Why would biogas plants choose to upgrade?

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Abstract

In Denmark it has been possible to upgrade biogas and achieve support as biogas-based heat and power production from 2014. Since then a large share of both new and old biogas production plants has chosen to upgrade the biogas.

We use a mixed integer programming model to find the optimal biogas value chain, and cooperative game theory to understand the real world observations compared to our results. More specifically we apply three profit allocation mechanisms to allocate the total profit between the heterogeneous owners in the value chain. We find, that Danish biogas plants should use a large share of manure combined with deep litter. Furthermore, we find that the input suppliers have a relatively poor bargaining power in the profit allocation negotiations due to poor alternatives. This may explain why livestock farmers tend to achieve a low payment for their input, and also why they may be hesitating to join a supply agreement with a biogas plant.

We find that the preference for upgrading has several reasons. If the natural gas price is expected to be high, it is preferable to upgrade compared to be using biogas directly in a local combined heat and power plant (CHP). With a lower natural gas price, upgrading could be a preferred choice for the biogas plant, since a CHP has better alternatives and therefore a better bargaining power before investments. When the value chain contains an upgrading plant, the biogas plant will have a greater bargaining power—in particular after investments.

Keywords: Cooperative game theory, Profit allocation, Mixed integer programming, Biogas, Biomethane, Renewable energy, Value chain

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1. Introduction

The Danish biogas production has developed remarkably the latest years since the change in regulation following the Energy Agreement back in 2012 (Danish Government, 2012), where it was agreed that biogas among other renewables should be strengthened compared to earlier. Several initiatives were started, where probably the most important part was that, after the EU ratification

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in 2014, it became possible to gain support when biogas is upgraded or used directly for industry, transport or in heat and power production(Danish Energy Association, 2013; European Commision, 2013).

The new changes have been a great success, and new biogas plants have been built all over Denmark the latest years (Harder, 2016), in particular the upgrading option have increased the possibility to take advantages of economy of scale independently of local heat demand (Skovsgaard and Jacobsen, 2017). Looking at the latest development and projections for new biogas plants, there is a clear picture of biogas plants choosing to upgrade instead of finding a local source of consumption. This development is both in relation to new plants, but also old biogas plants have chosen to upgrade and not proceed to deliver biogas for a local CHP (Harder, 2016). An explanation for this development could be a lack of heat demand and even a reduced heat demand along with new and cheaper heat production technologies. Furthermore, it could prove more profitable for the biogas plant to choose the upgrading solution independent of the overall optimal solution. This is the hypothesis of this paper, which we will investigate further.

The biogas value chain involves several actors from different sectors, that operate at diverse markets with diverse regulation; and input for biogas production is often a bi-product while biogas is one fuel out of many in the production of energy commodities. This may affect the opportunities for the biogas producers, the optimal pricing between the different actors in the value chain, and maybe also 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. This gives a challenge when profits should be allocated within the value chain.

Variations in ownership structures and potentials for vertical integration is out of scope for this paper. We are however aware that parts of the value chain can be considered as bilateral monopolies after investments; and that this can affect the production level in the value chain. The Myerson-Satterhwaite theorem (Myerson and Satterthwaite, 1983) states, that it is impossible to achieve ex. post efficiency in bilateral trade in cases of private information, and each time two owners stand in front of each other, there is a risk of adverse selection with the wrong design of profit allocation mechanism.

Blair et al. (1989) finds a great disagreement in the literature with regards to finding an optimal solution for the quantity and price between bilateral monopolies, they refer to Bowley (1928), Fellner (1947), and Machlup and Taber (1960) that all have found a joint profit maximizing solution under a variety of assumptions. Blair et al. (1989) concludes that the social optimal solution only can be found with joint profit optimization, and that the price between the parties is a way to share the maximized profit. Truett and Truett (1993) takes the step further and proved that under particular circumstances, hereunder perfect information, there will be only one stable and theoretically optimal price for the intermediate products between the two monopolies. This price would among other things depend on bargaining power between the two monopolies.

Within the cooperative game theoretic literature several (cost) allocation mechanisms are presented and tested both theoretically, e.g. (Tijs, 1986; Schmeidler, 1969; Megiddo, 1978; McCain, 2008; Hougaard, 2009) and empirically (Massol and Tchung-Ming, 2010; Frisk et al., 2010; Lozano et al., 2013; Nagarajan and Sošić, 2008). However, most of the literature is focused on homogeneous producer types with slightly different properties; this could be a cooperative of pig producers who slaughtered and sold the pigs together (Bogetoft and Olesen, 2007), a cooperation among liquefied natural gas suppliers (Massol and Tchung-Ming, 2010), or a cooperation of wood suppliers (Frisk et al., 2010). We will apply some of the payment schemes presented in the literature on the non-homogeneous owners in the biogas value chain. This has to our knowledge not previously been done.

In this paper we will not try to find one optimal price between the owners, and as already mentioned we will not investigate different ownership structures. Instead we will use a value chain optimisation model (Jensen et al., 2017) in order to see the potential profits which can be gained in the optimal biogas value chain under perfect information and to find the optimal biogas value chain design - which inputs are best and what is the best choice of energy converter under a specific set of assumptions, presented in chapter 2, this we do in chapter 4.

Drawing on *cooperative game theory* (McCain, 2008; Gibbons, 1992), *cost- and profit allocation theory* (Hougaard, 2009; Bogetoft and Olesen, 2007) and *principal-agent theory* (Mas-Colell, Andreu; Whinston, Michael D.; Green, 1995), we consider how a proper profit allocation mechanism could help to reach a relevant value chain design for non-homogeneous owners, and we discuss why the optimal design may not always be the preferred design. We discuss this in chapter 5 based on the theory presented in chapter 3.

2. How we find 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 optimization assuming perfect information between the owners.

The biogas value chain consists of several separate owners, o, who often operates on other markets in different sectors. The biogas value chain is depicted in figure 1 and the group of owners, $\mathcal{O}$, are in this paper defined as the livestock farmers, the substrate farmers, the plant and the energy converters. These parties delivers input and/or are involved directly in the biogas production and conversion process. Only the plant, and maybe in some cases the biogas upgrading facility, has biogas production as the primary purpose, whereas the farmers focus on the highly competitive agricultural sector. The energy converter, in the end of the value chain, focus on the end product; biomethane (upgraded biogas), electricity and/or heat. While the electricity and gas markets are exposed to a high level of competition, heat production can be considered as a natural monopoly, and is therefore monopoly regulated. As will be presented in section 2.1, the regulative design implies, that the biogas plant is highly dependent on waste input—in this paper defined as agricultural waste—in order to be *allowed* to receive support, and a demand from the energy converter in order to *receive* support. Both sectors are highly exposed to competition or is monopoly regulated.

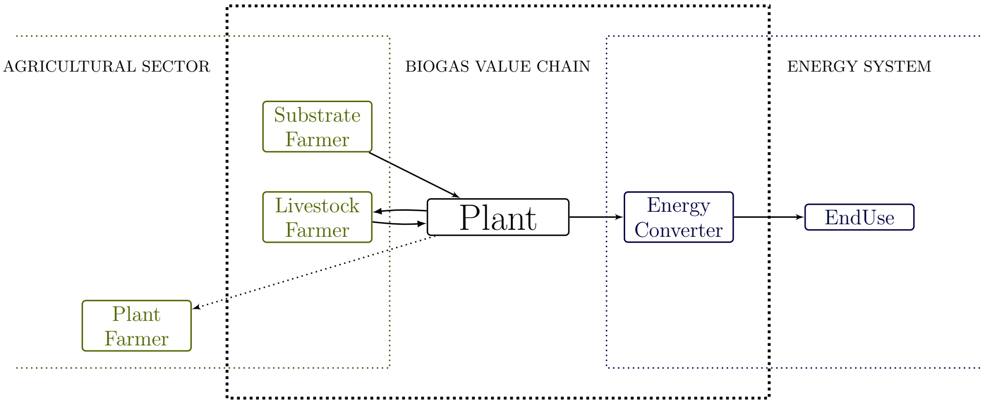

Figure 1: Ownership structure

The ownership structure within the value chain differs among plants, and in Denmark you find several variations. In one case, a group of farmers have invested in a biogas plant and an upgrading facility, e.g. Madsen Bioenergi (Madsen Bioenergi, 2017). In another case, one owner controls input and biogas production, while another owner controls the upgrading plant, e.g. Fredericia waste water (Wittrup, 2010). The specific choice of ownership structure depend on several factors hereunder cost of capital. As mentioned, this will not be a study on the optimal ownership structure and therefore not investigated further.

