Production of upgraded biogas
- optimization of costs and climate impact

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Summary of main report

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REPORT

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This report is a translation of the sections “Introduction” and “Summary and recommendations” in the report “Produktion af opgraderet biogas – optimering og klimaeffekt”. A few adaptations are made in the text, so this report can be read as a separate document. Please refer to Appendix 1 for a complete list of project reports (in Danish) disseminating all results from the project “Energy and cost optimization of biomethane production”.

1. Introduction

This report summarizes the results of the project "Energy and Cost Optimization of Biomethane Production". The participating project parties were Danish Gas Technology Centre (project manager), PlanEnergi, Aarhus University, Biogas Danmark (Danish association of biogas stakeholders), Evida and Dansk Fagcenter for Biogas (Danish technical centre for biogas). The project was partly funded by the Energy Technology Development and Demonstration Program (EUDP), which is a public grant scheme. The scheme supports new technology in the field of energy, which can contribute to meeting Denmark's objectives within energy and climate.

The project started in January 2019 and was completed by November 2020. This report is the deliverable of Work Package AP9 (WP9) - Evaluation of results of RDD catalogue (Research, Development, Demonstration) and was prepared by Danish Gas Technology Centre on the basis of calculations and reports by the project participants during the project.

Biogas production has taken place for decades, where the biogas has been used for heat production in boilers, or production of electricity and heat in engines. The first Danish biogas upgrading plant was established in 2011 at a wastewater treatment plant. Upgrading of agricultural-based biogas started on a large scale in 2015 when the current subsidy scheme came into force. By the end of 2020, 50 biogas plants with upgrading of biogas are expected to be connected to the gas system. In recent years, the trend has been towards very large biogas plants to reduce production costs.

At the beginning of 2019, the entry of new grant recipients was closed under the current grant scheme, however, with exemption options for facilities that were under establishment. The reason was that the government's expenditure was too high and that the Ministry of Finance did not have the opportunity to make budgets, as before the intervention there was no ceiling on the number of facilities and the extent to which they could obtain support. A new grant scheme is being established with a tender model as a basis for awarding grants. The new subsidy scheme will probably start in 2022.

Biogas production and upgrading to the gas system have benefits for agricultural recycling of nutrients and greenhouse gas emissions, and for the energy system due to substitution of fossil gas.
In October 2020 DCA - Danish Centre for Food and Agriculture - published the report "Bæredygtig biogas - klima- og miljøeffekter af biogasproduktion" (Sustainable biogas - climate and environmental impact of biogas production), ordered by the Danish Energy Agency under the Danish Ministry of Climate, Energy and Utilities. The report concluded that biogas production with upgrading to the gas system may contribute with a reduction of 55 and 77 kg CO_2 equivalents per GJ produced

gross energy (upgraded biogas exported to the gas system) depending on type of biogas plant and biomasses used.

Energy from upgraded biogas is significantly more expensive than energy from wind and solar but the advantage is that gas can be stored cheaply, both in the short and long term, in contrast to the fluctuating production from wind and solar. Producers as well as the government have a strong interest in reducing production costs for upgraded biogas.

The aim of this project was to identify and analyse optimization measures to increase revenues or reduce costs and climate impact of the production of upgraded biogas and export to the gas system. The optimization measures can be implemented with today's knowledge, known technology and equipment available on the market today.

Reference biogas plants of various sizes were modelled and operating and capital expenses for these reference plants were assessed. Based on the reference plants, various optimization measures were proposed and subsequently analysed. It is important to note the following:

- Production prices for the reference plants were determined to achieve a basis for assessing optimization measures. At the same time, production prices showed that upgraded biogas can be produced significantly cheaper than previously assessed.
- Externalities related to biogas production are not included in the economic assessment, e.g. less methane emissions from storage and spreading of manure, better fertilizer utilization, nitrogen leaching, increased ammonia evaporation, less odour, etc.

