the resource potential is not modelled.

In **paper C** we note that Denmark may have both goals for GHG-emission reduction and security of energy supply. It has not been the scope of this thesis to explore the relative weight of the goals. However, when considering the highly output focused biogas regulation in Denmark it could seem that security of energy supply have high priority. With the current development in the global climate this priority may shift, and while a priority change of goals may not change the regulation of wind– and solar power; it can have an effect on the biogas policy. As one priority may emphasise the value of GHG-emission reduction, while another priority may focus on properties of biogas and biomethane in relation to the fossil free energy-system and overall consumption in the future.

Chapter 6

Conclusions and outlook

In the later years, climate change issues have climbed up on the international agenda increasing the willingness to decrease greenhouse gasses (GHG)-emissions. EU target GHG-emissions with country goals for CO_2-emissions, Renewable Energy production, and Energy savings. Denmark is far with the development in renewable energy production primarily through wind power production, which is an inflexible type of power production. Biogas is renewable, could potentially function as regulating power, and based on manure it potentially has a reducing effect on GHG-emission.

Biogas has been produced and developed in Denmark since the 1970's; it is primary based on agricultural products, and the digestate from biogas production is commonly used as fertilizers on the fields, this is why focus for this thesis is on agricultural based production. The biogas value chain is characterised by sectors that are highly regulated and operates on a wide spectrum of markets i.e. ranging from monopolies to very competitive markets.

Until recently the development in biogas production has been slow; with the Energy Agreement in 2012 [27]; however, biogas support was increased and support was expanded to other applications. Probably more importantly; support for biomethane was put on the same footing as biogas applied directly in heat– and power production. This thesis was started shortly after the Energy Agreement and before the regulatory change was ratified; and **the main theme of this dissertation has been to evaluate the private economic consequences for the biogas value chain under this new regulation**

The overall research question is regarding private economic profitability in the biogas value chain with focus on *how existing regulation together with market–*

and ownership structures affect the biogas value chain and *which risk factors are most influential on feasibility and value chain choices*. The questions are treated in four journal papers based on a combination of micro-economics and model based policy analyses. Furthermore; a Socio-economic analysis regarding the value of biogas in the energy system is performed through energy systems modelling in a fifth journal paper.

Since 2012, the biogas production has more than doubled see figure 1.1, and the development has been in the direction of large new plants, that upgrade to biomethane. Analyses throughout this thesis help explaining this phenomenon, mostly considered in paper B and –E. For example, by the application of cooperative game theory to include **the strategic considerations**, which could be made by the plant owner. When she is faced with the opportunity to upgrade, and the alternative is a monopoly regulated CHP with good alternatives in the form of an untaxed biomass heat-boiler.

Both quantitative and qualitative analyses based on micro-economic theory are applied in the thesis, to extract the main risk factors facing the biogas value chain. And to explain the private economic incentives behind the choices made by investors regarding inputs, scale and output. The game theoretic implications are also analysed, when support in one part of the value chain is contingent on actions in other parts of the chain. All in all it is shown that regulation affect the value chain decision in several ways: regarding input types, the level of output, and final applications of the output.

The support level for biogas is high in Denmark; compared to the decreasing support tariffs for both wind— and solar energy. It may therefore be relevant to learn from regulation in other countries, as presented in paper C. **Denmark; could potentially learn from Norway by applying input support**, and at the same time reduce output support. If this should be considered; however, one should be aware that *pure* input support incentivises less biogas production. The best solution will depend on the overall goal for biogas support, whether it is GHG-emission reduction or fossil fuel replacement.

Outlook

Future analyses regarding economic feasibility of alternative input and output support mixes, could be performed by application of the plant level model (see explanation in paper E). Analyses from the biogas taskforce indicate that biogas should be applied in the transport sector or for industry [20]. *Future analyses could build on the results found in paper D and examine the socio-economic value of biogas applied in industry and transport*. Latest statistics indicate little biogas consumption in industry and transport. *It could therefore also be relevant to analyse how subsidy and tax systems could support this development. Given that biogas might not be supported with high subsidies in the future, could other tools also be investigated,* *such as blending demands for biofuels combined with sustainability certified biogas certificates*.

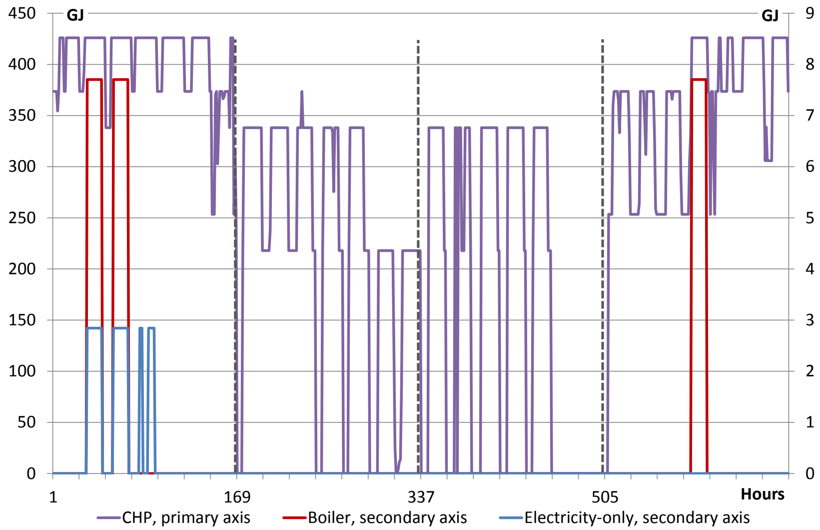

Figure 6.1: The graph displays the consumption pattern for biogas in Balmorel, when there are no consumption restrictions, the graph show tendencies for both seasonal– and regulating consumption; Source: Paper D

Other relevant applications of biogas could be with regard to biomethane as regulating power. In paper D we found indications for regulating system usage of biogas see figure 6.1; and this could be further investigated. Biogas upgraded through power to gas (PtG) technology [1], could alternatively be applied as downgrading technology. In paper E we found methanation to be the preferred upgrading technology when gas prices are high. *Biogas could thereby both add flexibility during deficit and surplus of electricity; however it still need to be examined whether biogas would be able to supply this flexibility to the energy system in a socio-economically feasible way, and if so, how this should be aided through the tax—and support system*

This dissertation has contributed with several results regarding the interaction between public regulation, private incentives, and profitability of the value chain. Specific contributions are analyses considering the interaction of flexible regulation with regard to biogas inputs, and risk for producers with suggestions for policy design. In addition, the potential value of biogas in the energy system is analysed in comparison to CO_2-damage cost. A contribution is furthermore the application of cooperative game theory on the value chain,

[1]when H_2 from electrolysis is added to biogas, converting surplus CO_2 into CH_4 and O_2.

illustrating how choices made regarding value chain design and participation can be explained by bargaining power and possible profit allocation.

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Part II

Papers A-E

Appendix A

Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting

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Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting

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ABSTRACT

Several countries have established a number of increased targets for energy production from renewable sources. Biogas production, which will play a key role in future energy systems largely based on renewable sources, is expected to grow significantly in the next few decades. To achieve these ambitious targets, the biogas production chain has to be optimised to obtain economic viability and environmental sustainability while making use of a diversified range of feedstock materials, including agricultural residues, agro-industrial residues and, to some extent, dedicated energy crops. In this study, we integrated energetic, GHG and economic analysis to optimise biogas production from the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). We found that utilising SB as a co-substrate improves the energy and GHG balances, mostly because of increased energy production. However, utilising SB negatively affects the profitability of biogas production, because of the increased costs involved in feedstock supply. The scale of the processing plant is neutral in terms of profitability when SB is added. The results indicate that medium-to large-sized biogas plants, using low shares of SB co-substrate, may be the preferred solution.

1. Introduction

Anaerobic digestion (AD) is one of the most efficient technologies for extracting clean and renewable energy from biomass with high water content [1]. In addition, AD is useful for recycling nitrogen (N) and phosphorus (P) from animal manure, which is in great need worldwide [2,3], and it is also considered to be the most effective technology for reducing greenhouse gas (GHG) emissions from manure management and at a low cost [4,5]. AD is fully integrated into Denmark's long-term strategy to be independent of fossil fuels before 2050 [6,7]. In accordance with this strategy, 50% of all animal slurry must be used in AD by 2020 [8], and 60% of organic waste from public services (up from the current level of 17%) will be collected and utilised for biogas production by 2018 [9]. In 2050, biogas plants are expected to be processing about 42 PJ of biomass, corresponding to >7% of all energy input for Denmark, while 16–22% of all biomass will be routed to energy production [10].

Abbreviations: AD, anaerobic digestion; BMP, biochemical methane potential; CHP, combined heat and power; CSTR, continuous stirred tank reactor; EF, emission factor; GHG, greenhouse gases; HRT, hydraulic retention time; PS, pig slurry; SB, sugar beet pulp silage; TC, total cost; TI, total income; TNI, total net income; TS, total solids; VS, volatile solids; VS_D, degradable volatile solids; VS_{ND}, non-degradable volatile solids; ww, wet weight.

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The AD of animal manure is in focus for two reasons: 1) large amounts of manure are available in Denmark [11] and 2) it allows for the better management of N and P nutrients at the regional level. In Denmark, manure is currently collected in the form of slurry, with a water content of about 95% and an organic matter content of ca. 4% [12]. Owing to this high water content, manure can only be used at the present time for biogas production, though hydrothermal liquefaction may represent an alternative to anaerobic biogas production in the future. Manure has a low biogas production potential [13], meaning that its digestion needs to be boosted by a more energetic co-substrate [14]. Suitable co-substrates include other agricultural residues, organic industrial by-products (e.g. from the food industry) and dedicated bioenergy crops.

The amounts of biogas to be produced and the portfolio of biomass materials to be used represent important logistical and management challenges, the combination of which hinders environmentally sustainable and economic viable biogas production in the country. Environmental and energetic issues related to biogas production are depicted rather comprehensively in the available literature, focusing for example on the digestion and/or co-digestion of manure (e.g. Hamelin et al. [15]; De Vries et al. [16]; Lansche & Mueller [17]), municipal organic waste (e.g. Møller et al. [18]; Bernstad et al. [19]; Boldrin et al. [20]; Levis & Barlaz [21]), industrial co-products (e.g. Berglund & Börjesson [22]; Tufvesson et al. [23]), sewage sludge (e.g Tarantini et al. [24]; Lederer & Rechberger [25]; Nakakubo et al. [26]), energy crops and/or cropping systems (Amon et al. [27]; Gerin et al. [28]; Jury et al. [29]; Schumacher et al. [30]; Blengini et al. [31]; Buratti et al. [32]; González-García et al. [33]). These studies indicate that biogas production from residual biomass is generally environmentally beneficial, but the modelling of biogas from energy crops somehow seems more complex, as it must consider carefully local conditions regarding crop cultivation and the supply chain [34]. The economic viability and optimisation of biogas production has also been investigated in a number of studies (e.g. Walla & Schneeberger [35]; Power & Murphy [36]; Gebrezgabher et al. [37]; Karellas et al. [38]; Stürmer et al. [39]; Brown et al. [40]; Delzeit & Kellner [41]; Møller & Martinsen [42]; Riva et al. [43]; Schievano et al. [44]), indicating that the profitability of biogas production is generally related to factors such as the plant size, the cost of feedstock, initial investment, costs for storage and transportation and biogas yield.

The integration of environmental and economic assessments was only attempted in a few cases. Most of these studies – e.g. Murphy et al. [45], Ayoub et al. [46], Ayoub et al. [47], Luo et al. [48], Santibanez-Aguilar et al. [49], Hennig & Gawor [50] –, however, focus on the use of dedicated energy crops and their conversion in complex and centralised biorefinery systems used for fuel production. Biogas production from residual materials is investigated, for example, in Yabe [51]. These studies nonetheless are static in nature, as the assessments are carried out at the scenario level. When looking at the co-digestion of residual biomass and energy crops, no studies were found to have attempted to optimise biogas production by dynamically modelling individual sub-parts of the biogas chain.

Therefore, the objective of the study presented herein is to develop a joint value-chain, energy and environmental model, to be used for optimising biogas chain production. This model is meant to provide advice to managers and decision makers in the form of a holistic evaluation of risks and benefits in producing biogas using sugar beet pulp silage (SB). This objective is achieved by 1) developing detailed economic, GHG emission, energy and mass models for the biogas chain, 2) integrating these models into a single framework capable of describing the relationships between economy, energy and emissions, while taking into consideration scaling effects, 3) applying the model to optimise the use of beet roots in manure co-digestion and 4) identifying the optimal scale of the biogas plant.

2. Materials and methods

2.1. The biogas production chain

As shown in Fig. 1, the biogas production chain assessed herein consists of five main process units, including:

- Raw material input: cultivation and harvesting stages
- Pre-treatment: washing, slicing and ensiling
- Transportation: transportation to the biogas plant and transportation to the farm
- Energy production: mixing tank, anaerobic digester, post-digestion plant and combined-heat-and-power (CHP) plant or gas upgrade for the gas transmission net
- Digestate process and fertiliser unit: after-storage and field stages

SB is first cultivated and then harvested between September and mid- or late November [52]. While harvesting, the root is separated from the beet top and left on the field. Beet roots carry a significant amount of soil, and so a cleaning step is thus required. Cleaning is normally performed at the farm level, but centralised cleaning can occur in some cases. The soil removed from the root is returned to the field. SB harvested in November are then stored in clamps covered with straw [52]. In February, the roots are chopped finely into beet pulp and moved into silos for 18 months (i.e. until September next year). Ensiling leads to the degradation of some organic pools, so that total solids (TS) and volatile solids (VS) contents change, while GHG are emitted. When needed, SB is collected and then mixed with pig slurry (PS) to a known ratio, and the mixture is then pumped into an AD reactor. PS is the main substrate, whereas SB is the co-substrate providing different benefits to the process: it contains abundant trace elements for microbial growth, it has a strong buffer capacity, thereby helping to maintain pH neutrality, and it is a good diluter for toxic compounds potentially contained in the manure. In the present study, the co-digestion of three mass-based ratios of PS and SB in the feedstock is analysed:

- PSSB-0: 100% PS, 0% SB
- PSSB-12.5: 87.5% PS, 12.5% SB
- PSSB-25: 75% PS, 25% SB

The additional use of SB (i.e. a 50/50 ratio) was attempted in preliminary tests; however, the AD operation was unstable with the accumulation of VFAs and a drop in pH level.

The main product of the digestion process is biogas (i.e. a mix of CO_2, CH_4 and other trace gases), which can be used for electricity and/or heat production, or fed to the natural gas grid. Depending on the final recipient and the energy conversion technology employed, biogas may need to be upgraded to remove most of its CO_2 and other trace compounds. The by-product of the digestion process is a type of slurry called "digestate," which is typically partly dewatered and further stabilised by means of aerobic composting. The finally cured digestate may be stored further until its final application to agricultural land as a fertiliser and soil amendment agent. The calculations herein considered a field-application scenario where digestate is applied in early spring, prior to seeding a spring cereal crop.

In the biogas production chain, the economy of scale can be a significant factor affecting the profitability of a project. In fact,

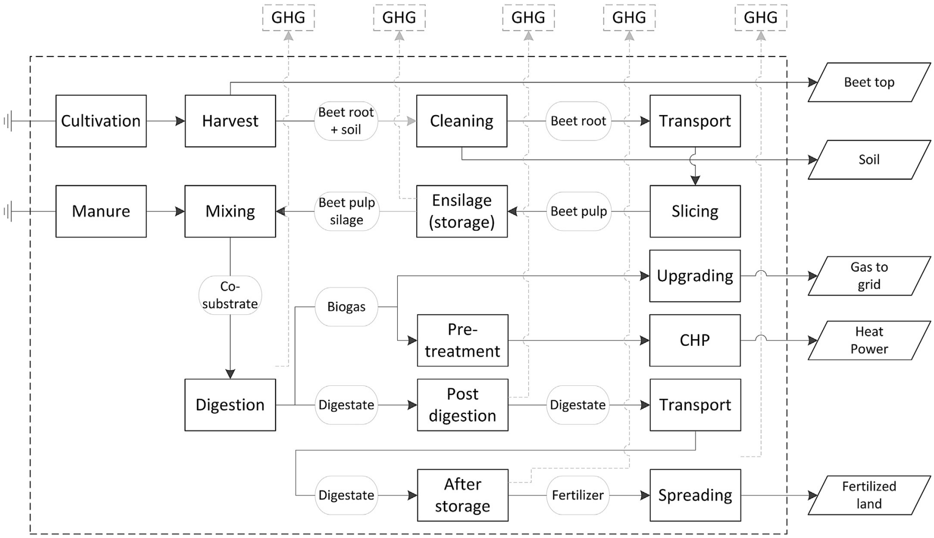

Fig. 1. Overview of the biogas chain model.

while production costs per unit of biomass handled may be reduced in large facilities, transportation costs may increase significantly, due to the larger size of the catchment area for the biomass. To assess the scale effect, economic analysis was thus performed on three facilities: small (i.e. using 110,000 Mg of biomass per year), medium (i.e. 320,000 Mg/year) and large (i.e. 500,000 Mg/year). The size of the plant is assumed not to have an effect on mass and energy balances.

2.2. The mass balance model

We based mass balance calculations on both the literature and experimental data. Input and outputs from individual processes in the biogas chain were modelled by tracking digestible (VS_D) and non-digestible (VS_{ND}) components of VS. In the model, we defined lignin as VS_{ND}, as it is non-degradable in an anaerobic environment [13]. The remaining VS (i.e. total VS minus lignin) was defined as VS_D. The basis for the mass balance calculation was 1000 kg of feedstock fed into a biogas digester. The mass balance model included stages shown in Fig. 1, as explained in the previous section. We reconciled and displayed mass and energy balances using STAN, a software package used for material and substance flow analysis [53].

For the harvested SB, we used data from Schoups et al. [54] and Thalbitzer [55], to determine mass distribution into roots, tops and soil. Harvested beet root accounted for 70.7% of the total mass, whereas beet tops were 25.6% and soil 3.8%. The total solids (TS) in the root were 226 g/kg, and VS was 208 g/kg. While the top is removed, the root and attached soil are moved further on to the cleaning step. The amount of soil left after the wet washing step was assumed to be 2.1% of TS. Since soil contains mostly ash (85% in TS), the VS concentration is slightly lower than the case where the root is without soil.

We assumed the pulping process would involve no mass loss, and we modelled the storage process for the beet root as employing two sub-processes, both responsible for significant VS degradation (i.e. ~28% and 12% respectively, Table S2 in supporting information) and any subsequent decrease in biogas production during AD. For the sake of simplicity, the two storage sub-processes were represented by one overall storage process in the mass balance model.

We experimentally measured the composition of SB and PS, as well as biogas production data during AD from different sources (details provided in the supporting information). We carried out physicochemical analysis of PS and SB according to the standard procedure (APHA standard method [56], see supporting information), and we determined biochemical methane potential (BMP) according to VDI 4630 (2006). We also investigated the AD of different feedstock mixes using a 20 L continuous flow stirred-tank reactor (CSTR) in a mesophilic condition (37 °C), with a hydraulic retention time (HRT) of 20 days. Data for the individual co-digestion mixing ratios are presented in Table 1, where it is evident that contributions of VS from SB and PS are considerably different for the analysed scenarios. For example, in the PSSB-25 scenario, 58% of VS is from SB while 42% is from PS, while approximately 63 and 37% of VS originates from SB and PS, respectively, in the PSSB-12.5 ratio. The prime feedstock (i.e. PS) had BMP of 296 NL_{CH4}/kg_{VS} (9.42 NL_{CH4}/kg_{WW}). The BMP of SB was 424 NL_{CH4} kg/kg_{VS} (54.8 NL_{CH4}/kg_{WW}). During CSTR experiments, 43.4–55.9% of VS was transformed into biogas (supporting information, Table S5). When only PS was digested, CH_4 production was 9.10 CH_4NL/kg_{WW}, while CH_4 productions from the PS and SB mixtures were 12.3 NL_{CH4}/kg_{WW} and 18.0 NL_{CH4}/kg_{WW} for PSSB-12.5 and PSSB-25, respectively. Using the equation provided by Sommer et al. [4], methane emissions post-storage were estimated at 0.30–1.99 NL_{CH4}/kg_{WW}. Additional details are provided in the supporting information.

Table 1
Composition of co-feedstock and biochemical methane potentials (BMP) for biogas production at different co-digestion mixing ratio scenarios.

Parameter	Unit	PSSB-0	PSSB-12.5			PSSB-25		
		PS	PS	BS	Co-feed	PS	BS	Co-feed
Wet mass	g	1000	875	125	1000	750	250	1000
TS	g	37.7	33.0	22.4	55.4	28.3	44.9	73.2
	% ww	3.8	3.8	17.9	5.5	3.8	17.9	7.3
Water	g	962	842	103	945	722	205	927
	% ww	96.2	96.2	82.1	94.5	96.2	82.1	92.7
VS	g	31.8	27.8	16.2	44.0	23.9	32.3	56.2
	% TS	84.4	84.4	72.0	79.4	84.4	72.0	76.8
Ash	g	5.9	5.2	6.3	11.4	4.4	12.5	17.0
	% TS	15.6	15.6	28.0	0.0	15.6	28.0	0.0
VS pools								
VS_D	g	28.2	24.7	13.8	38.5	21.1	27.6	48.7
	% VS	88.6	88.6	85.3	86.7	88.6	85.3	86.7
VS_{ND}	g	3.6	3.2	2.4	5.5	2.7	4.8	7.5
	% VS	11.4	11.4	14.7	13.3	11.4	14.7	13.3
Biogas potential								
BMP	NL_{CH4}/kg_{VS}	296	296	424	342	296	424	370
	NL_{CH4}/kg_{ww}	9.4	9.4	54.8	15.1	9.4	54.8	20.8

PS: pig slurry; SB: sugar beet pulp silage; VS_D: degradable VS; VS_{ND}: non-degradable VS; ww: wet weight; TS: total solids; VS: volatile solids; BMP: biochemical methane potential.

2.3. The energy balance model

For individual flows of materials in the system, we assumed an energy content (H_{aw}, ash- and water-free) of 20.5 MJ/kg_{VS} and 26.6 MJ/kg_{VS} for the VS_D and VS_{ND} respectively. As specific data for VS_D and VS_{ND} does not exist, we derived these values through data reconciliation, in order to fit the energy balance with respect to the energy content of the inputs, outputs and biogas production. These estimated values are in accordance with data reported for cellulose/hemicellulose and lignin materials. Energy related to the cultivation and harvesting of sugar beet was 0.334 MJ/kg, taken as cumulative energy demand for the Ecoinvent (v2.2) process 'Sugar beet, from farm'. We assumed the production of PS as being burden-free, meaning that energy and material consumptions utilised for animal growth were excluded from the calculation.

For transportation, we based diesel consumption on estimated driven distances (see later) and assumed a consumption factor of 0.02645 l/tkm (Ecoinvent process 'Transport, lorry >32t, EURO5'). For the energy balance, we assumed that diesel has an energy content of 43.1 MJ/kg, a density of 0.832 Mg/m^3 and a cumulative primary energy content of 54.8 MJ/kg (Ecoinvent process 'Diesel, low-sulphur, at regional storage'). We estimated energy consumption during ensilage at 150 MJ/Mg and 6.7 MJ/Mg, based on Ecoinvent processes 'Baling/CH' and 'Loading bales/CH', respectively, and assumed that each bale contained ~1.3 Mg of beet root. The spreading of digestate on land requires 0.26 L/m^3 of diesel (Ecoinvent process 'Slurry spreading, by vacuum tanker').

We estimated electricity consumption for operating the biogas plant at 30 MJ/Mg [22], while the energy requirement for heating up the feedstock was estimated at 121 MJ/m^3 of slurry (or 1800 MJ/Mg_{TS}). For the estimation, we assumed that the average temperature of the inlet material was $T_{in} = 8$ °C and that the slurry had a density and specific heat similar to water (i.e. 1000 kg/m^3 and 4.19 kJ/kg/K); additional details are provided in the supporting information. The biogas produced is combusted in an engine (i.e. Jenbacher 420), with conversion efficiencies of 40 and 42% for electricity and heat, respectively [57]. Part of the produced energy is used for operating the plant, while the surplus of electricity and heat is delivered, respectively, to the electricity network and district heating facilities. For electricity, cumulative primary energy was assumed at 2.47 $MJ/MJ_{electricity}$, as in ELCD process 'Electricity mix, AC, consumption mix, at consumer, 1kV-60 kV DK'. For heat, cumulative primary energy was assumed at 1.55 MJ/MJ_{heat}, as reported by the Danish Energy Agency [58].

2.4. The GHG model

We established the GHG balance using the conversion factors for diesel combustion, electricity and heat (reported in Table 2) applied to the individual energy inputs described previously. The loss of biogas due to fugitive emissions from the plant is rather uncertain, as very few measurement studies at full-scale plants have been conducted so far. In the present study, we assumed that the fugitive emission of CH_4 corresponds to 3.1% of the CH_4 production in the biogas plant, as estimated by Flesch et al. [59] for an agricultural biodigester, including storage of the digestate.

We predicted the short-term emission of N_2O using the N_2O sub-model developed by Sommer et al. [4], which considers N_2O emission to be a function of VS in slurry or digestate, reactive slurry nitrogen (N) and soil water potential (ψ). As explained in the supporting information, the model makes use of the VS_D and VS_{ND} introduced in section 2.2. For model calculations of N_2O emissions, we assumed an application rate of 100 kg NH_4^+-N/ha. Following Sommer et al. [4], the nitrification of reactive N in slurry hotspots was assigned an N_2O emission factor (EF) of 0.5%, and the nitrification of N from digestate or slurry in the surrounding soil was allocated an EF of 0.2%. We calculated total denitrification in the slurry clumps as a function of VS_D in the hotspot, and the resulting N_2O emission was estimated by assuming an EF of 2%. Total N_2O emissions produced by nitrification in clumps and soil, and by denitrification in clumps, were expressed on an area basis but also relative to slurry/digestate VS. The calculation considered a field-application scenario where slurry/digestate is applied in early spring, prior to seeding a spring cereal crop. We assumed an NH_3 loss of 10% during application, and soil-water potential was set to −0.015 MPa, i.e. close to field capacity.

We estimated VS_D in digestate and untreated feedstock from the short-term evolution of CO_2-C after incubating slurry/digestate in soil under aerobic conditions. We assumed that VS_D in applied materials would be fully degraded when CO_2 evolution rates became constant. The six incubation tests included three samples of digested material, two samples of raw feedstock and one control (i.e. only soil); each test included five replicates. The digestate samples were produced in CSTR experiments, as explained in

Table 2
Emissions factors for energy inputs to the biogas chain.

Process	Unit	Amount	Note, reference
Diesel combustion	kg CO2-eq/liter	3.1	Provision + combustion (Fruergaard et al., 2009)
Electricity production	kg CO2-eq/kWh	0.95	Hard coal, NORDEL (Fruergaard et al., 2009)
Heat production	kg CO2-eq/GJ	72	District heating, natural gas (Fruergaard et al., 2009)

section 2.2. The three samples of digestate corresponded to feedstock mixtures previously described (i.e. PSSB-0, PSSB-12.5, PSSB-25), while the two samples of raw feedstock included undigested PS and SB. The main physicochemical properties of the materials used for the incubation tests are reported in the supporting information (Tables S3 and S8), together with a description of the experimental setup (Table S7), the gas sampling procedure, the data analysis and the estimation of N_2O emissions for the analysed scenarios (Table S9 and Table S10).

We converted the emissions of different gases to CO_2-equivalent emissions, by using the following 100-year global warming potentials (GWPs): 1 kg CO_2eq/kg CO_2 for fossil CO_2, 28 kg CO_2eq/kg CH_4 for biogenic CH_4, 30 kg CO_2eq/kg CH_4 for fossil CH_4, 265 kg CO_2eq/kg N_2O for N_2O (according to IPCC [60]) and 0 kg CO_2eq/kg CO_2 for biogenic CO_2 [61].

2.5. The economic model

In the following, the economic model is described briefly, while additional details are provided in supporting information. The objective of the economic model was to determine the total net income (TNI) of different scenarios, where we define the $TNI(p_k,M_j,M_k,r_j,j,k)$ as (Equation (1)):

$$TNI(p_k,\ M_j,\ M_k, r_j,\ j,\ k)\ =\ TI(p_k,\ M_k) - TC(M_j, M_k, j, k) \tag{1}$$

where $TI(p_k,M_k)$ is the total income as a function of the price p_k of output k and the mass M_k of output k; $TC(M_j,M_k)$ is the total cost as a function of the mass M_j of biomass j and the mass M_k of output k and the index j and k are objects of the set J of input biomass (i.e. PS and SB) and the set K of output (i.e. digestate, biogas), respectively.

2.5.1. Income

Total income $TI(p_k,M_k)$ is the sum of the prices paid for the different outputs and is defined as (Equation (2)):

$$TI(p_k,\ M_k) = \sum_{k\in K} p_k M_k \tag{2}$$

where M_k is the mass of output k (i.e. digestate, M_{dig}, biogas, M_{gas}) and p_k is the price of output k.

The factor M_k is a function of the process yield, which is in turn a function of different operational parameters, such as feedstock composition and HRT in the process, as explained and estimated in section 2.2. We estimated the prices p_k of the digestate (p_{dig}) and biogas (p_{gas}) based on market considerations. In an agricultural context, digestate has some value because of its fertilising potential and reduced smell in the area. The p_{dig} depends on the specific supplier agreement between the operator of the biogas plant and farmers, thereby including the requirement of the farmer to dispose of the PS.

We estimated p_{gas} in Denmark based on the final use of the biogas and the level of public support. We considered the following two options:

- Biogas is upgraded and fed to the natural gas network.
- Biogas is used locally in a combined heat and power (CHP) plant.

When biogas production exceeds a specific amount, hereby estimated as 3.5 million m^3 per year, it was calculated that biogas was upgraded and fed into the natural gas grid. In this case (Equation (3)), the selling price of the biogas ($p_{gas,UP}$) is determined by the market price for the natural gas (p^{NG}), the support level (S) and a potential green factor (p^g), corresponding to the market price for "being green", determined from sales of green certificates.

$$p_{gas,UP}\ = p^{NG} + p^g + S \tag{3}$$

When biogas is used at a CHP plant, its price ($p_{gas,CHP}$) is a combination of the price of biogas as such and a market power value, as shown in (Equation (4)):

$$p_{gas,CHP} = p(p_{NG}, S,\ p_{HP}) - p_{MP} \tag{4}$$

where p_{NG} is the price of natural gas, S is the level of public support given to the CHP, p_{HP} is the price of heat and power generated and sold to the market and p_{MP} is the market power value, which depends on the structure of the power market (e.g. user and supplier are monopolist, or alternative supply/production options exist).

2.5.2. Costs

From the biogas plant perspective, total cost $TC(M_j,M_k)$ is expressed as (Equation (5)):

$$TC(M_j, M_k) = C_{trans}(M_j, M_k, GP_k) + C_{opex}(M_j, M_{gas,UP}) + C_{capex}(M_j, M_k) \tag{5}$$

where $C_{trans}(M_j,M_k,GP_k)$ is the transport cost, $C_{opex}(M_j,M_{gas,UP})$ is the operational cost and $C_{capex}(M_j,M_k)$ is the cost of investments. The C_{trans} is a combination of the costs borne for transporting PS and SB to the AD plant, as well as the costs for transporting digestate and biogas away from the plant, as shown in Equation (6).

$$C_{trans}(M_j, M_k, GP_k) = C_{trans,in}(M_j) + C_{trans,out}(M_{man}, M_k, GP_k) \tag{6}$$

where $C_{trans,in}$ represents the cost of transporting the PS/SB to the AD plant and $C_{trans,out}$ is the cost related to the transportation of digestate and biogas away from the AD plant.

The size of the plant will hence influence transportation costs significantly, as a larger plant will involve longer driving distances, to ensure the supply of the required biomass. To estimate transportation distances according to the size of the plant, the supply area was modelled using concentric circles around the biogas plant, whereby availability and supply cost of PS/SB could be estimated as a function of the radius (i.e. the distance from the plant). With respect to digestate transportation, it was considered that a share of the digestate could be transported back to the some farmers delivering PS. The maximum amount that could be returned to individual farmers was set to 115% of the PS they delivered; any excess sludge would involve additional costs for its transportation to other farmers. A detailed description of the calculation is provided in the supporting information.

Operational expenditures (C_{opex}) for the biogas plant are estimated as follows (Equation (7)):

$$C_{opex}(M_j, M_{gas,UP}) = C_{opex,input}(M_j) + C_{opex,oper}(M_j, M_{gas,UP}) \quad (7)$$

where $C_{opex,input}$ represents the cost of buying PS/SB beet according to the market prices and $C_{opex,oper}$ is cost related to operating the biogas plant, including the following factors (Equation (8)):

$$C_{opex,oper}(M_j, M_{gas,UP}) = C_{basis}\left(\sum_{j\in J} M_j\right) + (C_{wear} + C_{pow} + C_{man}) \cdot M_{sug} + C_{opex,UP}\left(p_{pow}, M_{gas,UP}\right) \quad (8)$$

where C_{basis} is the basis cost of a biogas plant with size $\sum_{j\in J} M_j$, C_{wear} is the cost of wear per Mg of SB, C_{pow} is the cost of power per Mg of SB, C_{man} is the cost of manpower per Mg of extra SB and M_{sug} is the total mass of SB. $C_{opex,UP}$ is the cost for biogas upgrading, which is a function of the amount of biogas upgraded ($M_{gas,UP}$) and the price of power (p_{pow}).

Investment costs (C_{capex}) depend on investments related cost-wise to input, production and output. As in this model it is assumed that all transportation is rented (i.e. no investment costs for trucks and other), and the C_{capex} is defined as (Equation (9)):

$$C_{capex}(M_j, M_k) = C_{capex,prod}(M_j) + C_{capex,output}(M_j, M_k) \quad (9)$$

where $C_{capex,prod}$ is the investment cost for production, including the biogas plant, the process heat boiler, the purchase of land, counselling and other elements, and $C_{capex,output}$ is the investment cost for output, including the storage of digestate, the storage of biogas and the biogas cleaning/upgrading facility. The depreciation time for the biogas facility is assumed being 20 years, as recommended by Ea Energianalise to the Danish Energy Agency [62].

3. Results and discussion

3.1. Mass and energy balance

We reconciled mass balances for the PSSB-0, PSSB-12.5 and PSSB-25 feedstock mixtures, including wet weight, TS and VS. An example of mass balance for PSSB-12.5 is presented in Figs. 2 and 3, while remaining figures are provided in the supporting information (section 4).

We found that, when looking at the wet mass, PS represents the most significant flow in all of the scenarios analysed. However, when SB is added to the feedstock in scenarios PSSB-12.5 and PSSB-25, this flow represents the major input of VS and TS into the system. We found similar results in the energy balance (Fig. 4), indicating that, as expected, even a relatively small addition of SB significantly increases the throughput of energy in the system while significantly boosting biogas yield (both total production and yield per Mg of input). PS indeed represents a preferable mean for diluting the high content of solids in SB instead of freshwater: besides the significant savings of water resources (and connected expenses), the use of PS as a prime co-substrate provides better nutrient balancing and increased buffering capacity.

Digestate represents the main output of the system, regardless of the feedstock mixture considered, the reason being the substantial amount of water carried as a result. With regards to VS, the situation is rather different, as the majority of VS is converted into gaseous compounds during the AD process. While biogas is used for energy production, the significant amount of gas forming during ensiling represents a loss of energy within the system; this loss, however, is almost unavoidable, as SB storage is needed to ensure the supply of feedstock to the reactor throughout the whole year. The addition of SB to the feedstock mixture has a clear effect on biogas production (per unit of input), which almost doubles – going from PSSB-0 to PSSB-25 (Table 3). This result is a combination of three aspects: an increase in the BMP of the input (Table 3), an increase in VS content in the feedstock (from 3.2% ww in PSSB-0 to 5.6% ww in PSSB-25) and a decrease in the ratio between biogas yield and the BMP (Table 3). The latter suggests that, when adding SB, some adjustments in the digestion process HRT may be needed, to exploit further the methane potential of the feedstock material.

VS degradation throughout the whole biogas chain is in the order of 45%–68% (Table 3) of VS input into the system, whereas VS degradation within the digestion process is in the order of 43–56%. This figure is in line with what was reported by Møller et al. [18] for cattle manure (i.e. 21–44%) and pig manure (i.e. 47–78%), while it is lower than findings for other substrates (e.g. 53–80 in Marañón et al. [63], Gebrezgabher et al. [37], Schievano et al. [64], Delzeit & Kellner [41]). The results in Table 3 show that, with a fixed HRT, the addition of SB as a co-substrate decreases CH_4 yield (as percent of

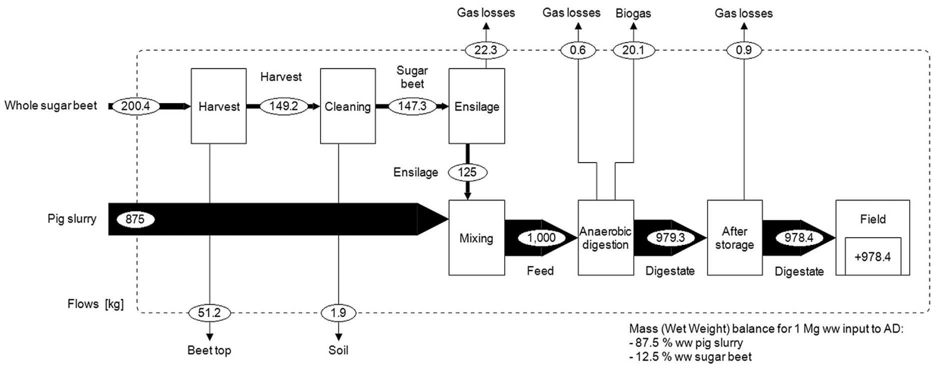

Fig. 2. Mass (kg, wet weight) balance of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

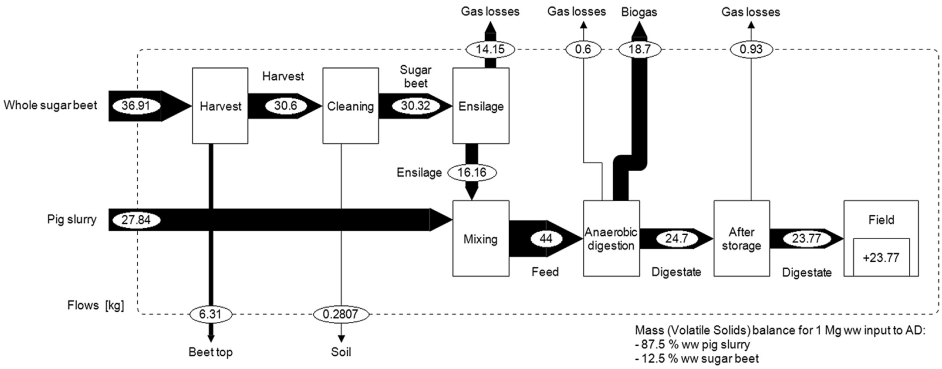

Fig. 3. VS (kg) balances of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-12.5, i.e. a mix of PS (87.5% ww) and SB (12.5% ww).