Instead, we focus on the optimal choice of value chain design by using the plant level model presented in section 2.2, that includes the basic assumptions presented in 2.3 and most of the regulation around the value chain. The regulation also influences on the choice of value chain design and is presented below.

2.1. Regulation

Focus in Danish biogas regulation span over several sectors and different priorities. Biogas support and the regulative set-up around biogas is designed in an energy focused mindset, while emphasis at the same time has been put on the need of sustainability and use of manure in the biogas production. These two focal points surround the Danish biogas policy and has a significant influence on the importance of the separate owners in the value chain

Two overall parts of the biogas regulation is presented in this section, and further described in Appendix A.

- Input: In order to receive biogas support, it is important, that a large share of the input in the biogas production consists of waste—preferable manure or waste water. This could also be waste products from slaughterhouses or dairy production, however these sources are limited. Alternatively, the biogas production can be supplemented with other waste products

such as straw or deep litter. Furthermore, it is allowed to use a limited amount of energy crops.
- Output: Biogas support is primarily paid in 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.

From this we identify three overall parties in the biogas value chain, that are necessary to include in order to receive support with the current regulatory setting; the livestock farmer, the biogas plant and the energy converter.

The regulation with regards to energy production and consumption is extensive in Denmark, where the general principles are that renewable energy is supported, and taxed as little as possible, while electricity and fossil fuels are taxed heavily with few exceptions. A further description with regards to biogas production can be found in Appendix A.

A large share of the heat supply in Denmark is covered by local heat production plants and distributed through a local grid. These are natural monopolies and therefore monopoly regulated. The regulation type is a cost-of-service-regulation, where profits for the producers should be zero (*hvile-i-sig-selv* in Danish). The principle is, that only heat production *costs* are covered by the consumer, who often is a co-owner. In order to assure as low costs for the heat consumers as possible, the heat producers are obliged to produce heat at the lowest possible costs, and this is monitored by the Danish Energy Regulatory Authority (DERA). One of the implications of this regulation is that profit allocation within the biogas value chain can be affected by the regulation, if the energy converter produces heat.

2.2. Plant level model

The model takes as a starting point the model from 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 choice of the chain from the farmer to the energy demand by finding the optimal choice of e.g. inputs to the plant and technologies for utilising the biogas. The modelled chain can be seen in figure 2. The supply chain is modelled such that the input side, i.e. until the plant, uses a weekly time scale, while the output side uses an hourly time scale. This allows us to capture the fluctuations of energy prices and still keeping the model as small as possible. The model combines both the strategic decision of sizing the processes, and tactical decisions, e.g. amount of manure used as input, when to store the biogas, etc.

The possible energy converters in the chain are a combined heat and power plant, a heat boiler, an upgrading plant, and upgrading through methanation. A traditional upgrading plant removes the CO_2 from the biogas such that the methane content of the resulting biomethane will be similar to that of natural gas. For methanation, hydrogen is produced through electrolysis and added such that the CO_2 from the biogas is converted to methane. Besides the added amount of biomethane from the methanation process compared to the traditional upgrading plant, process heat will also be generated of which some can be sold for district heating.

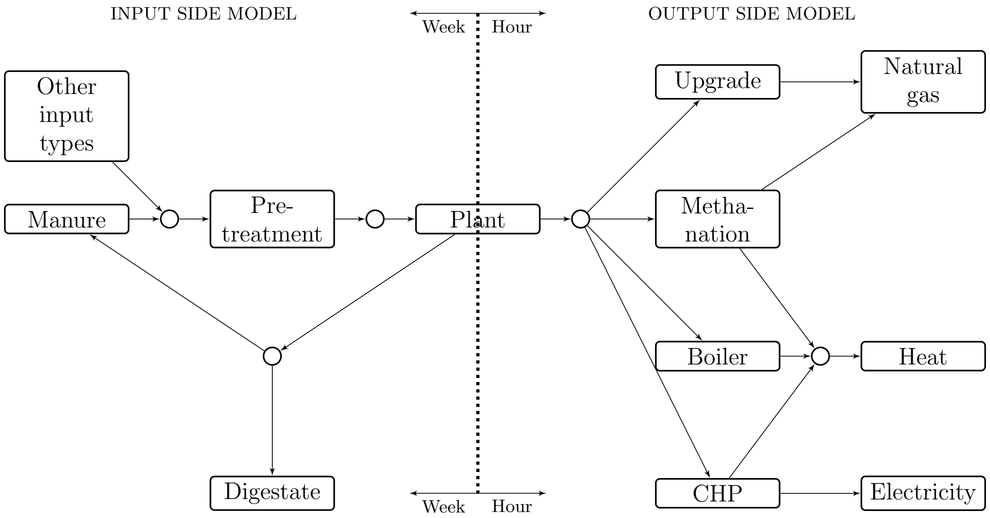

Figure 2: The biogas value chain from farmer to energy demand with the input side using a weekly time scale and the output side using an hourly time scale.

The objective function used in (Jensen et al., 2017) was profit maximisation. In this paper, the objective function is slightly different. In (Jensen et al., 2017), the farmer was only included by receiving a price for the delivered manure or crops. In this paper, the farmer is a potential owner and his costs must therefore be included in the total costs of the chain. For practical reasons related to profit allocation, see subsection 3.3, it was decided to move the transportation costs of the biomasses to the biomass producer instead of the biogas plant. 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, which are described in equation 1–5. We identified two more neccessary constraints that were not in the model from Jensen et al. (2017). These are given in constraints 6 and 7.

The objective function is now to maximise the sum of profit for the owners:

$$Max \sum_{o \in \mathcal{O}} \pi_o \tag{1}$$

Where π_o is the profit for each owner, o, in the project and is given by:

$$\pi_o = INC_o - C_o \quad \forall o \in \mathcal{O} \tag{2}$$

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:

$$
\begin{aligned}
INC_o = & \sum_{\substack{v=(p,t)\in \\ \overline{\mathcal{V}}^E \cap (\overline{\mathcal{P}}^E \times \overline{\mathcal{T}}) \\ |\mathcal{OP}(o,p)}} \Big(\sum_{a \in \overline{\mathcal{A}}^-(v)} (\overline{x}_a - x^{left}_{p,t})\, \eta^{price}_a \, \overline{\rho}_{p,t}\, \eta^{available} && \text{(3a)} \\
& + \rho^{support}_o + \sum_{\substack{p \in \mathcal{P}^{plant} \\ |\mathcal{OP}(o,p)}} x^{\neg manure}\, \rho^{dig} \qquad \forall o \in \mathcal{O} && \text{(3b)}
\end{aligned}
$$

