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Innovations in Nordic value chains for biogas: Maabjerg BioEnergy in Denmark

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1 Value chain characteristics

Maabjerg BioEnergy biogas plant is located in the western part of Denmark near the cities Struer and Holstebro. The plant was completed in 2011 and started operation in June 2012. It has three main goals: to utilize the biomass resources to support the community's energy balance and improve the climate, to limit the emission of nutrients to water courses and fjords, to help maintain jobs in the farming community and related businesses (Maabjerg Bioenergy, 2013)

1.1 Basic input/output structure of chain

The figure below illustrates the units and flows of Maabjerg BioEnergy.

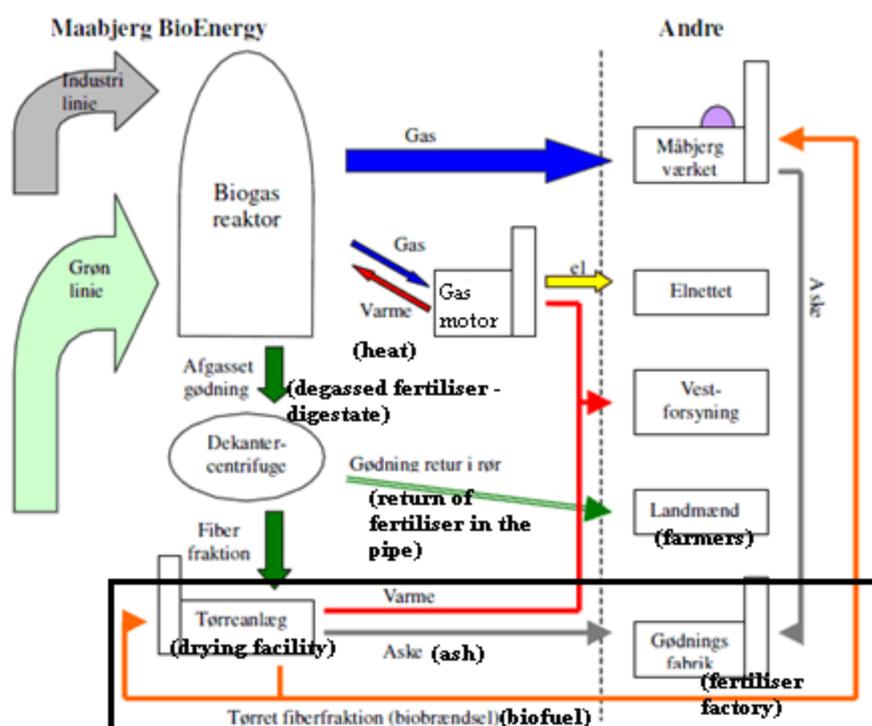


Figure 1 Maabjerg BioEnergy's flows and units (the part marked with black rectangle is not yet in operation)

1.2 Main segments and activities of the value chain

The table below shows the biogas value chain for Maabjerg BioEnergy, listing key activities and actors. The companies involved in each segment are mostly domestic and private and relatively small. The only place in the chain where larger companies get involved is equipment supply – for example biogas engines are produced by GE Jernbacher.

Value chain segment and activities	Actors
Feedstock supply	Farmers from Maabjerg Supply Association Dairy industry (Arla) Mink industry (several firms)
Primary processing- conversion: Waste management, food processing and energy component Engineering component	Maabjerg BioEnergy Maabjerg BioEnergy; equipment, bacteria and analytics producers
Distribution, transport and sales of biogas:	Maabjerg BioEnergy Vinderup CHP Maabjergværket
Production and distribution of heat and electricity	Maabjerg BioEnergy Vinderup CHP Maabjergværket District heating company
Biogas for transportation (not yet in operation)	Possibly: Public buses, bio-fuel vehicle owners, industry (gas from grid)
By-product consumption: digestate (fertiliser) fibres ash from fibres (not yet in operation)	Farmers from Maabjerg Supply Association Farmers from Maabjerg Supply Association (and Jutland) Expected: Farmers from Maabjerg Supply Association

1.2.1 Feedstock supply

1.2.1.1 Road transport

The manure feedstock is supplied by livestock farmers from Maabjerg Supplier Association. Each farm that supplies slurry to Maabjerg BioEnergy has an on-site storage tank containing the freshly produced manure. The smell is reduced with a lid placed on the storage tanks. When the tank is full a message is sent to Maabjerg BioEnergy through the program BioLink. To limit transport costs, only farms with 20 km diameter range can be suppliers. (Lunde, 2013) (Pedersen, 2013)

The slurry trucks are specially crafted and carry either the fresh manure to the biogas plant or the digested slurry back to the farmers. Each truck can contain 32 tonnes of manure and the Supplier Association owns five trucks, each running an average of 10 times a day. A provisional meter system

has been established through which the farmer pays according to the amount of time the truck spends on the farm. This is also meant to incentivize farmer to make the necessary investments for making the transport of manure between farm and biogas plant as quick and clean as possible. The cars are white, like milk tanker trucks, and cleaned regularly in order to give people an association of the plant handling the slurry in a clean way. (Lunde, 2013).

1.2.1.2 Pumping (not yet in operation)

It was originally intended to pump a portion of the slurry from rural areas to the installation, through a specially built pipeline from Maabjerg BioEnergy to a location outside Holstebro, with the possibility of extension. This part of the project has received some support from the EU and Maabjerg BioEnergy is committed to expanding with a second transfer station. However, no attempts at pumping raw manure into the plant have been made yet. Cattle manure cannot be pumped alone so mixing with other feedstock must be done first. One of the key issues is the pump capacity along the pipeline. The original plan contained pumps every 2-3 km but this has now been raised to every kilometre. If the pump station comes to run at full capacity, it will be able to reduce the transport into the plant with up to 30%. This will not necessarily improve the economy of feedstock handling overall, however, as the most time-consuming process, storage of the manure, must still be done. (Lunde, 2013)

1.2.2 Primary processing – Maabjerg plant

At the plant, there is a lab technician (uncommon at biogas plants in Denmark) that regularly analyzes the dry matter content to assess biogas potential of incoming biomass. Currently, a test takes ca. 30 days, but the equipment company is experimenting with methods for determination of biogas potential within a two-day period. (Lunde, 2013)

The Maabjerg BioEnergy facility is built to receive manure, energy crops (potato pulp), biowaste (whey), and sludge from the local sewage treatment plant, in a range up to 20 km, in an attempt to also service as many as possible mink farms.¹ (Lunde, 2013). The resources available for the plant are listed below. The manure received comprises of pig manure, cattle manure and mink manure.

Table 1-1 Planned resource use at Maabjerg

Resource	Quantity
Manure	457.000 tons
Energy crops (potato pulp)	2.000 tons
Biological waste (15-16% /7 % DM) (whey)	50.000 tons/100.000tons
Sludge line (3.5% DM)	120.000 tons
TOTAL	629.000 tons

Theoretically, this amount of resources should result in the production of biogas and fibre that allows producing the following amount of energy:²

¹ Denmark is the world's largest producer of mink skins (14 million skins annually) (Kopenhagen Fur).