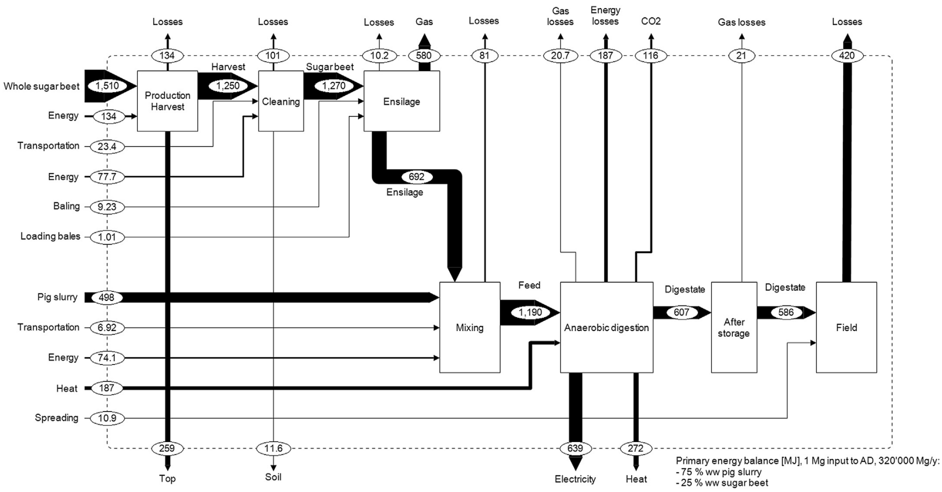

Fig. 4. Energy balance (MJ of primary energy) of the biogas chain relative to 1 Mg ww of input to the anaerobic digester. The input is PSSB-25, i.e. a mix of PS (75% ww) and SB (25% ww), while the size of the plant is 320,000 Mg/y.

Table 3
Overview of key parameters for the modelling of biogas production.

Parameter	Unit	PSSB-0	PSSB-12.5	PSSB-25
CH_4 yield	m^3/Mg_{ww} input	9.10	12.3	18.0
CH_4 yield	m^3/Mg_{VS} input	296	343	369
CH_4 yield	% of BMP	96.6	82.2	87.6
CH_4 concentration	% in biogas	57.2	57.1	57.2
VS degradation – system	% VS input to the system	44.8	66.4	67.6
VS degradation – digestor	% VS input to the digestor	43.5	55.6	51.2
VS_{ND} in digestate	% of total VS	20.6	29.4	27.8

the BMP), while the overall VS degradation increases slightly. This is due to the fact that SB contains a larger amount of slowly degradable VS, which in turn possibly requires longer HRT to reach high yields. In general, a significant share of the VS in the digestate is non-degradable in anaerobic conditions (i.e. 21% for PSSB-0, 17% for PSSB-12.5, 28% for PSSB-25).

3.2. GHG balance

Our findings show that increasing the share of SB in the feedstock mix results in a significant decrease in N_2O emissions from land application (Table 4). This is due to the fact that adding SB to the mix enhances both the C content and the C:N ratio of the digestate, thereby increasing CO_2 production and decreasing the formation of N_2O per unit of VS added (see supporting information, section 2.2).

An overview of GHG emissions from the analysed system is presented in Table 5, according to individual sub-processes in the biogas chain. We found that fugitive emissions of gases from the digestion process, and the storage and application on land of digestate, represent a significant contribution to the overall GHG balance (i.e. between 33 and 44% of direct emissions). Because of a lack of data, some of these estimations may, however, be associated with significant uncertainty. For example, in the present study we assumed fugitive emissions from digestion in the order of 3.1% of the produced biogas; however, other studies indicate that such a value may be subject to significant variability. For example, fugitive emissions in the order of 0.3–2.6% were estimated by Liebetrau et al. [65] for 10 agricultural biogas plants in Germany, and 2.1–4.4% were estimated by Yoshida et al. [66] for a biogas plant treating wastewater treatment plant sludge in Denmark. However, it is generally not well-clarified whether the age/technology of the biogas plant, as well as the feedstock material, has an influence on these emissions. The operation of the digester (i.e. pumping, heating, etc.) also makes some significant contribution to the overall GHG balance, in the order of 16 kg CO_2eq/Mg of feedstock. The use of SB as a co-substrate also significantly influences overall GHG emissions, in that it makes a significant contribution to direct emissions, albeit this is completely counterbalanced by increased biogas production. Energy production (i.e. electricity and heat) from biogas is the most important element in the GHG balance, as it may offset energy production somewhere else in the system (i.e. the results in Table 5 are displayed as negative contributions). In this context, the choice of the alternative source of energy production (herein coal, see Table S6 in supporting information) may have a significant influence on the results.

The results in Table 5 show that, regardless of the size of the plant and the subsequent distance driven, transportation does not make significant contribution to direct GHG emissions. This represents a substantial inconsistency compared with results regarding bioenergy production based solely on energy crops, where transportation did matter, as driven distances were much longer (e.g. Boldrin & Astrup [67]), while highlighting the importance of both using biomass residues and carefully selecting the location of the biogas plant to ensure the availability of locally (short distance) produced biomasses.

3.3. Economic analysis

We estimated total income (TI) for the biogas plant in the range 17.3–24.9 €/Mg of input into the biogas plant (Supporting Information, Table S33). Gas subsidies have a significant influence on income (Fig. 5 and Fig. S8), while market revenue for energy products is less pronounced. Without subsidies, the TNI of biogas production would be negative, thus confirming previous findings (e.g. Gebrezgabher et al. [37], Delzeit & Kellner [41], Mafakheri & Nasiri [34]). This highlights the importance of future support policies for the sustainability of biogas production in Denmark. Our findings show positive signs of economies of scale, whereas the composition of the feedstock has an even greater effect on the results, as increasing the utilisation of SB significantly enhances biogas production, albeit not enough to outweigh increased costs related to the SB.

We estimated total costs (TCs) for the biogas production chain in the range 15.8–26.5 €/Mg of input into the biogas plant (supporting information, Table S35). Costs, to a high degree, are connected to the feedstock supply, as the price of manure is closely linked to an agreement with farmers, whereby manure is returned in a treated form as digestate; feedstock costs are considered here only as SB costs and account for 0–39% of the costs, depending on the share of SB utilised (see Fig. S9 for details). This figure is in the lower range compared with previous findings by Schievano et al. [44] for maize (i.e. 40–62%), rye (i.e. 54–67%), triticale (i.e. 34–48%) and sorghum (i.e. 49–62%) cultivated in a Mediterranean climate. Particularly in the PSSB-0 cases, the positive scale effect on capital costs (C_{capex}) becomes clear, while operational costs (C_{opex}) dampen the economy of scale effect. The TC is significantly influenced by both the feedstock mix and the scale of the plant. In fact, the SB is so costly that it becomes the most important cost factor in the PSSB-25 cases. Moreover, the utilisation of SB also has an influence on the costs of transportation (which can add up to 20% of TC), as longer distances need to be covered to guarantee the supply of SB for biogas production. The scale of the plant also influences transportation and C_{capex} costs, as an increase in plant size requires a larger supply of feedstock with a subsequent increase in driven distance, which varies in the range 5.5–10.3 km for PS and 0–70.4 km for SB (supporting information, Table S15), depending on the plant size. These figures, however, depend strongly on local farming types (e.g. animal, plant), thereby suggesting that decision making should be based on regional considerations. We estimated costs for transportation in the range 1.1–4.1 €/Mg, with lower figures associated with small-scale plants not making use of SB. These values are in line with what is reported by, for example, Walla & Schneeberger [35]. Capital costs (C_{capex}) are estimated in the range of 3.1–5.2 €/Mg (supporting information, Table S36), with lower figures referring to large-scale plants. We estimated operation costs (C_{opex}) in the range 3.3–4.3 €/Mg (Table S36). The size of the plant has rather a small influence on the C_{opex}, while C_{opex} does increase when introducing SB to the feedstock, as additional manpower is needed for handling SB (additional details in supporting information).

An overview of total net income (TNI) is shown in Table 6. Based on existing subsidies, price assumptions for inputs and outputs and

Table 4
Emissions of N_2O from applying different digestates on land (NH_3 loss 10%, soil water potential −0.015 MPa).

Treatment	N_2O [g N_2O/kg$_{VS,applied}$]	N_2O from NH_3 loss [g N_2O/kg$_{VS,applied}$]	Total N_2O [g N_2O/kg$_{VS,applied}$]
PSSB-0	0.66	0.17	0.83
PSSB-12.5	0.59	0.12	0.71
PSSB-25	0.45	0.06	0.50

Table 5
Overview of GHG emissions [kg CO_2eq/Mg input] throughout the biogas production chain.

Stage	Process	GHG emissions [kg CO_2eq/Mg input]		
		PSSB-0	PSSB-12.5	PSSB-25
SB production	SB production		11.3	22.5
SB transportation	110,000 Mg/y		0.68	1.37
	320,000 Mg/y		1.04	2.08
	500,000 Mg/y		1.12	2.25
PS transportation	110,000 Mg/y	0.59	0.52	0.44
	320,000 Mg/y	0.82	0.72	0.61
	500,000 Mg/y	1.01	0.89	0.76
SB pre-treatment and storage	Washing		4.15	8.31
	Baling		0.71	1.42
	Loading bales		0.05	0.09
Anaerobic digestion	Milling + pumping	7.9	7.9	7.9
	Heat to digester	8.7	8.7	8.7
	Electricity production	−34.4	−46.7	−68.3
	Heat production	−9.9	−13.4	−19.6
	Biogas fugitive losses	5.6	7.6	11.2
Digestate storage	Gas losses	5.9	8.0	11.4
Application on land of digestate	Spreading	1.2	1.2	1.1
	N_2O in field	4.0	3.7	4.0

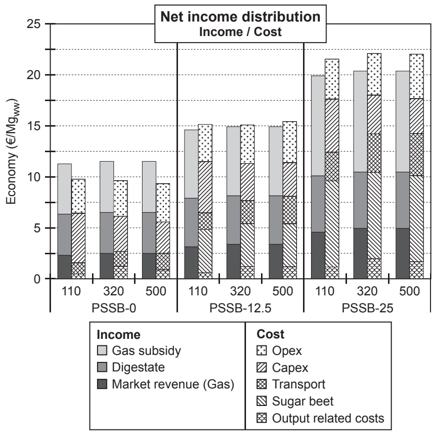

Fig. 5. Distribution of total income (TI) and total costs (TC) per Mg of input to the biogas plant.

the production technology (biogas yield), the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0). In this case the largest plant is the most profitable. Scenarios including SB utilisation as a feedstock (i.e. PSSB-12.5 and PSSB-25) result in negative TNI, as costs are greater than income, due to the fact that increasing costs related to SB input are not counterbalanced by

Table 6
Overview of total net income (TNI) [€/Mg] for the biogas chain, according to plant size and input mixture.

Treatment	Unit	Plant capacity (1000 Mg)		
		110	320	500
PSSB-0	€/Mg	1.52	1.88	2.18
PSSB-12.5	€/Mg	−0.54	−0.17	−0.50
PSSB-25	€/Mg	−1.64	−1.74	−1.66

increased biogas production and any associated revenue. Conversely, for the entirely PS-based case (i.e. PSSB-0), the result is positive, meaning that incomes exceed costs. The size of the plant does influence the TNI to some extent, in particular because of the costs associated with transportation (i.e. the larger the plant, the greater the distance) and investment (i.e. the larger the plant, the smaller the investment per unit input). The results presented in Table 6 differ from what was estimated by Delzeit and Kellner [41], as our figures indicate that large-scale facilities have a fundamental potential for better profitability compared with small-scale facilities. For those cases with SB, the benefits of increasing scale are not clear, as we find that the TNI per unit of input is almost neutral in relation to scale.

3.4. Comparison

Results for energy balance, GHG emissions and TNI are presented comparatively in Fig. 6, in which it is evident that utilising SB is a major factor influencing the results of the energy, GHG and economic analyses. However, a univocal conclusion cannot be drawn, because while the energy and GHG analyses may suggest that the utilisation of SB as a feedstock into the biogas plant may prove beneficial, the economic analysis indicates that this may be too costly in the long run. As previously described, the only viable input composition is a feedstock containing 0% of SB (i.e. PSSB-0), whereas increasing utilisation of SB results in negative TNI.

The scale of the plant has little influence on the energy and GHG balances, as also indicated in previous studies (e.g. Stephenson et al. [68]); the scale, however, significantly affects net income, while if the biogas plant is operated using solely PS as a substrate, a large-scale plant may be preferable. If an SB co-substrate is employed, it becomes less clear what is preferable. A similar conclusion was reached by Walla & Schneeberger's [35] study of biogas production in Austria using maize silage as feedstock.

With respect to the results in Fig. 6, we found that the most critical assumptions and main uncertainties are related to the price of SB (relative to manure) and biogas yield in the AD plant. The price of SB is about 4.5 times higher than the PS one. In general terms, production costs for energy crops must be reduced to make biogas production profitable [35,37,44]. The increased biogas yield obtained when using SB as a substrate results in better energy and GHG balances, but it does not compensate for increased costs, due to the larger input costs of SB. Biogas yield is indeed a very critical

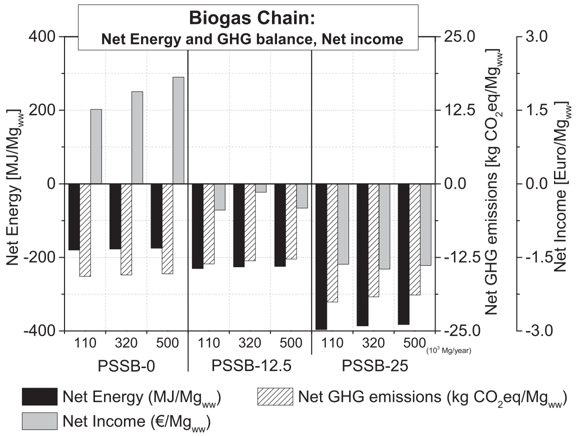

Fig. 6. Comparative overview of net energy balance (MJ/Mg), net GHG balance (kg CO_2eq/Mg), and Net Income (€/Mg) per Mg ww of input to the biogas plant.

factor for profitability. To reverse negative results for the TNI in Fig. 6, a further increase in gas yield (i.e. 5% for PSSB-12.5 and 13% for PSSB-25) is needed, thus suggesting that further optimisation of the process is required. The profitability of large-scale facilities seems more affected by biogas yield, as increased biogas generation would allow counterbalancing the costs for longer transportation journeys. In general, improving biogas yield may play an important role in relation to the profitability of biogas production [34,41,67].

Our results (Fig. 6) seem to indicate that the low-to-no use of additional co-substrate is preferable for the profitability of biogas production. However, while TNI on a unitary basis (per Mg input of m^3 biogas produced) is better, the overall production of biogas is significantly lower, meaning that achieving renewable energy targets would be more difficult. The TNI results are quite sensitive to biogas yield, SB price and transport distances, and thus small deviations could make adding SB a more profitable undertaking. With respect to the economy of scale, medium-to large-scale plants are probably most favourable. This would, however, require significant planning, where many factors (e.g. type and density of farms) would be taken into account and contextualised to local/regional conditions. Planning should make use of dynamic models to be used for optimisation purposes, taking into consideration a number of uncertainties, which could be a key aspect in decision making. Alternative scenarios to be investigated could include a price/value comparison between upgraded biogas to natural gas quality compared to the actual value of biogas used in local CHPs. In fact, biogas injected into the natural gas grid can be used for more diverse purposes and at more valuable times, thanks to storage advantages. In such a scenario, larger biogas plants may have an advantage in connection with the relatively high investment costs involved in upgrading facilities.

4. Conclusions

We carried out an integrated assessment of the biogas production chain based on the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). The assessment was based on detailed mass, energy and GHG balances, coupled with an evaluation of economic profitability. The influence of feedstock composition was studied using three different feedstocks (i.e. with 0% SB, 12.5%, and 25%). The assessment included three sizes (i.e. 110,000 Mg of biomass per year, 320,000 Mg/year and 500,000 Mg/year) of biogas plant to investigate economies of scale. The study was based ostensibly on experimental data and/or data collected specifically and referring to the Danish context.

We found that increasing the share of SB in the feedstock mix has a beneficial impact on energy and GHG balances. This improvement in energy balances is due mostly to increased biogas and energy production, whereas the transportation of feedstock plays a minor role (regardless of the size of the plant). Utilisation of SB was beneficial for the GHG balance, mainly because of reduced N_2O emissions after applying digestate to land. The results showed that fugitive emissions of CH_4 from the biogas plant may make a significant contribution to overall GHG emissions. The profitability of biogas, on the contrary, was negatively affected by the introduction of SB as a co-substrate, as the increase in income from selling biogas was less than the increase in costs associated with buying SB and the transporting it. The subsidy level was established as a key aspect in biogas profitability.

The size of the biogas plant does not significantly influence the energy and GHG balances, as the performance of the conversion process has little to do with scale. Conversely, though, size is important with regards to economic analysis, as an increase in size is associated with reduced capital costs, which are outweighed by SB-related costs in the PSSB-12.5 and PSSB-25 cases, in particular because of the transportation distances involved.

The results indicate overall that utilising energy crops as a co-substrate, while preferable from an energy and GHG balance point of view, is not profitable from an economic point of view. In this respect, we identified the price of SB and biogas yield as the most sensitive parameters for the results.

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Appendix A. Supplementary data

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Appendix B

Economies of scale in biogas production and the significance of flexible regulation

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Economies of scale in biogas production and the significance of flexible regulation

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ABSTRACT

Biogas production is characterised by economies of scale in capital and operational costs of the plant and diseconomies of scale from transport of input materials. We analyse biogas in a Danish setting where most biogas is based on manure, we use a case study with actual distances, and find that the benefits of scale in capital and operational costs dominate the diseconomies of increasing transport distances to collect manure. To boost the yield it is common to use co-substrates in the biogas production. We investigate how costs and income changes, when sugar beet is added in this case study, and demonstrate that transport cost can be critical in relation to co-substrates. Further we compare the new Danish support for upgraded biogas with the traditional support for biogas being used in Combined Heat and Power production in relation to scale economies. We argue that economies of scale is facilitated by the new regulation providing similar support to upgraded biogas fed into the natural gas grid, however in order to keep transport costs low, we suggest that the biogas plants should be allowed to use and combine as many co-substrates as possible, respecting the sustainability criteria regarding energy crops in Danish legislation.

1. Introduction

Denmark has a long tradition for biogas production; and since the Energy crisis in 1973 initiated the building of the first biogas test plants, biogas production have increased in Denmark in varies tempi (Raven and Gregersen, 2007). Biogas production is focused on using domestic resources to generate renewable energy along with reducing environmental damage from waste products in agriculture, industry and households. In Denmark the primary input is manure with various co-substrates added to boost the yield, the development in biogas production have been supported through R & D projects, temporary investment grants and support connected to the biogas output. The scale of plants have varied from decade to decade with focus on farm scale plants, then centralised plants and afterwards a revival of farm scale plants (Geels and Raven, 2007). Focus in biogas production has also changed through time from energy production to waste management, nutrients distribution, and green-house-gas reduction and lately back to energy production, where the newest development is towards centralised plants. Traditionally co-substrates have been waste products from the agricultural sector such as e.g. slaughterhouse waste, which the biogas plants were paid to receive. Today these recourses are already in high demand with rising prices and new biogas plants will have to find other resources. (Geels and Raven, 2007).

Earlier studies have already found economies of scale in biogas production e.g. (Jacobsen et al., 2013; Nielsen and Hjort-Gregersen, 2002; Raven and Gregersen, 2007), and while the collection of resources requires transport over longer distances, driving up unit costs of inputs (Mafakheri and Nasiri, 2014), economies of scale for capital expenditures (capex) drives unit costs down. Walla and Schneeberger, (2008) look into the optimal size of a biogas plant supplying a combined heat and power plant (CHP) and find that the increased costs of transporting silage maize is offset by the benefits of scale in terms of capital costs and generation efficiency. We extend this analysis to larger plant size and examine a similar co-substrate (sugar beet) for which there is a specific resource mapping in relation to our case location, distances are however long illustrating the consequences of high transport distances.

Support for biogas in Denmark does not vary with scale in contrast to e.g. in Austria and Germany (Brudermann et al., 2015; Lantz et al., 2007). However, until recently support was only provided to biogas used in local CHPs limiting the biogas production to fit the heat demand for the connected CHP. Since 2014 it has been possible to upgrade the biogas to biomethane for the extensive natural gas net and receive a similar support as for the CHPs. The specific aim of this paper is to determine whether the new Danish support for upgraded biogas allows the scale effects to be realised, compared to the traditional

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support for biogas being used in Combined Heat and Power production.

We therefore consider larger scales compared to earlier studies (Walla and Schneeberger, (2008) and a situation with manure as the primary input resource and allow the choice of upgrading biogas to the natural gas grid. Scale effects for Denmark reported in (Jacobsen et al., 2013) and (Skovsgaard and Klinge Jacobsen, 2015) indicated that economies of scale could be identified in some cases for biogas plants, but adding sugar beet did not provide clear results with respect to scale. We investigate this further and consider whether the current Danish regulation provides the incentives to exploit the economies of scale, and which policy changes that can be affecting this.

Section 2 documents the methodological modelling approach. In Section 3, the results are presented starting with scale effects in the 100% manure case and proceeding with the addition of sugar beet as a co-substrate which facilitates a higher yield, but also adds costs.

Section 4 performs a sensitivity analysis of the key parameters such as yield, sugar-beet prices and transport distances. Section 5 discusses the risk elements that are revealed by the sensitivity analysis and identified due to the regulatory risks. In Section 6, the results for economies of scale, earnings with co-substrates and risk elements are combined for their regulatory implications and policy advice. Finally, Section 7 draws the main conclusions.

2. Methodology and model

Based on a case study of an area in Denmark, we compare the two opposing scale effects for three specific sizes of a biogas plant. Like (Delzeit and Kellner, 2013), we include transport costs for manure, co-substrate (sugar beet) and the output (digestate). We extend our analysis to larger scale and include the option of upgrading to the gas grid, economies of scale is also included in the investment costs for upgrading. We use an excel model to calculate the costs of input collection, biogas production and cleaning or upgrading for further use. Revenues from the operation are based on the gas prices plus subsidies that can be obtained depending on various choices for supplying the biogas output to a local combined heat and power unit (CHP) or to the natural gas grid. The approach is to focus on private profitability regarding the choice of scale and input composition.

Cost data are estimated from Danish historical data, and transport costs are calculated on the basis of an actual location in Northern Jutland in an area, where manure is found in large amounts so it is suitable for large-scale biogas plants. The applied biogas yields are the results of actual experiments on co-digestion conducted as a part of the Biochain project (see Acknowledgements), the choice of co-substrate (sugar beet) is therefore dependent on the availability of consistent data within the project. In order to comply with the issue of case specificity we conduct a sensitivity analysis, and this confirms the importance of specific co-substrate availability (transport cost), price and yield assumptions, which is supporting our conclusions on the importance of regulatory flexibility with regard to co-substrate choice.

2.1. The model set-up

The model is used to calculate total costs for the biogas production based on required input amounts for each scale of operation. We examine scale effects on total costs and income both with a production entirely based on (pig) manure as input as well as the cost and income effects of adding a co-substrate (sugar-beet) to boost the biogas yield.

The value chain is depicted in Fig. 2.1, where the dotted parallelogram encases the economic work space for the biogas plant, and thereby the costs and income which is included in the calculations. Manure and sugar beet is bought from the farmers at a given price and then transported to the plant. Here the input is mixed and digested resulting in two products; the digestate, which is returned to the farmer, and biogas, which is either upgraded for the gas market or cleaned and sold to the local CHP.

Three different plant sizes are investigated. Small (110) with a capacity of 110,000 t of biomass input p.a., Medium (320) with a capacity of 320,000 t and Large (500) with a capacity of 500,000 t. Arguments for this choice of size can be found in the Appendix in the section on key data.

Three different cases of input mix of pig sludge (PS) and sugar beet (SB) in the feedstock are analysed for all scales: A case with manure only, PSSB-0: 100% PS, 0% SB and two cases where sugar beet is added: PSSB-12.5: 87.5% PS, 12.5% SB and PSSB-25:75% PS, 25% SB. The cases were selected on the basis of current and future Danish regulation (to achieve biogas support, the permitted maximum percentage of energy crops is 25% until 2017 and 12% subsequently[1] (Danish Energy Agency, 2012). This gives nine different results to analyse and compare.

To compare the scenarios, the total net income, $TNI\,(p_k, M_j, M_k, r_j j, k)$ for the different scenarios has to be found.

$$TNI\,(p_j, p_k, M_j, M_k,) = TI\,(p_k, p_{manure}, M_k, M_{manure}) - TC\,(M_j, M_k)$$

Where $TI\,(p_k, p_{manure}, M_k, M_{manure})$ is the total income for the plant as a function of the price of output k, p_k, the mass of output k, M_k and the price and mass of the input manure. $TC\,(M_j, M_k)$ represent the total costs as a function of the mass of biomass input, j, and the mass of output k. The sets J and K represent the set of input biomass (manure and sugar beet) and the set of output (gas and digestate).

2.2. Total costs

Total costs are expressed as:

$$TC\,(M_j, M_k) = C_{input}\,(M_{SugarBeet}) + C_{trans}\,(M_j, M_{digestate}) + C_{opex}\,(M_j) + C_{capex}\,(M_j) + C_{outputrelated}\,(M_k)$$

Where $C_{input}\,(M_{Sugar\,Beet}) = p_{sugar\,beet} \times M_{Sugar\,Beet}$, input- and output products are marked in green rectangles in Fig. 2.1. The pricing of manure is, however, closely linked to the output price of digestate and, therefore, input costs for manure are integrated in the income equation, this is further explained in Appendix A.

All capital expenditures are annuitized at a 5% discount rate with a depreciation period of 20 years.

2.2.1. Capital expenditures (Capex) and operational costs (Opex)

$C_{opex}\,(M_j)$ and $C_{capex}\,(M_j)$ are the investment and operational costs related to the actual production of biogas. In Fig. 2.1, this is depicted as the costs related to pre-storage, digestion and post digestion i.e. $C_{capex}\,(M_j)$ includes all necessary plant specific investment costs in storage tanks, digesters, buildings, land, process heaters, control systems, advisory services and so on. $C_{opex}\,(M_j)$, on the other hand, encompasses all operational costs directly related to the plant, i.e. manpower, fuel costs for process heating, maintenance and running costs (Ea Energianalyse, 2014).

Capex and Opex are estimated from data on the estimated costs for projected plants applying for investment support in 2012 in Denmark combined with model plants from the same period in time. The data estimations have been calculated from the equation of the best-fitting estimated trend line on these data, and are implemented in the model as the primary cost for Capex and Opex respectively (Table 2.1).

In the cases where sugar beet is added to the process additional Capex and Opex related to sugar beet are included.

To calculate the input cost for sugar beet pulp, a price of 27.46 Euro/tonne is used. The price is given by SEGES[2] (Abildgaard, 2015)

[1] In the experimental study it was decided to use 12,5% and not the regulated 12%, (Boldrin et al., 2016).

[2] SEGES is an independent consultant firm with focus on agriculture located in Denmark

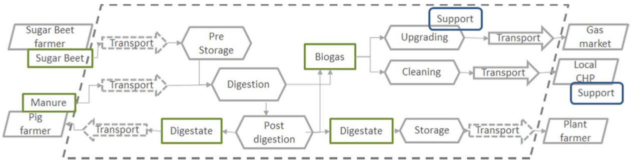

Fig. 2.1. Economic flow chart. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2.1
Details on the cost estimates.

	Nr. of plants	*Data year*	*Size interval in t/y*	*Equation in Euro/ t/y*	R^2
Capex	15	2012	42.000–491.000	Y=115,4–6ln(x)	0.40
Opex	12	2012	42.000–491.000	Y=9.87–0.46ln(x)	0.33

and the price is estimated for sugar beet pulp/sliced sugar beets.

Capex and Opex related to output is included in the output-related costs.

2.2.2. Output related costs

$C_{output\ related}(M_k)$ costs are depicted in Fig. 2.1 and include cleaning, upgrading, transport and storage. The output related costs are all additional costs related to the output, investment in upgrading equipment or biogas cleaners and the related operational costs along with gas compression costs. Also within the output related costs there are scale effects, see more in Appendix A . In case PSSB-25, where 25% of sugar beet is added, not all digestate can be returned to the animal farmers and, therefore, the remaining digestate has to be stored on site and transported separately to neighbouring plant farmers. These additional capital, operational and transport costs are also included in the output related costs.

The output related costs are found separately from several sources and added together. Further information on these data can be found in the section on key data in the Appendix.

2.2.3. Transport: collection costs and density of resources

$C_{trans}(M_j, M_{digestate})$, transport costs are the sum of transport costs for transporting input biomass to the biogas plant (PS and SB) and returning the digestate to farmers.

Transport costs are calculated on the basis of available data given by SEGES and typical km and load costs. We use the specific locations of the farms and calculate the necessary travel distance to collect the manure using concentric circles around the biogas plant modelling the estimated distance as a function of the radius (i.e. the distance from the plant). We assume that already treated manure/digestate is returned to the farmers on the same trip. Transport distances, type of vehicle, loading costs, etc. are taken into account as in (Walla and Schneeberger, 2008); the kilometre cost correspond to 62–81% of total transport costs; further information on the transport modelling can be found in (Boldrin et al., 2016).

Increasing the scale of operations results in longer distances to collect, but it varies substantially between the manure and the sugar beet. The plant is purposely placed in a high manure density area, which in itself reduces the distances and, thereby, transport cost for manure, the average distance is calculated to be in the interval of 5–10 km depending on scale and share of manure input. Furthermore, transport cost can be considered as shared with the output, digestate, as it is assumed that this is returned in the same trucks that deliver the manure. This is common practice in Denmark as manure is the most substantial part of the biomass input and the return of the digestate to the farmer is an integrated part of the value chain (Raven and Gregersen, 2007) in contrast to some biogas production plants in, for example, Austria and Germany (Brudermann et al., 2015; Lebuhn et al., 2014).

Sugar beets, on the other hand, are not produced in vast amounts close to the model plant, which results in longer transport distances; here the average distance is calculated to be in the interval of 22–70 km Furthermore, transport costs are "doubled" so to speak, as it is assumed that the sugar beet trucks drive empty in one direction. Due to this long transport distance for sugar beet, particularly in the PSSB-25 cases, a maximum distance assumption has been added to the model data with the larger scales. The assumption is that all sugar beet demand can be covered within the distance of 80 km – even when the data say otherwise. This constraint makes sense as sugar beet would normally not be transported more than 40 km (Abildgaard, 2015). The effect of this can be seen in the final results, but it does not affect the overall conclusions.

2.3. Total income

Total income is determined by price and quantity of the three products marked in green rectangles in Fig. 2.1 (biogas, manure and digestate), support (marked with blue rounded rectangles) is an integrated part of the price. Income is expressed as:

$$TI(p_k, p_{manure}, M_k, M_{manure}) = \sum_{k\in K} p_k M_k - p_{manure} \times M_{manure}$$
$$= I(p_{gas}, M_{gas}) + NI(p_{Digestate}, M_{digestate})$$

Where M_k is the mass of output k resulting from using a specific mix of biomass 1 and 2 from the set J. The digestate $M_{digestate}$ is the residual after gasification

Data on biogas yield, the digestate price and biogas prices can be found in the Appendix in the section on key data.

Income from digestate is defined as a net income where the input cost from manure is deducted from the income from sold digestate.

$$NI(p_{Digestate}, M_{digestate}) = p_{digestate} \times M_{digestate} - p_{manure}^{input} \times M_{manure}$$

This is due to a trade principle with the farmers, where digestate buyers and manure sellers in most cases are the same. Therefore, the net income expresses the actual value of the digestate.

Biogas income is defined as

$$I(p_{gas}, M_{gas}) = p_{gas} \times M_{gas},$$
$$\text{where } p_{gas,UP} = p^{NG,UP} + p^g + S_{gas,UP} \text{ and } p_{gas,CHP} = p^{NG,CHP} + S_{gas,CHP}$$

I is income, p is price, M_{gas} is the amount of m^3 biomethane. $P_{gas,\ UP}$ is the price of upgraded biogas, p^{NG}, price of natural gas (here referred to as the basis price), p^g, a potential green value and S equals the support value, depending on where the gas is delivered (at a local CHP or upgraded for the natural gas net).

Notice that all support for the biogas production is concentrated on the biogas yield.

2.3.1. Biogas price

The biogas price differs depending on whether the biogas is upgraded or sent directly to a local CHP.

$$p_{gas,UP} = p^{NG,UP} + p^{g} + S_{gas,UP} \text{ and } p_{gas,CHP} = p^{NG,CHP} + S_{gas,CHP}$$

In this model, it is assumed that $p^{NG,UP}=p^{NG,CHP}$ and $S_{gas,UP}\approx S_{gas,CHP}$. In real life, both $p^{NG,UP} and p^{NG,CHP}$ will most often be a function of the natural gas price, where it can be expected that the upgraded price will be closer to the actual market price, whereas the CHP-price is expected to be lower if biogas is the only input fuel to the CHP. This is because the CHP has a seasonal fuel demand and biogas production is almost the same throughout the year. Furthermore the $p^{NG,CHP}$ is pushed down by a looser regulation on the use of cheap biomass and the heat regulation setting a cap on the biogas price (Lybæk, 2014; Tafdrup, 2010).

The green value p^{g} is a green certificate which is sold along with the biogas. There is no actual support attached to this certificate, however it can be exchanged for CO_2-quotas and then it further represents the green value that some may be willing to pay for.

In the model $S_{gas,UP}\approx S_{gas,CHP}$ as we assume that all support is handed to the biogas producer. In real life it is probable that most support is given to the biogas plant when the gas is upgraded as support is paid directly to the upgrading facility, which often has the same owner as the biogas producer (Danish Parliament, 2012). Support for biogas used in a local CHP, on the other hand, is less likely to be entirely handed over to the biogas plant as the support is only paid indirectly through a tax reduction on fuel for heat and support to the power production. In many cases the CHP does not have the same owner as the biogas plant.

2.4. Upgrade vs. direct use

The biogas plant can send the biogas to a local CHP or upgrade to biomethane and connect it to the gas grid. With larger scales it becomes more relevant to upgrade due to the limited demand for the heat output from the CHP. Both choices involve additional capital and operational expenditures, where upgrading is the more expensive choice.

The choice between upgrading and local use is determined by actual conditions at the plant position. In the case considered here there is a local CHP using approximately 3.5 mill m^3 biogas per year. Therefore, the model determines whether to upgrade or not based on the expected biogas yield. If yield < 3.5 mill m^3 biogas p.a., the biogas is cleaned and sent to the local CHP otherwise *all* the biogas is upgraded and sent to the natural gas net.

Imbedded in this model decision is the assumption, that all gas is demanded when it is produced. In the case of upgraded biogas, there is unlimited storage and a larger market which can match the demand. In the case of local use, there is a higher risk that demand will not match the supply – for example during the summer season when demand for heat is lower. The larger the biogas production, the higher the risk that a local CHP will not be able to use all the biogas efficiently; therefore, upgrading can reduce the risk of insufficient demand, a risk that must be expected to increase with scale.

3. Results

The three scales of operation are compared: Small 110,000 t of input p.a.; Medium (320,000) and Large (500,000) each denoted by 110, 300 and 500. We are looking for scale effects and the most profitable case. To identify pure scale effects, we start with the simplest case; 100% manure.

3.1. Costs and scale, 100% manure

First costs are investigated in the case of 100% manure. As seen in Figs. 3.1 and 3.2 there is a tendency towards economies of scale

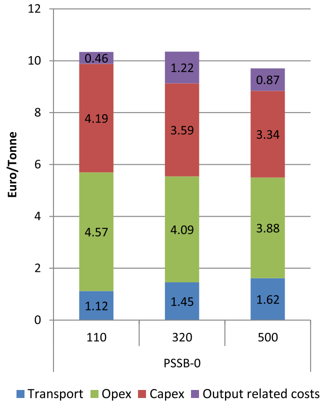

Fig. 3.1. Cost distribution, Euro/tonne.

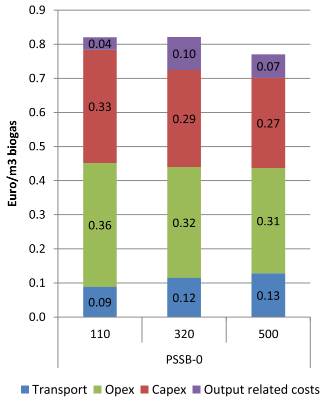

Fig. 3.2. Cost distribution, Euro/m3.

although the total unit cost only reduces by 6% while the plant becomes almost five times as large, it is clear there is a trade-off between rising transport costs (almost 50%) and falling investment and operational costs (approximately 18%).

It is also clear that output-related costs shift significantly between the three different scales. The first shift from small to medium size is the result of a technology shift from gas cleaning to upgrading, while the second shift is due to economies of scale within the upgrading technology.

3.2. Adding sugar beet

It is common to add co-substrates in order to boost the manure based biogas yield. To investigate whether the benefits from the higher yields outweigh the additional costs related to sugar beet, we therefore examine two cases where 12.5% and 25% sugar beet is added as co-substrate.

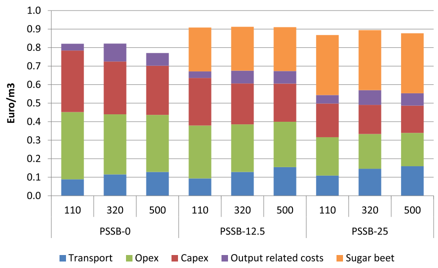

Fig. 3.3. Cost distribution when sugar beet is added, Euro/m3 biogas.

Scaling up the biogas plant reduces capital and operational costs per unit of input for all input compositions with 16–18%.

Total costs in Euros/m3 are depicted in Fig. 3.3, from which it becomes clear that the extra costs related to sugar beet are not outweighed by the sugar beet related boost to the biogas. Total cost per tonnes of input more than doubles when 25% sugar beet is added and the main contributor to this increase is the purchasing cost of sugar beet that determines the level of costs, but also the rising transport costs is an important factor. Both elements reveal the importance of securing low cost co-substrates and collecting the resources available close to the plant. When looking for scale effects in the sugar beet cases, we find an almost stable unit cost in all three different plant sizes. Thus there are no clear signs of economies of scale as found in the 100% manure case.