Here line 3a 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^{price}_a, 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 3b is the amount of support received by owner o, $\rho^{support}_o$, 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:

$$
\begin{aligned}
C_o = & \sum_{\substack{v=(i,p,t,e)\in \\ \mathcal{V}\cap(\mathcal{I}\times\mathcal{P}\times\mathcal{T}\times\mathcal{E}) \\ |\mathcal{OP}(o,p)}} \sum_{a\in\mathcal{A}^-(v)} x_a\,(c^{OPEX}_{i,p} + c^{OPEX,var}_{i,p,t}) + \sum_{\substack{v=(p,t)\in \\ \overline{\mathcal{V}}\cap(\overline{\mathcal{P}}\times\overline{\mathcal{T}}) \\ |\mathcal{OP}(o,p)}} \sum_{a\in\overline{\mathcal{A}}^-(v)} \overline{x}_a\,(\overline{c}^{OPEX}_p + \overline{c}^{OPEX,var}_{p,t}) && \text{(4a)} \\
& + \sum_{i\in\mathcal{I}} \sum_{\substack{p\in\mathcal{P} \\ |\mathcal{OP}(o,p)}} k_{i,p}\, \frac{T}{t^{min}_{i,p}}\, c^{CAPEX}_{i,p} + \sum_{\substack{p\in\overline{\mathcal{P}} \\ |\mathcal{OP}(o,p)}} \overline{k}_p\, \overline{c}^{CAPEX}_p && \text{(4b)} \\
& + \sum_{\substack{p\in\mathcal{P}^{plant} \\ |\mathcal{OP}(o,p)}} \bigg(\sum_{n\in\mathcal{N}} x^{SOS2}_n\, c^{OPEX,SOS2}_n + \sum_{n\in\mathcal{N}} k^{SOS2}_n\, c^{CAPEX,SOS2}_n \qquad \forall o \in \mathcal{O} && \text{(4c)} \\
& + \sum_{m\in\mathcal{M}} x^{trans,xdig}_m\, c^{TRANS,xdig}_m + \sum_{v\in\mathcal{V}^P} \sum_{a\in\mathcal{A}^-(v)} (x_a\,\eta^{plant} - x^{\neg manure})\, c^{HANDLING,dig} \bigg) && \text{(4d)} \\
& + \sum_{\substack{i\in\mathcal{I} \\ |\mathcal{IO}(i,o)}} \sum_{m\in\mathcal{M}} x^{trans}_{i,m}\, c^{TRANS}_{i,m} + \sum_{\substack{p\in\overline{\mathcal{P}}^{heat} \\ |\mathcal{OP}(o,p)}} \overline{x}^{heattax} + \sum_{\substack{p\in\mathcal{P}^{slurry} \\ |\mathcal{OP}(o,p)}} x^{should}\, \rho^{dig} && \text{(4e)}
\end{aligned}
$$

Line 4a and 4b 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 4c-4d is the OPEX and CAPEX of the plant and the transportation and handling costs of digestate. Line 4e 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 4e.

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:

$$x^{should} \geq \sum_{v \in \mathcal{V}^M} \sum_{a \in \mathcal{A}^+(v)} x_a \gamma - \Big(\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{P}^P \times \mathcal{T} \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \eta^{plant} - x^{\neg manure} \Big) \tag{5}$$

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:

$$x^{heattax} \geq c^{tax}_{p,p'} \Big(\Big(\sum_{v=(p,t) \overline{\mathcal{V}} \cap (\overline{\mathcal{P}}^{m^3} \times \mathcal{T})} \sum_{a \in \overline{\mathcal{A}}^+(v)} \overline{x}_a \Big) - \sum_{t \in \overline{\mathcal{T}}} x^{left}_{p',t} \Big) \quad \forall p \in \overline{\mathcal{P}}^{m^3}, p' \in \overline{\mathcal{P}}^H \tag{6}$$

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:

$$\sum_{\substack{v=(i,p,t,e) \in \\ \mathcal{V}^P \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} \gamma^{DM}_i x_a \leq \Gamma^{DM} \sum_{\substack{v=(i,p,t,e) \in \mathcal{V}^P \\ \cap (\mathcal{I} \times \mathcal{P}^P \times \mathcal{E})}} \sum_{a \in \mathcal{A}^-(v)} x_a \qquad \forall t \in \mathcal{T} \tag{7}$$

2.3. Assumptions

In our calculations we follow the recommendations for socio-economic analysis for Denmark with an interest rate of 4% for all capital expenditures (CAPEX) (Danish Energy Agency, 2013) and the depreciation time is set according to the data sources. If no data was available, we used a depreciation time of 20 years. Data on input and output process costs can be found in Appendix B, Table B.3 and B.6, where we also present a graph on the overall CAPEX used in the model,

Figure B.1. We assume economy of scale for the biogas plant, and constant return to scale with regards to the upgrading plants and pretreatment of substrates.

We assume that the farmers cover transportation costs to and from the plant. Data for transportation can be found in Appendix B, Table B.5. We also assume that the pretreatment of straw and deep litter is undertaken at the biogas plant, while the ensilage of maize and washing of the sugar beets is done by the farmer. The cutting and ensilage of sugar beets is done by the plant. For input to the plant, we set a maximum dry matter content of the total feedstock to be 13% (Jørgensen, 2013). Data for the input can be found in Appendix B, Table B.4. We assume that excess digestate can be sold for 8.85 €/tonnes and must be transported with the costs given in Appendix B, Table B.5.

The geographical position of the plant is in North West Denmark. This placement has the advantage of being close to a vast amount of manure and other substrates. A potential disadvantage of the area is a lot of other biogas plants, who would be interested in the same substrates, combined with a relatively low heat demand. We assume, that the model plant can be relatively certain of a demand from the local heat plant in the town *Vinderup*, which corresponds to approximately 36,000 MWh/year (Vinderup Kraftvarmeværk, 2014). This is the heat demand we use in the model. The heat price is set individually at each plant following the principle of cost-of-service described in section 2.1. The heat price has a large variation across the country so we use the heat price set by *Vinderup Kraftvarmeværk* as given by Danish Energy Regulatory Authorities, see (Energitilsynet, 2017).

2016 is the base year for our model year, meaning that all prices for power, heat, and natural gas are from 2016 and so are the regulatory tariffs. The power price is from the Nordpool Spot market, which is the trading place for the Nordic power market; while the natural gas is traded on GasPointNordic and the prices we use are the historic prices from 2016. An overview of the historical prices can be seen in figure 3. We apply the regulation given in Appendix A, Table A.1 and Table A.2.

3. Method to allocate profit

In section 4 we confirm the results from (Skovsgaard and Jacobsen, 2017) and (Jensen et al., 2017), that biogas production can be profitable with the current regulation; however, the value chain can be fragile without a proper profit allocation between the owners.

A basic principle for profit allocation could be to at least ensure feasibility for all participating owners in the value chain—meaning that profit should be greater than zero. This may not be enough, so in order to follow the idea from Blair et al. (1989) to find a way to share maximised profit, we use the overall principles from cooperative game theory with regard to cost allocation, and we focus on the fairness criteria *equality* and *individual rationality.* Our aim is *not* to identify the optimal allocation mechanism, as this can not be decided from a theoretical study (Tijs, 1986)