² The plant has not been yet in regular operation for a full year at the time of this study, so the operating data for a full year cannot be presented.

Table 1-2 Theoretical energy output from the plant

MWh	Heat	Electricity
Biogas	58200	49100
Fibre	15100	6900
TOTAL	73300	55000

The plant produces in total ca.2000-2300 m³ of biogas per hour or 18 million m³ per year. (Lunde, 2013)

After being delivered to the site, the feedstock is first sent to a large mixing tank of 2000 m³ volume, and then to pre-storage in large silos. The whey that comes from Arla's cream cheese dairy plant in Holstebro, is concentrated before being mixed in (from 100,000 tons to 50,000 tons with a doubled dry matter content). Next, the feedstock mix is sent through pipelines to sanitation in batches of 60 tons, remaining for a period of an hour and in a temperature of 70° C. Then it is passed in continuous mode into the reactor tanks, each with a capacity of 8000 m³. In connection with sanitation and reactor tanks, the heat from slurry is exchanged, so that the need for external heating is minimized. The plant is mesophilic, i.e. has a reactor temperature of 37° C. This also means that the hydraulic retention time, i.e. time the slurry is inside the reactor, amounts to 23 days. Since mink manure has a high content of ammonia, which acts as inhibitor to biogas production, it has been necessary to run the plant in a mesophilic mode, as the AD process is less sensitive to ammonia at low temperatures. The only inconvenience in this phase of the process observed so far is sand contamination in cattle manure. (Lunde, 2013)

Further on, the slurry is sent to a storage after which the remaining gas is collected before the slurry is separated into a dry and a wet fraction. The biogas is sent to two gas storage units that have capacity of 10,000 m³, equivalent to 10 hours of production. The wet fraction is stored in silos before being returned to the farmers. The fibre fraction is sent by truck trailers to neighbouring facility Maabjergværket where the fibre could be burnt in the future (currently it is allocated elsewhere). Phosphate could then be retrieved from the burned fibres and recycled in agriculture. (Lunde, 2013)

The system runs continuously, but there is around 10% tolerance for the amount of the output - lower in summer and higher in winter. (Lunde, 2013)

Except for the "green line" described above, there is also an "industry line" that differs in terms of sanitization – it happens not before the feedstock is sent to the reactors, but after degasification, by the addition of calcium hydroxide (so-called slaked lime). The division of the plant in two lines is due to Arla (the dairy company, supplier of whey) that requires a great degree of traceability of the fertilizer used for producing the feed for dairy cows whose milk is supplied to Arla. The hygienisation process is also important for bacteria removal. (Lunde, 2013)

There is pressure in the gathering halls and air evacuation facility from the fibre containers to prevent odours.

1.2.3 Use and sales of biogas

Biogas from Maabjerg BioEnergy is divided into three actors: as a first priority, it is sold to the adjacent Vinderup combined heat and power (CHP) plant (1/3 biogas), then to Maabjergværket, and

as a third priority: Maabjerg BioEnergy itself. The plant is equipped with a flare, so that any excess gas production (that cannot be sold or used onsite) can be burned. The burner has a capacity of 3.000 m³ biogas per hour. (Lunde, 2013)

1.2.4 Production and distribution of heat and electricity

Overall, the biogas produced at Maabjerg BioEnergy provides heating for 5,388 homes, and power for 14,381 homes.

Vinderup CHP produces heat and electricity from the biogas supplied from Maabjerg BioEnergy. The heat is supplied to the towns of Vinderup and Sevel via Vinderup CHP's own distribution network. (Sørensen, 2013)

Maabjerg BioEnergy plant also produces electricity, destined to the electricity grid and heat, out of which part is used onsite, and the remainder is sold to the district heating network. Maabjergværket's heat is sold to the same network, which may cause some conflict over who has the right to sell heat in summer, when Maabjergværket primarily burns waste. (Lunde, 2013).

1.2.5 Fibres, ash and degassed manure

As mentioned before, the farmers that belong to the Supplier Association have a right to receive the digestate and use it then as fertiliser. Therefore, the remaining by-product is fibre. The original plan with Maabjergværket was that the plant should accept the fibre fraction from the "green line" and burn it for heat production. The ash from incineration would then contain nearly pure phosphorus, which could be sold for fertilizer production. However, Maabjergværket has not been yet retrofitted to accept the fibres and has not obtained the necessary permits so that the fibre can be burned. The unit is contractually obliged to purchase fibre in at least 9 months a year. As it is now, the plant receives the fibres, but pays farmers in Jutland so that they use them as fertilizer. In the remaining three months the fibre is not separated from the digested slurry, which turns out to be good for farmers who otherwise would not have enough phosphorus in the digested slurry. This is partly due to the fact that the phosphorus content in the slurry has declined due to changes in the feed ingredients. (Lunde, 2013)

1.3 Organisational and governance structure of the value chain

1.3.1 Organisation of Maabjerg BioEnergy

In 2003, the structure of Maabjerg bioEnergy was as represented in the table below:

Table 1-3 Structure of Maabjerg BioEnergy in 2003 (Lunde, 2013)

2003				
Maabjerg BioEnergy A/S				
Maabjerg BioEnergy Supplier Association (200 farmers)	Vestforsyning A/S	NOMI (waste disposal company)	ELSAM (energy company)	
51%	31%	9%	9%	

In 2009, the Maabjerg BioEnergy A/S was divided into Maabjerg BioEnergy Operation A/S and Maabjerg Bioenergy Supply Association A.M.B.A (see table below)

Table 1-4 Structure of Maabjerg BioEnergy starting from 2009

2009		
Maabjerg Bioenergy Supplier Association a.m.b.a. (140-150 farmers)	Maabjerg BioEnergy Operation A/S	
	Vestforsyning A/S (main heat transmission)	Struer Forsyning
	71.4%	28.6%

Maabjerg Bioenergy Operation A/S owns and operates the production installation and decentralised storage tanks, as well as pipe network and biogas and heat and electricity connections. It is owned by Vestforsyning Varme A/S in 71.4% and Struer Fjernvarme A/S in 28.6%. The capital owned is: €6.8 million. (Lunde, 2013) (Maabjerg Bioenergy, 2013)

Maabjerg Bioenergy Supply Association A.M.B.A supplies manure and other biomass for the production facility and is responsible for the logistics of supplies from individual farmers. It consists of 150 farmers and has €1.3 million funds. (Lunde, 2013) (Maabjerg Bioenergy, 2013)

The change was caused by the fact that municipal utilities ownership would allow the installation to achieve a beneficial municipal loan for heat supply project from Struer and Holstebro towns (€52 million). The fact that this loan is characterised by stable low loan rate, was the important enabling factor for participation of farmers in the project. (Lunde, 2013)

The Supplier Association owns 5 trucks and is responsible for providing manure and other biomass for the production facility, as well as fertiliser deliveries to individual farmers.