The balance between, in particular, increased transport costs and the reduced capital and operational costs results in almost equal total unit costs for the large and small-scale in the PSSB-25 case, this is due to a combination of several counteracting effects. We find positive scale effects regarding the upgrading facility in the shift from a medium to a large-scale plant, while the 110,000 t case does not involve upgrading resulting in lower output related costs.

At the same time does the unit costs associated with transport increase so much that they exceeds capex in the large case. Along with the increased output related costs this outweighs the entire scale benefit from opex and capex.

3.2.1. Transport costs; adding sugar beet

Focusing on the transport costs, we find that sugar beet availability in the local area is dispersed and requires longer transport distances than the manure. Hereby, the total transport costs per unit increase by almost 150% when moving from zero to 25% sugar beet (represented by the vertical arrow) in Fig. 3.4. The figure presents the summed transport costs in all three cases of input mix and the cost of manure transport and sugar beet transport in the PSSB-12.5 case. For the sugar beet cases, the unit cost also increases with scale (represented by the horizontal arrow). The graph clearly shows that sugar beet transport costs increase faster than manure transport costs. Furthermore, as the level of transport cost is higher, the absolute increase in transport costs from 110 to 500,000 t results in a larger contribution to diseconomies of scale than for the zero sugar beet case. However even though transport costs increase with scale, they only account for 17–18% of the total costs, even in the large scale cases. This cost share seems quite small compared to other analyses such as (Yabe, 2013), who finds that transport costs account for around 56% of the yearly costs of biogas plants in Japan.

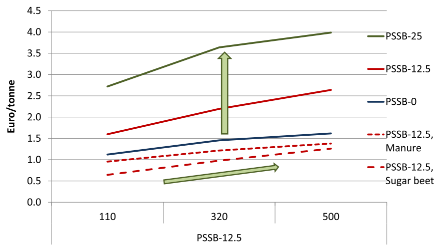

Fig. 3.4. Transport costs in Euro/tonnes of input.

3.3. Total costs and scale effect results

Only based on the graphs it is clear, that costs increases – in line with the amount of sugar beet that is added to the slurry. Furthermore it is difficult to detect a clear scale effect in the mixed manure and sugar beet cases. Purely based on the costs, the options with 110,000 t annually seem best in the sugar beet cases. However, as the income from the upgraded biogas is slightly higher, the options with upgrading may become more attractive considering the fact that the cost difference is marginal between scales.

When summarising the cost results we can say that:

- A unit cost reducing effect results from upscaling biogas plant size from 110,000 t of annual inputs to 500,000 t (together capex and opex per unit are reduced by 16–18%).
- A unit cost increasing effect results from scaling on transport costs (an increase of 45% for manure input and 47–65% for sugar beet input).
- The net effect (trade-off) results in almost equal costs per unit for all sizes in the PSSB-12.5 case and a small increase in the medium-sized cost in the PSSB-25 case, where the small and large-scale unit costs are otherwise almost the same. The benefit of upscaling to 500,000 t (biogas plant+upgrade capex) is outweighed by the increase in transport costs for both inputs and outputs.

3.4. Income

The biogas plant earns its income from both the treatment of manure (converting it to digestate), and from biogas.

Net income from digestate accounts for around one third of total income (Fig. 3.5). The basis price of the biogas accounts for around 20–25% of the income, and this is only slightly higher in the cases where the biogas is upgraded (in cases with medium and large-scale production). The remaining income can be assigned to the biogas support.

Consequently, around two thirds of the income is dependent on the

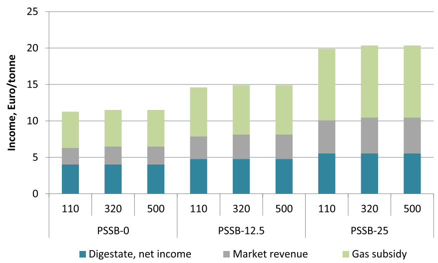

Fig. 3.5. Income distribution.

Table 3.1
Revenues, costs and net-income, Euro/tonnes.

Euro/tonnes		PSSB-0			PSSB-12.5			PSSB-25		
		110,000	320,000	500,000	110,000	320,000	500,000	110,000	320,000	500,000
Revenues	Biogas	2.31	2.49	2.49	3.13	3.37	3.37	4.58	4.93	4.93
	Support	4.94	4.99	4.99	6.70	6.76	6.76	9.79	9.89	9.89
	Digestate	4.02	4.02	4.02	4.77	4.77	4.77	5.53	5.53	5.53
Costs	Transport	1.12	1.45	1.62	1.60	2.19	2.64	2.72	3.64	3.99
	Capex	4.19	3.59	3.34	4.39	3.77	3.52	4.54	3.92	3.68
	Opex	4.57	4.09	3.88	4.87	4.39	4.18	5.18	4.69	4.48
	Output related	0.46	1.22	0.87	0.61	1.18	1.16	1.15	1.99	1.67
	Sugar beet	–	–	–	4.04	4.04	4.04	8.09	8.09	8.09
Net-income		0.93	1.15	1.79	−0.91	−0.67	−0.64	−1.77	−1.98	−1.56

level of biogas subsidies and, thereby, a high biogas yield.

3.5. Net income results

Based on existing subsidies, price assumptions for inputs and outputs and the production technology, the only viable input composition is PSSB-0, i.e. 100% manure, with the most viable size being the large-scale production plant (Table 3.1). The finding that the large-scale plant is the most profitable is in line with the findings for new Danish plants based on manure examined in Jacobsen et al. (2013), (table 4.16 and 4.17) where a plant size of 360,000 t is more profitable than smaller sizes.

Adding sugar beet to the production increases the biogas yield, although not enough to compensate for the additional costs related to the sugar beet, so that the net earnings become negative. For the PSSB-12.5 case, the result is close to break-even between investing or not.

The price of sugar beet is around 4.5 times the price of manure. The higher yield from adding sugar beet leads to increased earnings in the sugar beet cases which are almost high enough to achieve positive net earnings for the 12.5% sugar beet case, but the yield in the case with 25% sugar beet is not high enough to make up for the increased cost due to the higher input costs of sugar beet. This is not the result of increased transport costs, but rather the high price of sugar beet. A 30% reduction in the price of sugar beet could make all cases profitable. The price of sugar beet is, therefore, a key assumption and sensitivity has been conducted in the following section.

Biogas yield is also a critical factor for profitability. The negative results for the sugar beet cases are caused by the unexpectedly relatively lower yields for the sugar beet cases. The yields would have had to be somewhat higher to make these options more economical than the 100% manure case. Sensitivity analysis in the next section also examines this variable.

4. Sensitivity analysis

In this paper, we use a case study to form a general picture on the potential for scale effects in biogas production and relate it to the current regulation, given the wish to expand biogas production in Denmark. We are aware, that some factors and assumptions in a case study will be case specific and subject to insecurity. We therefore perform this sensitivity analysis in order to get a picture of the importance of certain factors in relation to the net-income for a biogas plant. We have chosen to use a constant symmetric variation in the sensitivity analysis in order to be able to compare the importance of the investigated factors to each other. We then assess the probability of variation qualitatively.

We perform a sensitivity analysis on four factors related to net-income: sugar beet prices, transport costs, yield and the biogas subsidy. As previously discussed, sugar beet prices and transport costs can have a significant influence on the profitability of the biogas plant and, therefore, these costs are examined. Furthermore, yield and support are investigated due to the high income share from support, which entirely focuses on the biogas yield.

The sensitivity analysis is conducted with regard to the net-income where the factors in question are halved and increased by 50%. This factor is chosen from the perspective of achieving substantial alterations in the results and in the same time sustains symmetry.

Table 4.1 presents a sensitivity analysis of transport costs for all three cases (PSSB-0, PSSB-12.5 and PSSB-25). As can be seen in most cases, a relatively large reduction/ or increase in transport distances is not enough to change the overall results regarding net-income.

In order to compare the importance of transport cost in relation to the sugar beet costs, a sensitivity analysis was conducted on sugar beet prices and plotted together with the transport distance as illustrated in Fig. 4.1.

While transport costs play a significant role, the sugar beet price, unsurprisingly, is an even more important factor regarding the net income result in the sugar beet scenarios. We find that while a 50% reduction in transport distance only just makes the business case positive in the larger cases, a 50% reduction in the sugar beet price leads to a positive result for all sizes. It is, however, unrealistic to assume that the price of sugar beet will be halved, as the modelled sugar beet price is relatively close to production costs (Abildgaard, 2015). Transport costs, on the other hand, particularly for sugar beet, may be expected to be significantly lower in cases where sugar beet is used as substrate (Abildgaard, 2015). In the Appendix, Fig. B1 presents the same sensitivity analysis for PSSB-25 with approximately the same result, although even a 50% reduction in transport distance is not enough to change the negative net income result.

Not only are costs important for the results, but also potential income in the form of biogas yield and biogas prices. When we compare the biogas yields used in this case study with what is actually produced annually at Danish biogas plants the yields generated in the cases with co-substrates seems relative low see for example (Jacobsen et al., 2014). When conducting the sensitivity analysis on the biogas yield and subsidy we find that a 50% increase in biogas yield improves profitability significantly in all cases. The best results are found in the PSSB-25 cases where net-income per tonne of biomass suddenly becomes larger for the PSSB-25 cases than for the PSSB-12.5 case for the large and medium-sized plants, and the higher yield compensates for the substantial increase in transport and sugar beet costs. Similar; only less pronounced results appears with changes in the biogas subsidy, also displayed in Table 4.2. This is not surprising given, that the subsidy covers a smaller part of the income.

The importance of the factors on the input and output side are compared in Fig. 4.2 through changes in net income when sugar beet prices are changed compared to changes in the yield.

The figure illustrates that even though the price of sugar beet has a

Table 4.1
Sensitivity-net income effects, when transport distances change, Euro/tonnes.

	PSSB-0			*PSSB-12.5*			*PSSB-25*		
	110,000	320,000	500,000	110,000	320,000	500,000	110,000	320,000	500,000
Net-income	0.93	1.15	1.79	−0.91	−0.67	−0.64	−1.77	−1.98	−1.56
50% distance	1.29	1.67	2.40	−0.42	0.12	0.23	−0.83	−1.09	−0.79
150% distance	0.57	0.62	1.18	−1.40	−1.46	−1.50	−2.71	−2.87	−2.33

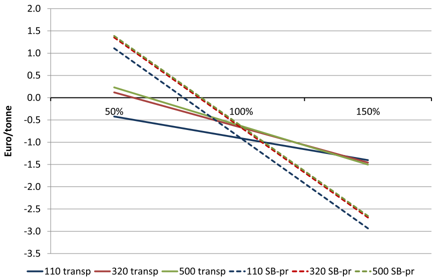

Fig. 4.1. Sensitivity–net income effect in the PSSB-12.5 case with changes in transport costs and sugar beet prices.

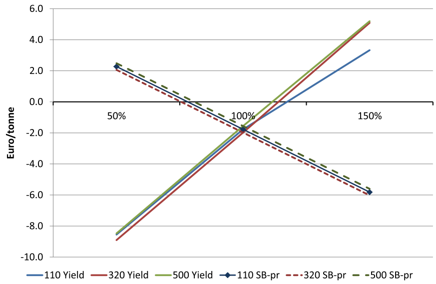

Fig. 4.2. Sensitivity - net income effect with changes in biogas yield or sugar beet prices, PSSB-25.

significant influence on the net income, the level of biogas yield has an even greater effect.

It is also clear that net income increases less in the small-scale case. This is because the biogas yield is so high that it becomes necessary to invest in upgrading, even in the small-scale cases. In the Appendix, Fig. B2 presents the same sensitivity analysis for the PSSB-12.5 case.

Upgrading costs matter for the net-income as seen in Fig. 4.2 and can be a critical option for achieving economies of scale. In our reference cases we assume that the plant upgrades when the biogas yield exceeds 3.5 mill m^3 p.a., this may however not be the optimal solution. In order to compare the choice between direct use and upgrading we explore this with a sensitivity analysis for the 12.5% sugar beet case in relation to yield variations and scale. In the case of direct use, it is assumed that the heat demand is completely covered with a biogas supply of 3.5 mill m^3 p.a. All biogas exceeding this level generates an electricity production which is supported, while all additional heat production is wasted (cooled). All biogas exceeding 3.5 mill m^3 will thus receive a lover price only related to the electricity production.

Fig. 4.3 illustrates the challenges for a biogas plant feeding into a local CHP with a limited heat demand. This challenge increases with scale as the risk of biogas excess supply increases, which then decreases the value of a higher than anticipated biogas yield. That yield is such an important factor is not surprising as two thirds of the income is based on the biogas yield and around two thirds of this is support. This shows

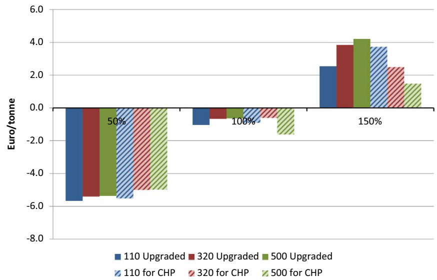

Fig. 4.3. Sensitivity - net income effect with changes in biogas yield depending on the choice to upgrade the biogas or direct usage in a local CHP, PSSB-12.5.

the importance of focus on the yield, but also illustrates a clear risk associated with yield and changes in support.

On the cost side, the results are relatively robust towards changes in the individual cost factors. Only the sugar beet cost has a significant influence on the net income results. So, even though changes in costs can have a significant influence on net income, there is still potential to

Table 4.2
Sensitivity - net income effects with changes in the biogas yield and support.

	PSSB-0			*PSSB-12.5*			*PSSB-25*		
Yield	110,000	320,000	500,000	110,000	320,000	500,000	110,000	320,000	500,000
Net-income	0.93	1.15	1.79	−0.91	−0.67	−0.64	−1.77	−1.98	−1.56
50% yield	−2.63	−1.71	−1.42	−5.53	−5.01	−5.37	−8.55	−8.91	−8.48
150% yield	4.35	4.81	5.36	3.72	3.84	4.20	3.33	5.09	5.19
Support									
50% subsidy	−1.54	−1.35	−0.70	−4.26	−4.05	−4.02	−6.67	−6.93	−6.51
150% subsidy	3.40	3.64	4.29	2.44	2.71	2.75	3.12	2.96	3.39

adjust other costs to achieve an improved net income, whereas the yield determines whether net income is positive or negative.

5. Main risks associated with input prices, yield and output prices

Managers of a biogas plant consider several risk factors when investing in technology and planning the operational strategy. In this paper, we focus on the risks associated with raw material inputs and output price/demand for biogas. The sensitivity analysis revealed some of the consequences from varying important parameters including input prices/costs and yield. We highlight the following risk elements:

- Sugar beet-price increase.
- Transport cost increase due to limited local availability of sugar beet.
- Technically poor performances of plant with low yield as a result - break-down and repair delays.
- Reduced yield due to varying/seasonal supply of co-substrates (sugar beet) and varying composition of primary input/manure.
- Output price variation (natural gas price excl. support) and fluctuating demand for heating from CHP plant - resulting in too low biogas demand and possible losses from flaring.

5.1. Input cost elements

The plant costs depend on changes in input prices and, in our case, specifically the sugar beet price for the cases with 12.5% and 25% sugar beet. A potential increase in the sugar beet price by up to 50% would have a severe impact on earnings (Figs. 4.1 and 4.2). This kind of price change is not entirely speculative, if the demand for sugar beet increases or supply decreases because farmers decide to grow more profitable crops. A parallel example could be the growth in demand for maize in Germany as the result of high biogas subsidies, adding a pressure on dairy farming (Jacobsen et al., 2014). The risk of fluctuations in the price of sugar beet in the future is serious and measures to reduce this risk or the effect of such price increases will have to be a focus of the biogas plant. Being dependent on only one secondary high-yield resource is risky. Therefore, measures that secure the technical use of alternative inputs and the availability of these can reduce the risks associated with input prices. A high price for sugar beet would call for a part/full substitution to other co-substrates as inputs and a more moderate cost increase on the input side. Flexible technology and the ability to substitute between co-substrates is a key strategy to reduce this risk element. One step could be to focus on waste products which are already common used at many biogas plants; this could be a cheaper and more sustainable solution. It can however also introduce other issues in terms of how to use the digestate containing waste products (Huttunen et al., 2014; Lantz et al., 2007) and already now the access to good waste products is reduced and prices have increased (Geels and Raven, 2007).

The distance and, thereby, transport costs are also important (Fig. 4.1), but the risk is probably lower than the risk of an increase in the sugar beet price. For manure, availability is relatively predictable and the resource is local so there is little competition regarding this input. Therefore, changes in livestock/pig populations would only increase the transport distance to collect manure gradually and with moderate increases in distance. One risk is that it would only be possible to use the same lorry to collect the manure and distribute back to the farmer directly to a limited extent, which would double the distance driven compared to our assumption.

For the secondary input, sugar beet, the transport costs are much higher per tonne and the resource is widely used with many alternatives. Our assumptions for distance are quite conservative (up to 80 km), but the risk is still substantial if sugar beet has to be transported from other regions of Denmark. The probable solution would be to use another and closer substrate, so risk will here be reduced if the plant technically and legally can use a variety of co-substrates instead of only one.

The entire revenue for the biogas plant depends on the output level and, therefore, the biogas yield is one of the main risk factors as revealed in the sensitivity analysis (Fig. 4.2). First, the general technology risk of the performance of the plant being lower than expected is a risk prior to investment. In particular, the lifetime of equipment along with necessary downtime for repair and cleaning will be risk factors regarding the realised annual yield. Using proven technology reduces this risk, but the use of different/flexible inputs necessitates the use of unproven technology to some extent. This is a major *ex ante* risk to the investment decision.

To optimise the yield, a steady input mix and controlled feeding with inputs of a constant quality is the best. The risk here is that the inputs will vary in availability and quality during the year/seasons (especially sugar beet which cannot be expected to have the same quality/availability throughout the year). This implies the risk that the average realised yield will be lower than the optimally controlled case. Also, the knowledge of the actual content and biogas potential of the inputs is not always perfect and, therefore, optimal feeding is not possible. The risks associated with lower yield due to these causes is probably less than the basic technology risk, but moderate assumptions of realised yield should be used.

5.2. Income risk elements

As described in the methods section, income consists of income from sales of digestate and income from sales of biogas output (here both the biogas used directly and upgraded natural gas).

$$I(p_j, M_j) = p_{gas} \times M_{gas} + p_{digestate} \times M_{digestate} = (p^{NG} + p^{g} + S_{gas}) \times M_{gas} + p_{digestate} \times M_{digestate}$$

The natural gas price fluctuates and constitutes one risk element on the income side, but the market price p^{NG} is only a smaller fraction of the biogas income, and this price risk can be hedged in the short to medium term. The support (S_{gas}) on top of the gas price is an almost fixed premium and constitutes around 2/3 of the revenue per biogas unit, which reduces the risk (variation) on the income side substantially, see more on this in Appendix A. In the case of sales directly to a local CHP plant which does not use upgraded biogas, the price risk is higher as the support is provided for the electricity generation of the CHP plant. Therefore, there is no guarantee that the biogas price is directly tied to the support. For this reason, the solution is often to reduce risk for the biogas plant by negotiating a long-term fixed price for the gas used by the CHP plant. However, there is also a volume risk associated with the sales to a CHP plant. If the biogas output is dimensioned relative to the heat demand supplied by the CHP, seasonal variation in heat demand will result in varying demand for biogas throughout the year. This is critical to the risk actually faced by the biogas plant and can be expected to reduce the average income realised. The sensitivity analysis presented in Fig. 4.3 further illustrates how the benefit of an extra yield increases with scale in the case of upgrading, whereas this benefit in fact decreases with scale when the biogas plant feeds directly into a local CHP with a predefined heat demand. In the long-term this risk can even be enhanced with structural changes if, for example, heat pumps, electric boilers or biomass boilers take over a larger fraction of the supply for the district heat grid and thereby even reduce biogas demand if heat demand decreases . This combination of a seasonal and long-term structural volume risk must be characterised as important and to some extent fundamental regarding the decision of whether to base a biogas plant on supply to CHP plants or to upgrade for input to the natural gas grid.

The biogas plant also generates income from the digestate output of the plant. The risk associated with the part that is returned directly to the farmer who supplies the manure is limited as the contract with the farmer often ties the supply of manure with the return of the treated manure with fixed prices for both. As long as the farmer receives a higher value product than he supplies, the contract and, thereby, the income must be assumed to be associated with low risk. Farmers are, however, quite financially exposed (high debt ratios) which means that there is a risk that some of them may go bankrupt and the contracts may not be continued with the farmer who takes over. Furthermore, there is a volume risk as the farmers may change the composition of livestock/pigs and the size of their activities, while the amount of dry matter in the manure may also vary. The dry matter has a substantial effect on the biogas potential and, therefore, poses a considerable risk to the biogas income.

Finally, the main income source is the support level set by the authorities. There is always a risk element associated with this kind of public support. In this Danish case, the support is a fixed premium (upgraded gas), which must be seen as guaranteed by the general Danish government principle of never changing support provided to existing plants (investors). Indirectly, the authorities can, however, change the effective level of support by modifications to the fees for entering the grid, regulations/requirements for emissions from biogas plants, etc. but this risk can be characterised as relatively low and with very moderate potential impact.

6. Regulatory implications

We find that input cost and transport cost can have a significant influence on the profitability of the biogas plant. Investment in the biogas plant is profitable in our case based on current support policies. The cases with added sugar beet are not profitable under the assumptions of sugar beet prices, yield and transport distances, but they are attractive from the perspective of replacing fossil fuels in the energy sector. The biogas output level is much higher in these cases and based on the public policy for replacing fossil fuels (natural gas) with biogas and reducing GHG emissions, these cases have the greatest environmental benefit (Boldrin et al., 2016). The sensitivity analysis illustrated that the price of the co-substrate (sugar beet) is critical for profitability and the risk discussion pointed to the option of reducing the associated risk for the cost of the co-substrate.

6.1. Input mix alternatives should be allowed

A biogas plant will be located close to a supply of manure, but it is also important to be located close to a cheap source of co-substrate. With the right pre-treatment and process, biogas plants can digest almost any co-substrate to increase the probability of profitable operations. In order to support flexibility and thereby profitability, regulation should set as few restrictions on the types of co-substrates as possible without undermining other objectives such as sustainability, food safety and the environment. Flexibility in the input mix will considerably reduce the risk associated with the co-substrate price, but also the risk regarding the necessary transport distances as a secondary benefit. If one co-substrate has to be collected from very far away to achieve the desired volume, the plant may choose to add an additional co-substrate even though its price is higher as its location is closer; thereby reducing transport costs so that the combined cost is competitive in relation to the first co-substrate. Current Danish regulatory policy limits the use of energy crops to 25% of total inputs, but in 2018, this will be reduced to 12%, which is the constraining factor for the design of new plants (Danish Energy Agency, 2012). This restriction does not seem critical in the cases analysed in this article as profitability in the 25% case is lower than in the 12.5% case. However, there may be co-substrate shares in the range 12.5–25% that are more profitable, but not tested in our case. As already mentioned these co-substrates could be various waste products which are already used with great success in Denmark (Geels and Raven, 2007; Holm-Nielsen et al., 2009), in order to assure flexibility but also food safety we suggest a safelist on waste products, which can be used in biogas production without damaging the benefits and the reputation of the digestate (Huttunen et al., 2014).

6.2. Yield focus is a result of support provided for end-use of biogas

We find that the biogas yield has a significant influence on the net-income. Therefore, the focus of the plant is on maximising yield. Net income is dominated by the income from biogas, particularly from the biogas feed-in tariffs which account for approximately 40–50% of the total net income. The fact that public biogas support is provided primarily for biogas output has the following implications:

- The biogas plant will not use biogas for own process use at the plant
- Yield maximisation drives demand for high yield co-substrates
- The incentive when upgrading to the natural gas grid is to maximise total annual biogas output

As mentioned in Section 2.3, the support for biogas used in a local CHP is for the electricity output and a tax reduction on the heat produced from biogas. For a CHP plant supplied with biogas, there is an incentive to maximise biogas-based electricity production independently of power demand on the grid, only conditional on the steady supply of biogas and heat demand. This is inefficient for the power system, where conditions include hours with low electricity demand and correspondingly very low or zero electricity prices. A final indirect implication of the Danish biogas support system is that the farmer has no incentive to support a high biogas yield, but only has to comply with manure characteristic requirements from the biogas plant.

6.3. Regulation, the choices of scale and whether to upgrade

Until recently, support for biogas production was only available indirectly via support for electricity and heat production in a local CHP. Regulation has now been modified to include support at a comparable level for biogas supplied to the natural gas grid. This change towards a more flexible regulation affects both the ability to exploit economies of scale and the choice of whether to upgrade or not.

We find economies of scale and to exploit this, the biogas plant has to either find a large district heating market or upgrade the biogas. The large district heating market should be situated in an area with a sufficient concentration of manure resources to limit transport costs. These requirements are quite restrictive and would, therefore, often hinder the full exploitation of economies of scale; with upgrading to the gas grid the biogas plant becomes independent of a large heat demand. Furthermore the exploitation of economies of scale is dependent on sufficient available input, allowing several alternative co-substrates would increase biogas output with lower costs even in areas where manure is less concentrated, if only few co-substrates are allowed this may in itself be a barrier to exploiting economies of scale.

Upgrade is a way to exploit economies of scale and reduce the dependence on a monopoly CHP buyer of biogas. An essential assumption in our model is that upgrading is possible with support levels similar to support for use in CHPs. Before the recent change in regulation, CHPs were monopoly buyers of the biogas, which forced the biogas plants into long-term contracts with relatively low biogas prices. Furthermore, the biogas producer would have an increased risk of demand when the contract expired, which would set a heat demand determined limit on the optimal size of the biogas plant and prevent economies of scale. With support for upgraded biogas, the CHPs have lost the monopoly power and the biogas producer has an improved better chance to benefit from economies of scale.

7. Conclusion and policy implications

In this Danish case study, we find that per unit transport costs for biogas plants increase with scale, which partly offsets the economies of scale found for capital and operational expenditures. A detailed modelling of available manure resources, the fixed and variable transport costs and digestate transport costs suggests that in certain areas of Denmark, centralised large-scale biogas plants are the most economical; provided that all biogas production can be upgraded to the natural gas grid and receive the available support.

When the biogas plant size is scaled up from 110,000 t of annual inputs to 500,000 t, the opposing contributors to scale effects and the net result found are:

- A *unit cost reducing* effect in capex and opex, where unit costs are reduced by 16–18%.
- A *unit cost increasing* effect from transport, with an increase of 45% for manure input and 47–65% for sugar beet input.
- For the 100% manure case, the net effect (trade-off) is a total unit cost reduction of 6%.
- For the two cases with sugar beet, the net effect is a slight increase in unit cost, where the economies of scale disappear due to faster rising sugar beet transport costs and output related costs.

The regulatory choices made by the authorities both concerning the level of support for biogas and the end use options supported are crucial for the profitability of biogas production and also for providing incentives for choosing the most efficient scale and inputs for operation.

Scale effects favour the choice of upgrading to natural gas quality as the biogas production becomes independent of local demand, both in relation to scaling of the plant, production variations and the risk of a decreasing and varying heat demand.

Additionally, the assumption that the entire subsidy for biogas used in the CHP plant accrues to the biogas plant is questionable for alternative ownership structures. We have assumed that either the CHP owns and builds the biogas plant as an additional activity or that the negotiating power of the biogas plant is sufficiently strong to secure the full subsidy. Alternative assumptions may further change the attractiveness of upgrading relative to the CHP solution, and authorities have to carefully consider both the level of support provided, but also differences in support for different end uses of biogas.

The sugar beet price and biogas yield were identified as critical assumptions for the results and sensitivity analysis carried out for these elements. We can conclude that there is a case for larger scale biogas plants in Denmark based on economies of scale regarding costs, but that the effect of co-substrates such as sugar beet requires availability relatively close to the plant combined with a low price for the co-substrate or a higher biogas yield. Alternatively other co-substrates could be considered emphasising the need for flexible input options as for example waste products in order to keep transport and substrate costs down and the yield up.

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Appendix A. Key data

Data for the model have primarily been found in Danish biogas literature estimated from public and less public data and collected in the BioChain project, see Acknowledgements.

Scale

Scale is represented in the form of mass input, which is typical for Danish analyses with most cost data being related to input size in tonnes. The input mix varies in the different cases as does the output in energy content. Therefore, the stable capacity factor is tonnes of input. Other analyses around Europe relate to energy output in the form of kW_{el} capacity which makes sense as regulation in most European countries is related to output in the form of kWh_{el} (Hjort-Gregersen et al., 2011). Under the new Danish regulation, which was finally ratified in spring 2014, biogas support was equalised regardless of whether biogas is upgraded for the gas net or cleaned for use in a local CHP. Furthermore, the support is independent of scale, contrary to biogas support given in other European countries such as Austria and Germany, (Brudermann et al., 2015; Lantz et al., 2007).

Three different plant sizes are investigated. Small(110) with a capacity of 110,000 t of biomass input p.a., Medium(320) with a capacity of 320,000 t and Large(500) with a capacity of 500,000 t. Plant size has been decided on the grounds of history, the size used in other analyses and future expectations in Denmark. The plant is considered as a centralised plant and the small scale (110) can be considered relatively large-scale compared to the sizes dealt with in both Delzeit and Walla who consider electricity capacities up to 1 MW (Delzeit and Kellner, 2013). Depending on the input mix, our small scale (110) plant could feed into a CHP plant of the size of 0.5–1 MW_{el}. The Medium (320) size case is considerably larger and corresponds to a size which is often used in Danish analyses and is relatively typical for a Danish central plant (COWI, 2013; Deloitte, 2013; Ea Energianalyse, 2014). Only a few large-scale (500) plants have been built, but several plants of this size have been planned for the future. As support is independent of size in Denmark, plants even larger than 500,000 t have been built in Denmark.

The output related costs

The output related costs are the sum of biogas treatment costs, storage and transport. The chosen technology for biogas cleaning is biological trickling filter and water scrubber for the biogas upgrading, water scrubber is a widely used technology, see e.g. Patterson et al. (2011). Depending on the size of the biogas yield, the model can choose between three different treatment sizes (Australian Meat Processor Corporation, 2013; Bauer et al., 2013). Again we find scale effects as unit costs decreases as the gas amounts increases. Storage costs relates to the biogas storage with a capacity which corresponds to one day of production – allowing temporary storage in cases where the biogas is polluted; and storage of digestate that cannot be returned to the animal farmer immediately. Only in the PSSB-25case, where sugar beet input is 25%, will some of the digestate be sold to other parties (plant farmers). In this case, additional costs are added as the extra digestate has to be stored at the plant until spring, when it can be delivered to the plant farmers. Transport costs for biogas include pipe and compression costs; assuming that the connected CHP and the distribution net is situated only 1 km from the biogas plant.

Table A1
Investment and operational costs associated with treatment of gas for upgrade or CHP, Euro/tonnes.

Ratio/Scale	*110,000*	*320,000*	*500,000*
Gas, Cleaning for CHP	0.15	0.15	0.08
Gas, Upgrading for the net	–	0.89	0.55

Table A2
Biogas yield, cubic metres biogas per tonne of input.

	PSSB-0	*PSSB-12.5*	*PSSB-25*
Biogas yield (70% NH4)	12.6	17.1	25.0
Biomethane yield (98% NH4)	9.0	12.2	17.8

The scale effect within the upgrading technology is illustrated by the figures in Table A1.

From the table, it is also apparent that there is a substantial difference in costs depending on whether gas is cleaned or upgraded. In this model, upgrading seems less attractive to the biogas producer, due to the higher treatment costs, combined with the assumption that price and support is almost independent of whether the gas is upgraded or cleaned for local use; similar results was found in Jacobsen et al. (2014).

Yield

The biogas yield has been estimated from our project partners in the Biochain project on the basis of micro-experiments with pig manure combined with sugar beet pulp in different ratios (Table A2). From these experiments, we also experienced that the results become difficult to use when the percentage of sugar beet exceeds 25% (Boldrin et al., 2016).

Prices

The Sugar beet price is given by SEGES and the price is estimated for sugar beet pulp/sliced sugar beets. This price is close to the production cost of Sugar beet, and according to SEGES this price has been constant for a long while (Abildgaard, 2015). Input and output prices for manure/digestate are also given by SEGES (Abildgaard, 2015) and are based on prices negotiated between the animal farmers and the biogas plant. There is both a price on manure and digestate, but the prices used for the calculations are the digestate and net-digestate prices (digestate price minus manure cost). The digestate price corresponds to the fertilizer value of the digestate (see for example (Lemvig biogas, 2016)) and the net-digestate price can be interpreted as the value added through the biogas process. The interlinkage between digestate price and manure costs implies our focus on the net-price of digestate. This also corresponds to models used elsewhere se for example (Jacobsen et al., 2014). The pricing of manure and digestate vary among biogas plants, depending on where they are situated (Table A3).

Biogas prices are calculated on the basis of the official feed-in tariffs and results from the Biogas Taskforce analysis on the expected basis price plus the expected green value (PlanEnergi, 2014). The feed-in tariff consists of three parts; 1) approximately 70% of the subsidy is without any time limit and indexed following 60% of inflation, 2) approximately 20% of the subsidy is also without a time limit and is negatively correlated with the gas price - thereby reducing the risk of income loss related to the natural gas price, and finally 3) approximately 10% of the subsidy is phased out in the period from 2015 to 2020 (Danish Energy Agency, 2016). This basically means that support is expected to decrease to some extent, however with a high certainty, so income losses on this account can be included in the calculations from the start.

As argued in Sections 2.3 and 5.2, it is debatable whether the biogas plant can expect the same price for the biogas when it is sold directly to the local CHP as if it was upgraded. This counts both for the natural gas price but also the expected share of the subsidy. The green value only relates to the case of upgrading, but this value is not considered to be high. The authors of "GGI" from blue energy planet have found indications of willingness-to-pay in the region of 1–10 Eurocent/NM3. When asked directly, however, they expect a price in the lower end of this range. The estimated value is uncertain, but is close to the current value of the CO_2-quota price, and therefore the best approximation we could achieve given the currently lack of an open market for green certificates in Denmark.

Table A3
Prices in Euro/tonnes and Euro/NM3 Biomethane.

	Basis price	*Support*	*Green value*	*Manure price*	*Total price*
Sugar beet, Euro/ tonnes	27.46				27.46
Digestate, Euro/ tonnes	10.05	–	–	−6.03	4.02
Biomethane, Euro/ NM3	0.26	0.55	0.02		0.83
Biogas CHP, Euro/ NM3	0.26	0.55			0.81

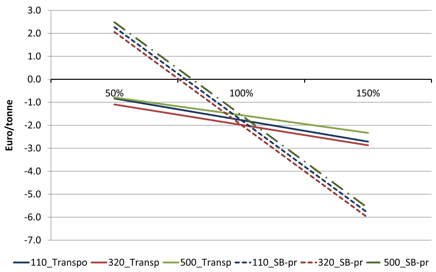

Fig. B 1. Sensitivity-net income effects with changes in transport costs and sugar beet prices, PSSB-25.

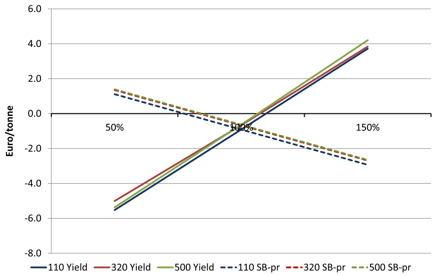

Fig. B 2. Sensitivity-net income effects with changes in yield and sugar beet prices, PSSB-25.

Appendix B. Additional sensitivity graphs

See Appendix Fig. B1 and B2.

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Appendix C

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

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

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Abstract

In this paper, we study the effects of politically motivated economic instruments on biogas value chains. This is done by comparing two European countries who each have implemented a set of regulations: Norway provides investment support and the support is mostly focused on the input side of biogas production, while Danish support is focused on the output side. The comparative study is done through an assessment of the costs and income of a Norwegian and a Danish value chain. Furthermore, the economic instruments were evaluated by assessing the economic consequences of implementing the Danish instruments on a Norwegian value chain, and vice versa. We find that both structural and regulatory conditions have a large impact on the configuration of the value chains. The policy implications of end-use support in Denmark is large-scale plants, maximising the output through co-digestion of manure and high yield substrates, while avoiding losses. Investment support in Norway has increased biogas production from organic waste with less emphasis on efficient gas usage, while input support regarding manure has led to an increase in the usage of manure as substrate. Current regulations do support the political objectives however; both countries can improve and learn from each other.

Keywords

Biogas

Environmental policy

Regulation

Value chain

1 Introduction

1.1 Anaerobic digestion of organic resources

Biogas production from organic resources is seen as a measure to reduce greenhouse gas (GHG) emissions in several sectors. A large variety of policies have been proposed and implemented to increase and improve biogas production. In this paper, we aim to investigate how these policies can affect biogas value chains, specifically by evaluating the effect of regulatory measures. This is done by comparing two countries that have implemented different sets of economic instruments. Denmark currently provides an end-use support through a feed-in tariff for electrical power and gas delivered to the grid, while Norway provide investments support for plants and support to farmers sending manure to biogas production.

Biogas is produced through an anaerobic digestion process using different substrates such as manure, sewage sludge and organic waste from households or industry. Two products are generated: biogas and digestate Biogas can be used to generate heat and electricity, or upgraded to a higher methane content and applied as a fuel in transport or fed into the natural gas grid as biomethane. Digestate can be used as a fertiliser on agricultural soils, if the co-substrates are allowed for this alternatively the digestate can be separated into a wet and a dry fraction, where the wet fraction is sent to waste water treatment and the dry fraction act as soil improvement.

There is a large diversity of biogas value chains in Europe. In Germany, Denmark and the Netherlands the substrate for biogas is mainly from agriculture (IEA Bioenergy, 2014), while in UK, Italy, Spain and France a large share of the biogas production originates from landfills (EurObserv'ER, 2014). In Norway, Sweden and Finland biogas is mostly produced from sewage sludge, or organic waste from household and industry (Huttunen, Kivimaa and Virkamäki, 2014; Olsson and Fallde, 2014). In many countries, biogas production is driven by the demand for renewable energy, and feed-in tariffs for electricity and gas production to the grid are used as incentives for production (e.g. Germany, Austria and Denmark). In Norway, Sweden and Finland, however, biogas is increasingly used as a fuel for transport (Lantz *et al*, 2007; EUROBSERV'ER, 2014; Jacobsen, Laugesen and Dubgaard, 2014; Brudermann, Mitterhuber and Posch, 2015).

Few studies have been done specifically on biogas in a context of political regulation. Raven and Gregersen (2007) made a comparative assessment between biogas development in the Netherlands and Denmark. They underline the importance of formal rules and concludes that subsidy grants and investment grants played a role in both countries. The long-term character of the financial support mechanisms in Denmark has been an important factor and proved to be successful compared to the ad hoc support in the Netherlands. Policy support was usually linked to broader regime development (e.g. energy strategy, manure handing problems, climate change).