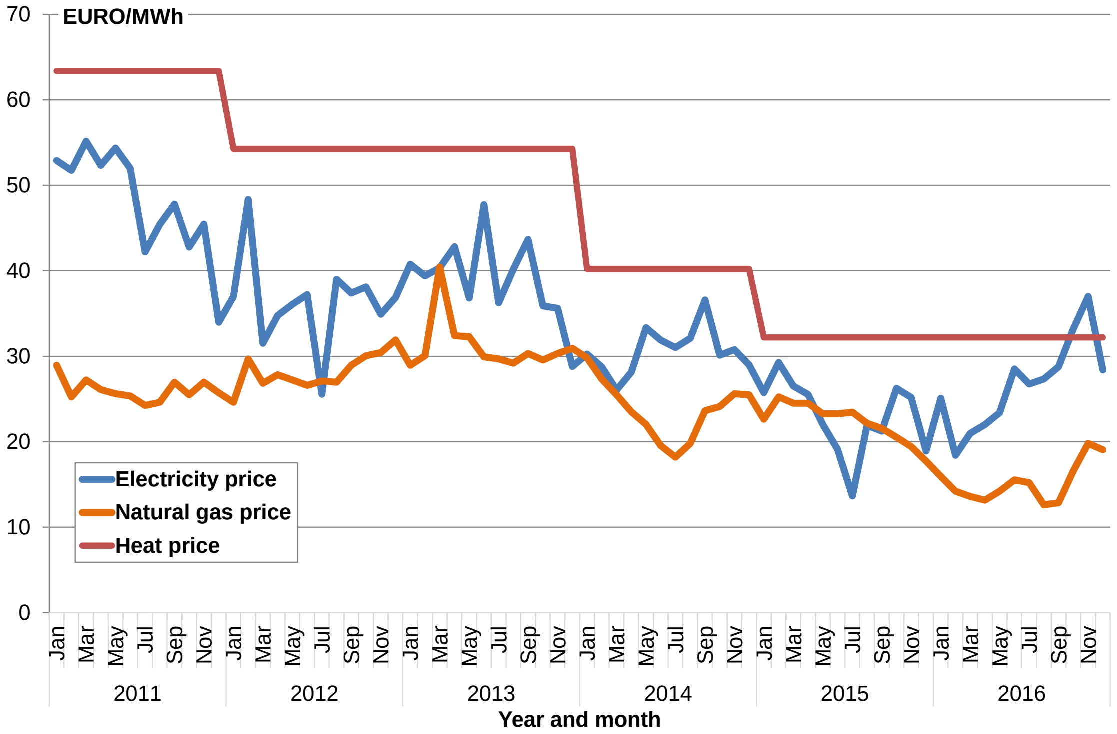

Figure 3: The historical prices for electricity, natural gas, and heat

and (Bogetoft and Olesen, 2007). Rather we try to understand the strategic considerations related to profit allocation and the following choices made by the owners, when the value chain design is made.

To make this assessment, we investigate three allocation mechanisms suited for the value chain, where profits are distributed through the prices in the chain. These mechanisms are:

- Full equality, that resembles the egalitarian cost allocation method presented in e.g. (Tijs, 1986)
- Proportionality, in cost allocation theory also presented as AVC (Average cost rule) (Hougaard, 2009)
- Individual rationality, inspired by the nucleolus as in e.g. (Massol and Tchung-Ming, 2010)

In section 3.3, we present how the profit allocation is modelled.

Before we continue the considerations with regards to profit allocation, we limit the cooperative to the absolute necessary owners in the value chain, assuming that the value chain prefers to keep the subsidies presented in section 2.1. These owners are the livestock farmer (no waste, no support), the plant (no plant, no biogas) and the energy converter (no energy converter, no support). This leaves out the substrate farmer, who will not be included in the cooperative, because support *can* be achieved without additional substrates, and substrates can be substituted. Instead, the substrate farmer is paid an amount for the substrate corresponding to the production costs for the substrate transported to the plant plus additionally 10% of the transportation costs. We are aware that there are other ways of determining the price, see e.g. (Giannoccaro et al., 2017), handling the availability based on the price of biomasses in a region, see e.g. (Bai et al., 2012), and that 10% for some substrates is too little, but this has not been the main focus of this paper.

3.1. Considerations for the choice of allocation

Several relevant fairness criteria for an allocation mechanism are presented in the literature. Bogetoft and Olesen (2007) presents a long list of potentially relevant criteria depending on the type of cooperative and the closest surroundings of the cooperative, e.g. the cooperative could be a group of pig farmers, who can affect the market prices for pigs. In this case it would be relevant to design the allocation mechanism to include an incentive for not producing too many pigs, and thereby drive the market prices down (Bogetoft and Olesen, 2007). Others present the fairness criteria at a more general level e.g. (Tijs, 1986; Hougaard, 2009).

As mentioned we focus on the 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). Other fairness criteria such as risks for the value chain and the risk of adverse selection are also considered.

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 (also known as the "split the pie game" (Gibbons, 1992)) would offer the other agent a zero share of the pie, which a 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 (2008) 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 (2009) argues that equality in some form, e.g. direct equality or maximin equality, can be found in most large religions and thereby social norms. We therefore consider this fairness criteria as crucial for our evaluation of the allocation mechanisms.

Another important element of *homo economicus* is individual rationality: "Does it make sense to join in? Or is there a better alternative?", we have therefore chosen to use individual rationality as the other fairness criteria to focus on. We present this further in section 3.4.

3.2. Payment schemes

Several allocation mechanisms have been found and compared within cooperatives with homogeneous owners. There is e.g. the proportional allocation, where profit is allocated: in accordance with cost (Equal return on capital) (Hougaard, 2009); according to the gain delivered to the cooperative (ACA) (Bogetoft and Olesen, 2007); or by using the Shapley Value, where each part in the cooperative gains a profit corresponding to the gain, that the part has contributed with (Lemaire, 1984; Massol and Tchung-Ming, 2010; Frisk et al., 2010). Other payment schemes focus on the egalitarian principle such as the egalitarian method, where profit is divided equally between all parties in the cooperative (Tijs, 1986; Lemaire, 1984; Massol and Tchung-Ming, 2010), or the nucleolus payment scheme, where the profit allocation depend on the alternative profit of the marginal participant (Massol and Tchung-Ming, 2010; Schmeidler, 1969; Frisk et al., 2010). Many of these allocation mechanisms could be relevant for a payment scheme between livestock farmers in a cooperative delivering manure to the biogas plant. In such a cooperative the producers would be homogeneous with slightly different properties, such as distance from the plant and content of dry matter in the manure, and a good allocation scheme would include incentives to deliver a high dry matter content.

An overall assumption in this paper is, that there is some kind of cooperative among the livestock farmers where all these mechanisms could be relevant, it is however not the focus point here. Instead we focus on the three overall owners in the value chain (livestock farmers, plant and energy converters), who are heterogeneous producer types with a large degree of interdependency. This implies that each party is as relevant as the other, even though one of the parties may take the initiative and by that may gain an upper-hand in the negotiations. We imagine, this could be the plant that only exists with the purpose of producing biogas, whereas biogas is a secondary product for the farmer, and for the energy converter the purpose is to produce a specific type of energy.

In this context, many of the above mentioned allocation schemes become irrelevant, however some of the principles from these schemes can be reused. In section 3.3, relevant versions of the egalitarian method, the proportionality principle, and a method inspired by the nucleolus—here called individual rationality—are presented.

3.3. Modelling the allocation mechanisms

After running the plant level model, the allocation is performed. A general allocation model is given below, where constraint 9 is mechanism specific and will be given for each of the used allocation mechanisms described in the following sections.

$$\begin{aligned}
\text{Max} \quad & z = \lambda && && (8)\\
\text{S.t.} \quad & \textbf{Feasibility constraint} && \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} && (9)\\
& \pi_o^{CA} = \gamma^{feas} C_o^* && \forall o \in \mathcal{O}^{sub} && (10)\\
& \pi_o^{CA} = \pi_o^* - \sum_{o' \in \mathcal{OTO}(o',o)} \rho_{o',o}^{CA} + \sum_{o' \in \mathcal{OTO}(o,o')} \rho_{o,o'}^{CA} && \forall o \in \mathcal{O} && (11)\\
& \lambda \geq 0 && && (12)\\
& \pi_o^{CA} \geq 0 && \forall o \in \mathcal{O} && (13)\\
& \rho_{o,o'}^{CA} \geq 0 && \forall o \in \mathcal{O}, o' \in \mathcal{OTO}(o,o') && (14)
\end{aligned}$$

The objective function 8 is to maximise the decision variable λ, which is specific for each of the used allocation mechanisms. Constraint 10 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 11, 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.