All the agreements concluded in connection with supplies from farmers and removal of biogas are made for a 20-year period. This is done to minimize risks and ensure a stable economy for the plant. (Lunde, 2013)

Maabjerg BioEnergy employs 8 people at the plant: a laboratory technician, an operator, 2 electricians, 2 blacksmiths, a secretary and a supply logistics manager. (Lunde, 2013)

1.3.2 Governance and economy of Maabjerg BioEnergy

A farmer that wants to become a supplier to Maabjerg Bioenergy, is obliged to deliver a specified amount of manure over a 20-year period. This obligation concerns the farm, not the owner and is therefore valid in case of change of ownership, but not in case of farm bankruptcy. Membership also guarantees a farm's right to receive digestate from the plant. This right could be possibly traded, in case stricter policies for slurry spreading on agricultural land are imposed by the authorities – for example if in the future the plant stops accepting new suppliers, the existing members could be interested in selling their rights to other farmers. Another reason for a farmer to buy rights could be the will to increase their animal inventory at the farm – in that case, the amount of manure would also increase and thus a degassing possibility would be needed. Currently, there is room in the plant for increasing manure supply by 10%. (Pedersen, 2013)

In order to become a supplier of manure to Maabjerg BioEnergy a farmer must pay an admission fee of DKK 525 per animal unit (one animal unit equals 36 pigs). Scheme entry also requires investment in tanks at farm level of around DKK 100.000 – 300.000. Farmers pay on average DKK 20/t slurry for handling manure from their farms, and receive in return approximately DKK 5/t of gas value of the manure. Another benefit for the farmer is that the degassed fertilizer has better fertilising properties than raw manure, can be spread on fields in larger amounts and that the odour is substantially reduced. (Pedersen, 2013)

The supplier agreement with Maabjerg BioEnergy contains, besides the manure handling charge, a "dry content charge" that applies if the manure has not obtained a certain solids content. On the other hand, the plant pays the farmer if the solids content exceeds the standard manure value. However, this system has caused economic problems (including debts) for some farmers who found it difficult to live up to the dry content requirements and who have paid a charge of around DKK 30-35/t. Due to those problems, a new agreement is planned, where both the required dry content amount will be lower, as well as penalties will be reduced. The new agreements will probably also mean that Maabjerg BioEnergy Operating will take over trucks and transport. (Pedersen, 2013).

Different actors in the value chain focus on different characteristics of the manure. For farmers, it is the amount of nitrogen in the digested slurry that is important. In addition, it is essential to reduce the amount of phosphorus that is bonded to the fibre fraction. Cattle farmers need potash to grow fodder for the cattle (more than they get back now). In this context, potash compensation for cattle farmers has been discussed. For the biogas plant it is important that the dry matter content is high (maximum 10% of the biomass). In addition, excessive levels of ammonia cause problems on the biogas plant. Finally, a high sand content can be detrimental to the systems and pumps. (Pedersen, 2013).

The net annual turnover of Maabjerg BioEnergy is expected to be around €5.85 million. (Maabjerg Bioenergy, 2013)

1.3.3 Governance of Vinderup CHP

Vinderup CHP has about 1400 customers from Vinderup and Sevel and employs four staff members.

Vinderup CHP has an obligation to purchase biogas in the amount sufficient to the capacity they have available. The gas contract between Maabjerg Bioenergy and Vinderup spans for 20 years, with $\frac{1}{4}$ of the price fixed and $\frac{3}{4}$ of the price tied to the net price index and thus the overall economic development. Vinderup has not agreed to let the price bind to natural gas prices, because their alternative fuel was not natural gas but solar energy. (Sørensen, 2013)

Maabjerg Bioenergy invested in the biogas pipes to the Vinderup plant, while the latter invested a total of DKK 20 million in the biogas engine, heat exchangers, electrical construction (pumps and frequency inverter), heat pumps, and a building. The risk of this investment was accepted because Vinderup estimated that using biogas would result in savings of 10-15% on the heating bills of district heating consumers, and this has been achieved. It is much cheaper for Vinderup to receive biogas locally from nearby Maabjerg BioEnergy than to receive upgraded biogas via the natural gas grid, as it is expensive to transport gas over larger distances, due to for example distribution fees charged by the natural gas firms. (Sørensen, 2013)

Regarding plans for the future, in 2018 the "basic support" for electricity generation at decentralized CHPs will be phased out. Vinderup therefore considers shutting down production on the two natural gas engines that deliver peak and reserve load (in the near future, they need major technical retrofitting). Alternatively, Vinderup will produce heat via either a new engine suitable for both natural gas and biogas, a new heat pump or a new solar heater. (Sørensen, 2013)

1.4 Environment

The MaabjergBioEnergy plant reduces CO₂ emission by 50,000 t/year, and nitrogen and phosphorus emission into water course is reduced by 109 and 311 tonnes per year, respectively. (Maabjerg Bioenergy, 2013)

2 Key technologies characteristics and assessment of their technological development stage

2.1 Conversion process

The biomass conversion to biogas at Maabjerg is an anaerobic digestion (AD) process, which has been known for decades, thus it is a fairly established technology. However, there is room for more development in terms of digestion efficiencies, feedstock mix and process speed.

2.2 Biogas upgrading

Currently, biogas upgrading is not applied at Maabjerg BioEnergy facility, although it could allow increasing the methane content in the gas, which now amounts for between 49-59%. Upgrading could be performed either in-situ or after the AD process.

2.3 Heat and electricity production

All of the biogas engines used in Maabjerg BioEnergy value chain were produced by GE Jernbacher, an Austrian company now under control of GE Energy (General Electric). Meters are mainly produced by various Danish producers.

Maabjerg BioEnergy facility is equipped with two biogas engines of 1.4 MW power generation, and a power efficiency of 43%. Heat generation has an efficiency of approx. 47%, i.e. a total efficiency of 90%. (Lunde, 2013)

Vinderup CHP has agreed with Maabjerg BioEnergy to accept an amount of biogas able to fuel one biogas engine with a capacity of 3 MW of electricity and 4.2 - 4.3 MW heat without additional use of a heat pump and 4.6 MW with it. The separate electrical efficiency of the engine is about 43% and heat efficiency of 55 -57%, while the total efficiency is 100% without heat and 104% with. The engine cannot be regulated, i.e. it runs either at full speed or not at all. This is caused by the fact that the engine has to handle the alternating methane content in biogas.³ Except for that, the plant has several natural gas-fired engines. The plant is equipped with heat storage of 21,000 m³, equivalent to two and a half days of district heating consumption in summer. In the winter season the heat demand peak in the area reaches 13 MW, therefore less than half of heat consumption can be covered by biogas, in the yearly perspective this number oscillates around 70-80% of heat demand in Vinderup and Sevel. (Sørensen, 2013)

³ The varying sulphur content is measured continuously and if it exceeds a given level, the engine is turned off, because too much sulphur in the smoke can erode the equipment. (Sørensen, 2013)

The development stage of equipment used at Maabjerg can be assessed as leaning towards mature, since they have been present on the market for decades, but their technical performances could still theoretically be improved.