Wirth *et al* (2013) examined how the effects of formal institutions depend on informal institutional structures through a comparative assessment of biogas technology in different Austrian regions. They found that the professional culture in which the farmers are embedded modulates the effects of feed-in tariffs and investment subsidies. This explain large differences in diffusions and technology in the regions, which cannot be explained on the basis of physical geographical conditions or prevailing economic structures in agriculture alone.

Lantz et al. (2007) analysed the regulatory landscape for biogas in Sweden and distinguished between production and utilisation of biogas, identifying both barriers and incentives. They concluded that the existing policy in Sweden was not enough to exploit the full potential for biogas production, which depend on a large variety of incentives and barriers within several sectors.

Larsson, Grönkvist and Alvfors (2016) performed an analyse of the development of upgraded biogas in the Swedish transport sector in relation to policy instruments and the availability of a natural gas grid. They concluded that investment support schemes and exemptions from energy and carbon dioxide taxes have been key instruments in initiating the establishment of new biogas production facilities and infrastructure. Carrosio (2013) studied policies and organisational models for biogas plants managed by farmers in Italy. His conclusion was that the intentions of the policies are thwarted because of the intuitional creation of a dominant unsustainable organisation model, and recommended thus a diversification in the use of biogas and reorganisation of the political incentives.

Clercq *et al.* (2017) performed a review of policies around the world regarding the conversion of food waste to biogas in South Korea, China, France, Germany and the United Kingdom. They identified best practices and challenges useful for policymakers in developing countries.

All of the studies above underline the importance of economic instruments and policies in general to facilitate the development of sustainable biogas value chains. In this study, we go beyond this, and investigates quantitatively how different economic instruments can affect the biogas value chains. We further discuss the results in the context of structural conditions and political goals.

1.2 Objective of this study

The main objective of this study has been to develop new knowledge about how national policies and regulatory systems influence the design and operation of biogas value chains. This was done by comparing how the economic instruments affect the economy of biogas value chains in Norway and Denmark, and by discussing the results in the context of the differences in political objectives and structural conditions. The results were used to evaluate how the instruments are contributing to obtaining the political goals and to discuss whether the countries will benefit from dissemination of knowledge across different regimes.

We have chosen to include two different substrates in the case study: organic waste (OW) (source separated food waste from households and solid organic waste from industry and service sector) and substrate from agriculture (manure and deep litter) because they were identified as the substrate types with the largest potential. Both countries have expressed ambitions to increase the amount of manure to biogas production, and the interest for recycling of organic waste is increasing due to the circular economy package and the European bioeconomy strategy. Sewage sludge was not included as a substrate in the case studies because it is not desirable to co-digest agricultural substrates and sewage sludge, due to legal restrictions on the use of digestate produced from sewage sludge. In addition, the use of sewage sludge for anaerobic digestion is decreasing in Denmark (Danish Energy Agency, 2017b) and is identified as the substrate with lowest future potential in Norway (Norwegian climate and pollution agency, 2013).

2 Conditions for biogas value chains in Norway and Denmark

The effect of economic instruments cannot be assessed without considering other aspects that will affect the value chain such as structural conditions, political goals and the regulatory system in general, as well as markets for substrates, biogas and digestate. These aspects are thus compared and discussed in the following sections.

2.1 Structural conditions for biogas production in the two countries

Norway and Denmark are countries closely located, with similar climatic conditions. There are, however, large differences in topography, total surface area and general framework conditions of biogas production. To understand these differences, we map the demographic and structural conditions for the relevant sectors in Table 1.

		NO	DK
Agriculture	Average livestock unit, small farms[1]	23	86
	Average livestock units, large farms[1]	61	681
Waste	Share of households with source separation of organic waste[2 3]	67 %	30%
	Logistics: Population density, inhabitants (inhabitants/km^2) Worldatlas (2017)	13	125
Energy	Share of renewables in gross final consumption of energy (2015)Eurostat (2016)	69.2 %	30.8 %
	Energy prices household consumers, 2016 (EURO/kWh) (Danish Ministry of Environment, 2016; Statistics Denmark, 2017)	0.163	0.308
	Energy prices industry, 2016 (EURO/kWh) [6]	0.081	0.094
	Natural gas prices industry, 2016 (EURO/kWh)Eurostat (2017b)	N/A	0.030
Transport	Share of renewable fuels for transport [5]	8.9 %	6.7%
	Fuel prices diesel net (EURO/liter)DKV Euro Service (2017)	1.148	1.014
	Fuel prices gross (EURO/liter) [8]	1.435	1.268

Table 1 Aspects affecting biogas production in the two countries

[1] (European Comission, 2017)
[2] (Norwegian Ministry of Climate and Environment, 2013).
[3] Own calculations based on (Norwegian Ministry of Climate and Environment, 2014)

Both Norway and Denmark are countries with ambitions of sustaining a productive agricultural sector; however, there is a substantial difference in farm structure. The Norwegian agricultural strategy is based on a wish to be self-supplying and maintain employment in the rural areas, while Denmark is a large exporter of a livestock based agricultural production that bears the mark of a highly efficient sector that competes at international markets, taking advantage of a low topography enabling a high degree of economy of scale. This affects the access to manure as substrate for biogas production. Large distances and smaller concentrations of manure in Norway is likely to result in higher transportation costs.

The share of households with source separation of OW is higher in Norway compared with in Denmark, despite lower population density. The large share of source separated OW in Norway indicates better access to OW resources for existing biogas plants. This access, together with the willingness to pay for high yield substrates in Denmark has led to export of pre-treated OW from Norway to Danish biogas plants. Martinsen (2012) estimated that about 470,000 tonnes of OW were exported per year to Denmark and Sweden.

Norway has (together with Iceland) the largest share of renewable energy in Europe, resulting in low electricity costs and heating mostly based on electricity. Denmark has a lower share of renewables and the highest energy prices in Europe, when taxes are included (Eurostat, 2016). With the low topography, there is almost no hydropower however; a large production of wind power has emerged due to good wind conditions and a profitable regulation.

Due to a highly developed natural gas grid and a large supply of local heat distribution grids in Denmark, it has been natural to use biogas in local heat and power production, as it is also used in other countries (Hjort-Gregersen, Blandford and Gooch, 2011). Today with the rapid expansion of wind- and solar power, local heat- and power plants (CHP's) are less profitable, and the development in Denmark is currently going in the direction of pure heat production based on biomass. Norway has a significantly larger production of natural gas and is today a large exporter of natural gas. Domestically, however, the use of natural gas is low, and the infrastructure of natural gas is limited.

The shares of renewable fuels in the transport sectors are similar in the two countries, but marginally higher in Norway. The diesel price in Norway is higher, indicating a larger revenue in the fuel transport market. In both countries, the interest in biogas as a renewable transport fuel is increasing.

2.2 Political goals in the two countries

Table 2 summarises the political goals relevant for biogas production and use at EU level and for Norway and Denmark. Norway is not part of the EU, but the country is collaborating closely through the European Economic Area (EEA-agreement) and has committed to the EU target of reducing at least 40% of GHG emissions by 2030.

	EU	Norway	Denmark
Agriculture	CO_2-reduction goals in agriculture	30% of manure to biogas production within 2020 [4]	50% manure in biogas by 2020[5]
Waste	70% material recycling or reuse for waste from households within 2030[6]	75% of waste to recycling within 2010, further escalation to 80%[7] Increased biogas production[8]	50% of waste to recycling within 2022[9]
Energy	The EU's Renewable energy directive sets a binding target of 20% final energy consumption from renewable sources by 2020. EU target of a 80-95% CO2-reduction by 2050[12]		A goal for an "ambitious expansion" of the biogas production, e.g. 17PJ biogas by 2020 Danish goal that heat and power production should be renewable by 2035, and the total energy consumption should be based on renewables by 2050[10]
Transport	- At least 10% of the energy used in the transport sector should be renewable within 2020 - CO_2-reduction goals in transport[11]	- Regional goals: e.g. Oslo: public transport non-fossil within 2020 - Biogas strategy (states that biogas should be used for transport)	Municipal goals, e.g. Randers Municipality have a goal of 30% of municipal biogas should be used for biogas[12]

Table 2 Political goals relevant for biogas value chains in EU, Norway and Denmark

Norway has a national goal of increasing the biogas production which is stated in the Biogas Strategy, though cost efficiency is a requirement (Norwegian Ministry of Climate and Environment, 2014). Denmark does not have a separate strategy for biogas, although a biogas task force was created to aid an increase in production along with new regulation (Danish Government 2012). Denmark has high goals for renewable energy production and for becoming independent of fossil fuels by 2050.

Norway is highly independent of fossil fuels and focuses on waste resources, with a goal of over 75% recycling. In Denmark, there is a long tradition for waste incineration with a large capacity. New initiatives have started to increase the recycling level in Denmark aided by EU recycling-targets and the resource strategy in 2013.

A white paper from 2009 states that 30% of the manure in Norway should go to biogas production within 2020 (The Norwegian Department of Agriculture and food, 2009) as a measure to

[4] White paper on agriculture (Danish Ministry of Environment, 2013)
[5] Green Growth agreement (Danish Government, 2012)
[6] Circular economy package (Danish Ministry of Climate, 2013)
[7] Norwegian waste strategy (European Parliament, 2009b)
[8] Norwegian cross sectional biogas strategy (European Parliament, 2009a)
[9] Facts on the ressource strategy (European Commission, 2014)
[10] Energy Agreement 2012 (Danish Government, 2012) and The Danish governmental climate plan (Danish Ministry of Climate, 2013)
[11] Renewable energy directive (RED) (Danish Government, 2012) and Transport fuel directive (Energinet.dk, 2017)
[12] Regional Bioeconomy profile, central Denmark (European Commission, 2014)

reduce GHG in the agricultural sector. Simultaneously a 50%-goal was set in Denmark (Danish Government, 2009a). This goal has not been ratified later.

There is no clear text concerning actual goals for biogas or renewable fuels in the transport sector for any of the two countries.

In summary, the Norwegian goals are mostly targeted towards management of manure and waste resources, indicating that policy makers focus on GHG-reduction and waste recycling. The objectives in Denmark are more directed towards renewable energy and secondarily the agricultural sector, which may originate from a focus on GHG-reduction *and* security of energy supply. This makes good sense, as Norway have a high degree of security of energy supply, while Denmark in near future could become dependent on foreign energy supply.

2.3 Biogas production in Norway

2.3.1 Development of biogas production

In Norway biogas production emerged primarily as a waste treatment option for sewage sludge and OW. Due to a large share of renewable and clean hydropower in the electricity grid and low prices on electricity, there has been few drivers for producing electricity from waste resources in Norway.

Historically the use of biogas has been inefficient. In 2007 about 19% of the biogas was flared, 53% was used for heat purposes, while only 2% of the gas was used for transport purposes (Raadal, Schakenda and Morken, 2008). In 2010 About 63% of the energy generated from biogas plants was used for heating of own premises and only about two thirds of the capacity of the biogas plants was exploited (Nedland and Ohr 2010). The share of biogas used for transport has increased to more than 30% of the consumed biogas in 2015 (Statistics Norway, 2016b). The total consumption was 308 GWh (1.1PJ), 48 GWh was used for district heating and electricity production, 105 GWh (0.4PJ) for transport, 30 GWh for industrial purposes and 126 GWh (0.5PJ) by other consumer groups. Biogas constitute about 3% of the total national biofuel use (Statistics Norway, 2016a) and has currently a marginal significance in the total energy use in Norway. According to the national waste statistics, about 48% of the solid organic waste went to biogas production in 2015 (Statistics Norway, 2017). A significant share of the available sewage sludge resources are currently being used for biogas production, and the future potential for biogas production is identified to be the organic waste and manure resources (Norwegian climate and pollution agency, 2013). The production capacity of biogas is expected to be up to 600 GWh (2.2PJ) in 2016 (Måge, 2015). The deviation between the estimated capacity and the national statistics on consumption indicates that there are still large amounts of gas being flared and that the total capacity of the plants is not being exploited.

About 58% of the gas is produced from sewage sludge in wastewater treatment facilities, while only 1% is produced at farms with small scale plants. The rest is produced based on OW and co-digestion plants (Lånke *et al.*, 2016 ,Norwegian climate and pollution agency, 2013).

Digestate is dewatered and composted in many plants, and the dry digestate is used as a soil improvement product. The experience related to use of liquid digestate on an industrial scale as a fertiliser is limited to a few, recently built plants.

2.3.2 The regulatory system

The regulatory system in Norway relevant for biogas production is shown in Table 3. Investors of industrial scale biogas plants can apply for investment support through the Enova programme. Applications are evaluated based on criterions related to cost efficiency and energy efficiency. The support has been limited to 30% of the capital costs of the anaerobic digestion plant (pre-treatment and upgrading not included). Farm scale plants can apply for investment support through Innovation Norway.

		Regulatory framework	**Economic incentives**
Input	**Access to substrates**	=>Public procurement on 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 (30%). =>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 to other transport fuels
	Digestate in agriculture	=>Restriction on spreading areas for waste water residues => Logistics: Cleaning of vehicles to avoid infections	

Table 3 The regulatory system in Norway relevant for the study objects

An economic incentive system with support to farmers per tonne of manure supplied to a biogas plant was recently introduced. The support is calculated based on the dry matter content of the manure delivered to the farm and is regulated in (FOR-2014-12-19-1815, 2015).

Municipally owned biogas plants must follow a cost of service regulation ("the self-cost principle"), as described in the national waste regulation (FOR-2004-06-01-930, 2004). This means that the income from treatment of municipal waste (gate fee) must cover the cost of treating the waste, and cannot pay for, or be financed by, other substrates treated in the plant. The rationale behind this is that the waste fee the inhabitants pay to the municipality to cover the treatment of their waste should reflect the actual price of the service.

Public procurement criterions affect the value chains both regarding income from treatment of waste and sales of biomethane. Municipalities that do have source separation of OW in the households, but do not have their own treatment facilities, performs a public procurement of the waste treatment service. The treatment plants are chosen through a request for tenders. Privately owned biogas plants and municipal plants from other areas can compete based on pre-defined criterions, such as price and environmental impact. The income from the treatment of waste make up a large portion of the income for Norwegian plants (66-78%) and there are large variations in the price per tonne waste treated (between 67 and 107 Euro/tonne treated) (Lyng *et al*, 2017). Biomethane is normally used in public transport and waste collection trucks, purchased through public procurement tenders.

Biogas used for transport has an advantage compared to fossil fuels because renewable fuels are exempted from road fee and CO_2-tax. The most common market competitors are vehicles running on diesel. Because the fees for the fossil alternatives are per litre, and because the efficiency in gas and diesel motors is different, the economic advantage for biogas as a fuel cannot be compared directly. In Table 4, the fees for diesel are shown per litre and per kWh before and after transmission losses in the diesel motor.

	Road fee	**CO_2 tax**	**Total**
Euro/Per litreMinistry of finance (2016)	0.4	0.1	0.5
Euro/kWh (before transmission losses)[13]	4.1	1.3	5.5
Euro/kWh (transmission losses included)[14]	1.7	0.5	2.2

Table 4 Avoided fees for biogas used as transport fuel compared to diesel in Norway in 2016

There is no economic support targeting the use of digestate or biogas for heat and electricity production. Other regulations affecting biogas plants includes the regulation of the need for sterilisation (FOR-2016-09-14-1064, 2016) and the fertiliser ordinance, which regulates use of digestate as fertiliser (FOR-2016-09-14-1064, 2016).

2.4 Biogas production in Denmark

2.4.1 Development of biogas production

The Danish biogas production emerged because of the oil crisis in the 1970's leading Danish farmers to look for an alternative energy supply. Later biogas was introduced as a mean to distribute

[13] Lower heating value for diesel 43,1 MJ/kg, 0,85 kg/litre
[14] Efficiency diesel motor 40%

nitrogen and phosphorous resources to avoid environmental problems and reduce odour (Lybaek, Christensen and Kjaer, 2013).

According to the Danish Energy Agency (2017b), approximately 85% of the biogas produced in Denmark is based on manure as a substrate. Most of this production includes an added co-substrate to increase the yield, mainly OW products (≈18%) and energy crops (≈2%). The most common energy crops are corn and sugar beet. The interest for energy crops are low due to a Danish regulatory limit on the usage of energy crops and to a large demand from Germany, which has resulted in increased prices (Jacobsen, 2014). Biogas producers therefore search for usable waste inputs. According to Raven and Gregersen (2007) and Lybaek, Christensen and Kjaer (2013) the lack of industrial OW has been a barrier for biogas production in Denmark. A few biogas producers have solved this problem by importing OW from for example Norway, which has proven profitable due to the differences in regulation between the two countries.

In contrast to Norway, most of the digestate is used as fertiliser and spread on the fields in the agricultural production. Only some of the digestate, mainly from wastewater treatment plants, is dewatered and composted. Consequently, producers with the choice of co-substrates will not risk inputs with even small levels of pollution. This limitation is due to Danish regulation and organisations within the agricultural sectors with requirements on which substrates may be used to produce digestate spread on agricultural soil that produces cow feed. There is a development towards using other agricultural waste products such as straw, deep litter and some experiments with grass and algae.

The usage of municipal OW is experiencing a growing interest, since more municipalities have started to implement sorting and the dairy sector have started to consider municipal OW as “uncritical” – (under specific conditions). Currently municipal OW constitute less than 1% of the total biomass input and approximately 2% of the co-substrates in the manure based biogas production (Danish Energy Agency, 2017c). The amount of sewage sludge and organic waste sent to anaerobic digestion constitute a small share of the total mass compared to other waste treatment methods.

Until 2012, the economic support was targeted towards the use of biogas for heat and power production, which resulted in a low amount of upgrading. In 2012 the support increased and changed so that also biogas upgraded for the natural gas grid could receive support (Danish Government, 2012). Consequently, biogas production has increased from approximately 1100GWh (4PJ) in 2012 to above 2200GWh (8PJ) in 2016 and is expected to be somewhere between 3600-5800GWh (13-21PJ) by 2020 (Harder, 2016). Biogas production is foreseen to play a marginal role in the total energy consumption, of approximately 750PJ by 2017(Danish Energy Agency, 2017a).

Currently most new biogas plants are upgrading the biogas for the grid, and also older plants have installed upgrading facilities (Harder, 2016). When the biogas is upgraded to biomethane the biogas can be sold as natural gas quality together with a green certificate and be used in industry or heat-and power production. While gas for transport have been almost non-existent in Denmark for many years, the transport industry has recently started to show interest for gas.

2.4.2 The regulatory system

The main driver for biogas development in Denmark is the output-based support; see Table 5. The secondary focus is on using agricultural residues such as manure from the large livestock production, which can contribute to reductions in GHG emissions, reduced smell and reduced nutrients emissions in the ground water. The economic incentives on this part are, however, weak and contradict the renewable energy focus at least regarding the usage of manure.

A maximum of 25% energy crops in weight input can be added to the biogas production and still be defined as sustainable. After August 2018 will this be reduced to 12% (Energistyrelsen, 2015). This does not seem to be a challenge for the biogas producers, since energy crops accounts for less than 1% of the total biomass in biogas production and approximately 2% of the input in manure based biogas.

In most cases, the digestate is returned to the livestock farmers and used as fertiliser for the fields. In consideration of the water environment, farmers are often restricted on the amount of fertilisers and thereby manure that they can add to the soil, through the statute on manure usage (Danish Government, 2017). In Denmark, these restrictions apply both for nitrates and in some areas phosphorus. The digestate has approximately the same fertilising effect as manure; however, the nutrient mix might be different and plants typically absorb the nutrients better. Still, the digestate is regulated as manure, which increases the fertilizer value.

Within the regulation on fertiliser for agricultural soils are also restrictions regarding the risk of spreading pollution on the soils. When OW products are mixed into the biogas production, restrictions apply on whether this input could be considered as pure agricultural waste (regulated following the statute on manure-usage) or as waste. If it is the last type, it is only allowed to spread a small share before the total mix will be regulated following the statute on sludge (Miljøministeriet, 2006). Forces are working on moving the categorisation of organic household waste away from potential polluted waste towards a cleaner product.

The biogas support was initially a feed-in tariff on electricity produced on biogas. As most of the biogas-based power-producing units are regulated by the combined heat and power demand, most of the biogas is also indirectly supported by a tax exemption on the fuel used for heat production[15]. Fossil fuels and electricity used for heat production are massively taxed while there are no taxes on fuels used for electricity production. The feed-in tariff on electricity is not dependent on scale as in other countries (Walla and Schneeberger, 2008; Delzeit and Kellner, 2013); instead the plant size is determined by heat demand in the given area, which may not result in the optimal size (Skovsgaard and Jacobsen, 2017).

[15] If the power producer also is supplied with other fuels such as natural gas, will the plant receive a feed-in premium for the electricity based on biogas

Table 5 Regulatory system in Denmark relevant to the study objects

		Regulatory framework	Economic incentives
Input	**Access to substrates**	=> Supported biogas should be based on manure, other waste or waste water =>(25%) 12% maximum of energy crops (Energistyrelsen 2015, Danish Energy Agency 2017)	
Plant	**Anaerobic digestion plant**	=>Planning regulation =>Requirements to sterilisation of waste water slurry	Occasionally investment support[16]
Output	**Biogas to Heat/CHP**	Monopoly regulation on district heat	*CHP* =>Feed-in tariff on electricity produced on biogas =>Tax exemption on fuel for heat *Industry* => lower support *Heat-only* => tax exemption and lowest support**Error! Bookmark not defined.**
	Biogas for upgrade	=>Gas quality requirements, wobbe-index =>Pressure demand from grid =>Biogas certificates[17]	=>Feed-in premium on upgraded biogas**Error! Bookmark not defined.** =>Same taxation as for natural gas (high taxes), when taken from the grid =>with a biogas certificate can CO2-quotas be avoided
	Biogas for transport	=>5.75% blending demand on biofuels =>0.9% blending demand on advanced biofuelsDanish Government (2009b, 2016) =>Many biogas plants can be certified to as producing advanced biofuels => this is not yet connected to the biogas-certificate and can thus – not yet – ad any value through upgrading for the net	=>Feed-in tariff for direct use in transport, same level as industry**Error! Bookmark not defined.**
	Digestate in agriculture	=>Restriction on spreading areas for waste water residues(The Norwegian Department of Agriculture and food, 2009)and organic household waste =>Ecological digestate compared to conventional (not allowed with complete mix of manure from Ecological and conventional farms)(Danish Government, 2009a) =>Excess phosphorus can be reshuffled Restrictions on digestate based on org. waste	=>A little more nitrate is allowed =>improved fertilizer value

Danish Government (2012) has decided to increase the support and expand it to other applications of the biogas. Upgraded biogas receive a feed-in premium corresponding to the support for

[16] See for example (Danish Government, 2012)
[17] See the homepage of the Danish TSO for electricity and gas (Energinet.dk, 2017)

biogas used in heat and power production, while biogas used directly for industry, transport or heat production receive a lower support, see Table 6.

	Direct use			Upgraded
2016	CHP	Heat	Industry & transport	
Unit	Euro/MWh	Euro/GJ	Euro/GJ	Euro/GJ
Feed-in tariff	108.6			
Feed-in premium	59.2		5.23	10.86
NG price dependent	45.0	4.50	4.50	4.50
Temporary	10.7	1.07	1.07	1.07
Total	**164.3**	**5.58**	**10.80**	**16.43**
Tax, when the gas is used for heating	-	0.0	0,0	9.6
Tax, when the gas is used for transport	-	-	11.2	12.9

Table 6 Feed in support for biogas in Denmark

The purpose is to increase the support temporarily by two additional fees, a temporary support that is declining and a fee that is negatively correlated with the natural gas price the year before. If the natural gas price increase, the support will decrease as the need is decreased, and vice versa.

If upgraded gas is used in the grid, it receives a higher support and the tax is only vaguely higher than in the case of direct use. It is thus likely that most biogas plants decide to upgrade the gas for the grid.

3 Method

In this comparative assessment, we study the effects of the regulatory system on the private economy of biogas value chains under the two support regimes. This is done by defining a typical value chain in each of the countries and compare their total cost and income. The effects of the political instruments are then evaluated by assessing the economy for the defined Norwegian value chain under Danish regulation and vice versa. Generally, the scales in tonnes of treated substrates at each plant are larger in Denmark than in Norway. In the case study, we have chosen to analyse a plant that is large in the Norwegian context, and small in the Danish context to ensure comparability.

The Norwegian case under Norwegian conditions (**NO**): A co-digestion plant treating OW and manure from cattle and pig, capacity is 110.000 tonnes of input and the plant is based on an actual plant situated in Vestfold County, which is currently the only large-scale plant in Norway receiving considerable amounts of manure from surrounding farms. For simplification, it is assumed 100% municipal waste. The biomethane is used as fuel for transport. The actors included in the assessment are livestock farmers and OW treatment plant (biogas plant including an upgrading facility), see Figure 1.

The farmers receiving the biofertiliser and the transporter using the biogas is outside the system boundary. Farmers are paid to receive digestate.

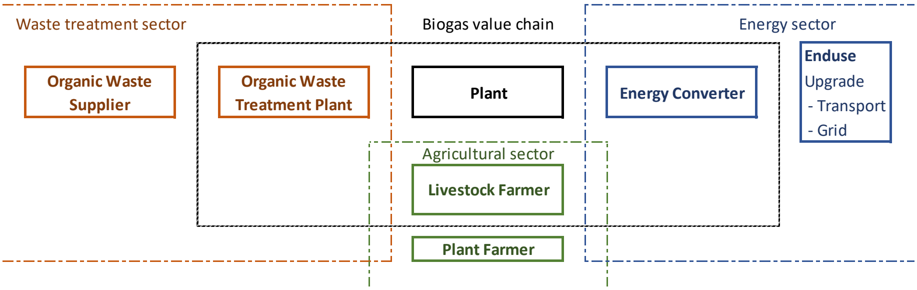

Figure 1 Actors in the Norwegian biogas value chain

The Danish case under Danish conditions (**DK**): A plant producing biogas from manure and deep litter from farms in Northern Jutland. The plant is a model plant with the capacity of 150.000 tonnes of input and geographically situated in Northern Jutland. This area is dominated by agricultural production, and has a vast supply of manure and potential co-substrates. Experience from using a plant optimization model described in Jensen, Münster and Pisinger (2017) show, that a substrate mix of 70% manure and 30% deep-litter is an optimal solution for a plant situated in this area, given a set of assumptions presented in Skovsgaard and Jensen (2017). The actors included in the assessment are: livestock farmers, biogas plant and energy converter (CHP plant), see Figure 2. The farmers receiving the digestate and the farmers supplying deep litter are outside the system boundaries. The digestate is assumed to represent an income.

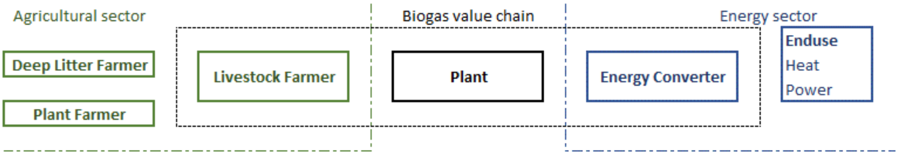

Figure 2 Actors in the Danish biogas value chain

When studying the Norwegian case under Danish conditions (NO → DK) (see Table 7), two major adjustments were done to make the case realistic: (1) We assume the same share of OW, however, the biogas plant does not invest in a pre-treatment facility. While treatment of OW is an income for Norwegian biogas plants, it is more likely that a Danish biogas plant must pay to get access to the substrate. We assume that the waste has been pre-treated before it arrives to the plant, resulting in a dry-matter content of 20%, compared to 33% in the NO-case, resulting in the typical dry matter content in an ordinary Danish biogas production (Jørgensen, 2013). The large share of municipal OW is unusual and requires a higher level of control of the digestate to allow it to be spread on agricultural soils.

	NO	NO->DK	DK	DK->NO
Capacity (tonnes)	110,000	110,000	150,000	150,000
Input (substrates)	45% organic waste, 55% manure	45% pre-treated organic waste, 55% manure	70% manure 30% co-substrate (deep litter)	70% manure 30% co-substrate (deep litter)
Biogas produced	7,113,750 Nm3 (43GWh)	4,200,000 Nm3 (26 GWh)	5,977,500 Nm3 (36GWh)	5,977,500 Nm3 (36GWh)
Output (Use of biogas)	Upgrade (for transport)	Upgrade (for natural gas grid)	Combined heat and power (CHP)	Heat plant
Investments	Pre-treatment food waste, digester, upgrading (water scrubber)	Digester, upgrading (water scrubber)	Digester, CHP plant	Digester, heat converter

Table 7 Definition of biogas value chains in Norway and Denmark

(2) It is assumed that the biomethane is fed into a natural gas grid rather than directly used for transport. Further, the market prices for biomethane and costs and income related to digestate is changed, and the investment support is removed, see Table 8. The transport costs are reduced because of larger farms and thus shorter transport distances.

		NO	NO -> DK	DK	DK -> NO
Input	**CAPEX** / **OPEX**	Pre-treatment organic waste	Payment for organic waste	Pre-treatment deep litter and input price	Pre-treatment deep litter and input price
	Income	Gate fee on waste Support for manure as input			Support for manure as input
Conversion	**CAPEX** / **OPEX**	Plant and after treatment (reactor size larger due to addition of water in pre-treatment process). Investment support 30% of Capex.	Plant and after treatment	Plant and after treatment	Plant and after treatment. Investment support 30% of Capex.
Output	**CAPEX**	Upgrading facility (and pressure regulation)	Upgrading facility and pressure regulation	CHP-plant	Heat converter
	OPEX	Payment to farmers receiving digestate			Payment to farmers receiving digestate
	Income	Sold biogas	Feed-in premium for biomethane, market price biomethane and sold digestate	Feed-in tariff electricity, heat price and sold digestate	Electricity and heat prices
Transport	**Total**	Norwegian transport cost	Danish transport cost	Danish transport cost	Norwegian transport cost

Table 8 Costs and income in each of the scenarios

The Danish case under Norwegian conditions (**DK →NO)** result in the following adjustments as shown in Table 8: As sale of electricity is assumed as not realistic, the plant produces heat from biogas and invest in a heat generator instead of a CHP plant. The transport costs are increased due to smaller farm sizes and larger transport distances. The market prices for heat are adjusted to Norwegian conditions and feed-in tariffs are removed, while investment support is introduced.

A large share of the income is related to direct- or indirect support. How this support is shared between the actors of the value chain is complicated and out of scope for this paper. Other studies have been done on profit sharing, see e.g. Skovsgaard and Jensen (2017). Profit sharing is left out by assessing the total profit of all the actors of the value chain, which are directly affected by the regulation in the respective countries. Economic transactions between the actors inside the system boundaries are not included. Assumptions for cost and income are presented in Appendix A. As the purpose of this study is to compare the effect of regulation, we have decided to use the same cost data in the two countries and assume the same cost level. This is a simplification as costs are likely to be higher in Norway. The hourly labour cost is about 20% higher in Norway than in Denmark (Eurostat, 2017b), and according to the OECD price level index, the general price level is about 5% (OECD, 2016). This is likely to lead to a discrepancy between the income and the costs for the Norwegian case, which will be discussed further in the result chapter. The results cannot be used to conclude on the profitability of the different scenarios or a direct comparison of the annual results. They are, however, suitable to discuss the effect of different regulations and to compare the differences in type of income, and keeps the regulations such as investment support at a comparable scale.

4 Results

4.1 Comparative analyses of biogas value chains in Norway and Denmark

As the development of biogas value chains is affected by a large range of other factors than the economic instruments, the structural conditions and political objectives described in Section 2.2 must be considered when assessing the effect of political instruments. The key differences in biogas production in the two countries are summarised in Figure 3. Biogas production is significantly larger in Denmark than in Norway: 500 GWh (1.8PJ) per year in Norway (Lånke *et al.*, 2016, Norwegian climate and pollution agency, 2013) and 1764 GWh (6.4PJ) in Denmark (Danish Energy Agency, 2017a).

The main difference in input is the use of OW from household and industry in Norway and of manure and other residues from agriculture in Denmark. While Norwegian plants in the past has had a history of flaring and use of heat in own premises, there is now a development towards using the gas as a transport fuel. In Denmark, biogas is mainly used to produce heat and electricity. There are no official statistics on the use of digestate in the two countries. The large share of substrate from agriculture in Denmark implies, however, that the use of digestate in agriculture is widespread because these plants are closely integrated with the farms. In Norway, however, the use of liquid digestate as a fertiliser on an industrial scale is limited to a few plants, and it is more common to use dry digestate as a soil improvement product.

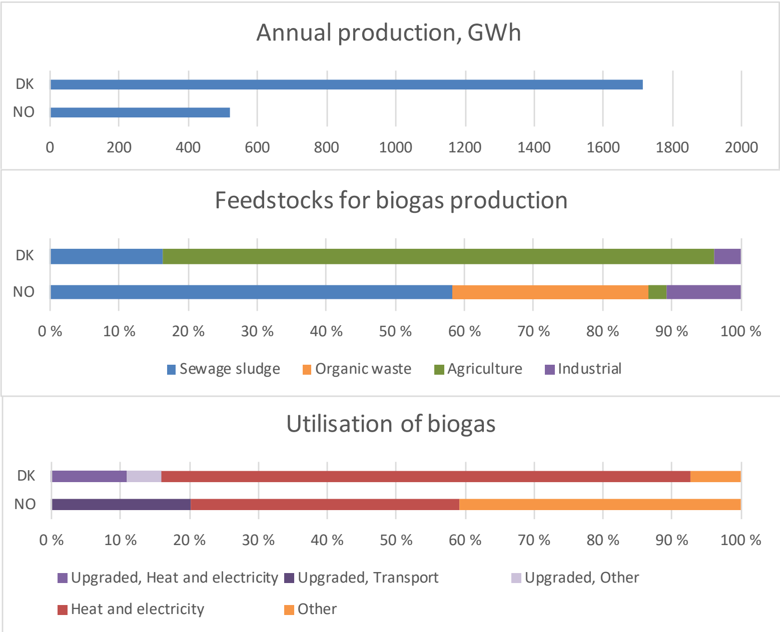

Figure 3 Production, feedstocks and utilisation of biogas in Norway and Denmark

The economic assessment of the Norwegian value chain under Norwegian conditions and the Danish value chain under Danish conditions are presented in Figure 4 and 5. The figures indicates the importance of the various cost and income factors. The profit in the Norwegian value chain is approximately $50 - 28 \approx 22$ Euro/tonnes input while the profit in the Danish value chain is approximately $21 - 16 \approx 5$ Euro/tonnes input. This is a large difference, which to a high degree can be explained by the assumptions made in the case study.

The high profit for the Norwegian value chain is likely to be explained by the assumption of the same cost level in the two countries, which result in an unrealistic difference between the income (which are based on Norwegian prices) and costs (which are based on Danish costs) as described in section 2.2. The income from treatment of OW is for most plants regulated by the cost of service regulation, described in section 2.3.2. Because the treatment cost of OW is regulated to reflect the actual cost of the service, profits would be lower as income from gate fees in reality would be adjusted. The profit for the Norwegian case is thus not realistic and cannot be used to conclude on whether the Norwegian biogas value chain is profitable or not. Results should therefore only be used to compare types of costs, and the effect from the regulatory systems on the value chains.

The total costs in Norway are higher due to inclusion of OW that requires pre-treatment and increased Capex and Opex. All cost factors are presented in Euro per tonne input, and for the Norwegian biogas value chain are largest cost factors the capital and operational costs for the digester

(3.9 €/t and 9.7 €/t) and capital costs and operational costs for pre-treatment of waste (4.6 €/t and 1.4 €/t) and transport costs (4.3 €/t).

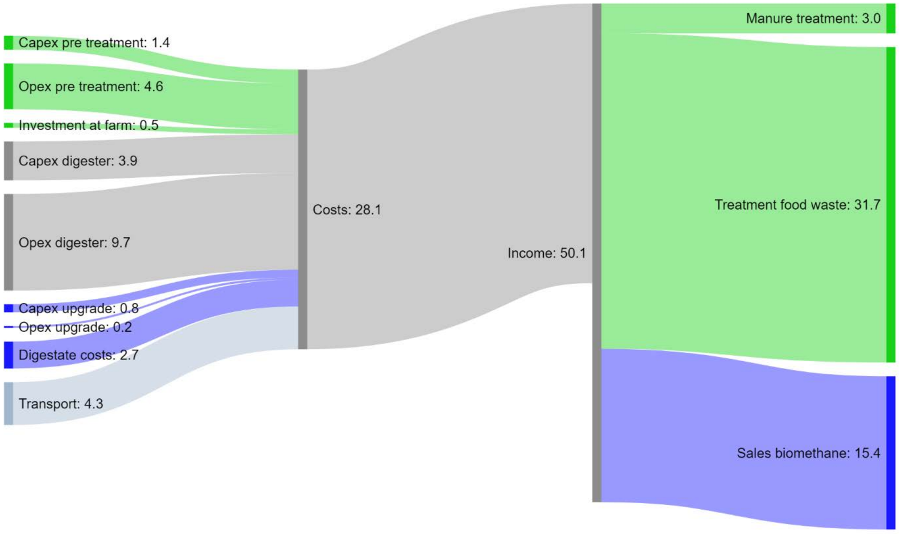

Figure 4 Distribution of cost and income in the Norwegian biogas value chain in Euro per tonne treated

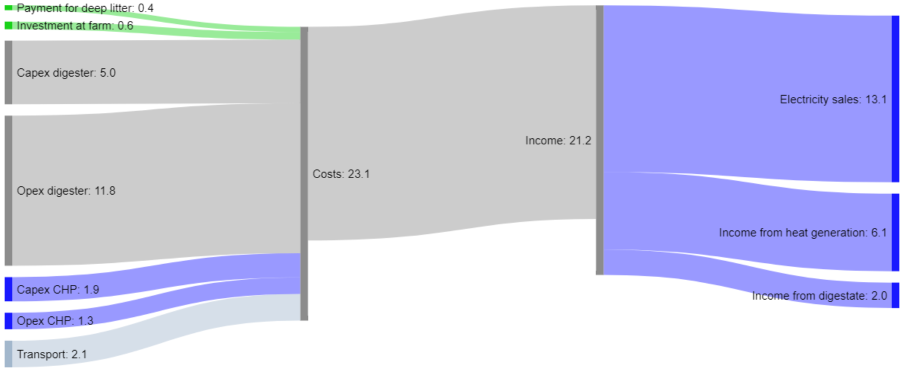

Figure 5 Distribution of costs and income in the Danish biogas value chain Euro per tonne treated

In the Danish, value chain, the largest cost factors are related to operation (6.6 €/t) and capital costs (4.0 €/t) of the anaerobic digestion facilities together with operational (1.3 €/t) and capital costs (1.9 €/t) of the CHP plant.

Estimated costs for transport is approximately 100% higher in Norway (4.3 €/t) than in Denmark (2.1 €/t), but even though transport of manure and digestate represent significant cost factors in both countries, they do not seem to have a determining effect on the final results in the two defined cases.