3.3.1. Full Equality, direct equality

The Full Equality method has many names, e.g. the egalitarian method, direct equality etc. The principle is that all owners share the total profit equally; irrespective of their total costs.

The feasibility constraint for the full equality allocation is:

$$\pi_o^{CA} = \frac{1}{|o \in \mathcal{O} \setminus \mathcal{O}^{sub}|} \sum_{o' \in \mathcal{O} \setminus \mathcal{O}^{sub}} \pi_{o'}^{CA} \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{15}$$

Here the profit of each owner who are not substrate owners, will be a share of the total profit for all non-substrate owners. The share relies on the number of non-substrate owners and is therefore divided by the number of non-substrate owners. For this 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 $\lambda = 0$.

An owner with a high cost would bear the highest risk using this mechanism, which most likely would not be considered fair. Furthermore, there is a minor challenge with adverse selection as full equality requires all owners to report their cost honestly, which implies a risk that an owner would report a higher cost than what he actually faces in order to keep some profit for himself.

3.3.2. Proportionality

The proportionality mechanism is not as simple as full equality. One must determine what element the profit should be proportional to, e.g. total costs, CAPEX or OPEX. Looking at the three primary parts of the value chain, livestock farmer, plant and energy converter, it becomes difficult to find one common parameter or variable that counts for all parts of the value chain and still doesn't give a challenge in relation to knowledge-sharing. In this paper, we choose to use the cost for each owner from the plant level model. This choice implies that all owners should have a cost assigned and this is why we have chosen to add the transport cost to the farmers unlike in the model from (Jensen et al., 2017).

The feasibility constraint for the proportionality allocation is:

$$\pi_o^{CA} = \lambda C_o^* \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{16}$$

Here λ will be the percentage of the cost that can be covered for each of the non-substrate owners.

The proportionality mechanism suffers from adverse selection to an even higher degree, as it gives an incentive to boost your own costs in order the achieve a higher share of the total profits. The method does not reflect, that all three parts of the chain are necessary to achieve support.

3.3.3. Individual rationality, maximin equality

The last mechanism that we apply is inspired by the maximin profit allocation, nucleolus. In the traditional nucleolus all combinations of participating owners and their alternative profits are used in the allocation, and profit for each owner is found by maximising the distance from the obtained profit to the alternative profit for all subsets of the participating owners. The owners in the traditional nucleolus are of the same type, see e.g. (Frisk et al., 2010), and the operability of the collaboration would therefore not be relying on each owner individually. In our case the owners are relying on each other to make the biogas chain running and the nucleolus can therefore not be directly applied.

Instead of looking at all subsets of the chain, we therefore maximise the distance from the obtained profit to the alternative profit that the owner would get by not participating. This ensures that the obtained solution is within the core, meaning that all owners are better of when they are part of the chain.

The feasibility constraint for the individual rationality cost allocation is:

$$\pi_o^{CA} - \pi_o^{ALT} \geq \lambda \quad \forall o \in \mathcal{O} \setminus \mathcal{O}^{sub} \tag{17}$$

Here λ is the gain from participating for all of the non-substrate owners, and π_o^{ALT} is the reported alternative profit for each owner o.

This allocation mechanism can seem more fair, as it is more equal, than the proportional distribution and takes more individual properties into account than the full equality distribution, however costs are not directly taken into consideration. Other challenges are the lack of transparency and a necessary high level of information in order to calculate the allocation; the last point opens up for dishonest reporting on the best alternative.

We do not know which allocation mechanism is used in the actual biogas value chain, and this would off course also depend on the ownership structure within the specific value chain. In chapter 5 we evaluate the results from the model and relate these results to individual rationality. We then assess the potential implications of this with regard to a possible preferred choice of value chain and profit allocation design.

3.4. Individual rationality

Truett and Truett (1993) argues that one specific price between two parties can be found, and the bargaining power between the two parties contribute in determining this price. But what determines the bargaining power? This—among other things—can depend on the level of information between the parties in the value chain (Radhakrishnan and Srinidhi, 2005) and maybe more importantly by how dependent each party is on the collaboration, which again is determined on the best alternative for each party. This is also highly relevant with regards to profit allocation, and is often referred to as the stand-alone profit. The allocation mechanism is unstable, if the profit allocated to an individual part in the group is below her stand alone profit. Furthermore, a profit allocation is stable if it is *within the core*, where the core is a set of profit allocations, where it is beneficial for all group members to cooperate, meaning that the profit allocation should result in a profit that exceeds the stand-alone profit for all in the cooperative (Bogetoft and Olesen, 2007).

The sample space of best alternatives is quite large, so in order to narrow this sample space down to a reasonable amount of calculations, we exploit that we have reduced the owner group to three overall parties, who are all necessary in order to make a profit. Some of the owners can to some extent be replaced after investments, though at the expense of the overall profit in the value chain.

Our approach is to consider the alternatives for the individual owners and the entire value chain. As capital costs are an extensive part of total costs in a biogas value chain, we both consider the choices before investments and after investments, as the after investment bargaining power might affect the preferences of each owner with regards to both the value chain configuration and the preferred allocation mechanisms before investments.

	Before investments	**After investments**
Livestock farmer	deliver manure to another biogas plant	deliver manure to another biogas plant
Substrate farmer	not deliver the substrate to a biogas plant	find another place to deliver the substrate
Plant	invest capital with 4% interest rate	sunk cost
Energy converter, CHP	biomass based heat boiler	sunk cost and biomass based heat boiler
Energy converter, upgrade	invest capital with 4% interest rate	sunk cost

Table 1: Stand-Alone profits

The alternatives we evaluate in chapter 5 are presented in table 1, and the results for the table—presented in table 5—are also used in the calculation of the individual rationality profit allocation. For the livestock farmer we assume that the best alternative is to deliver manure at another biogas plant. He could also choose to apply his manure directly on the fields, but this would not give the additional fertiliser value from the digestate. A common payment for manure is, that the biogas plant collect the manure and bring the digestate for free, in table 5 this alternative is presented as a zero profit, as the fertilizer value is not included in the calculations.

The alternatives for the substrate farmer, depends on the substrate. In the case of deep litter, the substrate would most often be considered a waste product. In the case of straw, the farmer might leave the straw on the field or sell it to a local CHP or an ethanol plant.

The plant would have several options, but in this analysis we assume that the plant invests the capital in safe investments at a interest rate corresponding to the socio-economic interest rate before investments, and sunk cost after investment. It is just as likely that the plant would try out other options in particular after investments have been made. We choose this simple alternative, as the more likely alternatives are presented in table 2 on the alternatives for the entire value chain.

In order to decide the best alternatives for the energy converter, we need to make some overall assumptions for the coverage of heat and power demand and realistic options around and within the model. The plant level model presented in chapter 2 can choose between different upgrading technologies, a heat- and power plant (CHP) and a heat boiler. With the current regulation it is unlikely that the optimal choice is to produce heat on biogas. We therefore do not consider this when constructing the table. With regards to the coverage of heat and power demand, we have two different markets to consider. The power market is highly competitive in Denmark, and a CHP is in many cases only viable in relation to a supported fuel as biogas. Heat is monopoly regulated and we assume that the energy converter in most cases will have to find an alternative to the heat production, if the biogas based CHP is dismissed. We therefore assume, that the best alternative to a biogas-based CHP would be a biomass-based heat boiler. This goes for both before and after investments. In the case of upgrading, we assume that the energy converter can freely choose between supplying the heat demand or not.