3 Biogas market characteristics

3.1 Statistical data

The primary energy production of biogas took off from very low levels in the late 1980s and grew steadily until the mid-2000s when growth slowed down and, after a short recovery, declined in the late-2000s (Figure 1). The main driver has been biogas use in electricity production while biogas use in district heating production is much lower and stabilized already in the early-2000s. The share of biogas in total renewable energy production, however, was only 3.0% in 2011, while the share of biogas in total biomass-based energy production was 4.5% (Danish Energy Agency, 2012). The deployment of manure-based plants is responsible for the recent years' growth in biogas production, while production from other plant types (industrial, land fill, and waste water treatment) has been constant or declined (Lybæk et al 2013).

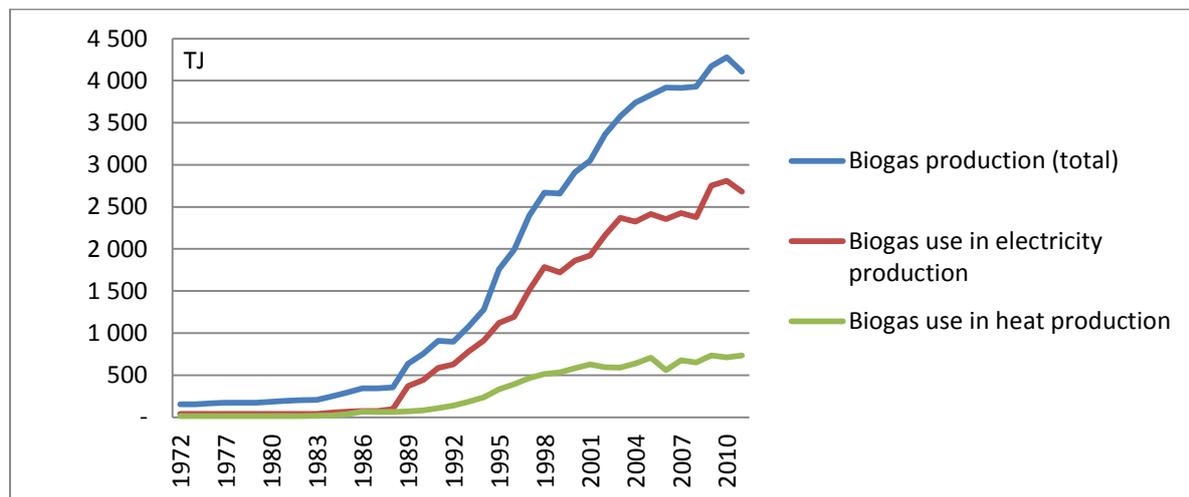


Figure 1 Trend in biogas production and use 1972 – 2011 (TJ)

Source: Danish Energy Agency (2012).

The contribution of different biogas production technologies to electricity and heat production is shown in Table 1. 82% and 77% of the biogas, respectively, is produced using 'other' fuels, which encompass mainly livestock manure – especially from pig farms.

Table 3-1. Biogas fuels in electricity and heat production (TJ)

	Electricity	Heating
Landfill	124	55
Sludge (municipal and industrial)	365	113
Other *	2191	565
<i>Total</i>	<i>2681</i>	<i>733</i>

Notes: * Decentralised agricultural plant, municipal solid waste methanisation plant, and centralised co-digestion plant. Source: Danish Energy Agency (2012).

The use of biogas by different energy production technologies is detailed in Table 2. About half of the biogas is consumed by small-scale (decentralised) CHP units, and one quarter is used in small CHP units whose primary purpose is not energy production (auto producers). Upgraded and compressed biogas can be distributed through the natural gas network to end users, or be used as a transport fuel, but these options have not been implemented in Denmark.

Table 3-2. Use of biogas in energy production (TJ)

	TJ
Large-scale CHP units	36
Small-scale CHP units	2137
District heating units (heat only)	94
Auto producers *	
- electricity	17
- CHP	1022
- Heat	107
Agriculture and Forestry	181
Manufacturing	153
Private Service	358
<i>Total</i>	<i>4106</i>

Notes: * Auto producers are small producers whose main product is not energy. They are dominated by CHP production and include manufacturing, horticulture and waste treatment enterprises. Source: Danish Energy Agency (2012).

3.2 Centralised and decentralised plants

In the legislation a central distinction between biogas produced on 'central' plants versus 'decentralised' plants exists. Central plants are large plants with a capacity of 100-600 tons biomass per day. They receive feedstock from multiple farms, and sometimes other sources, and are located in a way that allows pipeline connection to major energy infrastructure, i.e. larger CHP plants, and in the future possibly also the natural gas network and upgrading and compression facilities. To achieve sufficient scale economies and minimize feedstock transportation cost, these plants tend to be located near large livestock concentrations. Large plants usually employ several specialised staff. Decentralised plants can process 10-100 tons biomass per day. They typically get feedstock from a single farm, and sometimes from a few adjacent farms, and have no pipeline connection to other energy infrastructure. They have lower transportation costs than the large plants, but also smaller economies of scale. Small plants are operated by an individual farmer or his employee. In 2011, there were 24 central biogas plants, each one handling manure from up to 80-90 farmers, while there were about 60 decentralised biogas installations, most on pig farms (Landbrug & Fødevarer). Due to the effect of scale economies the trend is towards more centralised plants for both CHP and

'heat only' biogas production. Biogas plant operators are individual farmers for decentralised plants, and for large plants farmer cooperatives ('Amba') or municipalities. There are policy efforts to attract more 'commercial' operators to the industry through an improved support scheme (see section on Policy Context).

3.3 Geographical scope

The geographical distribution of centralised and decentralised plants is shown on the map below. Due to the agricultural development and connected presence of feedstock, it is mainly the Eastern Denmark where biogas plants exist. This is especially visible in case of the decentralised plants which are usually located in areas of significant livestock production.