The main difference in profitability of biogas value chains in Denmark and Norway is the organization of the economic incentives. In Norway, more than 60% of the total revenues originate at the input side as income from waste- and manure treatment. Capital expenditures on the anaerobic digestion facilities are reduced by an investment support of 30%.

The economic support to Danish biogas value chains is founded in energy supply from the biogas production (electricity and heat production), where more than 90% of the revenues originates from sales of energy with feed-in tariffs or a premium. In our case, the support accounts for 60-75% of the total income. Another income, which is not supported, is the sales of surplus digestate. In Denmark, the agriculture has a long tradition in using digestate, and it is considered as an improved fertiliser compared to manure. In contrast, the use of liquid digestate represent a cost for the farmers in Norway, due to the need to invest in infrastructure. Consequently, the biogas plant must pay the farmer to accept the digestate.

4.2 Case study on effect of economic incentives

The implications of the annual economic results when constructing the Norwegian value chain in Denmark and vice versa is shown in Table 9 (per tonne treated) and Table 10 (per GWh biogas produced, before transmission losses). The costs and income are categorised into their occurrence in the value chain: input, conversion, output and transport.

		NO	NO->DK	DK	DK->NO
	Input	**110,000 tonnes**		**150,000 tonnes**	
Input (substrates)	**CAPEX**	1.44	0.0	0,0	0
	OPEX	5.0	9.0	1.0	1.0
	Revenue, manure	3.0	0	0	3.9
	Revenue, waste	31.7	0	0	0.0
Conversion	**CAPEX**	3.9	4.2	4.0	2.8
	OPEX	9.7	8.1	6.6	6.6
Output (biogas and digestate)	**CAPEX**	0.8	0.6	1.9	1.1
	OPEX	2.9	0.2	1.3	6.0
	Revenue, digestate	0	1.8	2.0	0
	Revenue, gas	15.4	20.2	19.7	5.9
Transport	**Costs**	4.3	1.1	2.1	5.1
Total in Euro/tonnes input		**22.1**	**-1.2**	**4.9**	**-12.7**

Table 9 Results in Euro per tonne treated

The waste sector plays a large role in Norwegian biogas production, and the income from treatment of waste represents the main income for biogas plants. In Denmark, the treatment of OW appears to be less important and is motivated by the wish to increase the biogas yield. There is no support for the use of OW and it is seen as a challenge when it comes to quality of the digestate. There is, however, a movement towards a more sustainable treatment of the OW resources.

		NO	NO->DK	DK	DK->NO
	Production (GWh)	**43**	**32**	**36**	**36**
Input (substrates)	**CAPEX**	3667	0	11	11
	OPEX	12802	31223	4110	4110
	Revenue, manure	7756	0	0	16154
	Revenue, waste	80798	0	0	0
Conversion	**CAPEX**	10024	14436	16412	11488
	OPEX	24734	27877	27078	27078
Output (biogas and digestate)	**CAPEX**	2104	2104	7815	4445
	OPEX	7386	572	5557	24850
	Revenue, digestate	0	6107	8411	0
	Revenue, gas	39200	69717	81302	24566
Transport	**Costs**	10831	3924	8475	21208
Total in Euro/GWh produced		**56207**	**-4312**	**20256**	**-52471**

Table 10 Results in Euro per GWh produced (before transmission losses)

The NO value chain in a DK setting (NO->DK) loses the investment support, save the Capex and Opex costs from pre-treatment facilities for OW and will see a 75% reduction in transport costs. As the support per tonne manure disappears and the biogas plant is assumed to pay for the waste rather than receiving a payment for waste treatment, the total income is largely reduced. In Denmark, the goals of increasing the share of renewable energy are ambitious and this is reflected in the economic instruments through a feed-in tariff. The support for production of input of biomethane to the natural gas grid is considerable. Upgraded gas in Denmark is more likely to be inserted into the natural gas grid than to be used for transport with the current Danish regulation. In Norway, the use of biogas as a fuel for transport has increased substantially. An indirect economic support is provided, all though the national goals are unclear. In Denmark, the share of biogas used for transport is low and there are no specific political goals for this. There is some support for direct use in transport however, as the tax is high there is no clear policy.

The overall economic result for the NO->DK value chain is negative; however, with few alterations it could become profitable. This can be explained by a high level of support for biomethane, and that OW provides a reasonable yield, despite the water added in the pre-treatment process.

The DK plant in a Norwegian setting (DK->NO) is not profitable either, as there is a loss of revenue from the biogas output because the plant loses the feed-in tariff for renewable electricity. In Norway, there are no particular political goals or incentives to use biogas in the energy sector, due to the high share of renewable hydropower. The most probable solution for the plant in Norway is assumed to be production of heat only and not electricity. There is a small subsidy to the manure treatment in Norway, but this is not sufficient to outweigh the loss of output subsidy. The investment support represents reduced Capex, but not enough to compensate. The income from digestate is turned into a cost because the demand for digestate is lacking in Norway. The agricultural sector has been less important in Norwegian biogas production however, a new support system aims at including farms to reduce GHG emissions from manure handling. In Denmark, agriculture is a large sector and it plays a primary role in biogas production. Earlier analysis show, that biogas production is a socioeconomic costly way to reduce GHG emissions in Danish agriculture (Dubgaard and Jacobsen, 2013), however compared to Germany it is relatively cheaper (Jacobsen, Laugesen and Dubgaard, 2014). The goals for the sector are, however, unclear and support is only indirect.

The results per GWh produced (before transmission losses) in Table 10 show the significance of the support on the output side in Denmark. The income from the produced gas is lower for the two cases in Norway (NO and DK->NO), however the income from treatment of waste in the NO-case is in the same range as the income from the sales of biogas in the DK-case. The use of OW as an input increases the biogas yield, but at the same time costs are increased due to the need for pre-treatment and additional costs for the Capex and Opex for the digester.

5 Discussions of results

Two countries with fundamentally different support systems are compared in this study. The economic instruments have a visible effect on the value chains. One clear consequence of output support is that it incentivises the use of high-yield inputs and contributes to avoiding biogas losses. While input support result in less focus on the biogas yield, more flaring and own use in the production. What is most efficient depend on the overall goals for the biogas production.

5.1 GHG reduction in agriculture and management of waste resources

Biogas production can be used to obtain political goals on reducing GHG emissions in agriculture through degassing of manure and thereby converting methane- and nitrous emissions into CO_2-emissions. Furthermore, biogas production can potentially reduce the leaching of nutrients with the use of digestate as a fertiliser instead of manure and mineral fertiliser. Farms have different roles in the biogas value chain: as supplier of manure and as the user of digestate. While the agricultural sector is a part of most biogas value chains in Denmark, the inclusion of the agricultural sector is under development in Norway. The two countries have large differences in farm sizes and structure in agriculture. Wirth *et al.* (2013) concluded, however, that differences between biogas productions in different regions in Austria cannot only be explained based on physical geographical conditions or prevailing economic structures in agriculture, and that public support schemes also plays an important part.

Both countries have stated a political goal of increasing the amount of manure for biogas production, however, only Norway is targeting this specifically through a support to farmers per tonne of manure delivered. According to Raven and Gregersen (2007) an increased number of farm scale and centralised plants in Denmark did not emerge without a struggle, and was strongly aided by measures for interaction between social groups, long term action programme and financial support and policies for decentralised CHP. In Norway, there has been an increase in the use of manure for biogas, but the potential remains high, as there is no demand for decentralised energy production. This case study reveals that if the Norwegian support system for manure to biogas were to be introduced in Denmark, the magnitude of the economic support would be small compared to the other biogas support. In Denmark, the combination of biogas support and the sustainability criteria has led to high use of manure as a substrate and an increase in size of the plants. Introducing support on input in addition to output could contribute to increasing the amount of manure used for biogas production even more, and potentially reduce the search for high yield substrates. This may also contribute to an increase of manure treatment in areas with lower farm density and a decrease in socioeconomic costs of GHG-emission reductions, as pure degasification of manure can be less costly from a socioeconomic perspective according to Dubgaard & Jacobsen (2013).

In Norway, the emphasis is on increasing the biogas production, motivated by ambitions of a more sustainable management of waste resources. This has led to increased biogas production and increased amount of OW being source separated. Raven and Gregersen (2007) concluded that one of the most important factors causing reduction in establishment of new biogas plants in Denmark in the late 90's was limited access to organic waste. Clercq *et al.* (2017) identified lack of source separation as a common obstacle for increased anaerobic digestion of organic waste in several countries, and suggest that this should be addressed by policymakers.

The waste resource perspective is rising on the political agenda in Denmark due to the Circular Economy package adopted by the EU. Consequently, more municipalities have started to sort organic household waste. The economic instruments for biogas in Denmark are solely targeting the output, hence the use of OW is not supported other than indirectly because it can increase the yield when co-digesting with manure. Danish biogas plants are restricted by older regulations that do not reflect all concerns of the dominant dairy sector. This has resulted in reluctance towards use of digestate containing municipal OW however; new developments are on their way.

In Norway, income from treatment of waste is essential for the centralised biogas plants. As treatment of waste is less expensive in Sweden and Denmark, some OW is exported. In Denmark, the demand for waste for incineration has contributed to lack of incentives to introduce source separation. This shows that there are large differences in the demand for waste, which affects access of OW for the biogas plants and determines whether the treatment of waste represent a cost or an income.

Using municipal OW as a substrate comes with a high cost due to the need for pre-treatment and requirements for documenting the quality and content of the digestate. Acceptance from the user of the digestate can be challenging to achieve when the origin of the substrate is from the waste sector.

None of the countries seems to have specific political goals on using digestate from biogas production as a fertiliser in agriculture except in Denmark where it is implicitly a part of regulation, since farmers are obliged to find usage of the manure arising from their production. In Norway, the market for digestate as a fertiliser is still under development, while Danish farmers are experienced in using digestate from agricultural waste as fertiliser. Huttunen, Manninen and Leskinen (2014) identified end use of the digestate as one of the most critical points for biogas production in Finland. A premise for increased amount of OW for biogas production in Denmark seems to be a combination of more source separation clearer regulation to ensure quality of the fertiliser produced from digestate and increased knowledge about digestate from co-digestion of OW and manure. In Norway, the digestate represent a cost for centralised biogas plants, as there is no willingness to pay for the digestate. Because there are no incentives targeting recycling of nutrients, it is hard to predict whether the demand for digestate as a fertiliser will increase and represent an income rather than a cost in the future. Experience in using digestate in agriculture is, however, likely to increase due to the support to manure for biogas, because most farmers that supply manure to a biogas plant would expect to receive the digestate in return.

5.2 Renewable targets for energy and transport

Biogas value chains can contribute to phase out fossil fuels, both in the energy systems and in the transport sector. In Denmark, the regulatory system is developed with an emphasis on increasing the share of renewable energy, which can increase security of energy supply and reduce CO_2 *within* the energy system. The economic support on output incentivises the use of high yield substrates together with manure and an efficient use of biogas, while flaring and internal use of biogas is minimised.

There is a degree of flexibility embedded in the regulation, as the output support is given for upgraded biogas and for several applications of direct biogas usage. This allow each producer to design the value chain to fit his or her needs, however, the variation favours upgrading for the grid and electricity generation. Even though the support system could be more flexible and efficient, it does contribute to the goal of complete independence of fossil fuels by 2050.

The input based regulation (investment support) in Norway has led to an increase in biogas production. The system contains few incentives on the output side, which is likely to have contributed to a high amount of flaring and use of biogas internally. The lack of incentives on the output side became particularly clear when a Danish value chain was tested under Norwegian conditions, resulting in the worst result, despite low investment- and operational costs (DK prices). Without the output support, it would not be profitable to build a CHP plant or a heat generator. Due to the high share of hydropower and low demand for gas, the CHP solution is irrelevant in Norway, while in Denmark the existence of district heating systems has been important for the development of the biogas industry (Raven and Gregersen, 2007).

Biogas as a fuel for transport is relevant in both Norway and Denmark, as it has been proven difficult to reduce the use of fossil fuels in this sector. The use of biogas as a fuel for transport has increased, aided by an indirect support through an exemption from road fee and CO_2-tax compared to fossil alternatives. The increase in use of biogas as a fuel for transport is likely to lead to less flaring and better use of the production capacity in the plants. Tax exemption has also been crucial in Sweden (Larsson, Grönkvist and Alvfors, 2016), which is one of the European countries with the largest number of upgrading plants (EurObserv'ER, 2014).

Both Norway and Denmark have no specific goals for biogas in transport, all though they share the EU targets of 10% renewable fuels in the transport sector by 2020 and CO_2-reduction goals in transport. Pöschl, Ward and Owende (2010) identified upgrading of biogas for utilisation in the transport sector as the most promising option for use of biogas in the future in Germany, which is currently the largest producer of biogas in Europe. Except for the tax exemption in Norway, there are no instruments specifically targeting use of biogas in transport in the two countries.

If Denmark should be independent of fossil fuels by 2050, it could make sense to consider biogas in transport along with other renewable fuels. The direct support for biogas to transport is low and hence goals and regulation does not seem to be clearly aligned.

6 Conclusion and policy implications

We find that *several value chain designs for biogas can be profitable*, and we find viable value chains both in Norway and in Denmark. We do however also find that the *viability of a value chain is highly dependent on structural conditions and the regulation applied* directly on the biogas plants as well as the adjacent sectors.

When comparing the biogas value chains in the two countries, we see that agriculture dominates as the supplier of inputs in Denmark, which enables large-scale plants because of the abundant availability of agricultural waste products. In Norway, biogas production has been a part of the waste sector, and biogas and digestate have been secondary products.

The case studies demonstrate that the profitability of the value chain deteriorates remarkably, if Danish regulations were to be implemented on a Norwegian value chain, and vice versa. This is explained by the Norwegian value chain relying on *high incomes from the input operation* in the form of a waste treatment fee, while the Danish regulation remunerates a high biogas yield through *support on the output side*.

The difference in support both affects the value chain design and usage of biogas. Incentives for biogas output have been few in Norway, resulting in a large amount of flaring and self-use. In Denmark, this is kept to a minimum.

Overall, the national targets and regulation in both countries are directed towards *GHG-reduction*, though the emission sources are not equally targeted, as the *GHG-reduction* in Denmark is concentrated on *CO_2-displacement in the energy system*, and less focused on emission reduction in the agricultural sector. This is explained by the ambition to increase renewable energy shares and obtain fossil fuel independence. Norway already has security of energy supply through fossil resources and renewable based electricity supply by hydropower. Only transport is fossil fuel dependent in Norway, which directs the effort to increase renewables in this sector.

Goals and regulation in both countries are not completely aligned e.g. the low Danish support for biogas in transport does not encourage use of biogas in transport. Furthermore, we find that the national goals seem to be converging between the two countries presumably aided by common EU regulation, but the means for reaching the goals differ.

Though goals and structural conditions are not completely the same for the two countries, they can learn from each other and there are several **policy implications** based on this comparative assessment. If the main objective is domestic *GHG-reduction* in Denmark, the options for emission reduction on the input side should be equally supported as the fossil fuel reduction in the energy system as this may imply cheaper reductions.

In Denmark, most new biogas plants are upgrading for the natural gas grid, while receiving high support. It could be considered to *shift* some of this *support to the manure treatment*, and *thereby increase the incentives for GHG-reduction* and at the same time *distribute the support more evenly in the value chain*.

The Norwegian support for the transport use of biogas is less than the average support in Denmark, but the input support, gate fee and investment support compensate for this. The development in Norway shows that biogas can and will be used in transport with the right incentives. It could, however, be considered to supplement the tax-exemption with a corresponding feed-in premium for upgraded biogas, as *direct or indirect support towards the use of biogas can decrease flaring and lead to a more efficient use of the capacity at the plants*.

The digestate *can* be reused in agricultural soils, with the right input fractions and if the OW is sorted properly first. Clear regulation regarding quality and knowledge combined with acceptance in the agricultural sector is key to obtaining recycling of the nutrients in a productive manner.

Because biogas can be produced and used in many different ways, the design of the value chain is highly dependent on the opportunities for the producers in the form of infrastructure, restrictions and support.

We cannot conclude that one support system is superior to the other, as they are designed to fit different structural conditions and needs, however, it may be possible to increase regulatory efficiency if the countries take inspiration from each other.

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APPENDIX D

THE IMPACT OF CO2-COSTS ON BIOGAS USAGE

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The impact of CO_2-costs on biogas usage

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ABSTRACT

The Danish government has set a target of being fossil fuel independent by 2050 implying that a high degree of inflexible renewable energy will be included in the energy system; biogas can add flexibility and potentially has a negative CO_2-emission. In this paper, we investigate the socio-economic system costs of reaching a Danish biogas target of 3.8 PJ in the energy system, and how CO_2-costs affect the system costs and biogas usage.

We perform our analysis using the energy systems model, Balmorel, and expand the model with a common target for raw biogas and upgraded biogas (biomethane). Raw biogas can be used directly in heat and power production, while biomethane has the same properties as natural gas. Balmorel is altered such that natural gas and biomethane can be used in the same technologies.

Several CO_2-cost estimates are investigated; hereunder a high estimate for the expected CO_2-externality costs. We find that system costs increase with CO_2-costs in most cases, while the biogas target becomes socio-economically cheaper. In the case of a very high CO_2-cost, system costs decrease and biomethane becomes the primary fuel. Furthermore, biomethane functions as regulating power and the Danish fuel consumption increases due to a higher electricity export.

1. Introduction

The Danish climate strategy is shaped around a goal of being independent of fossil fuels in all energy consuming sectors by 2050, and one tool among many is biogas. First focus point have been the heat and power sector (from now on called the energy system) in which there has already been a large development in energy savings and implementation of renewable energy. Therefore, an energy system independent of fossil fuels by 2035 has been determined as a stepping stone towards the 2050 goal [1].

Biogas production have been developed in Denmark since the late 1970's with varying focus points [2]. Biogas is a renewable fuel that can be produced from a large variety of inputs such as manure, waste water and other wet substrates, which are expensive to use in other technologies. In Denmark, biogas is primarily based on manure of which there is an abundant supply from the large Danish agricultural industry. The degassed manure from the biogas process has an improved fertiliser value and can potentially improve the water environment as less nutrients are washed out from the fields. Furthermore emissions from the far more potent greenhouse gasses: methane (CH_4) and laughing gas (N_2O) are converted into CO_2-emissions—making biogas one of the few fuels that potentially can reduce greenhouse gas emission effects.

In Denmark, biogas has primarily been used in local, combined heat and power plants (CHPs). As biogas is produced constantly all over the year and it is expensive to store, it is also *used* constantly, i.e. producing a constant stream of heat and power. With an increase in volatile renewable power production, this is not necessarily the optimal usage of biogas. In 2014 new regulation was ratified, such that biogas is now also subsidised when it is upgraded to natural gas quality (biomethane). Biomethane can be transported in the natural gas grid, which allows it to be used *where* it is needed, *when* it is needed.

Biogas has been applied in other analyses on systems optimisation—in particular on the issue of waste as a fuel [3–5]. Biogas is often one fuel out of many and seldom turn out to be the preferred fuel as seen in e.g. Ref. [3] and the national biomass value chain model [6]. In our analysis, we turn our attention to biogas (hereunder biomethane) by including a separate target of biogas usage.

There is a variety of literature on energy systems optimisation using different optimisation models, e.g. Balmorel [7–9], MARKAL/TIMES [10–12], and EnergyPLAN [13–15]. An overview of existing energy systems models can be found in Ref. [16]. With the choice of

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model, it becomes necessary to assess whether the model can include varying properties of the two types of biogas and the target of biogas usage.

In this paper, we consider the year 2025 for which the Danish Energy Agency (DEA) has a prognosis of the biogas production [17], which seems to be aligned with the goal of being fossil fuel independent by 2035. We model biomethane as a substitute fuel for natural gas in an energy systems optimisation model and include a common goal on the use of biogas in the energy system. We allow the model to use biomethane as well as raw biogas and thereby we can compare the two options for the energy system. To our knowledge no other articles have included both raw biogas and biomethane in an energy systems optimisation model to evaluate their usage. The optimisation model is minimising the socio-economic cost of the energy system. From the model, the use of raw biogas and biomethane can be evaluated to find the socio-economic cost of a biogas target in the energy system both as a system cost and a marginal cost of the target. Furthermore, scenarios for different settings of the CO_2-cost is introduced to evaluate the effect on the system cost and the marginal cost of the target.

2. Biogas in Denmark

Biogas production has been developed in Denmark since the late 1970s [2], primarily based on manure and co-substrates from a large agricultural industry; and due to regulation biogas plants have primarily supplied heat and power locally.

As Denmark moves towards being fossil independent by 2050, it becomes necessary to find replacements for particularly coal and natural gas in the energy system. There is already by 2017 a massive development in Denmark where coal to a large extent has been replaced by biomass and wind power. However, the lack of flexibility and predictability among renewable energy sources such as wind and solar power [18] has become a repeated concern, when renewable energy is integrated into the energy system. One suggested benefit from biogas is the potential to add this needed flexibility. The traditionally, Danish biogas usage where biogas is sent directly through a dedicated pipeline to a nearby CHP-plant, can however not be expected to add much flexibility—in some cases it might even work against flexibility, since an effective production of raw biogas only can vary a little and due to high costs with local storing [19] it has to be used gradually while it is produced.

Raw biogas can also be upgraded to natural gas quality and sent as biomethane into the national gas grid. Raw biogas is made of approximately 65% methane and 35% CO_2, and the upgrading process consists essentially in removing this CO_2-surplus, converting the raw biogas into biomethane (98% methane and 2% CO_2). Alternatively, hydrogen from electrolysis could be added to raw biogas, converting the CO_2-surplus into additional methane [20]. This process would increase the biomethane production with roughly 70%. The biomethane can be transported in the gas grid, stored and used with the same flexibility as natural gas in the heat and power sector, in industry or in heavy transport.

2.1. Biogas targets

There is no particular target for Danish biogas usage in 2025. However, a target of using 50% of all manure for biogas production by 2020 was set in the Green Growth Agreement [21]. This is an extensive increase in the biogas production, as currently only 7–10% of the Danish manure is used for biogas production. If 50% of the manure were to be used for biogas production it would correspond to approximately 11 PJ.

The energy consumption prognosis from the Danish Energy Agency (DEA) [17], predicts a 7 PJ increase in total biogas consumption from 10 PJ in 2015 to 17 PJ in 2025. In Fig. 1 the latest and expected development in biogas consumption are depicted (left y-axis) and for comparison the natural gas consumption is also depicted (right y-axis). From this it is clear, that even with a high percentage increase in biogas consumption, it will still be far from the current natural gas consumption.

The latest calculations on future biogas potentials for Denmark corresponds to approximately 60–85 PJ [22,23]. But even with such high production it only corresponds to roughly 10% of the current total energy demand in Denmark, which is around 750 PJ. Furthermore, biogas is considered relatively expensive compared to other renewable technologies. The expected Danish energy consumption is depicted in Fig. 2 together with the energy consumption for the energy system for 2015 and a prognosis for 2025 from the Danish Energy Agency (DEA).

From the 2025 prognosis it becomes clear that an increased biogas production is not expected to be used in the heat and power sector. An increase in biogas consumption is most likely to happen in the transport and industrial sectors according to the Danish biogas task force analysis [24].

2.2. Regulation

As already mentioned, support for biogas was until recently only given indirectly to electricity produced on raw biogas in a local CHP. With the new regulation support is also given to upgraded biogas. The support for 2015 can be seen in Table 1 together with an approximation for the support in 2025. Since the support is dependent on both the natural gas price and the net price index, it is uncertain what the exact support will be in 2025.

With the current regulation, the support for raw and upgraded biogas is in many ways similar and since costs for upgrading are high, a private economic analysis could point to direct use as the preferred usage. According to [25], this is also the preferred choice as long as the plant is small. Following the inflexible production of biogas and the support design, when raw biogas is used in a local CHP, CHP is incentivised to produce constantly, independently of the electricity market. Support for biomethane is given before the biomethane is used and—except for a reduced CO_2-cost—biomethane is expected to have the same properties as natural gas and is taxed the same way. Therefore, the private economic competitiveness of biomethane can already be determined at the gate into the gas system: if the fuel costs including CO_2-costs are sufficiently low, biomethane could compete with natural gas, which may favour upgrading [26,27].

In conclusion, it is reasonable to expect that biogas will be used both raw and upgraded in the future energy system depending on the local conditions, e.g. the local district heating demand.

3. Biogas in the energy system

Based on the above, we find it reasonable to include both raw biogas and biomethane when we model biogas within a Danish energy system context. The raw biogas and biomethane should be included in the energy systems model with different properties, e.g. cost and efficiency, and the common target should be handled by the model.

3.1. Balmorel

We choose to use the energy system model, Balmorel [28], for analysing the use of raw biogas and biomethane. Balmorel is a bottom-up model in which the energy system can be optimised

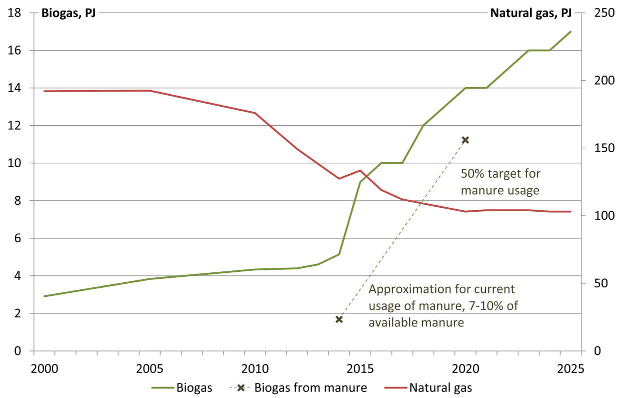

Fig. 1. Biogas target shown on the left y-axis compared to the natural gas demand on the right y-axis.

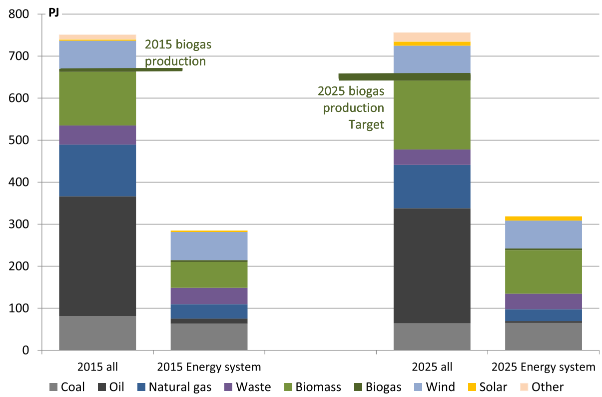

Fig. 2. Danish fuel consumption.

Table 1
Direct and indirect support for biogas, in 2015-prices.

Regulation type	2015	2025
Electricity feed-in tariff, CHP - raw biogas	16.8 Eurocent/kWh	12.8 Eurocent/kWh
Avoided fuel tax on heat, CHP - raw biogas	3.1 Eurocent/kWh	3.1 Eurocent/kWh
Biogas feed-in premium, biomethane	16.8 Euro/GJ	12.8 Euro/GJ

using an economic dispatch model, i.e. assuming all energy generating units are always online. The general economic dispatch model for electricity generation without investments can be written as:

$$\text{Min. } z = \sum_{t\in\mathcal{T}}\sum_{a\in\mathcal{A}}\sum_{g\in\mathcal{G}}\sum_{s\in\mathcal{S}} cost_g vge_{a,g,s,t} \quad (1)$$

$$\text{S.t. } vge_g^{min} \leq vge_{a,g,s,t} \leq vge_g^{max} \quad \forall a\in\mathcal{A}, g\in\mathcal{G}, s\in\mathcal{S}, t\in\mathcal{T} \quad (2)$$

$$\sum_{g\in\mathcal{G}} vge_{a,g,s,t} = d_{a,s,t} \quad \forall a\in\mathcal{A}, s\in\mathcal{S}, t\in\mathcal{T} \quad (3)$$

$$vge_{a,g,s,t} \geq 0 \quad \forall a\in\mathcal{A}, g\in\mathcal{G}, s\in\mathcal{S}, t\in\mathcal{T} \quad (4)$$

Line 1 is the total cost of producing on the installed technology type g. Here $cost_g$ is the cost of producing one unit of power on technology g and $vge_{a,g,s,t}$ is the amount of electricity produced on technology g in area a in all time periods given by season s and time t. Equation (2) ensures that each technology produces within its limits given by a minimum production limit, vge_g^{min}, and a maximum production limit, vge_g^{max}, in all areas and time periods. Equation (3) ensures that the electricity demand is met in all areas and time periods. Equation (4) ensures that the production is non-negative for all technologies in each area at all time periods. All used nomenclature can be seen in Appendix A. The economic dispatch problem can be extended to include heat-only technologies as well as combined heat and power technologies. This extension is not covered here, however, Balmorel includes both power and heat generation, as well as transmission within countries and between countries. The reader can refer to [28] for more details on modelling in Balmorel.

Balmorel is adoptable to any choice of geography, however it is used mostly in the Nordic and Baltic countries. Balmorel can be extended using several different add-ons, e.g. a unit commitment add-on, a policy add-on, and a time aggregation add-on. In this paper we use the economic dispatch model with optimisation of investments, and the combination technology add-on (Combtech) described in Section 3.3.

Balmorel performs an economic optimisation with a simplistic representation of a socio-economic analysis, which do not include all externalities. The socio-economic optimisation is a cost-based analysis, using neither national taxes nor subsidies, and costs used in the model are expected market prices.

3.2. Modelling of biogas in the energy system: limitations and delimitations

Balmorel is run using economic dispatch, meaning that the fuel with the lowest cost for the system is used first and the most expensive fuels are used as regulating power. Given the inflexibilities of biogas production and expensive local storage [19], raw biogas cannot be used as regulating power in the system. This could be included in the model by forcing the model to use the raw biogas constantly. This addition would make the model an integer programming model and would increase running time significantly. With a long running time already before this addition, it is not considered a viable solution and the model is kept linear. Alternatively, the model could be forced to flare a certain percentage of the raw biogas. This, however, would require that the raw biogas is used as base load and, as described in Section 6.2, the main investments for biogas are made in regulating power technologies. We therefore address this issue manually in the result analysis; and to avoid an extensive usage of raw biogas as regulating power—giving raw biogas an incorrect competitive advantage compared to biomethane—we do not allow the model to invest in new plants using raw biogas as fuel.

Aggregation is widely applied in Balmorel to make the model both faster and—as in the case of fuel usage—more specific. Time aggregation is applied by using a number of weeks during the year with a number of hours per weeks specified by the user. These choices will make the model faster than running the full year and—with a clever choice of weeks over the year—the results will be close to the full year model.

Fuel usage aggregation means that each technology has a specific fuel assigned to it with specific properties, hereunder efficiencies. One plant in the real world with different fuel inputs, would therefore be displayed in Balmorel as a number of technologies corresponding to the number of fuel inputs. Balmorel then optimises the fuel usage considering fuel costs, technology properties, capacity availability and so forth. At the same time, many plants in a given area are aggregated into one representative plant, meaning that in each area in Balmorel there can only be one plant of each technology.

A combined heat and power plant (CHP) using raw biogas cannot easily substitute the biogas with another fuel. A CHP using natural gas can however substitute the natural gas with biomethane, as this is essentially the same.

3.3. Combtech: combination of two technologies

The relevant add-on for combining two technologies is called Combtech. To our knowledge, Combtech has only been used in one paper [5], where it is used to evaluate how waste should be used in the energy system. Combtech can combine two technologies, a primary technology and a secondary technology, with similar characteristics, e.g. efficiencies, lifetime, and fuel type. In our case, the only characteristic biomethane and natural gas technologies do not share is the fuel type, which results in different CO_2-emissions and fuel costs.

To allow substitution of fuels in a specific plant, the following constraints must be revised in Balmorel:

- Capacity constraints for existing and new energy conversion capacities
- Loss of electricity generation per unit of heat generated on extraction units for existing and new capacities

The capacity constraint is defined for existing electricity units, existing heat units, new electricity units, and new heat units. For the sake of simplicity, this constraint is only given for the existing electricity units but can easily be transferred to the other types by a name change in variables and sets. The existing electricity units g are in the set $\mathscr{G}^{elec,1}$ and $\mathscr{G}^{elec,2}$, where the first set is for the primary technologies and the second for secondary technologies. $vge_{a,g,s,t}$ is the production of electricity in area a, on technology g, season s and time t. The primary and secondary technologies are given from g by $\mathscr{G}^1(g)$ and $\mathscr{G}^2(g)$, respectively. The capacity of technology g in area a is given by $c_{a,g}$ and the combination of areas and technologies where capacity exists is given by the set $\mathscr{AGK}$. The capacity constraint is:

$$vge_{a,g,s,t} + \sum_{g_2 \in \mathscr{G}^2(g)} vge_{a,g_2,s,t} \leq c_{a,g} \quad \forall a \in \mathscr{A},\ g \in \mathscr{G}^{elec,1}, \{a,g\} \in \mathscr{AGK}, s \in \mathscr{S}, t \in \mathscr{T} \tag{5}$$

Here the generation on the primary technology and all related secondary technologies are added and can not exceed the installed capacity.

An extraction unit can generate both heat and power, but in contrast to a back-pressure unit, the ratio between heat and power is not fixed. Instead the extraction unit will have a loss of electricity produced per unit of heat generated. The loss, which is given by the so-called Cv-line, is defined for both existing units and new units and is given here for the existing units. As for the capacity constraint, the constraint for the new units is similar and can be derived by a name change in variables and sets. The electricity loss of the extraction unit $g \in \mathscr{G}^{ext,1}$, is modelled using the parameter, C_g^v, which is assumed constant. The loss of electricity generation per unit of heat generated by extraction units is given by:

$$vge_{a,g,s,t} + \sum_{g_2 \in \mathscr{G}^2(g)} vge_{a,g_2,s,t} \leq c_{a,g} - C^v_g vgh_{a,g,s,t} - \sum_{g_2 \in \mathscr{G}^2(g)} C^v_{g_2} vgh_{a,g_2,s,t}$$
$$\forall a \in \mathscr{A},\ g \in \mathscr{G}^{ext,1},\ \{a,g\} \in \mathscr{AGK}, s \in \mathscr{S}, t \in \mathscr{T} \quad (6)$$

When optimising, Balmorel can then decide whether to use natural gas or biomethane in the production—taking fuel prices and restrictions into consideration.

3.4. Modelling the biogas target

The common biogas target for raw biogas and biomethane is included by a new constraint. The model is based on the abbreviations used above and the following is added. $\mathscr{A}(c)$ is the areas related to country *c*. $vgf_{a,g,s,t}$ is the used fuel in area *a* on technology *g* in season *s* in time *t* on installed capacity and $vgfn_{a,g,s,t}$ is the same for new capacity. $fuel(g)$ is the fuel type used on technology *g*. The parameter called $GMIN2F_{c,f,f'}$ is added to the model with the target described in Section 4 and represents the target for fuel *f* and *f′* in the country *c*. The target should be given in GJ.

The common target can be handled by the following constraint:

$$3.6 \cdot \sum_{a \in \mathscr{A}(c)} \left(\sum_{\substack{g \in \mathscr{G} | \\ fuel(g)=f}} \sum_{s \in \mathscr{S}} \sum_{t \in \mathscr{T}} \left(vgf_{a,g,s,t} + vgfn_{a,g,s,t} \right) + \sum_{\substack{g \in \mathscr{G} | \\ fuel(g)=f'}} \times \sum_{s \in \mathscr{S}} \sum_{t \in \mathscr{T}} \left(vgf_{a,g,s,t} + vgfn_{a,g,s,t} \right) \right) \geq GMIN2F_{c,f,f'} \qquad \forall c \in \mathscr{C}, f \in \mathscr{F}, f' \in \mathscr{F} \quad (7)$$

The first line represents the amount of fuel type *f* that is used and the second line represents the amount of fuel type *f′* used in the model. As the amount of fuel used is given in MWh and the target in GJ, the left hand side is multiplied by 3.6. Only the countries and fuels for which there are a specified target are bound by the constraint.

4. Assumptions and data

For this analysis we simulate the Nordic countries and Northern Germany with a focus on Denmark, i.e. only a Danish target of biogas consumption. The countries are further divided on a regional level corresponding to the regions on Nordpool—except for Northern Germany, which is divided into three regions. The regions are further divided in up to 10 areas based on the demand, size and geography.

We model one year, 2025, using four full weeks, one in each season. Furthermore, we perform a simple socio-economic analysis, i.e. cost prices from a Danish viewpoint together with no taxes nor subsidies. CO_2-emission is the only externality included in the optimisation and is represented by a socio-economic cost of CO_2. Focus is on climate targets, as this is where biogas has a competitive advantage due to a negative CO_2-emission in CO_2-equivalents. This assumed negative emission is based on avoided methane and N_2O -emissions when manure is treated and thereby converted into biogas and digestate instead of being distributed directly on the fields. The CO_2-emission value has been calculated by using the data from Refs. [29,30].

Fuel costs are mainly international market prices, following the assumption that most fuel prices will not be affected significantly by Danish fuel consumption. The primary source for fuel costs is the Danish Energy Agency (DEA) 2016-prognosis for socio-economic analysis, which is estimated on the basis of IEA prices [31]. The natural gas price is for example based on IEA prices adjusted to Danish price levels.

Fuels with high transportation costs, which do not enter the international markets, such as some biomasses, have an estimated cost which follows the closest substitute [31]. In the case of for example straw, the closest substitute is wood chips. Biogas costs are estimated on the basis of production costs found by using a profit optimising plant model with an input combination of manure and straw [27]. The straw price is the same as used in the energy systems analysis. The plant is large, using as input 600.000 t/y and generating a biogas yield of approximately 34 Mm3/y. Costs are found both in relation to raw biogas and when upgrading costs for the biomethane are included. The upgrading to biomethane is done by water scrubbing.

Type of fuel cost method, fuel costs and CO_2-emissions are listed in Table 2. All costs are in €2015 prices.

4.1. The significance of price changes

The Danish Energy Agency (DEA) assumes that fixed fuel prices will increase over the years, however, not extraordinarily [31]. There is a possibility that particularly biomass prices will increase more rapidly than expected, which could change the overall system results significantly. As we use the straw price as input to the biogas production, higher biomass prices will have an effect on the biogas costs and thereby an effect on the biogas target. However, higher biomass costs would improve the competitiveness of biogas compared to biomasses, as straw is a minor part of the biogas costs. The most important factor in relation to price changes is expected to be price changes for the nearest substitute, in this case natural gas.

4.2. Targets and maximum consumption

As mentioned in section 2.1 there are currently no biogas targets, so we set the biogas target following the biogas consumption prognosis for biogas in the heat and power sector from DEA [17], where biogas consumption in the energy system is expected to decline from 4.3 PJ to approximately 3.8 PJ. This assumption follows the conclusions from the Biogas Taskforce as well as the general development in the Danish energy system, where natural gas based combined heat and power production is crowded out by primarily wind power [32]. The used target and limitations can be seen in Table 3.