	Before investments	**After investments**
Livestock farmer	Longer transport distance	Longer transport distance
Substrate farmer	Other substrate	Other substrate and sunk cost in pre-treatment
Energy converter	Other energy converter	Other energy converter and new investments

Table 2: Alternative profits for the value chain, when 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 another position with regards to the bargaining power. We assume that all the other parties can be substituted at the expense of total profit in the value chain.

The content of the table is derived through the plant level model. In the case of the livestock farmer, we take advantage of the assumption that the livestock farmer is a cooperative and not a single farmer. It is therefore realistic that some farmers in the cooperative could decide to go for another alternative and not join the value chain. In order to choose a simple case we assume, that one third of the manure at each distance radius leaves the livestock farmer cooperative. The new data on manure access are then fed into the model, and a new optimum is found with a lower profit.

In the case of the substrate farmer and energy converter, the model is run first with the restriction of *not* to choose the optimal choice of substrate. Afterwards the model is run without restriction on the substrate, but with a restriction on the optimal energy converter. We then find the new optimal solution and the corresponding alternative profits.

4. The optimal choice of value chain

4.1. Scenarios

In this section we consider a base scenario, where the model determines the optimal size of the plant, the optimal substrates to add in the production, and the optimal energy converter—given the substrate, transportation, and investment costs in relation to potential income.

The plant level model is a very detailed model, that finds the optimal plant set up considering a large spectrum of choices with regards to substrate inputs (price, investment costs, distances), plant size options (with regard to input options, energy demand and economy of scale) and energy conversion (with regard to biogas output, energy demand and investment and operational costs). All this is optimised together, and in order to keep calculation time down, the optimisation is done for one year, where investment costs are estimated as yearly costs. Therefore, the model does not consider price and cost variations over several years. As energy prices on both the input and output side has great influence on the optimal investment choice and these prices can vary significantly, we run two rounds of sensitivity analysis:

- Sensitivity, where one parameter is changed
- Sensitivity, where a group of parameters are changed

First, we consider the electricity costs that can have great influence on whether it is profitable to use the methanation technology. A large part of the electricity costs in Denmark are energy taxes and fees. In the case of process usage as we assume methanation is, taxes and fees will consist mostly of the Public Service Obligation (PSO). Since the PSO will be phased out until 2022 (The Danish Ministry of Energy, Utilities and Climate, 2016), we find it relevant to see whether it would affect the optimal solution. Therefore we make a scenario where the PSO is set to zero. This scenario is called *PSO zero*.

Another relevant parameter is the natural gas price. The natural gas price was quite low in our base year compared to the previous years, so the optimal solution might change with the natural gas price. We therefore use the time series for the natural gas price from 2013—where the prices were almost the double of the prices in 2016—and see the effect of natural gas prices. In the scenario *NG high* we use the natural gas price and set all other data equal to those of the base scenario.

	Electricity cost		**NG-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	Mid	22.3	Mid	32.2	Low
2013	24.0	Semi-High	31.4	High	54.3	High

Table 3: Investigated scenarios

The energy system is to a high extent interrelated: when natural gas prices are high one can expect that this will be reflected in the heat prices in the areas, where natural gas is used as fuel. As Denmark becomes more dependent on renewable energy as wind, solar, and hydro power it can be expected, that the electricity price is less dependent on the natural gas price—except when the renewables are insufficient to cover the electricity demand. We therefore expect less convergence between the natural gas price and electricity costs, however, due to variations in weather conditions we can also expect a certain variation in the electricity price. In the second group of scenarios *2013* and *2015* we test the model with regards to a group of energy costs and prices. In these scenarios we use the fundamental costs from the base-scenario, but use the electricity price + taxes and fees, the natural gas price and the heat price from the years 2013 and 2015.

4.2. Results and preliminary conclusion

The results from the plant level model is seen in Table 4. The biogas plant is as large as possible in all scenarios, 600,000 tonnes per year, and the preferred substrate is in all cases deep litter. In the base scenario a combined heat and power plant is installed. The type of energy converter installed seems to depend mainly on the natural gas price, as the PSO zero scenario still gives us a combined heat and power plant as energy converter, while methanation is preferred in cases with a higher natural gas price. In the scenarios with a higher natural gas price, the total profit also shows to be larger than in the base case.

The amount of support given in each scenario also depends on the energy converter. Here it shows that the given support is lowest in the base scenario, however, the support given per unit of energy is lower when using methanation. In the scenarios using a CHP, the support is

	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 (ccgt)	CHP (ccgt)	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: Scenario results

97.93€/MWh, and in the scenarios using methanation, the support is 32.41€/MWh, so for less support, more energy is provided. The methanation process, besides getting less support per unit of energy, also pays taxes in the form of electricity tax on the used electricity and excess heat tax.

When biogas producers have chosen to upgrade the later years, it could be explained with an expectation of higher gas prices in the future—an expectation shared with the Danish Energy Agency (Danish Energy Agency, 2012b, 2017). One should be aware that the model chooses the methanation technology, which is not fully commercialised yet.

The NG high scenario gives the highest profit across all of our scenarios by only changing one parameter. We consider this scenario further as a relevant alternative to the Base scenario in the analysis in section 5.

5. A useful profit allocation and the implications

In this section we apply the methods from Bogetoft and Olesen (2007) together with Hougaard (2009), in order to 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 for discussing the effects of applying the allocation mechanisms full equality, proportionality and individual rationality. The results from the plant level model makes it possible to write up the alternative profits for each owner in the chain, which is given in table 5.

	Before investments		**After investments**	
	Description	**Alternative profit**	**Description**	**Alternative profit**
Livestock farmer	Other biogas plant	0 €/ton	Other biogas plant	0 €/ton
Substrate farmer, deep litter	Not delivering substrate	0 €/ton	Leave on field	0 €/ton
Plant	No investment, base	0.07 m.€/y	Sunk cost, base	-1.82 m.€/y
	No investment, NG high	0.07 m.€/y	Sunk cost, base	-1.67 m.€/y
Energy converter, CHP	Heat boiler, base	0.53 m.€/y	Sunk cost CHP plus heat boiler profit	-1.26 m.€/y
Energy converter, Upgrading	No investment, NG high	0.07 m.€/y	Sunk cost	-1.84 m.€/y

Table 5: Alternative profits for the owners in the value chain

5.1. Results from the profit allocation

As seen in figure 4, the profit is allocated quite differently depending on the decided profit allocation mechanism. For the proportionality mechanism the allocation would most likely not be considered as equal with the relatively high profits we find in chapter 4.