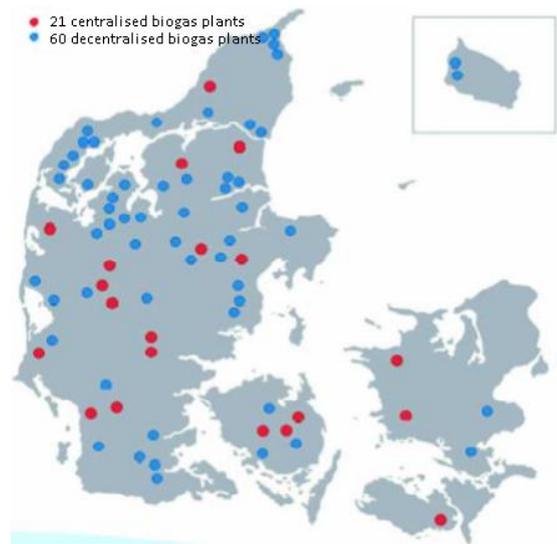


Figure 2. Geographical distribution of biogas plants in Denmark (Danish Biogas Trade Association)

4 Institutional context

4.1 General

Policies

A change in the Danish planning law obliges municipalities to plan the biogas plant installations in the upcoming revision of municipality plan in 2013.

According to the Energy Agreement (Danish Government, 2012), the following changes in the support model for biogas development will be implemented, allowing overall subsidy to biogas (used in CHPs or gas networks) at up to €15/GJ:

- the existing support of €10/GJ biogas used in CHPs continues as basic support
- biogas delivered to the natural gas network will also receive €10/GJ
- a new support for process biogas used in industry and transport of €5/GJ
- launching support is increased from 20% to 39% in 2012

- implementation of support of €3.4/GJ for all uses of biogas. The support will be gradually decreased in relation to increasing natural gas prices, with €0.13/GJ, when natural gas price increases by €0.13/GJ.
- a support of €1.3/GJ for all uses of biogas will be implemented, gradually decreased with €0.26/GJ from 2016 to €0/GJ in 2020

Municipal natural gas companies get a possibility to engage in biogas production as an activity connected to their commercial activities.

Currently, Denmark, among other nine EU countries has set up regulations enabling biogas to be injected into the natural gas grid (Euro Observ-ER, 2012).

Institutional actors

Biogasrejseholdet – The Biogas "Task Force"⁴ – is a team under Danish Nature Agency (Naturstyrelsen), which between 2010 and 2015 will be helping municipalities with the promotion of biogas. The free service provided by the team includes analysis of location, planning process, and problem solving. (Miljøministeriet-Naturstyrelsen). The Task Force interacts with actors such as KL (an organisation of all 98 municipalities in Denmark), Danish Energy Agency (Energistyrelsen), The Danish AgriFish Agency (NaturErhvervstyrelsen), The Regional State Administration (Statsforvaltningen), trade associations, agricultural organizations etc.

A second team, the Danish Energy Agency **Biogas Task Force** has the aim to research concrete biogas projects in order to ensure realisation of the planned biogas development until 2020 (DEA). If the development of new projects is too slow, the parties agree in 2014 to discuss other opportunities to promote biogas development, including specific proposals involving purchase obligation. €1.7 million is intended in 2012-2015 to the DEA's Task Force to support expansion of biogas (Danish Government, 2012).

4.2 Institutional context of Maabjerg BioEnergy

4.2.1 Policy

As discussed in section 1.5, several changes in the legislation regarding biogas plants support are to be implemented, with existing subsidy becoming a basic support of 10€/GJ and additional schemes amounting to up to 15 €/GJ overall. It is anticipated that in the future part of the subsidy will be gradually decreased, if natural gas prices increase. Moreover, Denmark has set up regulations that enable biogas transport with natural gas net.

It is noticeable that the biogas policy structure in Denmark is quite beneficial for biogas installations and most of the future uses (electricity and heat production, transport, natural gas grid injection) are to be supported in the very near future. However, it is biogas used in industry and transport, as well as delivered to the natural gas network that will receive the highest subsidy in 3 years and thereafter. This means that it would pay off to Maabjerg plant to invest in those areas.

⁴ No to be confused with the Biogas Taskforce under Danish Energy Agency, described below.

4.2.2 Finance

The money for the Maabjerg BioEnergy project was borrowed from the municipal loan because the project can be characterized as a heat supply project. This helps to ensure a fixed low interest rate, which has been crucial in allowing farmers to participate in the project. (Lunde, 2013)

5 Path dependencies and innovation

5.1 Biogas R&D activities in Denmark

Several innovative approaches to biogas production are being researched at universities, and others are being tested in new plant construction projects – although so far not on a commercial scale. The ones discussed below address challenges at the stage of biogas production (efficiency, resource alternatives and mixes), biogas upgrading, and use of the digestate as fertilizer.

Academic research seems to focus on upgrading of biogas. Most of the currently used methods focus on post-treatment of biogas using methods such as water-washing or pressure swing adsorption. These processes take place outside the bioreactor and thus require additional costly equipment. Therefore, a research project financed by The Danish Council for Independent Research and carried out by the Technical University of Denmark (DTU), analyses a biogas upgrading inside the reactor with hydrogen produced by water electrolysis (using excess electricity from wind mills). In this process, hydrogen is added to bioreactors and then biologically converted (by bacteria/Archea) by binding CO₂ to methane (CH₄) in biogas reactors. It is hypothesised that this method offers cheaper upgrading cost of biogas due to lowering CO₂ content in the biogas, as well as increased energy efficiency and storage possibility due to the better utilization of the wind mill-produced electricity. This research proposes a new approach to the traditional operational biochemistry of AD processes, where no external hydrogen was introduced. It is an on-going project and at its conclusion results are expected on maximum biogas potential of hydrogen, stability of the process, and economic performance and sustainability (Luo & Angelidaki, 2013) (DTU, 2012). This method is also being optimised by introducing new ways of increasing the availability of gaseous hydrogen to the liquid phase in the reactor. This can be done, e.g. via so-called bubbleless gas transfer through a hollow fibre membrane (HFM) module. Such a novel system is claimed to achieve CH₄ content in biogas higher than 90% (Luo & Angelidaki, 2013).

Research is also conducted in decreasing the losses in biogas production through removal of ammonia (NH₃) from biogas digesters. The high production of ammonia in feedstock in Danish plants is due to the high share of animal manure used in relation to more optimal (less alkaline) organic wastes. Ammonia is an issue because its molecules are able to penetrate bacterial cells, forcing some ions out of the cell and thus disturbing the functionality of the cells. Ammonia removal can be done by the gas circulation method, where air bubbles free of NH₃ are forced through the upper 30 cm of the liquid phase in bioreactor. It is still to be confirmed whether this method will prove sustainable (Nielsen, Christensen, & Møller, 2013).

A novel method of producing biogas and fish feed is being researched at DTU from 2013-17 (DTU Orbit). Food waste such as vegetable peelings, dairy leftovers products, meat trimming etc. can be converted into fish feed ingredients, using un-purified biogas (mix of CH₄, CO₂, H₂S) as intermediate. First, the food waste will be converted to biogas, then, together with the liquid effluent from the reactor, it will become a source of carbon, energy and nutrients to the mixed methanotrophic/

heterotrophic/ sulfidotrophic microorganisms, converting the gas into fish feed ingredients. Any remaining biogas will be used either directly to generate electricity or will be further upgraded to biomethane and then used.