Production costs have previously been calculated, for instance in the Danish Energy Agency's Technology Data catalogues. The information in the Technology Data, however, has not been updated in relation to market development in the size of biogas plants and upgrading plants, composition of biomass and retention times. A number of reports are covering the costs of biogas and upgraded biogas production and the possibilities of lowering these production costs. However, it is difficult to extract mutually consistent plant data from the reports for all steps of the production process. Therefore, the project chose to build a technical bottom-up model for eight model plants in four different sizes, where prices for all expenditures have been found, costs for the individual steps have been calculated, and these figures have been summed up to a total production price for upgraded biogas exported to the gas system.

This report summarizes the main results and the optimization potentials. All optimization measures are described in detail in separate project reports (in Danish). Appendix 1 gives a complete list with report titles etc. and contact information.

In this report, production costs are considered positive (+). Cost reductions of production prices are considered negative (-), increases of production costs are considered positive (+)

2. Summary and recommendations

The results of the project show that upgraded biogas can be produced significantly cheaper than previously assessed, and that there is potential to reduce the production price further. Optimization potentials have been identified between 10% and 16%, depending on plant size and configuration, within the areas:

- Manure handling and pre-treatment
- Biomass pre-treatment
- Biogas production
- Biogas upgrading
- Energy integration of biogas production and biogas upgrading.

Figure 1 shows production costs for upgraded biogas and optimization potentials identified in this project.

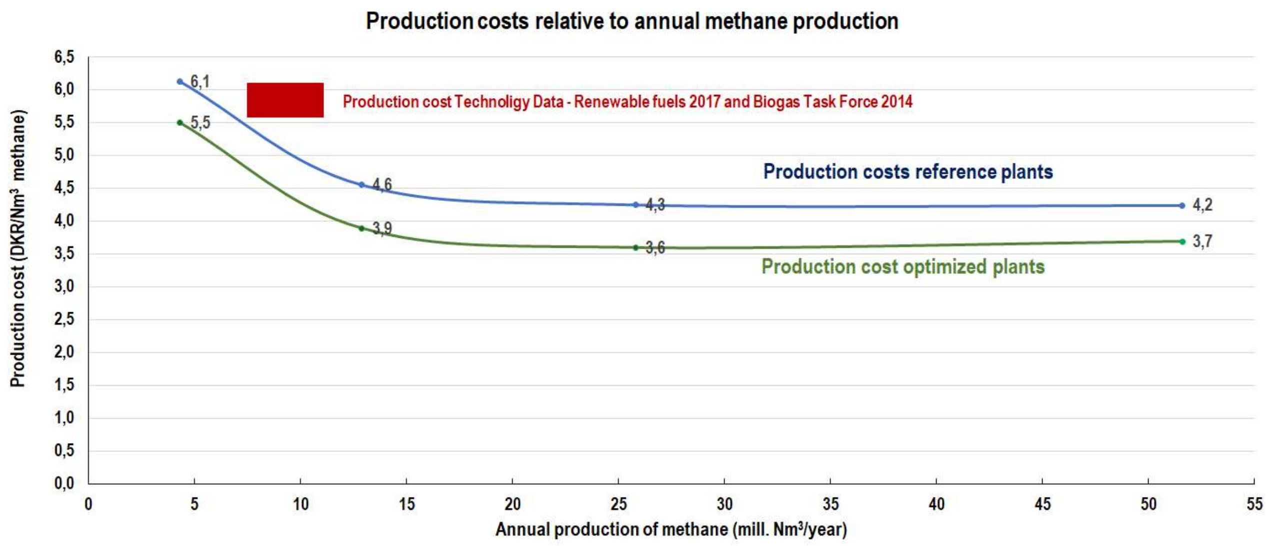

Figure 1 Production costs for reference plants and optimization potentials relative to annual methane production. Costs are positive figures (+). The production prices of the project are corporate finance prices calculated with an interest rate of 10%. Production prices from Technology Data and Biogas Task Force are socio-economic prices calculated with an interest rate of 5%.

The figure shows that the production price can drop below 4 DKK/Nm^3 methane. The Danish Energy Agency's and Energinet's Technology Data[1] state a socio-economic price of 5.5 DKK/Nm^3

[1] Technology Data - Renewable fuels. Danish Energy Agency and Energinet 2017. Data from Section "81 Biogas Plant, Basic conf." and Section "82 Biogas, upgrading", calculated with an interest rate of 5%.

methane. Prices are only stated for a "typical" biogas plant size of 7.5 million Nm^3 methane/year. In a report[2] prepared for the Danish Energy Agency's Biogas Taskforce, Ea Energianalyse states a socio-economic production price of 5.5-6.0 DKK/Nm^3 methane, depending on the biomass composition, for a biogas plant size of 11.2 million Nm^3 methane/year.