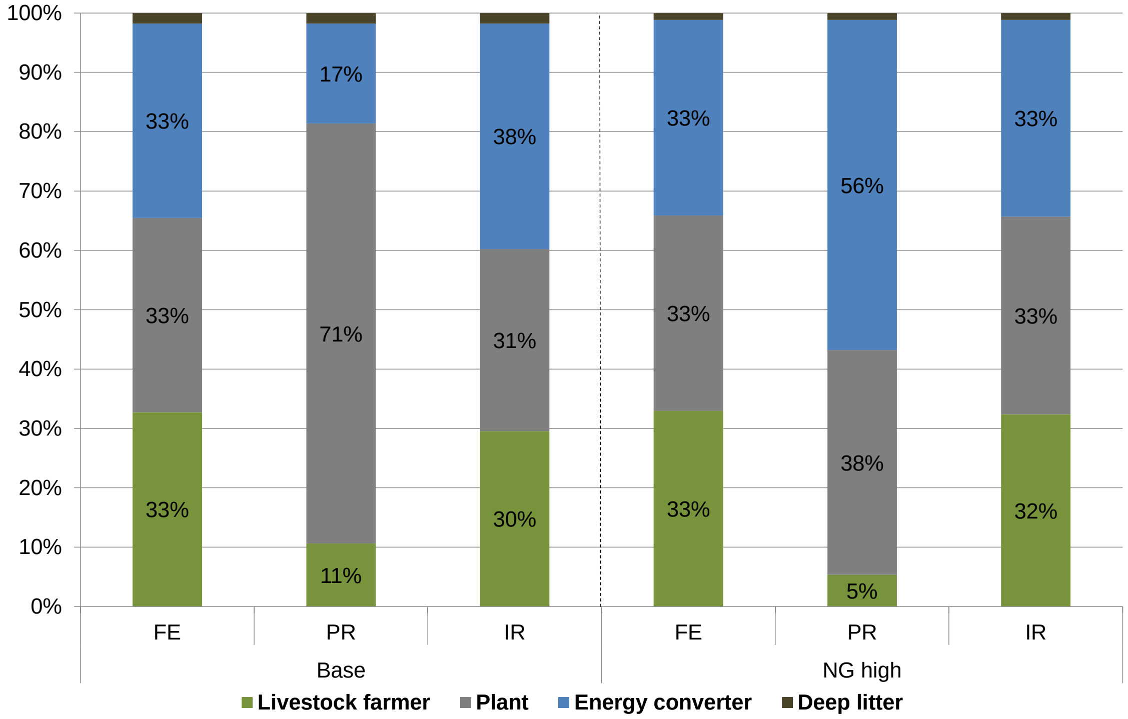

Figure 4: The percentage of the total profit for each owner in all scenarios

It is obvious that the plant owner would prefer the proportionality distribution, where the highest percentage of the profit can be gained. This is underlined by the exact numbers for the profit for each owner using the allocation mechanisms described in 3.3 that is shown in table 6. We find, that the plant owner would prefer the proportional allocation in both scenarios, while the livestock farmer would always prefer the full equality. More specifically we find in the base scenario, that the livestock farmer and the energy converter—as opposed to the plant owner—would prefer the full equality or the individual rationality mechanism, which gives them a higher total profit. In the NG high scenario, both the plant and the energy converter would prefer the proportionality mechanism. The change in results from the energy converter's perspective can be explained by the higher costs related to the methanation, which is only reflected in the proportional allocation. The livestock farmer would still prefer the full equality or the individual rationality mechanism.

		Base			**NG high**		
	Unit	**FE**	**PR**	**IR**	**FE**	**PR**	**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

In the base scenario, the highest biogas price is found using the proportional allocation. This is where the plant would gain the highest profit even though the total profit is lower compared to the NG high scenario. In the NG high scenario, the proportionality mechanism results in the lowest cost of the biogas as the highest profit with this mechanism is given to the energy converter, meaning that less amount of money should be paid to the rest of the chain.

5.2. Risk and adverse selection

Following the notions from Bogetoft and Olesen (2007) and Hougaard (2009) about individual rationality in the profit allocation, we examine whether our profit allocation can be considered to be in the core.

Each owner in the value chain is expected to consider their own gain from participating in the value chain compared to be doing something else. In order to reach a viable value chain it is necessary to find a viable profit allocation, both in order to assure investments and to assure that the most important partners stay in the value chain.

If one owner retracts from the value chain, the profit will be reduced compared to the results in table 4. The new profits obtained is given in table 7 as the percentage of the optimal profit from the base and NG high scenarios, see also section 3.4.

	Before investments		**After investments**	
	Description	**Percentage of profit**	**Description**	**Percentage of profit**
Base				
Livestock farmer	Longer transport distance	97%	Longer transport distance	97%
Substrate farmer	Straw	55%	Straw and sunk cost	51%
Energy converter	Water scrubbing	63%	Water scrubbing and sunk costs	47%
NG high				
Livestock farmer	Longer transport distance	98%	Longer transport distance	98%
Substrate farmer	Straw and sugar beet	75%	Straw, sugar beet and sunk cost	72%
Energy converter	Water scrubbing	56%	Water scrubbing and sunk costs	45%

Table 7: The implications on profit in the biogas value chain when an owner retracts

We find that the importance of the livestock farmer is small as the profit for the entire value chain will only be affected marginally, if 1/3 of the optimal livestock farmers decides to withdraw from the collaboration. This puts the collaboration of farmers in a weak negotiating position, and in particular in a value chain with upgrading, the livestock farmers could risk that the other parties would agree on a proportional allocation principle leaving the livestock farmers with a low profit share, since their costs are also quite low. With a proportional allocation mechanism however, there would be a risk that livestock farmers found this distribution of profits too unequal and unfair, that they would defect and there would be the risk of adverse selection, where farmers would tend to lie costs higher than they are or deliver manure at a lower dry-matter content than promised.

The best alternative to deep litter is to use straw as additional substrate. This would result in a significant lower profit for the value chain, especially if investments have already been made. This votes for finding a good payment to the deep litter farmer even though cheaper alternatives than straw might be possible to find. So 10% of the costs may not be enough.

The relationship between plant and energy converter is more complicated and the risks are high on both sides. In the base scenario where natural gas prices are so low that the preferred solution for the entire value chain would be direct usage in a local CHP, the best alternative (upgrading by water scrubbing) results in a significantly lower profit. Before investments the energy converter does have a fairly good alternative to biogas in the form of a biomass based heat boiler. This could put a pressure on the biogas plant away from the proportional allocation towards full equality or the individual rationality profit allocation. When investments have already been made and if one part decided to withdraw from the collaboration, both parties would loose in the form of sunk costs.

In the NG high scenario, upgrading with methanation is the preferred choice of energy converter and the best alternative is water scrubbing with a profit just above the result from the base scenario. After investments both the plant and the energy converter will have a risk of sunk costs in case the collaboration breaks down, however, while the upgrading plant will have difficulties using the upgrading facility to something else, the plant would probably be able to find alternative options. This leaves the plant in a better negotiating position *before* and in particular *after* investments.

5.3. Discussion of the implications of the results

Danish biogas production have increased remarkably the later years, and among other things there have been two tendencies: that most plants decide to upgrade, and that especially the larger plants have difficulties in finding enough farmers who would commit themselves to deliver the needed manure as input. We argue, that the results presented above can help explaining these tendencies.

5.3.1. Why farmers are hard to involve

The best alternative for the livestock farmers given in table 5, is a common payment of farmers to deliver manure into the biogas plant. They get their manure treated for nothing and in return they are paid nothing (Lemvig Biogas Plant, 2017). This alternative profit is lower than what they could achieve by staying in the value chain with any of the profit allocation mechanisms we have chosen to investigate. Furthermore, the single farmer is often replaceable at low costs cf. table 7. This leaves the farmers in a bad negotiating position and would probably mean that they as a group would accept the proportionality allocation mechanism even if it seem unfair. Instead they may try to be co-owner of the plant in order to achieve more of the profit, and this corresponds well with what we can observe in Denmark, where it is common that farmers are co-owners. So if 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 unfair and therefore not worth any risk.

5.3.2. Why biogas plants would want to upgrade

From the results in Section 4.2, we find that upgrading is the preferred choice when the natural gas price is high. As the prognosis for the natural gas price shows an increase in natural gas prices, it is logical to assume that the new investments in biogas plants have been based on positive projections for the natural gas price implying that upgrading would be the preferred choice (Danish Energy Agency, 2012b, 2017). The "defections" we have seen in real life—when biogas plants have started to upgrade instead of supplying the local CHP (Harder, 2016)—have probably happened when a larger part of the CAPEX is written of, and when contracts should be renewed.

An explanation for *not* choosing CHP could be found in the alternatives for the heat producing energy converter. At first glance, the plant could prefer a CHP as energy converter with a proportional profit allocation, as this could guard the value chain for years with low natural gas-prices, however, this risk may be outweighed by additional profits in years with high natural gas prices, *and* the biogas plant is not guaranteed a proportional distribution.