Increasing the safety of the digestate used as fertilizer has potentially large health and economic benefits. In large biogas facilities various types of feedstock are used from various sources, and so using the digestate as a fertiliser may carry the risk of contaminating farm land with parasites and weed seeds. An innovative project analysed what kind of practice in Danish plants will allow the most optimal contamination risk reduction of the digestate. The results show that the thermophilic digestion is more efficient than mesophilic in suppressing animal parasites and weeds (Johansen, et al., 2013).

An example of an innovation concerning co-digestion of biomass resources is the biogas plant project in Solrød Municipality (Zealand region). The project was awarded an EU grant in 2012 and Solrød municipality has contributed €1.2 million (Taylor, 2013). The plant will receive cast seaweed from nearby beaches at Bay of Køge (22,600 tons/year), as well as organic waste from the local pectin production facility (79,400 tons/year) and manure from local pigs and cattle farms (52,800 tons/year) (Municipality of Solrod, 2012) (EC IEE). Solrød municipality is part of Covenant of Mayors signatory and has submitted a SEAP (Sustainable Energy Action Plan) where it commits to achieve a 55 % GHG emission reduction by 2025. In 2009 the first analyses of biogas feasibility were conducted. Initially, the sole feedstock to be used was seaweed, but it turned out that 50% more biomass would be needed to make the project profitable. To solve this, an additional source of biomass was included, namely a local pectin producer for whom supplying the biogas installation would mean a cheaper removal of the organic waste than the current practice of delivering it to local farmers as cattle feed. This introduced another problem, however: the risk of too high pH of biomass in the reactors. This was addressed by involving local farmers as suppliers of manure, who in return will get access to the digestive as low nitrogen-content fertiliser. It is claimed that due to this feedstock mix, the achievable biogas potential of the plant will be up to 4 times higher than the currently most productive biogas plants in Denmark (Taylor, 2013). The total expected investment cost is EUR 12,467,000 (EC IEE). The expected results are: annual reduction of CO₂ emissions with 40,100 tons (28 % of the municipality's current CO₂ emissions) and the production of 55 GWh of energy (mainly for district heating). Other expected benefits will be a decrease in the nutrient load of the bay, a reduction in odours from rotting seaweed, and improved access to digestate as fertiliser. A high replication potential for their concept of biogas plant in coastal European areas is an additional expected benefit (EC IEE).

As it can be seen, the innovation in biogas value chains takes place mainly in the feedstock supply segment (using new feedstock types, such as seaweed), conversion (co-digestion of seaweed and pectin; ammonia removal to reduce production losses; consequent biogas and fish-feed production), as well as upgrading (*in-situ* biological hydrogen conversion to methane) and by-product consumption segment (thermophilic digestion efficiency in suppressing parasites and weeds in digestate).

The aforementioned novel approaches show that the biogas technology offers possibilities for further innovation and improvements in terms of feedstock types, conversion and upgrading as well as the consumption of by-products, allowing higher efficiency and versatility of the process.

5.2 Innovations at Maabjerg BioEnergy

The Maabjerg BioEnergy project has been underway since 2002. At that time large amounts of nutrients (especially phosphorus) were observed in local streams, lakes and fjords to the extent that it started to threaten local livestock production. This was because farmers soon needed to acquire more land to spread their manure in order to comply with environmental standards for nutrient run-off to fresh water bodies. To maintain the same level of livestock production in a time of rising land prices, it was therefore necessary to start handling the manure in a way that caused less harm to the water bodies. (Lunde, 2013)

A biogas installation allowed degassing and separating the slurry in a wet and a dry fraction. Since phosphorus binds to the dry matter in the slurry, it has been possible to remove it, and to prevent it from coming back to the field. The original rationale for the plant was thus improved handling of manure (nutrients) rather than renewable energy production. This also means that the slurry degasification is understood as a benefit that farmers pay for. (Lunde, 2013)

There was initial strong opposition among people living nearby the plant, but what persuaded them was that an existing local wastewater treatment plant was built with a technology that kept the plant almost odourless. At Maabjerg BioEnergy manure is collected from trucks in a closed room and is treated by extractor hood to minimise the odour. (Lunde, 2013)

While assessing the innovation of Maabjerg BioEnergy value chain, the following innovation "instances" take place: the method of odour minimising at the facility itself, the enzyme and bacteria research at Novozymes and analytics innovation at BioProcess. Moreover, an innovative combination of two-way pipe lines constructed in "star formation" and road transport was initially planned in Maabjerg in order to reduce traffic and smell. As of now, only trucks are used, but the initial solution has not been excluded yet. (Maabjerg Bioenergy, 2013)

5.2.1 The Maabjerg Energy Concept

In the future, the biogas facility will not be the only installation at the site but will become a part of a larger project called Maabjerg Energy Concept. The idea appeared in 2010, when DONG Energy announced that they would like to sell the nearby biomass-fired cogeneration plant Maabjergværket. This cogeneration plant was commissioned in January 1993 and produces electricity and district heating from straw, wood chips, domestic waste and sewage processing sludge, and natural gas. (Maabjerg Bioenergy, 2013)

A local consortium was formed. However, because of problems in sourcing fuel both currently and expectedly in the future, the partners proposed to DONG Energy that they work together to develop a completely new installation, based on the newly developed concept. Therefore, it has been decided that Maabjergværket would be revamped to primarily use 120,000 tons of lignin from the bioethanol process, 45,000 tons of fibre from the production of biogas, and 16,000 tons of RDF waste, as its future fuel. Incineration at Maabjergværket will provide district heating for 20, 000 households in Holstebro and Struer, as well as electricity for the grid. (Maabjerg Bioenergy, 2013)

A third installation, called Maabjerg Bioethanol, is to be built on the site next to Maabjerg BioEnergy. Novozymes will participate by validating their enzyme technology at a commercial scale. The feedstock for bioethanol will be 300 000 to 400 000 tons of wheat straw, corresponding to using about 6 to 8 % of the agricultural land in a 50 km radius from Maabjerg. The by-products from the

production of ethanol will be used at biogas facility, doubling the amount of biogas produced. Finally, by adding hydrogen – produced from wind turbine electricity – it will be possible to store and transport the biogas in the natural gas network. (Maabjerg Bioenergy, 2013)

The project is going through the feasibility process and is expected to be completed by 2016. A large new facility will produce bioethanol from straw – when fully implemented the project could produce 73 million litres ethanol and 99 million m³ of biogas annually. Out of this, 76 million m³ of biogas will be purified and upgraded to 47 million m³ natural gas that will be used in the natural gas network. (Maabjerg Bioenergy, 2013). The waste product from biogas installation, fibres from manure, will be sold to a subcontractor that will use them as a fertiliser on agricultural soil. (Biofuels Digest (Jim Lane), 2012)

Maabjerg Energy Concept will be an operationalization of the 'industrial symbiosis' concept, which is based on industries sharing services, utility, and by-product resources with the purpose of adding value, reducing costs and protecting the environment. A residual product originating from one enterprise becomes the raw material of another enterprise, benefiting both the economy and the environment. The residual products traded will include steam, dust, gases, heat, slurry and other waste products. (Maabjerg Bioenergy, 2013)

5.3 Discussion: Path dependencies in biogas

TO BE COMPLETED

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Annex 1. Biogas plants and pilot projects in Denmark

Lemvig Biogasanlæg A.m.b.A.