However, plant size has grown considerably over the last 5 years, and as shown in Figure 1, production costs depend very much on plant size. Earlier analyses of production costs did not focus on this effect.

Optimization potentials

The identified optimization measures can be implemented with today's knowledge, known technology and equipment available on the market today. There are several other effects that can also reduce the production price of upgraded biogas. These effects are not quantified, but qualitatively described in the Danish version of this report. The effects can be:

- Operation of several plants in the same organization
- Expansion of markets through the establishment of many new biogas plants
- General learning and development in the biogas industry
- Methane loss measurement programs.

Total optimization potentials have been identified between 10% and 16%, depending on plant size and configuration. Production prices for upgraded biogas for reference plants and optimization potentials are shown in Table 1.

[2] "Anvendelse af biogas til el- og varmeproduktion. Analyser for Biogas Taskforce. Ea Energianalyse 2014. (Utilization of biogas for production of electricity and heat. Analyses for Biogas Task Force)

Table 1 Production prices for reference plants and optimization potentials. Costs are positive figures (+). Savings are negative figures (-).

Production costs for upgraded biogas for reference plants and optimized plants	Plant:	Small biogas plant		Medium biogas plant		Large biogas plant		Very large biogas plant	
	Upgrading:	Membrane	Amine scr.	Water scr.	Amine scr.	Water scr.	Amine scr.	Amine scr.	Amine scr.
	HRT:	70 days	70 days	35 days	35 days	35 days	35 days	35 days	65 days
All prices in DKR /Nm^3 methane	No:	Plant 1-M	Plant 1-A	Plant 2-V	Plant 2-A	Plant 3-V	Plant 3-A	Plant 4a-A	Plant 4b-A
Reference plants: Cost methane incl. financing		**6,16**	**6,10**	**4,58**	**4,53**	**4,30**	**4,20**	**4,23**	**4,26**
Total optimization potential		**-0,66**	**-0,60**	**-0,70**	**-0,63**	**-0,69**	**-0,62**	**-0,61**	**-0,47**
		-10,7%	***-9,8%***	***-15,3%***	***-13,9%***	***-16,0%***	***-14,8%***	***-14,5%***	***-11,1%***
Optimized plants: Cost methane incl. financing		**5,50**	**5,51**	**3,88**	**3,90**	**3,62**	**3,58**	**3,61**	**3,79**

The plants in Table 1 (and Figure 2 and Figure 3) cannot be directly compared, if, for instance, you would like to investigate the effect of making plants larger. "Smaller biogas plants" (Plant 1-M and 1-A) are typical large farm-based biogas plants / small centralized biogas plants with long retention times. "Medium-size biogas plants" (Plant 2-V and 2-A), "Large biogas plants" (Plant 3-V and 3-A) and the first "Very large biogas plant" (Plant 4a-A) are directly comparable, as they have the same biomass composition and short retention times. The second "Very large biogas plant" (Plant 4b-A) has a different biomass composition and long retention time.

Figure 2 shows optimization potentials split in main groups of measures. The largest potentials are in biomass pre-treatment, biogas production, and upgrading and desulphurization. In the biomass pre-treatment, re-digestion / selective digestion contributes approx. 2/3 of the potential, and DisRuptor with the rest. In biogas production, reduction of downtime contributes approx. 1/3 of the potential, the remaining part is optimization of electricity and heat consumption, as well as reduction of methane loss. For upgrading, the primary potential is the choice of optimal desulphurization technology.

For manure handling, reduction of washing water, rapid removal of pig manure and admixture of deep litter in the manure contributes approx. half of the potential, and a filter box for separation the other half. For energy integration, the potential is made up of heat pumps on pre- and post-storage tanks, heat exchange and regular cleaning of pipes and heat exchangers.