We do not use a target for natural gas consumption, however we set a limit following the DEA estimated use by 2025. In this estimation, it seems that the goal of a renewable founded heat and power production by 2035 is taken into account. Furthermore,

Table 2
Fuel data.

	Type of price	Price, €/GJ	CO_2-emissions, kg/GJ
Fossil Fuels	Market prices [31]	Predicted avg. prices	Standard figures [31]
Biomasses	Comb. of market and cost prices [31]	Predicted avg. prices	Avg. figures calculated on expected usage [30]
Raw biogas	Cost calculated [27]	10.2	−77 [30]
Biomethane	Cost calculated [27]	12.1	−77 [30]
Natural gas	Market prices	6.7 [31]	56.8 [31]
Straw	Comb. of market and cost prices	6.3 [31]	11 [29]

Table 3
Forecasts and targets [17].

	Actual, Energy system, 2015	Forecasted, Energy System, 2025	Target or Maximum
Biogas	4.3 PJ	3.8 PJ	Target
Natural gas	34.5 PJ	28 PJ	Maximum

there is a fixed usage of waste which is based on calculations using the FRIDA model [33] using the recycling targets from Ref. [34]. Last, an upper bound on wind potential is used, which is based on the IEA report [35].

4.3. Production capacity

We apply the existing generation capacity in the model by 2025, which for the Danish capacities are based on data from the Danish counting of energy production capacity by 2016 [36]. These capacities have been projected up to 2025 following expected remaining lifetimes and efficiencies. We allow the model to invest in further capacity in order to fill the gaps from existing, depreciated capacity and new demand. The given technology costs are found in the technology catalogues from DEA [37] and new investments are depreciated with a 4% interest rate following the instructions for socio-economic analysis in Denmark [38,39]. Furthermore, it is assumed that all investments have a 20 year lifetime.

In Table 4 the existing capacities for technologies using biogas are shown along with their average efficiencies. The model is allowed to invest in new capacity using natural gas/biomethane, but it is not allowed to invest in capacity using raw biogas. This is due to the challenges with raw biogas, where it is difficult to resemble reality and force the model to use the same amount of biogas all over the year, as explained in section 3.3. As it turns out, this will only be an issue in one scenario.

5. Scenarios

In order to understand the socio-economic costs from setting a target for biogas usage in the Danish Energy System, two primary scenarios are considered. A Base-scenario with no biogas target and a Target-scenario, with a target for biogas. A determining factor for the result is the socio-economic cost of CO_2. When the socio-economic cost of CO_2 is high, fossil fuels becomes relatively less competitive. In the case of biogas, this becomes even more relevant, as biogas is assumed to have a negative CO_2-emission. Therefore three secondary scenarios are added investigating the importance of the CO_2-cost. The settings used can be seen in Table 5. In Fig. 3, the CO_2-cost is added to the fuel cost to illustrate the significance of the CO_2-cost. It becomes clear that the closest substitute to biogas, natural gas, continue to be cheaper than biogas—even in the high CO_2-cost scenario, given the expected development in natural gas prices.

Table 5
Settings for the scenarios.

Scenario	Target	CO2-cost level	CO2-cost, €/ton
Base	−	Average	15.3
Target	+	Average	15.3
CO2High/Base	−	High	23.1
CO2High/Target	+	High	23.1
CO2Low/Target	+	Low	7.5

The actual socio-economic cost of CO_2-emissions from the Danish energy production is difficult to estimate correctly. Therefore, we followed the recommendation from DEA [31] to use different prognoses for the CO_2-quota price, assuming, that this to some extent corresponds to the socio-economic cost. We used the DEA 2015-prognosis for the high and low CO_2-quota price which is based on current CO_2-quota prices and the IEA World Economic outlook prognosis from 2015. Finally, we used the average of the two scenarios. All scenarios are shown in Table 5.

5.1. CO_2-externality cost scenarios

The European CO_2-quota prices are based on the expected marginal costs of CO_2-emission reduction given the political decided cap on CO_2-emissions within the CO_2-quota affected sectors. As the cap is politically decided it is not necessarily related to any expectations for the actual CO_2-externality costs, and compared to the literature, these costs also seem rather low. In Ref. [40] several estimations for the CO_2-externality costs from the

Table 4
Technology data [36,37].

	Existing capacity		Efficiency	
	Raw biogas	Combination technology	Raw biogas	Combination technology
Heat Only	19 MW	3161 MW	80.7%	95.6%
CHP	107 MW	934 MW	89.9%	90.5%
Electricity Only	0.3 MW	0.8 MW	31.7%	44.0%

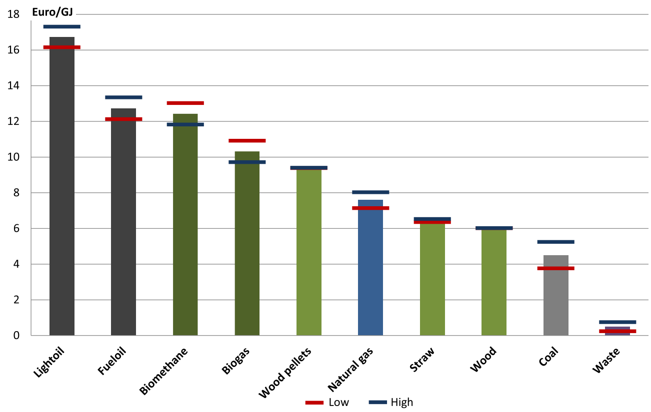

Fig. 3. Fuel costs, when the CO_2-cost is added; for average, low, and high CO_2-costs.

literature are collected and evaluated, and from this a lower bound for the social cost of CO_2 is formed. This bound is high compared to other cost estimates in the literature [40].

To see what happens to the biogas consumption when a higher CO_2-cost is used in the model, we include this lower bound as the Van den Bergh CO_2-cost in the CO2Bergh/Target scenario. Further, we use the lower estimate from Ref. [41] in the CO2Dice/Target scenario to compare the results from the DEA estimates on marginal CO_2-emission reduction costs to the estimated CO_2-externality costs from Refs. [40] and [41]. The used CO_2-costs and the resulting fuel costs for natural gas, biomethane, and biogas can be seen in Table 6 for the scenarios with high CO_2-cost.

It is noticeable that the Dice CO_2-externality costs are quite close to the estimated high CO_2-quota price from the DEA.

6. Results

Seven scenarios have been run: two primary and three secondary, as well as two sensitivity analysis scenarios of the CO_2-costs.

6.1. System cost

Five parameters are presented in Table 7 giving the overall results from the scenario runs. The objective function value, OBJ, constitute the total system costs of the given scenario in Million Euro. Whereas Δ OBJ shows the additional system cost of a scenario in relation to the base scenario. The system cost increases when a biogas target is added, as the model would otherwise have used the biogas already. However, the results show, that the system cost

Table 6
CO_2-costs for the high CO_2-cost scenarios, €2015/ton.

Scenario	CO2-cost	Natural gas	Biomethane	Biogas
CO2High/Target	23.1	8.0	11.8	9.7
CO2Dice/Target	30.3	8.4	11.3	9.2
CO2Bergh/Target	99.2	12.4	6.0	3.8

increase is low, compared to a high CO_2-cost. This makes sense as biogas corresponds to approximately 1.6% of the fuel usage in the target scenario while fossil fuel usage corresponds to approximately 36% of the fuel usage in all scenarios. Furthermore, we find that it becomes relatively less costly to add a biogas target as the CO_2-cost increases, which is due to the negative CO_2-emissions from biogas.

The marginal cost of forcing a biogas target of 3.8 PJ on the system is between 1.23 and 3.36€/GJ depending on the CO_2-cost. In order to make biogas socio-economically worthwhile, the actual CO_2-externality cost should prove to be even higher in order to call the biogas target socio-economic beneficial. Alternatively, other benefits from biogas production could be considered, such as positive externalities from e.g. reduced smell, increased quality of agricultural fertilisers, possible reduced nutrient releases to groundwater, or job creation in rural areas.

The last parameters, CO_2-total and CO_2-DK, show the amount of CO_2-emissions for the scenarios. Here it shows that a biogas target changes the CO_2-emissions in Denmark more than the high CO_2-cost. The Danish biogas target has an effect on the total CO_2-emission. This can be seen by the total CO_2-emission in the target scenarios being reduced more than the Danish CO_2-emissions and can be explained by an increase of electricity transmission to Germany, which reduces the use of coal in Germany and therefore a decrease in the CO_2-emissions.

6.2. Fuel and capacity usage

In Table 8 it shows that the upper bound on natural gas usage is binding through all the scenarios. In all scenarios, however, only approximately 11–12% of the installed capacity is used, and only a small fraction of the used capacity is using biomethane. An explanation of this low usage combined with new investments could be that gas primarily is used for regulating power. This is substantiated by 80–98% of the new investments in combination technologies are in power producing capacity. Both raw biogas and biomethane are used in the target-scenarios, however, raw biogas is preferred to biomethane due to the lower fuel costs. The model does not distinguish between raw biogas and combination technologies as

Table 7
Results of the five scenarios. OBJ is the objective function value, ΔOBJ is the change in the objective function from the Base scenario, MTE is the marginal value of the biogas target constraint (7), and CO_2-total and CO_2-DK are the CO_2-emissions from the total energy system and for the Danish energy system.

	Base	Target	CO2High/Base	CO2High/Target	CO2Low/Target
OBJ, M€	35,798	35,804	37,928	37,931	33,385
ΔOBJ, M€	–	6	2,130	2,133	−2,414
MTE, €/GJ	–	2.22	–	1.23	3.36
CO_2-total, MT	296.7	296.3	253.1	252.7	320.7
CO_2-DK, MT	8.0	7.8	8.1	7.8	7.8

Table 8
Fuel usage, basic results. BM-COMB represents the percentage usage of biomethane in the combination technologies and %-COMB represents the percentage that the combination technologies are used.

	Base	Target	CO2High/Base	CO2High/Target	CO2Low/Target
Biogas usage, GJ	485,731	2,083,290	776,758	2,517,432	1,964,166
Biomethane usage, GJ	–	1,716,710	–	1,282,568	1,835,834
Natural gas usage, GJ	28,000,000	28,000,000	28,000,000	28,000,000	28,000,000
BM-COMB	0%	5.8%	0%	4.5%	6.1%
%-COMB	11.7%	12.1%	11.0%	11.3%	11.8%
New COMB-capacity, MW	525	568	352	389	735

we have not included the problems with flexible usage of raw biogas in the model, see section 3.2. These observations emphasise the need of not allowing the model to invest in new capacity using raw biogas.

Fig. 4 displays the normalised fuel usage in the base and target scenarios in order to compare how fuel consumption differs. As the biogas target represent a small share of the total energy consumption it is no surprise, that the overall fuel consumption is quite similar. However, it can be seen that the additional biogas usage is substituting use of oil and heat pumps, but also biomass.

Fig. 5 presents the three target scenarios and displays the significance of the CO_2-costs on fuel usage. The figure shows, that the usage of coal, natural gas, waste, wind, and sun does not change through the scenarios. Relating this to Fig. 3, an explaining factor can be that neither coal, natural gas nor waste changes position in the ranking of fuel costs with these changes in the CO_2-costs. When the CO_2-cost is low, it is preferred to use heat pumps, oil, and surplus heat in the system, whereas biomass and biogas is preferred when the CO_2-cost is high.

For the CO2Low/Target scenario, the usage of biomethane is

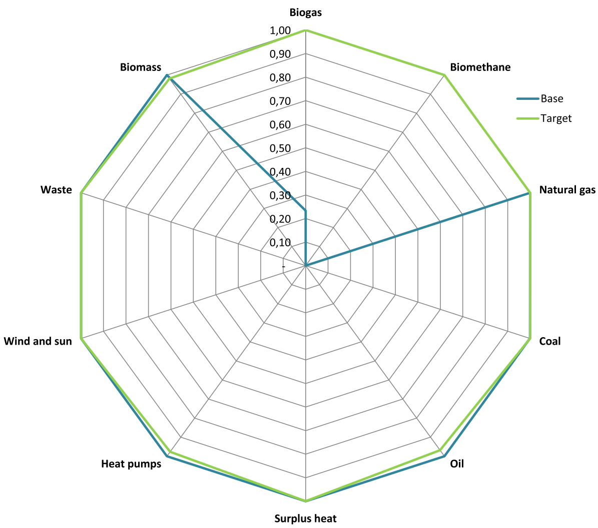

Fig. 4. Normalised fuel usage for Denmark in the base and target scenario.

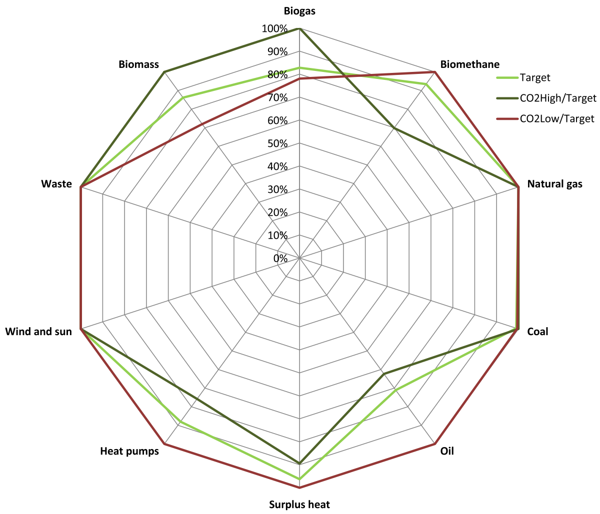

Fig. 5. Normalised fuel usage for Denmark in the target scenarios.

higher than in any other scenario. This is due to the fact that when comparing raw biogas and biomethane, the fuel costs become relatively closer to each other when the CO_2-cost is low compared to when the CO_2-cost is high. Biomethane is still more expensive, but when the costs are relatively closer, other factors become more determining for the result. These factors are e.g. technology efficiency, investment and operational costs, and the relative demand between heat and power.

Waste, wind, and sun are used equally across all scenarios. This is due to the fact that the maximum restrictions on these energy sources are binding in all scenarios. It is out of the scope of this paper to evaluate further on the restrictions. The results, however, indicate that the restrictions have an influence on the final results.

6.3. Usage of raw biogas in the system

Raw biogas is preferred to biomethane in all scenarios due to the lower fuel costs of raw biogas while not all inefficiencies from the real world are implemented in the model, as e.g. the need for an almost constant use of raw biogas. Fig. 6 represents the usage of raw biogas in the CO2High/Target scenario, where the biogas usage in GJ for CHP-units relates to the right y-axis and boilers plus electricity-only units relates to the right y-axis. It is clear, that raw biogas primarily is used in CHP-units and mostly during winter and autumn (first and last period) and as regulating power during spring and summer. If a real world biogas based CHP had this consumption pattern, it would result in approximately 30% of the gas being flared, which would increase the cost of using raw biogas considerably. More likely, the plant would produce constantly, thus decreasing the value of the output for the system and thereby also the value of the raw biogas.

6.4. When the CO_2-externality costs are implemented

While the first scenarios presented in this paper relate to estimated CO_2-cost from a CO_2-quota system, the CO_2-costs in the last two scenarios are related to estimations of the actual CO_2-damage costs: a low and a high estimate. As given in Table 6, the estimated CO_2-costs in the CO2Dice/Target scenario are quite close to CO2High/Target scenario, which is also reflected in the result summary in Table 9. However, the interpretation of the costs is not the same. Total system costs increase slightly from the CO2High/Target to the CO2Dice/Target scenario, while the marginal costs of having a target for biogas usage approaches zero, so it seems that the CO_2-costs approaches a breaking point where the needed biogas would be used without a target.

Total system costs are low in the CO2Bergh/Target scenario compared to the other high CO_2-cost scenarios. This decrease in system costs is based on fuel costs of raw biogas and biomethane, which are low due to their negative CO_2-emission. This also result in a high use of biomethane, which by far exceeds the target and thereby reduces the marginal cost of the biogas target to zero.

In Table 9 we see a small decrease in both usage and installation of combination technologies in the CO2Dice/Target scenario, and in Fig. 7, we see that biomass seems to have become relatively more attractive in the CO2Dice/Target scenario. In the CO2Bergh/Target scenario on the other hand, both the degree of capacity usage and investments increase, which could also be expected considering the increased usage of biomethane—reflected in Fig. 7.

The CO_2-emissions show to be negative for both Denmark and the total energy system for the CO2Bergh/Target scenario as shown in Table 9. The negative CO_2-emission in Denmark is explained by the excessive usage of biomethane in Denmark as shown in Fig. 7. For the total system, the important contributor to negative CO_2-emissions is Germany where biomethane is also used to a large

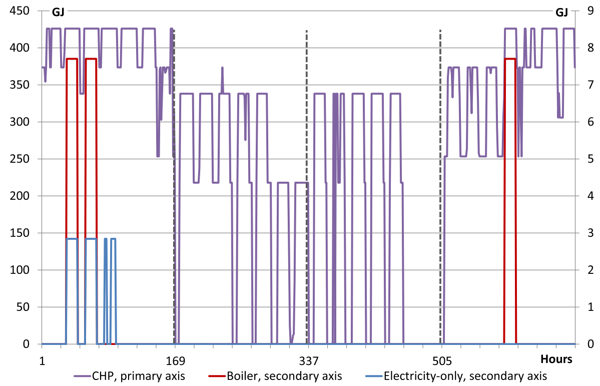

Fig. 6. Usage distribution of raw biogas in the CO_2 High/Target scenario.

Table 9
Results of the high CO_2-scenarios. MTE is the marginal value of the biogas target constraint (7) and %-COMB represents the percentage that the combination technologies are used. The capacity installed on the combination technologies are given by New COMB-capacity, and the CO_2-emissions for the system and for Denmark is given by CO_2-total and CO_2-DK.

	CO2High/Target	CO2Dice/Target	CO2Bergh/Target
OBJ, M€	37,931	39,685	36,437
MTE, €/GJ	1.23	0.13	–
%-COMB	11.3%	10.7%	44.3%
New COMB-capacity, MW	389	352	3443
CO_2-total, MT	252.7	232.4	−178.4
CO_2-DK, MT	7.8	7.7	−13.3

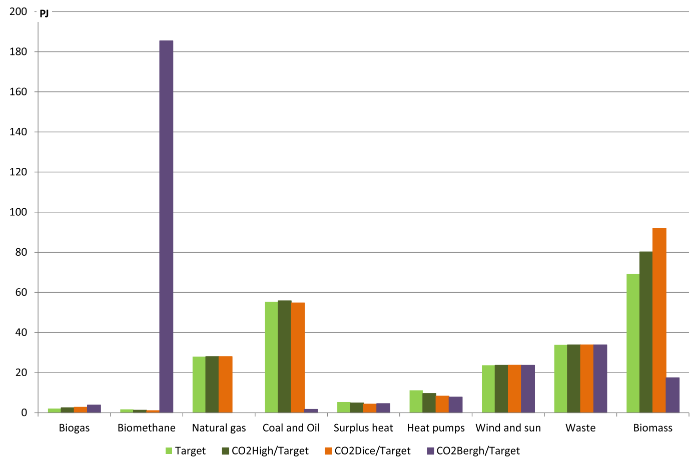

Fig. 7. Fuel usage in Denmark for the scenarios with high CO_2-cost.

extent—resulting in negative CO_2-emissions for the whole system.

The accumulated amount of fuels used in the CO2Bergh/Target scenario exceeds the fuel usage in any of the other scenarios. This can be explained by electricity based on biomethane becoming cheap enough to substitute a large amount of electricity production in Germany, resulting in an increased electricity export and a higher fuel usage in Denmark.

The natural gas consumption in this scenario has been replaced completely with biomethane, which then function as a base load provider during winter and autumn, and provider of regulating power during the summer period. This underlines, that biomethane can indeed function as a fuel for regulating power, using the gas transmission net as energy storage—in a scenario where CO_2-costs are very high.

The suggested biomethane consumption in CO2Bergh/Target scenario exceeds by far the sketched biogas potential in section 2.1, which means that more biogas would have to be produced. This could be through the addition of imported biomasses or e.g. grown algaes, which are not considered in the current prognosis for biogas potentials [22,23]. Furthermore, biogas could be upgraded by methanation where hydrogen is added to the raw biogas, such that excess CO_2 and hydrogen are converted into CH_4 and thereby increase the biomethane production by approximately 70% [42]. The hydrogen could be produced when electricity prices are low. Potentially, this can help even-out the electricity price and give an effective way to store electricity when there is an oversupply. How the additional biomethane is produced and interacts with the energy system is out of scope of this paper. It can, however, be expected that biomethane made by methanation will affect the assumed CO_2-emission related to biomethane such that less CO_2 will be reduced per GJ biomethane produced. When fed into the calculation, this should make the model less eager to use the large amount of biomethane.

7. Conclusion

In this paper we investigated the socio economic system costs of having a biogas target in Denmark, and how CO_2-costs affect the system costs and biogas usage. To do this, we used the energy system model Balmorel with the possibility to combine natural gas with biomethane in one technology. Furthermore, we set a target for raw biogas and biomethane corresponding to the predicted amount used in the heat and power sector in 2025. First, the model was applied using predictions of CO_2-costs from the Danish Energy Association. Then, we added two sensitivity analysis scenarios where we applied higher CO_2-costs corresponding to estimates for the actual CO_2-externality costs found in the literature.

From our analysis, we see that we need a very high CO_2-cost estimate in the area of the CO_2-costs estimated by Van den Bergh [40] before biogas or biomethane is worthwhile using in large amounts. When increasing the CO_2-costs, the biogas target becomes less costly while the total system cost increases. First when CO_2-costs are very high, biogas becomes worthwhile and used to such an extent, that total system costs decline. Even though the very high CO_2-cost might not be justified, there could still be arguments for forcing the system to use biogas, as there are other positive externalities from biogas than CO_2-reductions. This has, however, not been investigated further in this paper.

There are investments in combination technologies in all scenarios, but the usage of the natural gas technologies is relatively low, and the existing combination technologies are not used much. This suggests that gas primarily is used as regulating power. However, with very high CO_2-costs, combination technologies are used as base-load during winter and regulating power during summer. Furthermore, there is an increase in export of electricity in this scenario, which can be explained by the fact that the high CO_2-cost reduces the biomethane cost, and thereby increases biomethane's competitiveness compared to other electricity sources in the surrounding countries.

The scenario with the CO_2-cost estimate by Ref. [40] leads to an extensive usage of biogas that exceeds the potentials described in Ref. [22]. The lack of biogas resources could partly be overcome by biogas upgrading through methanation where hydrogen is used to upgrade the biogas. This could be investigated further in an energy system where the upgrading of biogas is included. This requires new estimates of the biogas CO_2-emissions, since upgraded biogas through methanation contains a lower share of manure per GJ and thereby also another level of CO_2-emissions.

Acknowledgement

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Nomenclature

Sets

$\mathscr{AGK}$	Combination of areas and technologies where capacity exists
$\mathscr{A}(c)$	All areas in country c
$\mathscr{A}$	All areas
$\mathscr{G}^2(g)$	Secondary technologies for primary technology g
$\mathscr{G}^{elec,1}$	Primary technologies producing electricity
$\mathscr{G}^{ext,1}$	Primary technologies that are extraction units
$\mathscr{S}$	All seasons
$\mathscr{T}$	All time periods

Variables

$vge_{a,g,s,t}$	production of electricity in area a, on technology g, season s and time t
$vgf_{a,g,s,t}$	usage of fuel in area a, on existing technology g, season s and time t
$vgfn_{a,g,s,t}$	usage of fuel in area a, on new technology g, season s and time t
$vgh_{a,g,s,t}$	production of heat in area a, on technology g, season s and time t

Parameters

C_g^v	Amount of electricity generation reduction per unit of heat generated on technology g
$GMIN2F_{c,f,f'}$	Common target in country c for fuel type f and f'
$c_{a,g}$	Capacity of technology g in area a
$cost_g$	The cost of producing electricity on technology g
$de_{a,s,t}$	The demand of electricity in area a in season s and time t
$fuel(g)$	Fuel type used on technology g
vge_g^{max}	The maximum electricity production on technology type g
vge_g^{min}	The minimum electricity production on technology type g

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APPENDIX E

RECENT TRENDS IN BIOGAS VALUE CHAINS EXPLAINED USING COOPERATIVE GAME THEORY

Recent trends in biogas value chains explained using cooperative game theory

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Abstract

In Denmark, since 2014, it has been possible to upgrade biogas to a gas grid and achieve support in line with biogas-based heat and power production. Since then, most new biogas production plants have chosen to upgrade their biogas. In this study, a mixed integer programming model is used to find the optimal biogas value chain, and cooperative game theory is used to understand real world observations compared to this study's results. Specifically, three profit allocation mechanisms are applied to allocate the profit between the heterogeneous owners in the value chain. It is found that Danish biogas plants should use large shares of manure combined with deep litter. Furthermore, it is found that input suppliers have relatively poor bargaining power in the profit allocation negotiations due to poor alternatives. This may explain why livestock farmers tend to receive little payment for their manure, and why they are hesitant to join biogas projects.

Finally, it is found that biogas plants prefer to upgrade their biogas for several reasons. First, if the natural gas price is expected to be high, it is preferable to upgrade biogas than to use it directly in a local combined heat and power plant (CHP). Second, if the natural gas price is expected to be low, it is preferable to upgrade because the CHPs have better alternatives and therefore better bargaining power before investments (ex ante). Third, when the value chain contains an upgrading plant, the biogas plant has a greater bargaining power—in particular ex post.

Keywords: Cooperative game theory, Profit allocation, Mixed integer programming, Biogas, Biomethane, Renewable energy, Value chain

1. Introduction

Danish biogas production has developed remarkably recently since a change in regulation following the Energy Agreement in 2012 (Danish Government, 2012), where it was agreed that biogas, among other renewable energy sources, should be strengthened economically. Thus, several initiatives began. The probably most important initiative was that, after an EU ratification in 2014, it

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became possible to gain support when biogas is upgraded for the gas grid, used directly for industry or transport, or used directly for heat and power production (Danish Energy Association, 2013; European Commision, 2013). The new initiatives have been successful, and new biogas plants have been built throughout Denmark the latest years (Harder, 2016). Moreover, biogas upgrading has increased the possibility to take advantage of economies of scale independent of local heat demands (Skovsgaard and Jacobsen, 2017).

Considering these latest developments, as well as projections for new biogas plants, it is clear that there is a trend in which biogas plants often choose to upgrade theor biogas instead of finding local sources for biogas consumption. This development is in relation to not only new biogas plants but also existing biogas plants have chosen to upgrade their biogas and not proceed to deliver biogas to local CHPs (Harder, 2016). An explanation for this development could be a lack of heat demand, or at least a reduced heat demand, along with new, cheaper heat production technologies. However, two other possible explanations are investigated in this paper. The first is that an assumption on higher natural gas prices in the future yields higher expected profits for value chains in which biogas is upgraded than value chains in which biogas is used directly to produce heat and power. The second is that strategic considerations regarding potential profit allocations among members of the value chain after investments (ex post) can affect ex ante investment choices.

The biogas value chain involves several actors from different sectors that operate in diverse markets with diverse regulation. Moreover, the input for biogas production is typically a bi-product for the farmers, and biogas is one possible fuel out of many for the production of energy commodities. These factors may affect opportunities for biogas producers, the optimal pricing between the different actors in the value chain, and the optimal production decision. Additionally, both input and output prices can be difficult to estimate as there are no or imperfect markets for both inputs and output. These issues can be a challenge when profits should be allocated within the value chain.

Furthermore, parts of the biogas value chain can be considered bilateral monopolies after investments; these ex post consequences can affect investments in the value chain ex ante; such effects are discussed in this paper. The Myerson-Satterthwaite theorem (Myerson and Satterthwaite, 1983) states that in cases of private information, it is impossible to achieve ex post efficiency in bilateral trade; each time two owners meet, there is a risk of adverse selection with an inappropriate design of profit allocation mechanism. A solution to this challenge is vertical integration (Swami and Shah, 2011; Buzzell, 1983), of which there are several examples in biogas value chains; however, this solution is not always feasible.

Blair et al. (1989) finds a disagreement in the literature with regard to finding an optimal solution for quantity and price issues between bilateral monopolies. The researchers refer to Bowley (1928), Fellner (1947), and Machlup and Taber (1960) who found a joint profit maximising solution with a variety of assumptions. Blair et al. (1989) concluded that the social optimal solution can be found only with joint profit optimisation, and that a price between the parties is a way to share the maximised profit. Truett and Truett (1993) extended this and proved that under particular circumstances, hereunder perfect information, there is only one stable and theoretically optimal price for the intermediate products between two monopolies. This price depends, among other things, on the bargaining power between the two monopolies. Therefore, since vertical integration is not always an option, an alternative is to form a cooperative within which profits are maximised jointly, after which profits are allocated.

Within cooperative game theoretic literature, several allocation mechanisms have been presented and tested both theoretically, e.g. (Tijs, 1986; Schmeidler, 1969; Megiddo, 1978; McCain, 2008; Hougaard, 2009), and empirically, e.g. (Massol and Tchung-Ming, 2010; Frisk et al., 2010; Lozano et al., 2013; Nagarajan and Sošić, 2008). However, most literature is focused on homogeneous producer types with slightly different properties, where the cooperatives are alternatives to horizontal integration. Examples of this are a cooperative of pig producers who slaughter and sell the pigs together (Bogetoft and Olesen, 2007), a cooperative of liquefied natural gas suppliers (Massol and Tchung-Ming, 2010), and a cooperative of wood suppliers (Frisk et al., 2010). A typical allocation mechanism is *proportional allocation* with which profit is allocated: in accordance with cost (an equal return on capital) (Hougaard, 2009); in accordance with the marginal cost (*alternate-cost-avoided*) (Bogetoft and Olesen, 2007); or in accordance with the gain delivered to the cooperative (*Shapley value*) (Lemaire, 1984; Massol and Tchung-Ming, 2010; Frisk et al., 2010). Other payment schemes focus on the *egalitarian principle*, such as the *egalitarian method*, with which profit is divided equally between all parties in the cooperative (Tijs, 1986; Lemaire, 1984; Massol and Tchung-Ming, 2010), or the *nucleolus* payment scheme, with which profit allocation depends on the alternative profit of the marginal participant (Massol and Tchung-Ming, 2010; Schmeidler, 1969; Frisk et al., 2010).

In this paper, we apply some of these payment schemes to the non-homogeneous owners in the biogas value chain. Such application of cooperative game theory has been investigated theoretically, e.g. in (P. Cachon and Netessine, 2004), but to our knowledge, empirical applications are limited. In (Hubert and Ikonnikova, 2011) the bargaining power between Russia and central transit countries is compared for the Eurasian supply chain for natural gas. The study investigated several new investment options, including extensions of existing routes and entirely new transit routes. The bargaining power was evaluated by applying both the *Shapley value* and the *nucleolus* allocation mechanisms, the results of which were compared to empirical data on prices.

In this paper, we investigate the best value chain designs and analyse the empirical evidence for new investments in a game theoretic context. We apply a value chain optimisation model (Jensen et al., 2017) in order to determine the profits that might be gained under various energy price scenarios, assuming joint profit maximisation under perfect information; this is presented in Section 3. Applying the model, we find the optimal biogas value chain design including the optimal inputs and the optimal energy converter, given a specific set of assumptions; this result is presented in Section 5.1. Moreover, drawing on cooperative and non-cooperative game theory

(McCain, 2008; Gibbons, 1992) and cost and profit allocation theory (Hougaard, 2009; Bogetoft and Olesen, 2007), we compare the results of three profit allocation mechanisms and discuss how ex post bargaining power may affect ex ante choices made by key owners through backward induction with regard to value chain design. We then argue that such effects can change the preferred design more than anticipated. We discuss this in Sections 5.2 and 5.4, based on the theory presented in Section 4. Finally, we present the policy implications in Section 6.

2. Biogas production in Denmark

The biogas value chain, see 1, consists of several separate owners, who often operate in various markets in different sectors. In this paper, the group of owners comprises livestock farmers, substrate farmers, a biogas plant and energy converters. These parties deliver inputs and/or are involved directly in biogas production and conversion processes. However, only the plant, and in some cases the biogas upgrading facility, have biogas production as the primary purpose; the farmers focus on the highly competitive agricultural sector. The energy converter, at the end of the value chain, focuses on the end products of the chain: biomethane (upgraded biogas), electricity and/or heat. Heat production is considered a natural monopoly, and is therefore monopoly regulated, while electricity and gas markets are exposed to high levels of competition.

As Section 2.1 explains, the regulatory design implies that in order to be allowed to receive support, the biogas plant is dependent upon waste input (defined in this paper as agricultural waste) and in order to receive support, the biogas plant is dependent upon a demand from an energy converter. Both the agricultural and energy sectors are highly exposed to competition or monopoly regulated.

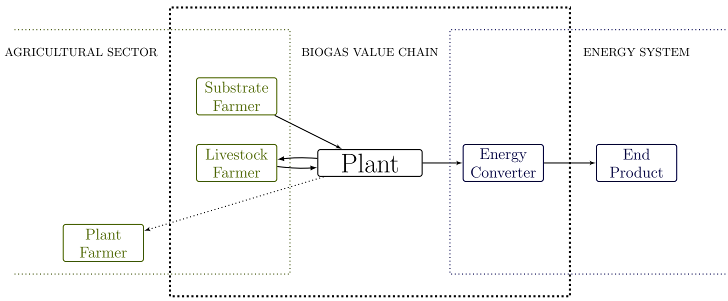

Figure 1: The biogas value chain and the ownership structure

The ownership structures of biogas value chains vary by plant, and in Denmark there are several variations. For example in one, a group of farmers invested in a biogas plant and an upgrading facility, i.e. Madsen Bioenergi (Madsen Bioenergi, 2017). In another, one owner controls inputs and biogas production, while another owner controls the upgrading plant, i.e. Fredericia Wastewater and Energy (Wittrup, 2010). This is because specific ownership structure choices depend on several factors; for example, heat and power plants are often restricted from investing in biogas plants as regulators often consider such investments as high risk. Moreover, some farmers have limited access to low interest rate capital as they have significant amounts of capital invested in their farms. A solution to these issues is to have both farmers and external investors, such as the energy companies E.ON, Nature Energy and Ørsted, as investors in biogas plants. It should be noted that some value chains are vertically integrated in ownership, while others are not; for value chains with limited integration, the strategic considerations with regard to profit allocation are particularly interesting.

2.1. Regulation

Danish biogas regulation spans several sectors and different priorities. Biogas support and the regulatory set-up are designed in an energy focused mindset, while at the same time considering the need of sustainability and, therefore, the need of using manure for biogas production. These are the focal points of the Danish biogas policy and they have a significant influence on the importance of each owner in the value chains. Two aspects of biogas regulation are presented in this section, and described in more detail in Appendix A:

- Input: In order to receive biogas support, a large share of the inputs for biogas production must consist of waste—preferably manure or waste water. Waste products from slaughterhouses and dairy production can also be used; however, these sources are limited. Moreover, biogas production can be supplemented with other waste products, such as straw and deep litter. Finally, limited amounts of energy crops may be used.
- Output: Biogas support is primarily given at the end of the value chain, i.e. to the energy converter. The energy converter can be an upgrading plant, a CHP, a heat producer, industry or transport.

The regulation regarding energy production and consumption is extensive in Denmark, where the general principles are that renewable energy is taxed as little as possible while electricity and fossil fuels are taxed heavily. Denmark and the surrounding countries have a highly competitive power market. Therefore, fuels used for electricity production are not taxed; rather, electricity consumption is taxed. Furthermore, if electricity is not used for processes, then consumption taxes and fees are limited—the highest fee being the Public Service Obligation (PSO), which will be phased out in 2022 (Danish Ministry of Energy, Utilities and Climate, 2016).

In contrast, gas is highly taxed and considered a rather expensive fuel. However, gas is a common fuel in decentral CHP production in Denmark, for which only gas used for the heat share of the production is taxed. Heat is not subject to competition in the same way as gas and power; instead, it is monopoly regulated.

Energy prices vary over time, and though electricity prices vary more than gas prices across day, month and years, gas prices can also change significantly, being for example twice as high in

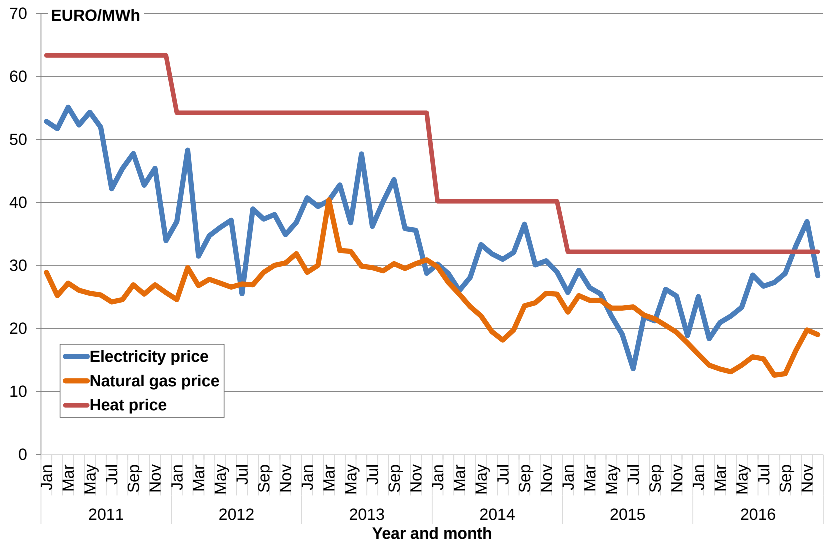

Figure 2: The historical prices of electricity, natural gas, and heat in Denmark, (Pool (2018), Gaspoint Nordic[1] and Danish Energy Regulatory Authority (2017)).

2013 as in 2016. Similarly, heat prices can vary from year to year, as shown in Figure 2; notice that the heat price is for one specific heat plant, and that the prices vary across heat plants.

A large share of the heat supply in Denmark is covered by local heat production plants and distributed through a local grid. These local plants are natural monopolies and therefore monopoly regulated. The regulation is a cost-of-service regulation, with which the profits of producers must be zero, i.e. *hvile-i-sig-selv*, in Danish. The principle is that heat production costs are covered by the consumers, who are often co-owners. In order to ensure costs are as low as possible for the heat consumers, heat producers are obliged to produce heat at the lowest possible costs, and this is monitored by the Danish Energy Regulatory Authority. One implication of this regulation is that profit allocation within the biogas value chains can be affected by the regulation, if the energy converter produces heat.

3. Modelling the optimal choice of value chain

In this chapter, we follow the track of Blair et al. (1989) and consider a situation with joint profit optimisation, assuming perfect information between owners.