Lemvig Biogas is currently the largest thermophilic digestion (55°C range) biogas unit in Denmark, existing since 1992 and using manure from ca. 75 farms. The feedstock used is: household and industrial waste. Biogas is bought by local small gas CHPs, that converts biogas to over 21 million kWh electricity (supplying 14.000 people) and over 18 million kWh heat (supplying over 1.000 households) annually, in Lemvig and Klinkby (Lemvig Biogasanlæg , 2012).

The Lemvig plant receives a large variety of biogas feedstocks, such as: sorted organic household waste, waste from slaughter houses, farms, food production and processing companies (dairy, fish, bakery, and brewery), soap and medicine manufacturers etc (Lemvig Biogasanlæg , 2012).

Another activity at Lemvig Biogas is slurry exchange: fresh manure from a farm (within 10 km range) is picked up with a truck about every 14 day. The manure stays at the plant for 26 days, after which the degassed manure (biogas slurry) is delivered back into the plant storage tank. The service is for free: in exchange of transporting and degassing the manure, the plant gets biogas for which it does not pay (Lemvig Biogasanlæg , 2012).

The plant has also a slurry fiber receiving point accepting slurry fibers and chicken manure (with a biogas potential). The delivering company is paid 0 - 100 Euros per tonne manure fibers / chicken manure depending on the nature of the product, nutrient content and daily prices for the disposal of nutrients. Lemvig Biogas rents out vacuum trailers available for slurry and water transport (Lemvig Biogasanlæg , 2012).

Pilot projects at the Nature Agency website

Nature Agency has initiated a €990,000 project, financed by strategic philanthropic association Realdania, that focuses on three elements: biogas, architecture and landscape, with an aim to develop and disseminate knowledge and tools to ensure the architecture and landscape of planning, location and design of biogas plants. In the project, an advisory group consisting of COWI A / S, Gottlieb Paludan Architects A / S, Dash Architects and the Biogas Secretariat at Nature Agency develop plans (sketches and draft plans) for architecture and landscape adaptation of seven pilot projects. The project comprises of seven pilot projects, representing different architecture and landscape, where the knowledge and tools developed will be made available to all interested parties - from farmers, authorities, energy companies for architects and landscape architects, etc. (Miljøministeriet - Naturstyrelsen, 2013)

Those pilot project differ from other, as complex planning of plants is implemented, where not only technical aspects, but also architectural and landscape challenges and opportunities are considered in the beginning of the planning process. For example, the plant is drawn by architects to find the optimal visual design. This may be considered an innovation in plant planning (?)

Comparison of the pilot projects - based on (Miljøministeriet - Naturstyrelsen, 2013)

Name	Size and fuel	Investment	Owner	Biogas use	Status as of Feb. 2013
Arla Biogas, Videbæk	4 ha area 550.000 ton biomass; 31 million m ³ biogas/year (16 million Nm ³ methane) based on supplies from 50-100 local farmers and waste from two Arla's factories: Arinco and Danmark Protein	€36.4 million ⁵	Videbæk Biogas A/C (50% Arla and 50% Xergi) Xergi's role ⁶ : project development, construction, operation and maintenance	Supply the nearby Arla factories with gas: Danmark Protein and Arinco.	End of project development phase, commercial operation by July 2015
BIO-Center, Gudenå	3.5 ha area 500.000 ton biomass (manure and maize ensilage) 11.8 million m ³ biogas (7.7 million m ³ methane)	€12.6 million ⁷		Biogas for Bjerringbro Heat Plant. Additionally: a visitor centre with facilities for public	
Bionaturgas Korskro⁸ (close to Esbjerg)	13 ha Two phases; 1 st : 690.000 ton biomass (85 % livestock manure, 15%: energy crops and other), 29 million m ³ biogas yearly (17 million m ³ upgraded biogas). 2 nd : increase to 1.000.000 ton biomass, 41 million m ³ biogas yearly (24 million m ³ upgraded biogas).NOTE: When ready, this will be the largest biogas plant in Denmark.		Bionaturgas Korskro is a subsidiary of Bionaturgas Danmark A/S (which in turn is part of Naturgas Fyn ⁹) and is jointly owned by 145 farmers from supply association Sydvestjysk Biogas Amba and Bionaturgas Danmark Naturgas Fyn owns all the 14 Danish cars running on natural gas	About 80% of produced biogas upgraded to natural gas and fed into the natural gas network (and possibly further used in cars). 20% used in gas turbine internally at the site.	Ready by the end of 2014
Decentralised biogas network in Ringkøbing-Skjern	Consists of five decentralised biogas plants: Ådum-1, Ådum-2, Østergårde, Sdr. Vium and BorrisSyd, placed in municipalities of Ringkøbing-Skjern and Varde (within		A private-public owned company BioEnergy Vest A/S is involved in planning, establishing and operating the plant.	Will supply CHP in Skjern.	Planning in progress

⁵http://www.biogasbranchen.dk/Om_os/Temadage/~/media/biogasbranchen/Temadag%2013%20marts%20012/Kristian%20Hagemann.ashx

⁶ http://www.eco-food.eu/download/frank_rosager_xergi.pdf

⁷ http://www.bio-center.dk/?page_id=20

⁸ <http://www.bionaturgaskorskro.dk/Anlaegget>

⁹ Naturgas Fyn aims at becoming involved in up to 75 % of all upgraded biogas in Denmark.

Name	Size and fuel	Investment	Owner	Biogas use	Status as of Feb. 2013
	the distance of 10 km). In the future, up to 60 decentralised and 1-2 centralised biogas installations ¹⁰ .				
Biogas Horsens Nord	Area:1.5 ha Livestock manure: 190,800 t, other biomass (e.g. energy crops): 39,600 ¹¹		Horsens BioEnergy ApS	Biogas used for process heating internally and the rest upgraded to be used in natural gas network.	
Køng-Lundby Biogas	3 ha 240.000 t biomass (mainly local livestock manure).			Supply the municipality with biogas	In planning phase
Thy Øko-biogas (in Snested)	1,7 million m ³ biogas yearly.	€4.9 million(20 % subsidy, 20 % own financing and 60% municipal guaranteed loan) ¹²	Association of 17 organic farmers	Supplying local CHP in Snested	In planning phase

Other planned projects are shown in the table below:

Name	Size and fuel	Investment	Owner	Biogas use	Status as of Feb. 2013
Bevtoft (Haderslev municipality)	Expected to be the world's largest biogas unit? ¹³		Cooperation between Sønder Jysk Biogas and E.ON. 86 farmers are part of the organization		Building is expected to start in the end of 2013, biogas production to start in the beginning of 2015
Biogas Tønder	Expected to be the largest in the Nordic region, supplied with 700,000 ton manure and ca. 200,000 other biomass from 120 farmers,	Investment cost: €65 million, founding from a foreign investor and a public	The project is realised by ENVO Biogas Tønder A/S and an unspecified Argentinean investor	CHP	The building of the plant is to start in autumn 2013 and is expected to be ready in summer 2014.