If a CHP is installed to satisfy a heat demand, the best alternative would often be to install a biomass based heat boiler, resulting in a low heat price in the given area. This alternative gives the CHP a good negotiation power before investments are made, and even though the proportional allocation within the value chain may give a better result than the best alternative with biomass, the alternative could put pressure towards another profit allocation.

After investments are made, both the biogas plant and the CHP would loose, if one of the parties chose to defect and break the chain; however, the actual risk would be lower for the energy converter as he would probably be able to pass on most of the additional cost to the heat consumers. Furthermore, the energy monopoly regulator, DERA (Danish Energy Regulatory Authority) may force the energy converter to pay less for the biogas, for example by demanding an individual rationality profit allocation, and thereby reducing the opportunities for profit for the biogas plant (Danish Energy Regulatory Authority, 1999).

For an investor, an upgrading plant could be a very profitable investment, in particular if a 4% discount rate is the best alternative. From the perspective of the biogas plant an upgrading facility could add good profits to the biogas plant with the right profit allocation. A deviation from the value chain after investments would result in significant costs for the upgrading facility owner, as it would be difficult to use the capacity for something else, so investment costs would be sunk. The biogas plant on the other hand, would also have a risk of sunk cost, but would have a better chance of finding a good alternative usage of the capacity. For example for heat and power production or another upgrading plant. This puts the biogas plant in a much better negotiating position before and after investments, compared to the negotiations with a local CHP. Furthermore, it may be more likely that they can agree on a profit allocation principle.

All these arguments talks in favour for upgrading when looking from the perspective of the biogas plant, who is likely to be the initiator of the project.

6. Conclusion

After it became possible to obtain a similar support for upgraded biogas as biogas used directly in a local CHP, there has been a development where both new and old biogas plants have chosen to upgrade the biogas. Furthermore, new biogas plants tend to have a challenge in achieving enough contracts with livestock farmers who will supply the biogas plant with manure. In order to understand these observations we have combined *optimisation of the biogas value chain* with applied *cooperative game theory* with regards to *profit allocation theory* where focus is on the fairness criteria *equality* and *individual rationality.*

First, we found the optimal configuration of the biogas value chain using a mixed integer optimisation model with a large variety of design options, both with regards to input and investments. We find that the optimal solution is to build a large biogas plant with a high share of manure and a cheap supplementary input substrate; with the specific geographical position of our model plant the optimal input combination is approximately 70% manure and 30% deep litter. We find that 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. We also find that electricity prices affect total profit in the value chain, however not the optimal choice of technology—at least not to as large an extent as natural gas prices does.

After the optimal configuration was found, we implemented models for allocating the profit using the full equality, proportionality and an individual rationality mechanism. We have concentrated the analysis on the owners from the value chain, that we consider absolutely necessary to achieve support and thereby a proper profit. These owners are a cooperative of livestock farmers, the biogas plant and an energy converter. Our results indicate, that farmers have a low bargaining power in such a group of owners, as their alternative profits are quite low and a least a group of livestock farmers are replaceable. This could result in a profit allocation mechanism as the proportional allocation form, which the farmer collaborative would probably accept, however with low interest in participation. This could result in adverse selection or defection unless the farmer decided to invest in other parts of the value chain.

If the energy converter in the value chain is a CHP, he would have a strong bargaining power before investments are made due to the good alternative of a biomass based heat boiler. It is therefore likely that he could force a profit allocation on the value chain similar to the individual rationality allocation mechanism, where the biogas price is significantly lower than with a proportional allocation. After investments, the bargaining power between the biogas plant and the CHP is more equally distributed, since both would suffer from high losses with new investments. However, the CHP could be supported by the national monopoly regulator (DERA) to force the biogas price down; which has happened several times in the past.

When the energy converter on the other hand is an upgrading facility, the bargaining powers of the biogas plant owner and the upgrading facility owner becomes similar before the investments.

After investments, can the biogas plant owner be considered to be in a better situation since she eventually can choose an alternative energy converter, while alternative applications are hard to find for the upgrading facility, unless the facility is mobile. Furthermore, it is likely that they can agree on a profit allocation mechanism, since all three allocation mechanisms we have investigated result in fairly high profit shares for both the biogas plant and the upgrading plant.

All in all, we find several arguments from theory and our modelling, that supports the observations found with regards to the choices made by Danish biogas value chains within 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 fertilizers to the soil. These fertilizers would typically be a combination of manure and mineral fertilizers, 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 fertilizers 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 fertilizer.

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 energy is supported and

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

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 (The Danish Ministry of Energy, Utilities and Climate, 2016), which will reduce the electricity cost significantly for industrial production such as methanation.

Appendix B. Data

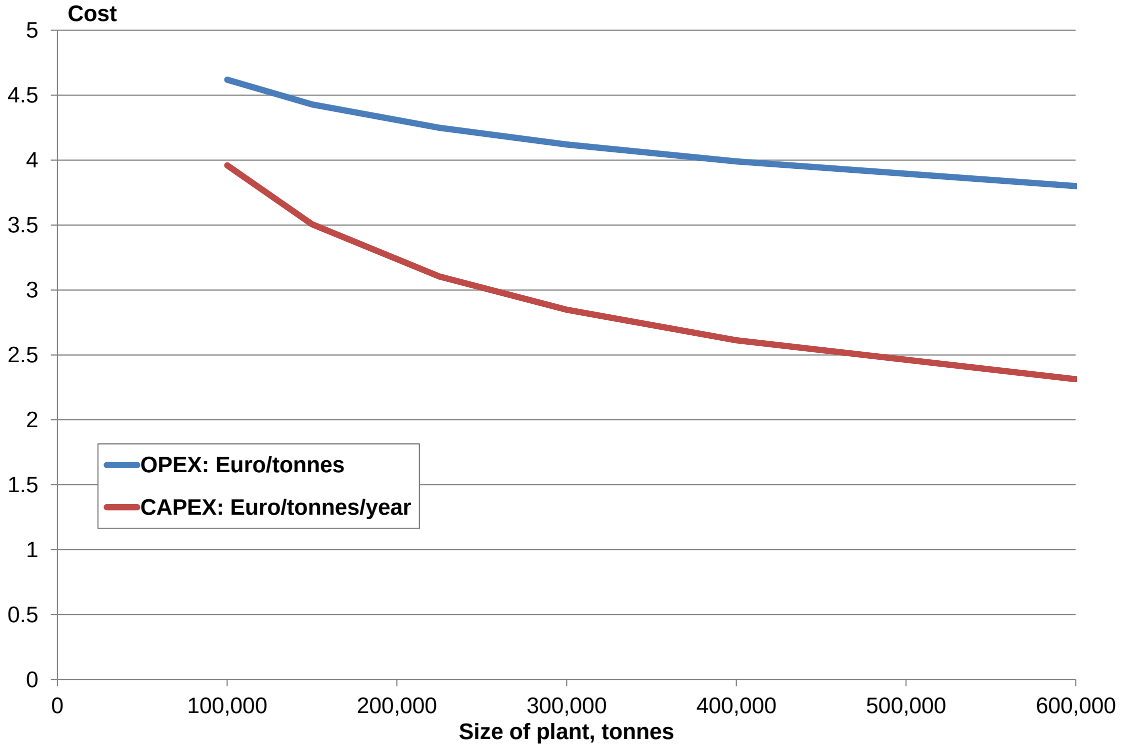

Figure B.1: OPEX and CAPEX for the biogas plant is based on a fitted trendline on the OPEX and CAPEX reported by plants applying for financial support in 2012 in Denmark through the Danish Energy Agency and model plants in the same time. To linearise it, we have used the same break points as in (Jensen 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 B.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^3BG/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 B.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 B.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 B.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 annualized 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.