[1] Personal communication

3.1. Plant level model

The model used to find the optimal biogas value chain, is based on a model by Jensen et al. (2017), where a mathematical optimisation model for the biogas supply chain was presented. The aim of the model is to find the optimal chain, from the farmers to the energy demands, by finding the optimal choice of e.g. plant inputs and technologies for utilising the biogas. The modelled chain can be seen in Figure 3. The supply chain is modelled such that the input side, i.e. all processes until the plant, uses a weekly time scale, while the output side, i.e. all processes from the plant, uses an hourly time scale. This allows us to capture the fluctuations of energy prices but keeping the model as small as possible. The model combines both strategic decisions regarding process sizing and tactical decisions, e.g. how much manure to use as input and when to store the biogas.

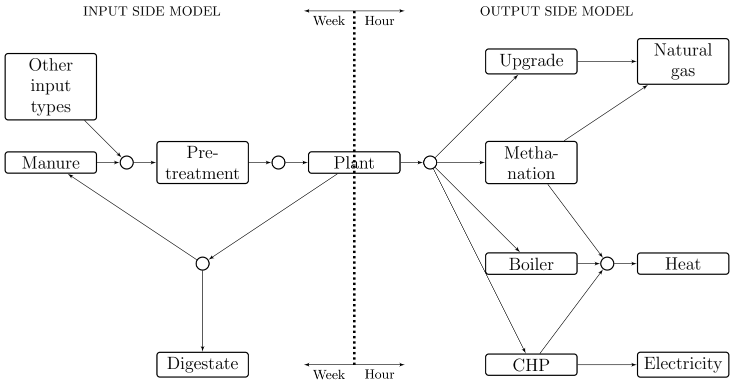

Figure 3: The biogas value chain from farmer to energy demand with the input side using a weekly time scale and the output side using an hourly time scale. The small circles represent the possibility of storages.

When biogas has been produced, the biogas plant has two products: digestate and biogas. The digestate is send back to the farmers, whose primary reason for participating is the fertiliser value of the digestate, which is better than that of manure. The biogas is sold to an energy converter. The possible energy converters in the chain include a CHP, a heat boiler, an upgrading plant, and an upgrading plant that upgrades through methanation. A traditional upgrading plant removes CO_2 from the biogas so that the methane content of the resulting biomethane is similar to that of natural gas. However, an upgrading plant upgrading through methanation adds hydrogen produced through electrolysis so the CO_2 from the biogas is converted to methane. Aside from the extra amount of biomethane generated during the methanation process, unlike traditional upgrading plants, process heat is generated, which can be sold for district heating.

The objective function used by Jensen et al. (2017) was profit maximisation. In this paper, the objective function is slightly different. In (Jensen et al., 2017), farmers were only included by receiving money for delivered manure or crops. In this paper, farmers are potential owners, and their costs must therefore be included in the total costs of the chain. For practical reasons related to profit allocation, see Section 4.3, it was decided to move transportation costs for biomasses from the biogas plant to the biomass producers.

The full model can be found in Appendix B.1; only a simplified explanation of the objective function is given here. The objective function is now to maximise the sum of profits for owners:

$$Max \sum_{o \in \mathcal{O}} \pi_o, \tag{1}$$

where π_o is the profit for each owner, o, in the project. It is found using:

$$\pi_o = INC_o - C_o \quad \forall o \in \mathcal{O}, \tag{2}$$

where INC_o and C_o are the income and total cost of each owner in the project. The income for each owner is found using:

$$INC_o = INC_o^{energy} + INC_o^{support} + INC_o^{digestate} \qquad \forall o \in \mathcal{O}, \tag{3}$$

where income from selling the energy produced is denoted by INC_o^{energy}, support received by an owner is denoted by $INC_o^{support}$, and income from selling digestate is denoted by $INC_o^{digestate}$.

The total cost of each owner is found using:

$$C_o = C_o^{OPEX} + C_o^{CAPEX} + C_o^{trans} + C_o^{tax} + C_o^{digestate} \qquad \forall o \in \mathcal{O}, \tag{4}$$

which comprises operational expenditures, C_o^{OPEX}; capital expenditures, C_o^{CAPEX}; transportation and handling costs, C_o^{trans}; taxes paid, C_o^{tax}; and an extra cost for buying fertiliser if an agreed-upon amount of digestate is not delivered to the livestock farmers, $C_o^{digestate}$.

3.2. Assumptions

In our calculations, we follow the recommendations for socio-economic analyses of Denmark with an interest rate of 4% for all capital expenditures (CAPEX) (Danish Energy Agency, 2013), and the depreciation time is set according to data sources. If no data were available, we used a depreciation time of 20 years. Data on input and output process costs can be found in Appendix C in Table C.3 and Table C.6, and a graph on the overall CAPEXs used in the model can be seen in Figure C.1. We assume economy of scale for the biogas plant, and a constant return to scale in regard to energy converters and pretreatment of substrates.

Moreover, we assume that the farmers cover transportation costs to and from the plant. Data for transportation can be found in Table C.5. We also assume that the pretreatment of straw and deep litter is completed at the biogas plant, while the ensilage of maize and washing of the sugar beets is completed by the farmers, and the cutting and ensilage of sugar beet is completed by the plant. For inputs to the plant, we set the maximum dry matter content of the total feedstock to be 13% (Jørgensen, 2013). Data for the inputs can be found in Table C.4. Finally, we assume that excess digestate can be sold for €8.85 per tonnes (Birkmose et al., 2013) and is transported according to the costs given in Table C.5.

The geographical position of the plant is set to be Northwest Denmark. Additionally, we assume that the modelled plant can expect a demand from the local heat plant in the town Vinderup that corresponds to approximately 36,000 MWh/year (Vinderup Varmeværk, 2014). Thus, this is the heat demand we use in the model, and we apply the heat price set by Vinderup Varmeværk as given by the Danish Energy Regulatory Authorities, see (Danish Energy Regulatory Authority, 2017).

Finally, 2016 is the base year for the model, which means that all prices for power, heat, and natural gas are actual prices from 2016, as are the regulatory tariffs. The power price is from the Nord Pool Spot market, which is the trading place for the Nordic power market, while the natural gas price is from Gaspoint Nordic. We apply the regulation given in Appendix A in Table A.1 and Table A.2.

4. Profit allocation method

In Section 5.1, we confirm the results in (Skovsgaard and Jacobsen, 2017) and (Jensen et al., 2017); the results were that biogas production can be profitable with current Danish regulation; however, value chains can be fragile without proper profit allocations between owners. We limit the cooperative in the value chain to necessary owners, with the assumption that receiving the subsidies Table A.1 and Table A.2 is preferred. These owners are livestock farmers (no waste—no support), the plant (no plant—no biogas) and the energy converter (no energy converter—no support), as shown in Figure 1. However, substrate farmers are excluded, because support can be achieved without adding substrates to the manure and substrates can be substituted. Instead, substrate farmers are paid a fixed amount for substrates corresponding to the production costs of substrates transported to the plant, plus 10% of the costs. It should be noted that there are other ways of determining prices. Examples include a method discussed by Giannoccaro et al. (2017), with which availability is handled based on biomass prices in a region, and a method discussed by Bai et al. (2012), which considered 10% too low for some substrates. However, investigating these methods was not the main focus of this paper.

4.1. Allocation choice considerations

Applying cooperative game theory is a way to include strategic considerations in cost and profit allocations (Tijs, 1986). Cooperative game theory was first presented by Von Neumann and Morgenstern (1944), who, with other game theorists, found it difficult to determine one unique solution to allocation problems. Nash (1953) proposed an axiomatic approach with which a set of conditions were stated for an appropriate allocation mechanism, and suggested that allocation mechanisms be evaluated according to this method. This approach is similar to the fairness criteria discussed in allocation literature. Formal examples of fairness criteria can be found in (Tijs, 1986) and (Hougaard, 2009). Moreover, as aforementioned, Bogetoft and Olesen (2007) presented a long list of potentially relevant criteria depending on cooperative; for example, a cooperative of pig farmers could try to avoid low market prices with an incentive that limited pig production.

In this paper, we focus on two fairness criteria: equality and individual rationality. These properties are considered in most cooperative game theoretic literature related to cost allocation (see, e.g. (Tijs, 1986; Bogetoft and Olesen, 2007; Frisk et al., 2010; Schmeidler, 1969; Megiddo, 1978; Hougaard, 2009)). However, other fairness criteria are considered as well, such as value chain risks and the risk of adverse selection.

Equality can be interpreted in many ways. Denmark has a long tradition of cooperative movements in the agricultural sector, and 'one man, one vote' was a general principle of many cooperatives. In contrast, non-cooperative game theory follows the hypothesis that a rational agent in a one-shot ultimatum game[2] would offer another agent a zero share, which a rational agent would accept. However, several empirical studies show that most agents would not take an entire share, and if they did other agents would retaliate and such offers. McCain (2008) presented this as an argument for including social norms and reciprocity motives into cooperative game theory to obtain theoretical findings closer to empirical findings. Hougaard (2009) argued that equality in some form can be found in most large religions and thereby in most social norms. Therefore, we consider this fairness criterion as crucial for our evaluation of the allocation mechanisms.

An important element of *homo economicus* is individual rationality; an agent may query, 'Does it make sense to join the cooperative? Are there better alternatives?'. Therefore, we have chosen to focus also on individual rationality. Truett and Truett (1993) argued that one specific price between two parties could be found, and the bargaining powers of the two parties could contribute to determining this price. The bargaining powers could depend upon levels of information between the parties in the value chain (Radhakrishnan and Srinidhi, 2005), or, perhaps more importantly was the participant's dependence upon the collaboration. This dependency could be approximated by determining the best alternative for each participant.

Indeed, best alternatives (often referred to as stand-alone profits) are highly relevant to profit allocation. With individual rationality, an allocation mechanism is unstable if a profit allocated to a coalition is below an agent's stand-alone profit. Furthermore, a profit allocation is stable if it is within the core that is a set of allocations with which profits are more beneficial for all group members than stand-alone profits or profits from another coalition (Bogetoft and Olesen, 2007).

[2] A one-shot ultimatum game is a game in which two agents share, for example a pie. The first agent decides the division of the pie, and the other agent decides whether to reject or accept the division; this game can be extended so that if the second agent rejects the division, he or she can suggest a new division, etcetera (Gibbons, 1992).

In Section 4.4, we present how individual rationality is taken into the evaluation.

4.2. Payment schemes

A basic principle for profit allocation is to ensure feasibility for all participating owners in the value chain—that is, to ensure that overall profits are greater than zero. However, ensuring this may be insufficient for motivating the owners, so in order to find a way to share the maximised profit between the three overall owners in this study's value chain, i.e. livestock farmers, the biogas plant and energy converters, we use the overall principles of cooperative game theory in regard to cost allocation. The owners are heterogeneous producers with large degrees of interdependence, and this implies that each party is as relevant as the others, even though one of the parties could take initiative and gain an upper hand in the negotiations. We imagine, this party could be the plant, which has the single purpose of producing biogas.

In this context, many of the allocation schemes presented in the introduction become irrelevant; however, some principles from the schemes can be reused. In Section 4.3, relevant versions of the egalitarian method, the proportionality principle, and a method inspired by the nucleolus, i.e. individual rationality, are presented. We try to understand the strategic considerations related to profit allocation and choices made by the owners when the value chain is designed, instead of considerations related to the optimal allocation mechanism. We investigate three allocation mechanisms suitable for the value chain, with which profits are distributed through prices in the chain. In Section 5, we evaluate the results of using the the model and relate these results to individual rationality. Then, we assess the potential implications in regard to possible preferred value chain and profit allocation choices.

4.3. Allocation mechanism modelling

After using the plant level model, profit allocation is performed. To allocate the profit between the owners, a mathematical model is used to determine the price of the products sold by each owner. The price is set using the following constraint:

$$\pi_o^{CA} = \pi_o^* - \sum_{o' \in \mathcal{OTO}(o',o)} \rho_{o',o}^{CA} + \sum_{o' \in \mathcal{OTO}(o,o')} \rho_{o,o'}^{CA} \qquad \forall o \in \mathcal{O} \qquad (5)$$

The profit of each owner using the cost allocation method, π_o^{CA}, is calculated as profit obtained with the plant level model, π_o^*, minus a price paid for buying inputs, $\rho_{o',o}^{CA}$, plus money obtained by selling outputs, $\rho_{o,o'}^{CA}$. Moreover, as substrate farmers are not considered necessary in the chain, their profit is fixed to a percentage of their costs, but a price is also set using Equation 5.

Each of the three profit allocation mechanisms are applied using a feasibility constraint; these constraints are presented in Sections 4.3.1-4.3.3. For the proportionality and the individual rationality mechanisms, λ is maximised. However, the interpretation of λ is different in the two mechanisms and is described in the corresponding sections.

4.3.1. Full equality

The full equality method has many names, e.g. the egalitarian method and direct equality. The principle is that all owners share the total profit equally, regardless of their total costs. The feasibility constraint for full equality allocation is:

$$\pi_o^{CA} = \frac{1}{|o \in \mathcal{O} \setminus \mathcal{O}^{sub}|} \sum_{o' \in \mathcal{O} \setminus \mathcal{O}^{sub}} \pi_{o'}^{CA} \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{6}$$

The profit of each owner, except substrate farmers, will be a share equal to that of each owner after payments for substrates are deducted. The share equals the total profit divided by the number of owners. The owner with the highest cost has the highest risk using this mechanism, which most likely will not be considered fair by this owner. Furthermore, there is a challenge with adverse selection as full equality requires all owners to report their costs honestly; this implies the risk that an owner would report a higher cost than what he or she actually has in order to increase his or her profit.

4.3.2. Proportionality

Proportionality is not as simple to consider as full equality. One needs to determine which elements profit needs to be proportional to, e.g. total costs, CAPEX or OPEX. Considering the three primary parts of the value chain, i.e. the livestock farmers, the plant and the energy converters, it is difficult to find one common parameter or variable for all parts of the value chain that does not present knowledge-sharing challenges. In this paper, we chose to use the cost of each owner from the plant level model. This choice implies that each owner has a cost assigned, and this is why transportation costs are added to the farmers, unlike in (Jensen et al., 2017).

The feasibility constraint for proportionality allocation is:

$$\pi_o^{CA} = \lambda C_o^* \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub}, \tag{7}$$

where λ is the percentage of the cost that can be covered for each non-substrate owner. This mechanism has a higher risk of adverse selection, as it gives an incentive to owners to boost their own costs in order to achieve a higher share of the total profit. Moreover, the method does not reflect that all three parts of the value chain are necessary for achieving support.

4.3.3. Individual rationality

The final mechanism that we apply is inspired by the maximin profit allocation, the nucleolus mechanism. In the traditional nucleolus mechanism, all combinations of participating owners and their alternative profits are used for the allocation, and the profit for each owner is found by maximising each distance from each obtained profit to each alternative profit for all subsets of participating owners. Nucleolus allocation is per definition in the core. The owners when applying the traditional nucleolus mechanism are typically all the same type; see, for example, (Frisk et al., 2010), and the operability of the collaboration is therefore not one in which each owner is relied upon individually. In regards to this study, the owners rely on each other to ensure the biogas chain operating, so the nucleolus mechanism can not be directly applied.

Instead of considering all possible coalitions, as in the nucleolus mechanism, we consider the revenue gain of each owner independently by maximising each distance from each obtained profit to each alternative profit that could be obtained through a lack of participation. This ensures that the obtained solution is within the core, which means that all owners benefits the most as part of the chain. The allocation mechanism ensures that all owners get the same revenue gain. This is in contrast to the nucleolus mechanism, where coalitions with the smallest revenue gains get the greatest revenue gains, which means that not necessarily all coalitions end up with the same revenue gain.

The feasibility constraint for individual rationality allocation is:

$$\pi_o^{CA} - \pi_o^{ALT} = \lambda \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub}, \tag{8}$$

where λ is the participation gain for all non-substrate owners, and π_o^{ALT} is a reported alternative profit for each owner, o. This allocation mechanism may seem fair as it is more equal than the proportionality mechanism and considers more individual properties than the full equality mechanism; however, costs are not directly considered. Moreover, there is a lack of transparency and a necessarily high level of information is needed in order to calculate the allocation; the latter allows dishonest reports regarding each owner's best alternative.

4.4. Inclusion of individual rationality

In the value chain, the sample space of best alternatives is large; in order to decrease it to a reasonable amount of calculations, we exploit having reduced the owner group to the three parties. Some of the owners can, to some extent, be replaced after investments, though this is done at the expense of the overall profit. The approach is to consider the alternatives for the individual owners and the entire value chain. As capital costs are extensive parts of total costs in biogas value chains, both choices before investments (ex ante) and after investments (ex post) are considered, as ex post bargaining power can affect the preferences of each owner in regard to both the value chain configuration and the preferred allocation mechanisms before investments. We evaluate the alternatives in Section 5, starting with the results presented in Table 1. In the calculation for individual rationality profit allocation, the results presented in Table 5 are also applied.

For livestock farmers, we assume that the best alternative is to deliver manure to another biogas plant. The farmers could choose to apply manure directly to the fields, but this would not provide the additional fertiliser value from the digestate. A common payment for manure is one in which the biogas plant collects manure and delivers digestate for free; in Table 5, this alternative

	Before investments	After investments
Livestock farmer	Deliver manure to another biogas plant	Deliver manure to another biogas plant
Plant	Invest capital with a 4% interest rate	Sunk costs
Energy converter, CHP	Biomass-based heat boiler	Sunk costs and a biomass-based heat boiler
Energy converter, upgrade	Invest capital with a 4% interest rate	Sunk costs

Table 1: The stand-alone profits

is presented as a zero profit, as the fertiliser value is not included in the calculations.

For the biogas plant, several options exist, but for this analysis, it is assumed that the plant invests its capital in safe investments at an interest rate that corresponds to the socio-economic interest rate before investments, and that the plant has sunk costs after investment. However, it is just as likely that the plant would try out other options, especially ex post.

In order to determine the best alternatives for the energy converters, we need to make some overall assumptions. The plant level model in Section 3 allows different technology choices: upgrading technologies, a heat and power plants, and a heat boiler. With current regulation, it is unlikely that the optimal choice is to produce heat with biogas, so this alternative was not considered further. Moreover, with regard to coverage of heat and power demands, there are two different markets that need to be considered. As the power market is highly competitive in Denmark, a CHP is, in many cases, only a viable option if it is fuelled by a supported fuel. In most cases, the energy converter would have to find an alternative to the heat production if the biogas-based CHP is dismissed. Therefore, we assume that the best alternative to a biogas-based CHP is a biomass-based heat boiler, both before and after investments. Finally, for upgrading, we assume that the energy converter can freely choose to either supply or not supply the heat demand.

	Before investments	After investments
Livestock farmer	Longer transportation distance	Longer transportation distance
Substrate farmer	Other substrate	Other substrate and sunk costs in pretreatments
Energy converter	Other energy converter	Other energy converter and new investments

Table 2: The alternative profits for the value chain if an owner retracts

The overall principle for alternatives in the value chain is that the plant cannot be substituted, if the value chain should remain. This gives the plant a good position with regard to bargaining power. We assume that all other parties can be substituted at the expense of total profits in the value chain.

The content of Table 2 is derived using the plant level model. For the livestock farmers, the assumption that the farmers are a cooperative, and not a single farmer, is exploited. It is therefore realistic that some farmers in the cooperative could decide to choose another alternative and not join the value chain. For simplicity, we assume, that one third of the livestock farmers leave the livestock farmer cooperative. New data on manure access is then fed into the model, and a new optimal solution is found with a lower profit. Finally, for the substrate farmers and the energy converters, the model is run with the restriction of not choosing the optimal choice, first for the substrate and second for the energy converter. Thereby, a new optimal solution and corresponding alternative profits are found.

5. Application and results

5.1. Optimal value chain

In this section, we consider a base scenario in which the model determines the optimal size of the plant, the optimal substrates to use for production, and the optimal energy converter—considering the substrate, transportation, and investment costs in relation to the potential income. The plant level model is a detailed model, and in order to ensure a short calculation time, optimisation is done for one year, and investment costs are estimated as yearly costs. Therefore, the model does not consider price and cost variations over several years. As energy prices for both the input and the output side of the model significantly influence the optimal investment choice, and these prices can vary significantly, we run a number of sensitivity analyses.

First, we consider the electricity costs that can influence whether it is profitable to use methanation. As the PSO is phased out in 2022, a scenario was created in which the PSO is zero. This scenario is called PSO zero. Second, we consider the natural gas price. The natural gas price is quite low in the base year, compared to previous years, so the optimal solution could change with the natural gas price. Therefore, we use the time series for the natural gas price from 2013—when the prices were almost double the prices in 2016—to see the effects of the natural gas prices. In the scenario called NG high, we use the natural gas price from 2013 and all other data was set to be equal to the data in the base scenario. An overview of the scenarios can be seen in Table 3.

	Electricity cost		**Natural gas price**		**Heat price**	
Scenario	Average €/MWh	Level	Average €/MWh	Level	€/MWh	Level
Base	26.5	High	15.2	Low	32.2	Low
PSO zero	15.1	Low	15.2	Low	32.2	Low
NG high	26.5	High	31.4	High	32.2	Low
2015	22.6	Medium	22.3	Medium	32.2	Low
2013	24.0	Semi-High	31.4	High	54.3	High

Table 3: The tested scenarios

The energy system is, to a great extent, interrelated; when natural gas prices are high, one can expect that this will be reflected in heat prices in areas where natural gas is used as fuel. For example, as Denmark becomes more dependent on renewable energy, such as wind, solar, and hydro power, it can be expected that the electricity price is less dependent on the natural gas price—except when renewable energy is insufficient to meet the electricity demand. Therefore, we expect less convergence between the natural gas and electricity price; however, due to variations in weather conditions, we can also expect certain variations in the electricity price. Finally, in the second group of scenarios, i.e. in the 2013 and 2015 scenarios, we test the model in regard to a group of energy costs and prices. In these scenarios, we use the fundamental costs of technologies and inputs from the base scenario, but use the electricity price + taxes and fees, and the natural gas and the heat prices for 2013 and 2015.

5.1.1. Results and preliminary conclusions

The results from using the plant level model is seen in Table 4. The biogas plant is as large as possible for all scenarios, i.e. 600,000 tonnes of biogas per year is produced, and the preferred substrate for all cases is deep litter.

	Unit	**Base**	**PSO zero**	**NG high**	**2015**	**2013**
Netincome	m €	6.31	6.31	9.56	6.72	8.05
Total cost	m €	9.67	9.67	18.19	16.82	19.02
Total income	m €	15.98	15.98	27.75	23.55	27.07
Support	m €	11.41	11.41	13.44	13.43	13.44
Input						
Cow slurry (manure)	% of input	0.0%	0.0%	0.0%	0.0%	0.0%
Pig slurry (manure)	% of input	69.4%	69.4%	69.4%	69.4%	69.4%
Deep litter	% of input	30.6%	30.6%	30.6%	30.6%	30.6%
Output						
Energy converter	Type	CHP	CHP	Methanation	Methanation	Methanation
Capacity of energy converter	MW	9.9	9.9	19.8	20.3	20.4
Energy produced	GWh	116	116	415	414	415

Table 4: The scenario results

In the base scenario, a combined heat and power plant (the combined cycle gas turbine) is installed. The type of energy converter installed seems to depend mainly upon the natural gas price as the PSO zero scenario results in a combined heat and power plant being installed as the energy converter, while the upgrading using methanation is preferred for all cases with higher natural gas prices than in the base scenario. Moreover, in the scenarios with higher natural gas prices, the total profit is larger than in the base case.

The amount of support received in each scenario also depends upon the energy converter. The received support is lowest in the base scenario; however, the support received per unit of energy is lower using methanation. In the scenarios using a CHP, the support is €97.93 per MWh, and in the scenarios using methanation, the support is €32.41 per MWh, so for less support, more energy is provided. The methanation process, besides receiving less support per unit of energy, also pays taxes in the form of an electricity tax on used electricity and excess heat tax.

The decision of biogas producers to upgrade in later years, could be explained by an expectation of higher gas prices in the future—an expectation shared by the Danish Energy Agency (Danish Energy Agency, 2012b, 2017). One should be aware that although the model chooses the methanation technology, this technology is not fully commercialised yet.

The NG high scenario gives the highest profit across all the scenarios by only changing one parameter. We consider this scenario further as a relevant alternative to the base scenario in the analysis presented in the following sections.

5.2. Results of applying the allocation mechanisms

In this section, we assess three profit allocation mechanisms in relation to viability. We then consider the implications of these allocation methods with regard to the individual choices in the value chain.

Based on the results from the plant level model, we use the base scenario and the NG high scenario to discuss the effects of applying the following allocation mechanisms *full equality*, *proportionality* and *individual rationality*. In order to calculate the *individual rationality* allocation, we need to know the alternative profits for each owner in the chain.

Applying the assumptions stated in Section 4.4, we calculate the alternative profits for each owner in the chain, should they decide not to participate in the value chain. The results are presented in Table 5.

	Before investments	
	Description	**Alternative profits**
Livestock farmer	Other biogas plant	0 €/ton
Plant	No investment, base scenario	0.07 m €/y
	No investment, NG high scenario	0.07 m €/y
Energy converter, CHP	Heat boiler, base scenario	0.53 m €/y
Energy converter, methanation	No investment, NG high scenario	0.07 m €/y

Table 5: The ex ante alternative profits for the owners in the value chain

5.2.1. Results from the profit allocation

As seen in Figure 4, the profit is allocated quite differently depending on the chosen profit allocation mechanism. For the proportionality mechanism, the allocation would most likely not be considered equal in any of the scenarios.

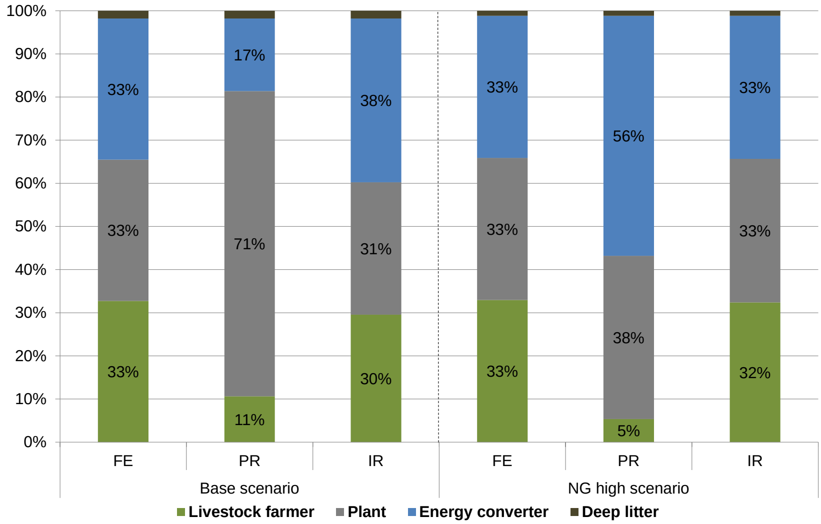

Figure 4: The percentage of total profit for each owner in all scenarios

It is obvious that the plant owner would prefer the proportionality distribution in both scenarios as this is where the highest percentage of profits can be gained. This is underlined by the results presented in Table 6, showing the intermediate prices within the value chain and the profits for each owner under the selected scenarios for each type of allocation described in Section 4.3.

We find that the biogas plant would prefer proportional allocation in both scenarios, while the livestock farmer would always prefer full equality. More specifically, we find that in the base scenario, the livestock farmer and the energy converter—as opposed to the plant owner—would prefer the full equality or individual rationality mechanism, both of which would give them a higher total profit. In the NG high scenario, both the biogas plant and the energy converter would prefer the proportionality mechanism. The change in results for the energy converter's perspective can be explained by the higher costs related to methanation, which is only reflected in proportional allocation. The livestock farmer would still prefer the full equality or individual rationality mechanism.

In the base scenario, the highest biogas price is found using proportional allocation. This is where the plant would gain the highest profit even though the total profit is lower compared with the NG high scenario. In the NG high scenario, the proportionality mechanism results in the lowest cost of biogas because the highest profit with this mechanism is given to the energy converter, meaning that less money has to be paid to the rest of the chain.

	Unit	Base scenario FE	Base scenario PR	Base scenario IR	NG high scenario FE	NG high scenario PR	NG high scenario IR
Netincome	m €/y	6.31	6.31	6.31	9.56	9.56	9.56
- Livestock farmer	m €/y	2.06	0.67	1.86	3.15	0.51	3.10
- Deep litter	m €/y	0.11	0.11	0.11	0.11	0.11	0.11
- Plant	m €/y	2.06	4.46	1.94	3.15	3.62	3.18
- Energy converter	m €/y	2.06	1.06	2.40	3.15	5.32	3.17
Price per unit sold							
Manure	€/ton	7.18	3.83	6.70	9.79	3.45	9.66
Deep litter	€/ton	6.75	6.75	6.75	6.75	6.75	6.75
Biogas	€/MWh	63.48	69.29	61.56	78.25	65.68	78.14

Table 6: Results from the allocation using the full equality (FE), proportionality (PR), and individual rationality (IR) mechanisms

5.3. Ex ante considerations

Following the notions from Bogetoft and Olesen (2007) and Hougaard (2009) regarding individual rationality in profit allocation, we examine whether our profit allocation can be considered to be in the core.

The individual owners in the value chain are expected to consider their own gain from participating in the value chain rather than doing something else. In order to reach a viable value chain, it is necessary to find a viable profit allocation, both to assure investments (ex ante) and to assure that the most important partners stay in the value chain (ex post).

The owners also have to consider the risk that other owners will retract from the coalition, and they must consider how this would affect profits in the value chain both before and after investments are made. This risk influences both expected profits for the value chain and the bargaining power of each owner when the allocation of the profits is negotiated.

Next, we distinguish between ex ante and ex post considerations, as risks change depending on whether investments have already been made or not. If one owner retracts from the value chain before investments, the remaining value chain will have to find an alternative owner, and profits will be reduced in comparison with the results in Table 4. The new profits obtained are given in Table 7 as the percentage of the optimal profit from the base and NG high scenarios that was presented in Table 4.

We find that the effect of the livestock farmer on profits is small overall, as the profit for the entire value chain would only be affected marginally if 1/3 of the optimal livestock farmers decided to withdraw from the coalition. This puts the coalition of farmers in a weak negotiating position. In a value chain with upgrading plants, the livestock farmers could face the risk that the other

	Base scenario		NG high scenario	
	Description	**Percentage of profit**	**Description**	**Percentage of profit**
Livestock farmer	Longer transport distance	97%	Longer transport distance	98%
Substrate farmer	Straw	55%	Straw and sugar beet	75%
Energy converter	Water scrubbing	63%	Water scrubbing	56%

Table 7: The effects on profit in the biogas value chain when an owner retracts before investments

parties would agree on a proportional allocation principle, leaving the livestock farmers with a low profit share since their costs are also quite low.

The relationship between the biogas plant and energy converter is more complicated, and the risks are high on both sides. In the base scenario where natural gas prices are low, the preferred solution for the entire value chain would be direct usage in a local CHP; the best alternative (upgrading by water scrubbing) would result in a significantly lower profit. The CHP has a fairly good alternative to biogas in the form of a biomass-based heat boiler. This could put pressure on the biogas plant to turn away from proportional allocation towards full equality or the individual rationality profit allocation preferred by the CHP.

In the NG high scenario, upgrading with methanation is the preferred choice for the energy converter, and the best alternative is water scrubbing, with a total profit just above the result from the base scenario (approximately €5.35 million per year). This is, however, quite a reduction compared to the profits from methanation, so the value chain has an interest in methanation.

5.4. Ex post risks affecting investment decisions

When investments have already been made, both the biogas plant and the energy converter will lose money due to sunk costs if one member of the value chain decides to withdraw from the collaboration. As it is displayed in Table 8, the biogas plant risks the largest sunk costs if investments are made for direct consumption in a local CHP. At the same time, sunk costs are lower for the CHP investor.

If instead the biogas plant has made a coalition with an upgrading plant, the energy converter will face the highest sunk costs. Furthermore, the upgrading plant needs biogas to operate, while the biogas plant will probably be able to find alternative options. This leaves the biogas plant in a better negotiating position before and, in particular, after investments.

The livestock farmers would have no direct costs from leaving the coalition unless they had signed a contract ex ante that imposed a cost in cases of ex post defection. If a proportional allocation mechanism was decided ex ante, resulting in low profit shares for the livestock farmers, there would be a credible risk that the livestock farmers would find this distribution of profits too

	After investments	
	Description	**Alternative profit**
Livestock farmer	Other biogas plant	0 €/ton
Plant	Sunk cost, base scenario	-1.82 m €/y
	Sunk cost, NG high scenario	-1.67 m €/y
Energy converter, CHP	Sunk cost CHP plus heat boiler profit	-1.26 m €/y
Energy converter, methanation	Sunk cost	-1.84 m €/y

Table 8: Ex post alternative profits for the owners in the value chain

unequal and unfair. This could bring a risk of defection, as a cost-effective option for the livestock farmers; or, if defection costs were increased due to contracts, there could be a risk of adverse selection, where farmers might pretend that costs were higher than they were or might be more likely to deliver manure at a lower dry-matter content than promised.

	Base		NG high	
	Description	**Percentage of profit**	**Description**	**Percentage of profit**
Livestock farmer	Longer transport distance	97%	Longer transport distance	98%
Substrate farmer	Straw and sunk costs	51%	Straw, sugar beet and sunk costs	72%
Energy converter	Water scrubbing and sunk costs	47%	Water scrubbing and sunk costs	45%

Table 9: The effects on profit in the biogas value chain when an owner retracts after investments

The best alternative to deep litter is to use straw as an additional substrate. This would result in a significantly lower profit for the value chain, especially if investments have already been made. Since the deep litter farmer is faced with no costs for defecting and may not even be bound by any contracts, a reasonable payment to the deep litter farmer is necessary even though cheaper alternatives than straw might be available. Hence, the 10% cost coverage may not be sufficient.

6. Policy insights

Danish biogas production has increased to a remarkably extent the later years, and there have been two tendencies: 1) most plants decide to upgrade, and 2) the larger plants especially have difficulties in finding enough farmers who will commit to delivering the manure needed as input. We argue that our results can help to explain these tendencies.

6.1. Implications for farmer involvement

The best alternative for livestock farmers, given in Tables 5 and 8, is a payment commonly used for the farmers to deliver manure to the biogas plant. They get their manure treated at no cost, and in return, they are paid nothing (Lemvig Biogas Plant, 2017). This alternative profit is lower than the profit they could achieve by staying in the value chain using any of the profit allocation mechanisms we have chosen to investigate. Furthermore, an individual farmer is often replaceable at low costs, cf. Tables 7 and 9. This leaves the farmers in a bad negotiating position and might prompt them as a group to accept something in line with the proportionality allocation mechanism, even if it seems unfair. Alternatively, they may try to become co-owners of the plant to attain more of the profit, and this corresponds well with observable trends in Denmark, where it is common for farmers to be co-owners. If the farmers find it difficult to raise capital to become co-owners, they may not be interested in committing themselves to deliver manure at a low price, simply because they find the profit allocation to be unfair and, therefore, not worth any risk.

Policy makers could affect these challenges by moving some of the support from energy converters to the beginning of the chain. While Danish biogas support is currently focused on the energy output, regulators in Norway, for example, have focused some of the support on the input side by giving support to the manure treatment (Lyng et al., 2018). This could increase the alternative profit for the farmers, and thereby their bargaining power, in cost allocation discussions.

6.2. Implications for the choice of value chain design

From the results in Section 5, we find that several considerations should be taken for the choice of value chain design. First, it is relevant to make sure there is an actual heat demand. The fact that new investments have been made primarily in upgrading plants could be due to a low heating demand. Similar arguments could apply for existing plants, combined with disagreements on the profit sharing when existing contracts are to be renegotiated.

The next few considerations involve the expected profits for the total value chain. Our results have shown that high gas prices would make upgrading the preferred choice, while low gas prices would favour a value chain ending with a CHP. As the prognosis for the natural gas price shows an increase, it is logical to assume that new investments in biogas plants could be based on positive projections for the natural gas price, implying that upgrading would be the preferred choice (Danish Energy Agency, 2012b, 2017).

The actual development in the natural gas price has, however, shown a downward trend in recent years due to the financial crisis, shale gas (primarily in the US) and an increase in renewable energy substituting gas-driven CHPs. It is therefore likely that some biogas producers would be inclined to choose the CHP solution. A reason why so few have actually made that decision could be strategic considerations. An analysis including both ex ante and ex post considerations shows that the owners of a biogas plant using backward induction would most likely prefer to join a value chain design with upgrading, even if expected profits for the total value prove to be higher with a

CHP. This can be understood by examining how profits can actually be expected to be allocated based on the value chain design when both ex ante and ex post bargaining powers are accounted for.

If a CHP is installed to satisfy a heat demand, the best alternative to biogas is to install a biomass-based heat boiler. This alternative gives the CHP good ex ante bargaining power. After investments are made, both the biogas plant and the CHP will lose if one of the parties chooses to defect and break the chain; however, the energy monopoly regulator, the Danish Energy Regulatory Authority, may force the energy converter to pay less for the biogas than first agreed upon, thereby reducing the opportunities for profit for the biogas plant (see, for example, (Danish Energy Regulatory Authority, 1999)).

This means that a biogas plant will be reluctant to involve itself in a value chain with direct consumption in a CHP, even though the resulting feed-in tariff on produced electricity could yield the highest potential profit for the value chain at the lowest risk. Backward induction shows that the *proportional allocation* will most likely be discarded either ex ante or ex post for the benefit of an allocation mechanism more in line with *full equality* or *individual rationality*, following the preferences of the energy converter.

Conversely, if the value chain ends with an upgrading plant, it will be the biogas plant that has the upper hand. For an investor, an upgrading plant could be very profitable, particularly if a 4% discount rate is the best alternative, while from the perspective of the biogas plant, an upgrading facility could add good profits with the right profit allocation. An ex post deviation from the value chain would result in significant sunk costs for the upgrading plant's owner, as the capacity cannot be used for anything else than biogas. The biogas plant would also have a risk of sunk costs, but but its chances are better than those of the upgrading plant for finding a good alternative usage of the capacity, such as for heat and power production or another upgrading plant. This puts the biogas plant in a much better ex post negotiating position, compared to the negotiations with a local CHP. Furthermore, it is more likely that the biogas and the upgrading plant can agree on a profit allocation principle in line with the proportional allocation, as this is the preferred allocation for both. All of these arguments are in favour of upgrading when looking from the perspective of the biogas plant, which is likely to be the initiator of the project.

If policy makers intend to increase the number of value chains ending with direct consumption, a policy implication from this analysis is that they can consider decreasing support for upgrading (or increasing support for direct consumption). If they instead give preference to upgrading, this analysis indicates that the status quo in regulation may not change the pattern in value chain designs even, if natural gas prices continue to stay low in the near future.