¹⁰ The biogas network in Ringkøbing-Skjern is part of the municipal strategy to become 100% self-sufficient with renewable energy in 2020, using 80% of manure produced in the municipality and energy crops from 5% of agricultural land.

¹¹ Biogas Horsens Nord –Miljøgodkendelse <http://www.horsenskommune.dk/Default.aspx>

¹² http://www.folkecenter.dk/dk/news/int/thyoeko_energi/

¹³ <http://www.mynewsdesk.com/dk/pressroom/e-on-danmark-a-s/pressrelease/view/projekteringen-af-soenderjysk-biogas-anlaeg-ved-bevtoft-koerer-upaaklageligt-809362>

Name	Size and fuel	Investment	Owner	Biogas use	Status as of Feb. 2013
	producing 63.6 million m ³ biogas, resulting in 20 million m ³ upgraded gas and degassed digestate ¹⁴ .	support. ¹⁵			
Toftlund/Vojens	440,000 tons manure and 136.000 tons maize, from local farmers, producing 20 million m ³ of gas		Supplier Association Southern Jutlandic Biogas (Sønderjysk Biogas a.m.b.a.)	To be distributed via natural gas network and to cover the needs of around 12.500 households	
Ørbæk on Funen¹⁶			Naturgas Fyn		
Haderslev area¹⁷			E.ON energy company		
Vejle Vesteregns¹⁸	230.000 tons manure and maize				

Price supplement (Energinet.dk, 2013)

Biogas price subsidies can be divided into two groups: for biogas in plants using 94% biogas or above (called 100% biogas), and for biogas in plants with 93% biogas or less (called mixed-fired). In case of 100% biogas-fired plant, it is in purchase obligation - that is, that Energinet.dk is responsible for their balancing. According to the Renewable Energy Act, such a plant is eligible for a fixed price consisting of both spot price and the indexed annually surcharge (see table).

In mixed-fired plant, the unit is commercially responsible for balancing (?), except for installations commissioned before 22 April 2004, that receive three-tier tariff (?) in addition to biogas allowance. Mixed-fired plants are eligible for a fixed price supplement for biogas share.

The table below shows the previous year's adjustments. (€/kWh)

	2010	2011	2012	2013
100 % biogas	10.0	10.2	10.3	10.4
Under 94 % biogas	5.4	5.5	5.6	5.7

¹⁴ <http://envogroup.dk/envo-biogas-toender-as>

¹⁵ http://www.energy-supply.dk/article/view/89472/tonder_far_danmarks_storste_biogasanlaeg
http://www.energy-supply.dk/article/view/89824/kaempe_biogasanlaeg_holder_flyttedag

¹⁶ <http://epn.dk/brancher/energi/article2733539.ece>

¹⁷ <http://www.eon.se/dk/Eon2StartpageContainer/www.eondk-ny/Ovrigt/Nyheder/Sonderjysk-Biogas-og-EON-vil-opfore-biogasanlag-i-Haderslev-kommune/>

¹⁸ <http://epn.dk/brancher/energi/article2733539.ece>

Annex 2. Interview guide Maabjerg Bioenergy

TEKNOLOGI OG SPOR AFHÆNGIGHED (PATH DEPENDENCY)

1. Hvordan fungerer anlægget?

- a. Input- out struktur/flows
- b. Links til de andre anlæg

2. Hvilke særlige karakteristika har anlægget (ifht andre lignende anlæg)?

- a. Hvilke dele af anlægget?
 - i. Udstyr, bakterier, reaktoren, flows/rørforbindelser,
- b. Hvem har leveret og udviklet teknologien?
- c. Hvilke investeringer har det krævet?
- d. Hvilke udviklings- og forskningsaktiviteter ligger til grund?
- e. Hvorfor valgte i netop de her teknologier og system?
- f. Hvilke problemer er der forbundet med den valgte teknologi?
- g. Med den viden og teknologi der findes i dag, ville i stadigvæk have valgt det samme system/teknologi? Hvilke muligheder er der for justeringer i teknologi og bredere system?

3. Strategi for fremtiden

- a. Hvilke planer er der for yderligere teknologisk udvikling?
 - i. Biogasanlægget
 - ii. Opgradering af gas
 - iii. Links til andre anlæg, inklusiv bioetanol

GOVERNANCE

4. Hvordan er ejerskab og styring/management?

- a. Hvem er ejere, hvem driver det, hvem tager strategiske beslutninger, etc?
- b. Hvordan fungere relationen til leverandører?
 - i. Landmænd, rensningsanlæg, fødevareindustri, etc
- c. Hvordan fungere relationen til aftagere af biogas og 'effluents', hvad angår aftaler/kontrakter, tekniske standarder, priser, etc.?
 - i. Gas (hvem?)
 - ii. Tørret fiberfraktion (Maabjergværket)
 - iii. Strøm fra egen gasmotor (el net - hvem?)
 - iv. Gødning i rør (landmænd – hvem af dem?)
 - v. Aske (gødningsfabrik – hvilken?)
- d. Hvilke private aktører 'sætter dagsordenen' ifht. udvikling af biogas sektoren?
- e. Hvilke er de centrale leverandører af teknologi og systemer?

HISTORIE

5. Baggrunden for etableringen af Maabjerg Bioenergy?

- a. Hvilke problemer skulle det løse? Hvilke fordele/indtægter?
- b. Hvilke aktører og institutioner var centrale?
- c. Hvilken forskning gjorde man brug af?

- d. Hvilke politikker var afgørende for beslutningen? Hvordan har de ændret sig siden?

OVERALL PERFORMANCE

6. Teknisk performance

- a. Gas volumen produceret, gylle aftaget, affald forarbejdet etc
- b. Operationel stabilitet (vil vi vide det??)
- c. Ressource og energi effektivitet (vil vi vide det??)
- d. Lugt og forurening?

7. Økonomisk performance

- a. Indikatorer – hvordan måles og opgøres det?
- b. Priser på inputs og outputs – hvordan sættes de, etc?
- c. Regnskab (Lau)

8. Bredere samfundsmæssig performance

- a. Accept fra lokalbefolkningen?
- b. Accept fra landbruget?
- c. Beskæftigelseseffekt (job skabelse)?
- d. Løsning af affaldsproblemer i landbrug, industri og husstande?