7. Conclusion

Danish biogas production has developed remarkably since regulation was changed so upgraded biogas was supported at the same level as biogas applied directly in a local CHP. Several new plants have been built, where most plant owners have chosen to upgrade the biogas, and older plants are also upgrading. New biogas plants, however, tend to face barriers in achieving enough contracts with livestock farmers who will supply the biogas plant with manure.

We have combined the optimisation of the biogas value chain with applied game theory to understand these observations. We started with profit allocation, focusing on the fairness criteria og *equality* and *individual rationality*, and we then discussed the application of backward induction to analyse the strategic approaches to the investment options.

We have found that this approach broaden the perspective of the strategic considerations made by the essential parties in the biogas value chain but also on the empirical evidence we found. To our knowledge, the approach has not yet been applied to a biogas value chain analysis; in fact, the best example we could find for an applied analysis was the study of Hubert and Ikonnikova (2011), which considers the bargaining power in the Eurasian gas market transit. Hubert and Ikonnikova (2011) apply allocation mechanisms as an indicator of bargaining power, whereas we consider the results as possible outcomes of a negotiation. The likelihood of these outcomes depends on the bargaining power of each participant, which is assessed through the potential alternatives before and after investments—assuming individual rationality.

The optimal configuration of the biogas value chain is found using a mixed integer optimisation model. The optimal solution is to build a large biogas plant with a high share of manure and a cheap supplementary input substrate—in our case, deep litter. The optimal choice of energy converter is a local CHP when natural gas prices are low and an upgrading facility using methanation when natural gas prices are high.

Using the optimal configuration, we implemented three mechanisms for allocating the profit: full equality, proportionality, and individual rationality. Comparing the solutions between using a CHP and an upgrading facility as the energy converter, the following conclusions are drawn.

First, farmers have low bargaining power, which can result in low profit shares and, eventually, a lack of attendance or defection if the farmers have already agreed on attendance. Policy makers could overcome this obstacle by moving some of the support from the energy converters to the farmers, thereby increasing the bargaining power of the farmers.

Second, the negotiating position of the biogas plant is the best if the energy converter is an upgrading plant and is relatively bad if the energy converter is a CHP. It is also likely that the plant will be able to agree on the allocation mechanism with an upgrading plant; at least, they could do so by looking at the three mechanisms applied in this study. These points can help to explain the clear preference for upgrading we find empirically. If policy makers were to change this development, they could decrease the support given to biogas upgrading relative to the support given for direct consumption of biogas.

Overall, we have found several arguments, based on theory and our modelling, that support the observations found regarding the choices made by Danish biogas value chains in recent years.

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Appendix A. Regulation

Appendix A.1. Regulation related to inputs

The primary input for biogas production must be waste in order to achieve support for biogas in Denmark. Waste can be waste water, manure, or e.g. other agricultural waste products such as waste products from dairy production or from slaughterhouses. While some of these waste products give a high biogas yield, other inputs such as manure will only give a low yield, and as some waste products are limited biogas plants have experimented with energy crops in a mix of manure. However, in order to keep a sustainable biogas production authorities have set restrictions on the level of energy crops (e.g. maize and sugar beet) which can be added in the biogas production. By 2018 this limit will be on a maximum of 12% energy crops that can be added (Danish Energy Agency, 2012a).

Agricultural output is dependent on the amount of nutrients in the soil, and in conventional farming it is common to add a proper amount of fertilisers to the soil. These fertilisers would typically be a combination of manure and mineral fertilisers, however not all the added nutrients are used by the crops and are instead washed out into the ground water. In 1985, with the first Danish waste water action plan, it was decided to set restrictions on the amount of manure and mineral fertilisers that could be used on Danish soils (Environmental Protection Agency, 1985).

A property of digestate (de-gasified manure) is, that nutrients become more usable for the crops, which decreases the need for extra mineral fertilisers in order to achieve the same yield. With the current regulation farmers have been allowed to fertilise the soil in the same way with digestate as with untreated manure. This means that the crops are more fertilised with digestate than with untreated manure. Besides a potential profit from the biogas plant, the primary gain for a participating livestock farmer is an improved fertiliser.

Appendix A.2. Regulation related to output

Biogas support is given to the energy producer from the value chain. Until 2012, the Danish regulation followed some of the same principles as used elsewhere in Europe, where support was given to the produced electricity (EuroObserv'ER, 2014; Lantz et al., 2007; Brudermann et al., 2015). Since the Energy reform in 2012 (Danish Government, 2012), regulation have changed so that biogas upgraded to biomethane and sold on the gas market (through the gas grid) is put on the same regulatory footing as biogas used locally for heat and power production.

The support tariffs for 2016 can be seen in table A.1. The support will last until 2023, however, a part of the support will be phased out from 2016 to 2020 and another part of the support depends negatively on the natural gas price, and thereby reduce the risk of price variations for natural gas.

Appendix A.3. Regulation for methanation

As methanation is a new technology, it has not been implemented in the current support scheme, but following the fundamental principles of the support structure where production of renewable

Regulation type and description	value
Feed-in tariff on electricity based on Biogas	164.9 Euro/MWh
Feed-in premium for heat-only based on Biogas	55.8 Euro/MWh
Feed-in premium for Biomethane from biogas	59.2 Euro/MWh
Fuel tax on biogas for heat	0 Euro/MWh
Fuel tax on natural gas for heat	34.3 Euro/MWh

Table A.1: Support and tax for upgrading and biogas-based CHP, in 2016-prices

energy is supported and not energy conversion (according to personal communication with Bodil Harder, Danish Energy Agency), we assume that the extra biomethane gained from electrolysis will not gain any support. The support and taxes for methanation are shown in table A.2.

Regulation type and description	value
Feed-in premium for Biomethane from biogas	59.2 Euro/MWh
Feed-in premium for Biomethane from electrolysis	0 Euro/MWh
Fuel tax on electricity for heat based on electrolysis	22.9 Euro/MWh
Tax and transport tariffs on electricity for electrolysis	42.8 Euro/MWh

Table A.2: Support and taxes for methanation, in 2016-prices

Electricity is taxed even more than fossil fuels when electricity is used by private households and for heat production. This also counts for surplus heat. The tax is considerably lower, when electricity is used for industrial production, however any surplus heat from this production used for heating will then be taxed heavily afterwards, this in effect means, that a potential income from the heat generated through electrolysis is close to zero, when the tax is deducted.

A part of the electricity tax is the PSO (public service obligation), which basically is a way to make electricity consumers pay for the development of renewable electricity. The PSO fee is high and even though it is reduced a bit for large consumers it increases total electricity costs significantly. The PSO is phased out from 2017 to 2022 (Danish Ministry of Energy, Utilities and Climate, 2016), which will reduce the electricity cost significantly for industrial production such as methanation.

Appendix B. Mathematical models

Appendix B.1. Plant level model

Parameters

$AM_{i,n'}$ Accumulated amount of biomass for biomass type i in breakpoint n'
A_j Area of circle j
T Hours on the input side
T Number of weeks in a year
ΔA_j Average area of circle j and circle $j-1$
$\Delta d_{i,n'}(\Delta d^{dig}_{n'})$ Average transportation distance for biomass i (digestate) in breakpoint n
Δr_j Average distance from center to the biomasses in circle j
Γ^{DM} Allowed dry matter content in the mix
η^{EC} Percentage energy crops allowed in input mix
$\eta^{available}$ Amount not flared
η^{plant} Mass after biogas plant %
$\eta_{i,p',p}/\overline{\eta}_{p',p}$ Mass left after process p coming from process p'
γ^{DM}_i Dry matter content of input i
γ Percentage of mass of supplied manure that can be returned as digestate
$\overline{\eta}_i$ Initial biogas yield of biomass i
$\overline{\rho}_{p,t}$ Price of end product p in time t
$\overline{c}^{tax}_{p,p'}$ Tax applied on amount flowing from process p to process p'
ρ^{dig} Price of digestate
$\rho^{support}_p$ Support process p
$am_{i,m}(am^{dig}_m)$ Amount of biomass (digestate) transported on segment m
$am_{i,n'}(am^{dig}_{n'})$ Amount of biomass (digestate) in the annulus between n' and $n'-1$
b^{plant}_n Max. capacity of plant in breakpoint n
$b_{i,t}$ Biomass i available at time t
$c^{HANDLING,dig}$ Handling cost of digestate
$c^{OPEX,SOS2}_n/c^{CAPEX,SOS2}_n$ OPEX/ CAPEX in breakpoint n for the plant
$c^{OPEX,var}_{i,p,t}/\overline{c}^{OPEX,var}_{p,t}$ Variable OPEX for biomass (gas) process p for input type i and time t
$c^{OPEX}_{i,p}/c^{CAPEX}_{i,p}$ $(\overline{c}^{OPEX}_p/\overline{c}^{CAPEX}_p)$ OPEX/CAPEX for biomass (gas) process p for input type i
$c^{TRANS}_{i,m}(c^{TRANS,xdig}_m)$ Transport cost for biomass type i (digestate not sent to the manure supplier) on each segment m
c^{prod}_i Production cost of biomass type i
c^{load}_i/c^{unload}_i $(c^{load,dig}/c^{unload,dig})$ Cost of loading/unloading biomass i (digestate)
$c^{truck}_i(c^{truck,dig})$ Cost of using truck for biomass i (digestate)
$c^{TRANS}_{i,n'}$ Cost of each biomass type transported to the plant in each breakpoint n'
$c^{TRANS,xdig}_{n'}$ Transportation cost for digestate not delivered to the manure suppliers in breakpoint n
$d_{p,t}$ Demand of end product in hour t—only defined for heat
f_p Fixed amount going to process p from a $\mathcal{P}^K-$ *process*
$k^{truck}_i(k^{truck,dig})$ Capacity of the truck used for transportation of biomass i (digestate)
r_j Radius of circle j
$t^{min}_{i,p}$ Minimum process time of process p for input type i
$t^{load}_i/t^{unload}_i(t^{load,dig}/t^{unload,dig})$ Time used for loading/unloading biomass i (digestate)
$v_i(v^{dig})$ Velocity of truck used for transportation of biomass i (digestate)

To include ownership in the model, we have included a new set of constraints to run the model with in order to see this effect. We also identified two more neccessary constraints that were not in the model from Jensen et al. (2017). The changes to the model are presented first, and after this, the rest of the model is presented.

The objective function is now to maximise the sum of profit for the owners:

$$Max \sum_{o \in \mathcal{O}} \pi_o$$

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Sets

$\mathcal{A}(v',v)(\overline{\mathcal{A}}(v',v))$ Arcs from vertex v' to vertex v
$\mathcal{A}^-(v)/\mathcal{A}^+(v)(\overline{\mathcal{A}}^-(v)/\overline{\mathcal{A}}^+(v))$ Input (output) side arcs entering/leaving vertex v
$\mathcal{A}^-_{cap}(v)(\overline{\mathcal{A}}^-_{cap}(v))$ Arcs to vertex v used in capacity constraint
$\mathcal{A}_{proc}(v,v'')(\overline{\mathcal{A}}_{proc}(v,v''))$ Process time arcs from vertex v to vertex v''
$\mathcal{E}$ The set of possible energy content
$\mathcal{IO}(i,o)$ Owner o producing biomass i
$\mathcal{I}^{EC}$ Subset of biomasses that are energy crops
$\mathcal{I}$ Biomass types
$\mathcal{M}$ Line segments
$\mathcal{N}$ breakpoints
$\mathcal{OP}(o,p)$ Processes p owned by owner o
$\mathcal{O}$ Owners in the chain
$\mathcal{P}(\overline{\mathcal{P}})$ Input (output) processes
$\mathcal{P}^F$ Farmer processes
$\mathcal{P}^I(\overline{\mathcal{P}}^I)$ Inner processes
$\mathcal{P}^P(\overline{\mathcal{P}}^P)$ The plant process on the input (output) side
$\mathcal{P}^S$ Livestock farmer processes
$\mathcal{P}^T$ Transportation processes
$\mathcal{T}/\overline{\mathcal{T}}$ Input (output) time steps
$\mathcal{V}(\overline{\mathcal{V}})$ Input (output) vertices
$\mathcal{V}^F$ Vertices of farmer processes
$\mathcal{V}^I(\overline{\mathcal{V}}^I)$ Vertices of the inner processes
$\mathcal{V}^M$ Vertices of the manure farmer's process
$\mathcal{V}^P(\overline{\mathcal{V}}^P)$ Plant vertices on the input (output) side
$\mathcal{V}^T$ Vertices of the transportation processes
$\overline{\mathcal{A}}^+_{decide}(v)$ The set of arcs leaving vertex v which defines the capacity of the process it leaves
$\overline{\mathcal{A}}^+_{extra}(v)$ The set of arcs with origin in vertex v but not of the main type
$\overline{\mathcal{A}}^+_{main}(v)$ The set of arcs leaving vertex v and arriving in a process that are of the main type
$\overline{\mathcal{P}}^E$ End processes
$\overline{\mathcal{P}}^H$ End process for heat
$\overline{\mathcal{P}}^J$ Processes on the output side with capacity specified on output
$\overline{\mathcal{P}}^K$ Processes where the inflow is fixed
$\overline{\mathcal{P}}^{m^3}$ Methanation processes
$\overline{\mathcal{V}}^E$ Vertices of the end processes
$\overline{\mathcal{V}}^H$ End vertex for heat
$\overline{\mathcal{V}}^J$ Vertices on the output side with capacity specified on output
$\overline{\mathcal{V}}^K$ Vertices where the inflow is fixed

Variables

C_o Cost of owner o
INC_o Income of owner o
π_o Profit of owner o
k^{SOS2}_n If the size of the plant is near breakpoint n
$k_{i,p}/\overline{k}_p$ Capacity of biomass/gas process p for biomass type i
$x^{left}_{p,t}$ Not sold due to lack of demand
$x^{\neg manure}$ Digestate not sent to manure suppliers
$x^{heattax}$ Tax paid for excess heat production
x^{should} Amount of digestate that should have been to manure suppliers
$x^{trans,xdig}_m$ Extra digestate transported on segment m
x^{SOS2}_n Biomasses to the plant in breakpoint n
$x_a/\overline{x}_a$ Flow on biomass/gas arc a
$x^{trans}_{i,m}$ Biomass i transported on segment m

Where π_o is the profit for each owner, o, in the project and is given by:

$$\pi_o = INC_o - C_o \quad \forall o \in \mathcal{O}$$

Where INC_o and C_o are the income and cost for each owner in the project. The income for each owner is described by:

$$INC_o = \sum_{\substack{v=(p,t)\in \\ \overline{\mathcal{V}}^E \cap (\overline{\mathcal{P}}^E \times \overline{\mathcal{T}}) \\ |\mathcal{OP}(o,p)}} \Big(\sum_{a\in\overline{\mathcal{A}}^-(v)} (\overline{x}_a - x^{left}_{p,t})\, \eta^{price}_a\, \overline{\rho}_{p,t}\, \eta^{available} \tag{B.1a}$$

$$+\rho_o^{support} + \sum_{\substack{p \in \mathcal{P}^{plant} \\ |\mathcal{OP}(o,p)}} x^{\neg manure} \rho^{dig} \qquad \forall o \in \mathcal{O} \tag{B.1b}$$

Here line B.1a is the income from selling the energy. This is only earned if owner o owns the end process as given by the set $\mathcal{OP}(o,p)$. The amount produced on the arc a, $\overline{x}_a$, is reduced by the amount that cannot be sold, which is only relevant for heat as the heat demand is the limiting factor. Then the result is multiplied by a price parameter, η_a^{price}, which reduces the price obtained. This reduction is only applied when biomethane is produced to reflect the heating value of the produced biomethane compared to that of natural gas. Last, we multiply with the price of the end product, $\overline{\rho}_{p,t}$, and an expected percentage of which the production can occur, $\eta^{available}$. Line B.1b is the amount of support received by owner o, $\rho_o^{support}$, and the income, ρ^{dig}, from selling the digestate, which cannot be send back to the livestock farmers, $x^{\neg manure}$.

The cost is given by:

$$C_o = \sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V} \cap (\mathcal{I} \times \mathcal{P} \times \mathcal{T} \times \mathcal{E}) \\ |\mathcal{OP}(o,p)}} \sum_{a \in \mathcal{A}^-(v)} x_a \left(c_{i,p}^{OPEX} + c_{i,p,t}^{OPEX,var}\right) + \sum_{\substack{v=(p,t) \in \\ \overline{\mathcal{V}} \cap (\overline{\mathcal{P}} \times \overline{\mathcal{T}}) \\ |\mathcal{OP}(o,p)}} \sum_{a \in \overline{\mathcal{A}}^-(v)} \overline{x}_a \left(\overline{c}_p^{OPEX} + \overline{c}_{p,t}^{OPEX,var}\right) \tag{B.2a}$$

$$+ \sum_{i \in \mathcal{I}} \sum_{\substack{p \in \mathcal{P} \\ |\mathcal{OP}(o,p)}} k_{i,p} \frac{T}{t_{i,p}^{min}} c_{i,p}^{CAPEX} + \sum_{\substack{p \in \overline{\mathcal{P}} \\ |\mathcal{OP}(o,p)}} \overline{k}_p \, \overline{c}_p^{CAPEX} \tag{B.2b}$$

$$+ \sum_{\substack{p \in \mathcal{P}^{plant} \\ |\mathcal{OP}(o,p)}} \Big(\sum_{n \in \mathcal{N}} x_n^{SOS2} c_n^{OPEX,SOS2} + \sum_{n \in \mathcal{N}} k_n^{SOS2} c_n^{CAPEX,SOS2} \qquad \forall o \in \mathcal{O} \tag{B.2c}$$

$$+ \sum_{m \in \mathcal{M}} x_m^{trans,xdig} c_m^{TRANS,xdig} + \sum_{v \in \mathcal{V}^P} \sum_{a \in \mathcal{A}^-(v)} \left(x_a \, \eta^{plant} - x^{\neg manure}\right) c^{HANDLING,dig} \Big) \tag{B.2d}$$

$$+ \sum_{\substack{i \in \mathcal{I} \\ |\mathcal{IO}(i,o)}} \sum_{m \in \mathcal{M}} x_{i,m}^{trans} c_{i,m}^{TRANS} + \sum_{\substack{p \in \overline{\mathcal{P}}^H \\ |\mathcal{OP}(o,p)}} \overline{x}^{heattax} + \sum_{\substack{p \in \mathcal{P}^S \\ |\mathcal{OP}(o,p)}} x^{should} \rho^{dig} \tag{B.2e}$$

Line B.2a and B.2b are the OPEX and CAPEX of each process and is added to the cost of the owner if he owns the process as defined by the set $\mathcal{OP}(o,p)$. Line B.2c-B.2d is the OPEX and CAPEX of the plant and the transportation and handling costs of digestate. Line B.2e contains three elements. First, the transportation cost of all biomasses, which must be paid by the producer of the biomass as defined by the set $\mathcal{IO}(i,o)$. Second, the tax on excess heat delivery to the district heating network is added for the owner of the heat process. This is only relevant in the case of methanation where heat is generated as excess heat. In the model from Jensen et al. (2017), heat tax was not included. The primary reason for livestock farmers to send their manure to a biogas plant is the gains of having their manure treated and thereby a better fertiliser. If the livestock farmers do not receive the digestate, it represents a loss in the value chain corresponding to the digestate value, ρ^{dig}. This cost is added as the final element in line B.2e.

The livestock farmers may take up to a certain percentage of the digestate, γ. The amount that is not sent back to the livestock farmer but should have been, according to the amount he is willing to take, can be calculated as:

$$x^{should} \geq \sum_{v \in \mathcal{V}^M} \sum_{a \in \mathcal{A}^+(v)} x_a \gamma - (\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{P}^P \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \eta^{plant} - x^{\neg manure})$$

Where the first term on the right hand side represents the amount the farmer is willing to take, and the second term is the amount of available digestate minus the amount of digestate sent elsewhere.

The heat tax is the amount of heat generated and delivered to the heat demand, $p' \in \overline{\mathcal{P}}^H$, from the methanation process $p \in \overline{\mathcal{P}}^{m^3}$, i.e. excluding the heat produced which cannot be sent to the demand, $x^{left}_{p',t}$. The total heat tax is calculated by the following equation:

$$x^{heattax} \geq c^{tax}_{p,p'} \Big(\Big(\sum_{v=(p,t) \overline{\mathcal{V}} \cap (\overline{\mathcal{P}}^{m^3} \times \mathcal{T})} \sum_{a \in \overline{\mathcal{A}}^+(v)} \overline{x}_a \Big) - \sum_{t \in \overline{\mathcal{T}}} x^{left}_{p',t} \Big) \quad \forall p \in \overline{\mathcal{P}}^{m^3}, p' \in \overline{\mathcal{P}}^H$$

In the model from Jensen et al. (2017), the amount of dry matter allowed in the total mix was not modelled. However, this is necessary to consider the problems obtained by the biogas plants as the dry matter content of inputs differs significantly and there is a limit on the total dry matter content of the mix. Therefore, we add another constraint that sets a limit on the dry matter content of the input mix by using the allowed dry matter content of the input mix, Γ^{DM}, and the dry matter content of each input, γ^{DM}_i. The constraint is given by:

$$\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} \gamma^{DM}_i x_a \leq \Gamma^{DM} \sum_{\substack{v=(i,p,t,e) \in \mathcal{V}^P \\ \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \qquad \forall t \in \mathcal{T} \tag{B.3}$$

The remaining constraints are the same as in Jensen et al. (2017), and is briefly explained below.

Ensuring that the flow through the chain is remained, is accounted for by the flow conservation constraints:

$$\sum_{\substack{v'=(i',p',t',e') \in \\ \mathcal{V} \cap (\mathcal{I} \times \mathcal{P} \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}(v',v)} x_a \, \eta_{i,p',p} = \sum_{a \in \mathcal{A}^+(v)} x_a \qquad \forall v = (i,p,t,e) \in \mathcal{V}^I \cap (\mathcal{I} \times \mathcal{P}^I \times \mathcal{T} \times \mathcal{E})$$

$$\sum_{\substack{v'=(p',t') \in \\ \overline{\mathcal{V}} \cap (\overline{\mathcal{P}} \times \overline{\mathcal{T}})}} \sum_{a \in \overline{\mathcal{A}}(v',v)} \overline{x}_a \, \overline{\eta}_{p',p} = \sum_{a \in \overline{\mathcal{A}}^+(v)} \overline{x}_a \qquad \forall v = (p,t) \in \overline{\mathcal{V}}^I \cap (\overline{\mathcal{P}}^I \times \overline{\mathcal{T}})$$

Minimum process time for each process is ensured through:

$$\sum_{\substack{v'=(i,p',t',e')\in\\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})|p\neq p'}} \sum_{a\in\mathcal{A}(v',v)} x_a\,\eta_{i,p',p} \leq \sum_{\substack{v''=(i,p'',t'',e'')\in\\ \mathcal{V}\cap(\mathcal{P}\times\mathcal{T}\times\mathcal{E})|p\neq p''}} \sum_{a\in\mathcal{A}_{proc}(v,v'')} \frac{x_a}{(\eta_{i,p,p})^{t''-t}}$$

$$\forall v=(i,p,t,e)\in\mathcal{V}^I\cap(\mathcal{I}\times\mathcal{P}^I\times\mathcal{T}\times\mathcal{E})$$

$$\sum_{\substack{v'=(p',t')\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})|p\neq p'}} \sum_{a\in\overline{\mathcal{A}}(v',v)} \overline{x}_a\,\overline{\eta}_{p',p} \leq \sum_{\substack{v''=(p'',t'')\in\\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}})|p\neq p''}} \sum_{a\in\overline{\mathcal{A}}_{proc}(v,v'')} \frac{\overline{x}_a}{(\overline{\eta}_{pp})^{t''-t}} \qquad \forall v=(p,t)\in\overline{\mathcal{V}}^I\cap(\overline{\mathcal{P}}^I\times\overline{\mathcal{T}})$$

The capacity of the processes are not to be exceeded. This is ensured by the following capacity constraints:

$$\sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}} \sum_{a\in\mathcal{A}^-(v)} x_a + \sum_{v=(i,p,t,e)\in\mathcal{V}\cap\mathcal{E}} \sum_{a\in\mathcal{A}^-_{cap}(v)} x_a \leq k_{i,p} \qquad \forall(i,p,t)\in\mathcal{I}\times\mathcal{P}\times\mathcal{T}$$

$$\sum_{v=(p,t)\in\overline{\mathcal{V}}} \sum_{a\in\overline{\mathcal{A}}^-(v)} \overline{x}_a + \sum_{v=(p,t)\in\overline{\mathcal{V}}} \sum_{a\in\overline{\mathcal{A}}^-_{cap}(v)} \overline{x}_a \leq \overline{k}_p \qquad \forall(p,t)\in\overline{\mathcal{P}}\times\overline{\mathcal{T}}$$

The following constraint ensures that not more than the available input is used:

$$\sum_{a\in\mathcal{A}^+(v)} x_a \leq b_{i,t} \qquad \forall v=(i,p,t,e)\in\mathcal{V}^F\cap(\mathcal{I}\times\mathcal{P}^F\times\mathcal{T}\times\mathcal{E})$$

The maximum percentage of energy crops allowed in the mix is handled by:

$$\sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^P\cap(\mathcal{I}^{EC}\times\mathcal{P}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} x_a \leq \eta^{EC} \sum_{\substack{v=(i,p,t,e)\in\mathcal{V}^P\\ \cap(\mathcal{I}\times\mathcal{P}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} x_a \quad \forall t\in\mathcal{T}$$

The following constraints set the SOS2-variables to account for OPEX and CAPEX using stepwise linear functions for the biogas plant:

$$\sum_{v\in\mathcal{V}^P} \sum_{a\in\mathcal{A}^-(v)} x_a = \sum_{n\in\mathcal{N}} b_n^{plant}\, x_n^{SOS2}$$

$$\sum_{n\in\mathcal{N}} x_n^{SOS2} = 1$$

$$\sum_{n\in\mathcal{N}} b_n^{plant}\, k_n^{SOS2} = \sum_{i\in\mathcal{I}} \sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}}\, k_{i,p}$$

$$\sum_{n\in\mathcal{N}} k_n^{SOS2} = 1$$

$$b_1^{plant} \leq \sum_{i\in\mathcal{I}} \sum_{p\in\mathcal{P}^P} \frac{T}{t_{i,p}^{min}}\, k_{i,p} \leq b_{end}^{plant}$$

Change of time resolution between input and output side from week to hour is done by:

$$\sum_{\substack{v=(p,t)\in\\ \overline{\mathcal{V}}^P\cap\overline{\mathcal{P}}^P}} \sum_{a\in\overline{\mathcal{A}}^+(v)} \overline{x}_a = \sum_{\substack{v=(i,p,\lfloor\frac{t}{7\cdot 24}\rfloor+1,e)\\ \in\overline{\mathcal{V}}^P\cap(\mathcal{I}\times\overline{\mathcal{P}}^P\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} \frac{x_a\,\overline{\eta}_i\,e}{7\cdot 24} \qquad \forall t\in\overline{\mathcal{T}}$$

For processes where the capacity is determined by the output amount, the following constraint is necessary:

$$\sum_{a\in\overline{\mathcal{A}}^+_{decide}(v)} \overline{x}_a \leq \overline{k}_p \qquad \forall v=(p,t)\in\overline{\mathcal{V}}^J\cap(\overline{\mathcal{P}}^J\times\overline{\mathcal{T}})$$

For the methanation and the CHP processes, a fixed range of the two outputs are ensured by:

$$\overline{x}_a = f_p \sum_{a'\in\overline{\mathcal{A}}^+_{extra}(v)} \overline{x}_{a'} \qquad \forall v=(p,t)\in\overline{\mathcal{V}}^K\cap(\overline{\mathcal{P}}^K\times\mathcal{T}),\ a\in\overline{\mathcal{A}}^+_{main}(v)$$

If the demand of heat is lower than the produced demand, the excess cannot be sold. This is ensured by the following demand constraint:

$$\sum_{a\in\overline{\mathcal{A}}(v)} \overline{x}_a \leq d_{p,t} + x^{left}_{p,t} \qquad \forall v=(p,t)\in\overline{\mathcal{V}}^H\cap(\overline{\mathcal{P}}^H\times\overline{\mathcal{T}})$$

The transportation constraints related to input substrates are:

$$\sum_{m\in\mathcal{M}} x^{trans}_{i,m} = \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^T\cap(\mathcal{P}^T\times\mathcal{T}\times\mathcal{E})}} \sum_{a\in\mathcal{A}^+(v)} x_a \qquad \forall i\in\mathcal{I}$$

$$x^{trans}_{i,m} \leq am_{i,m} \qquad \forall i\in\mathcal{I},\ m\in\mathcal{M}$$

The transportation constraints related to digestate are:

$$x^{\neg manure} \geq \sum_{\substack{v=(i,p,t,e)\in\\ \mathcal{V}^P\cap(\mathcal{P}^P\times\mathcal{T}\times\mathcal{E})}} \sum_{a\in\mathcal{A}^-(v)} x_a\eta^{plant} - \sum_{v\in\mathcal{V}^M} \sum_{a\in\mathcal{A}^+(v)} x_a\gamma$$

$$x^{trans,xdig}_m \leq am^{dig}_m \qquad \forall m\in\mathcal{M}$$

$$\sum_{m\in\mathcal{M}} x^{trans,xdig}_m \leq x^{\neg manure}$$

Finally, restrictions on the variables are given by:

$$x_a \geq 0 \qquad \forall a\in\mathcal{A}$$

$$\overline{x}_a \geq 0 \qquad \forall a\in\overline{\mathcal{A}}$$

$x_{p,t}^{left} \geq 0$	$\forall p \in \overline{\mathcal{P}},\, t \in \overline{\mathcal{T}}$
$k_{i,p} \geq 0$	$\forall i \in \mathcal{I},\, p \in \mathcal{P}$
$\overline{k}_p \geq 0$	$\forall p \in \overline{\mathcal{P}}$
$x_n^{SOS2}, k_n^{SOS2} \in SOS2$	$\forall n \in \mathcal{N}$
$x_{i,m}^{trans} \geq 0$	$\forall i \in \mathcal{I},\, m \in \mathcal{M}$
$x_m^{trans,xdig} \geq 0$	$\forall m \in \mathcal{M}$
$x^{\neg manure} \geq 0$	
$x^{heattax} \geq 0$	
$x^{should} \geq 0$	
$\pi_o \geq 0$	$\forall o \in \mathcal{O}$
$INC_o \geq 0$	$\forall o \in \mathcal{O}$
$C_o \geq 0$	$\forall o \in \mathcal{O}$

Appendix B.2. Profit allocation

The general allocation model is given below, where constraint B.5 is mechanism specific as given for each of the used allocation mechanisms.

$$\text{Max} \quad z = \lambda \tag{B.4}$$

S.t. **Feasibility constraint** $\quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub}$ (B.5)

$$\pi_o^{CA} = \gamma^{feas} C_o^* \qquad \forall o \in \mathcal{O}^{sub} \tag{B.6}$$

$$\pi_o^{CA} = \pi_o^* - \sum_{o' \in \mathcal{OTO}(o',o)} \rho_{o',o}^{CA} + \sum_{o' \in \mathcal{OTO}(o,o')} \rho_{o,o'}^{CA} \qquad \forall o \in \mathcal{O} \tag{B.7}$$

$$\lambda \geq 0 \tag{B.8}$$

$$\pi_o^{CA} \geq 0 \qquad \forall o \in \mathcal{O} \tag{B.9}$$

$$\rho_{o,o'}^{CA} \geq 0 \qquad \forall o \in \mathcal{O}, o' \in \mathcal{OTO}(o,o') \tag{B.10}$$

The objective function B.4 is to maximise the decision variable λ, which is specific for each of the used allocation mechanisms. Constraint B.6 sets the profit of each of the substrate owners equal to a parameter, γ^{feas}, representing the percentage of its costs from the plant level model, C_o^*, that should be covered. In constraint B.7, the profit for each owner using the cost allocation method, π_o^{CA}, is calculated as the profit obtained from the plant level model, π_o^*, minus the price paid for buying input to the process plus the price obtained from selling the output from the owner.

For the full equality allocation, λ is not used in the feasibility constraint. This means that there is no upper bound on λ and the problem gets unbounded. To avoid this, we simply set $\lambda = 0$.

Appendix C. Data

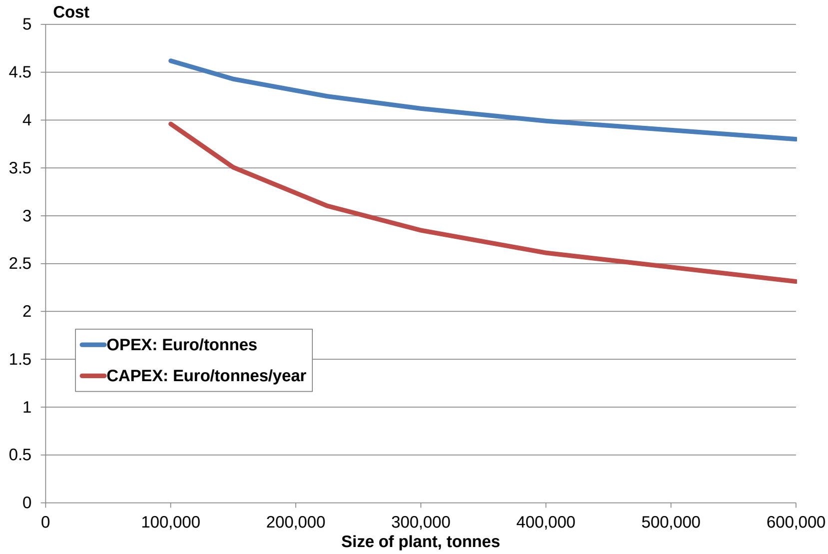

Figure C.1: OPEX and CAPEX for the biogas plant is based on a fitted trendline on the OPEX and CAPEX reported by plants applying for financial support in 2012 in Denmark through the Danish Energy Agency and model plants in the same time. To linearise it, we have used the same break points as in (Jensen et al., 2017).

Cow slurry, manure					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.12	0	0	1	4
storage 2	0.12	0	0	1	4
Pig slurry, manure					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.12	0	0	1	4
storage 2	0.12	0	0	1	4
Deep litter, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.07	0	0	1	52
storage 2	0.07	0	0	1	52
pretreatment	0.01	0	0.13	1	1
Maize, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
ensilage	0.00	0	0.78	26	52
storage	0.30	0	0	1	17
Straw, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	1.72	0	0	1	52
pretreatment	3.61	0	10.19	1	1
storage 2	0.86	0	0	1	52
Sugar beet, substrate					
Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
storage 1	0.26	0	1.61	1	16
Washer	0.00	0	2.14	1	1
storage 2	0.26	0	1.61	1	4
cutter	0.00	0	2.14	1	1
ensilage	0.17	0	1.61	26	52
storage 3	0.17	0	1.61	1	4

Table C.3: Data for the case study—input side. OPEX are in €/ton and all CAPEX are annualised with a rate of return of 4% and the given lifetime of the process (20 years are used when no data) and are in €/ton/year. All data are from Abildgaard (2017) except for sugar beet that are from Boldrin et al. (2016).

Biomass type	Production cost and transport to farm €/ton	Biogas yield $Nm^3 BG/ton$	Dry matter percentage	Extra CAPEX €/ton/year	Extra OPEX €/ton
Cow slurry	0	18	7.5%	0	0
Pig slurry	0	17	5.5%	0	0
Deep litter	0	92	30.0%	1.54	7.51
Maize	30	138	34.0%	0.49	2.41
Straw	27	308	89.0%	4.24	15.42
Sugar beet	26	115	22.0%	0.49	2.41

Table C.4: Production costs and biogas yields of the biomass types. The biogas yield, dry matter percentage and production costs, i.e. without any storage costs etc., as well as transportation costs to the farm are given by Abildgaard (2017), where we assume a transportation distance to the farm from the field of 1.5 for maize, sugar beet, and straw. The extra CAPEX and OPEX for the feedstock are from "EA Energianalyse" (2014).

	Cow slurry		Pig slurry		Deep litter		Digestate	
Radius	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{m}^{TRANS,dig}$
10	75489	1.20	138548	1.20	16298	3.44	51320	1.20
20	543450	2.20	279770	2.20	56260	5.39	109521	2.20
30	690273	3.31	767346	3.31	259280	7.56		
40	819144	4.43	1032999	4.43	83638	9.76		
	Maize		Sugar beet		Straw			
Radius	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$	$am_{i,n'}$	$c_{i,m}^{TRANS}$		
10	8004	2.55	1771	2.55	45363	6.72		
20	50609	3.44	6539	3.44	94926	8.73		
30	72005	4.43	8741	4.43	126407	10.96		
40	96998	5.44	9949	5.44	173821	13.23		
50	88888	6.46	14241	6.46	186082	15.52		
60	99251	7.47	11504	7.47	152538	17.81		
70	143800	8.49	13085	8.49	172816	20.10		
80	167910	9.52	17224	9.52	280636	22.39		

Table C.5: Data for the case study—transportation. All costs are in €. Further, the handling price of digestate, $c^{HANDLING,dig_{all}}$, is 0.40€/ton. Data for the last radii is kept out for the types where it is not needed due to too large costs etc. The amount of input in each circle are data from Maabjerg Energy Center (2017), and transportation costs for all substrates as well as amount of digestate delivered in each circle is from Abildgaard (2017).

Process	CAPEX	OPEX fix	OPEX var	Min. process time	Max. process time
gasstorage	2.16	0	0	1	12
ironadsorption	25.90	162.4	0	1	1
bioscrub	54.74	32.5	0	1	1
biothrick	44.81	8.1	0	1	1
waterscrub	110.37	30	0	1	1
orgphysscrub	125.09	34	0	1	1
pressswingabsorp	110.37	75	0	1	1
chemscrub	110.37	45	0	1	1
methanation	1471.64	430	0	1	1
boiler	3840.72	2000	1.1	1	1
scgt	38407.18	20000	4.5	1	1
ccgt	57610.77	30000	4.5	1	1
gasengine	64011.96	10000	8	1	1
7to40	52.61	20	0	1	1
1to40	105.22	40	0	1	1
heatstorage	11.92	1.13	0	1	12
Nm3ToMWh	0.00	0	0	0	0
flaring	8093.99	0	0	0	0

Table C.6: Data for the case study—output side (Danish Energy Agency, 2012c; Evald et al., 2013; Pizarro, 2014). All costs are in €, and all CAPEX and fixed OPEX are annualised with a rate of return of 4% and the given lifetime of the process (20 years are used in case of no data). For Boiler, Single-cycle gas turbine (SCGT), Combined-cycle gas turbine (CCGT), and Gas engine CAPEX and OPEXfix are in €/MW/year and OPEX in €/MWh. For the other technologies, CAPEX and OPEXfix are in €/Nm3/h/year and none of these has any assigned variable OPEX. We have used a higher heating value of methane of 39.8 MJ/Nm3 and a lower heating value of 35.9 MJ/Nm3 and assume the methane content of biogas to be 65%, while the methane content of biomethane differs depending on the upgrading technology used.