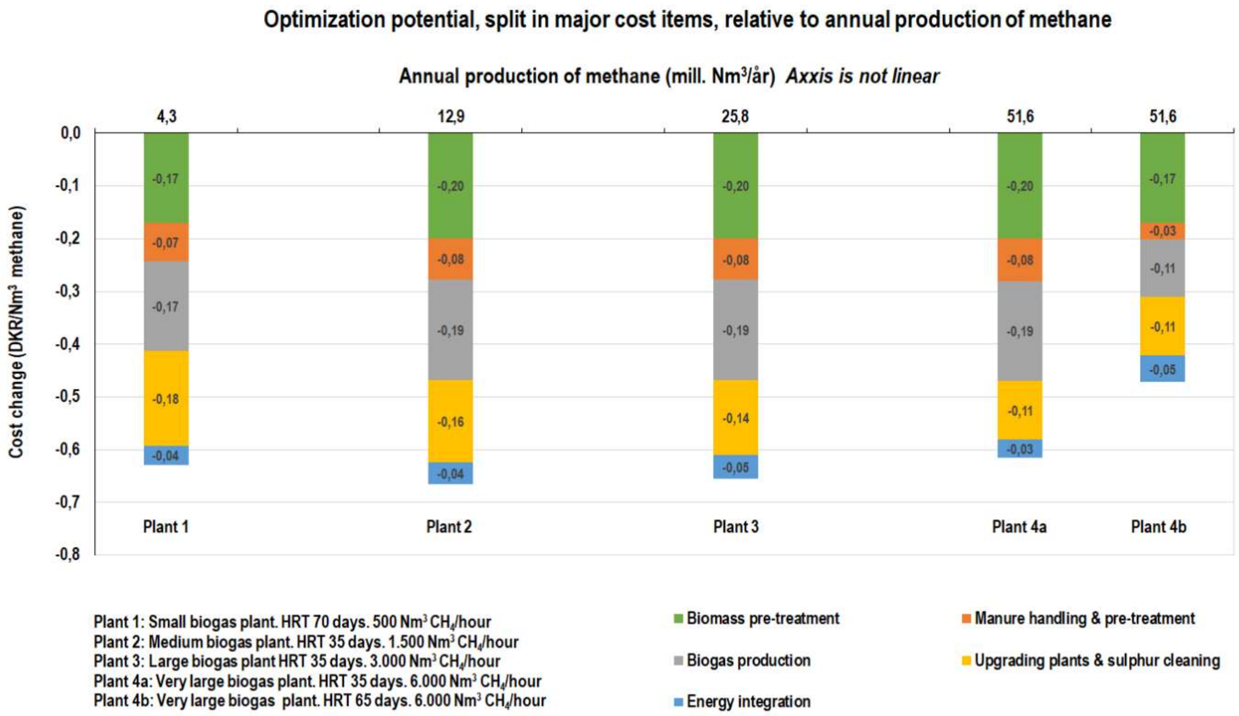

Figure 2 The effect of optimization measures split in main groups of measures relative to annual methane production. Negative figures (-) are savings.

An optimization measure with a large climate impact, but limited savings, is more frequent removal of manure from pig stables. When pig manure is removed from stables more frequently, the methane loss to the surroundings is reduced and the biogas plant gets manure with greater methane potential. The measure has a negative CO_2 shadow price and is, therefore, an attractive climate measure for agriculture. More frequent removal of manure leads to greater costs for the agriculture sector, and the biogas plant gets increased revenues due to larger methane production. If the measure is to be realized on a large scale, it the financial incentive shall be appropriate.

Some optimization measures do have a climate impact but lead to increased costs. This is the case for reduction of methane emission from the CO_2 exhaust from water scrubbers and membrane upgrading plants. The reduction is done by oxidizing the methane to CO_2 in a Regenerative Thermal Oxidizer (RTO).

Pumping manure via pipelines as an alternative to road transport will also provide a certain climate impact but, on the other hand, will lead to increased costs. Pump pipelines will reduce road transport and may be a requirement for achieving an environmental approval for a biogas plant, though.

Reference plants

As a starting point for calculating the effect of optimization measures, the production price for upgraded biogas is calculated for reference plants in four sizes. Figure 3 shows production prices for the different plant sizes and how the production price is split in major cost items.

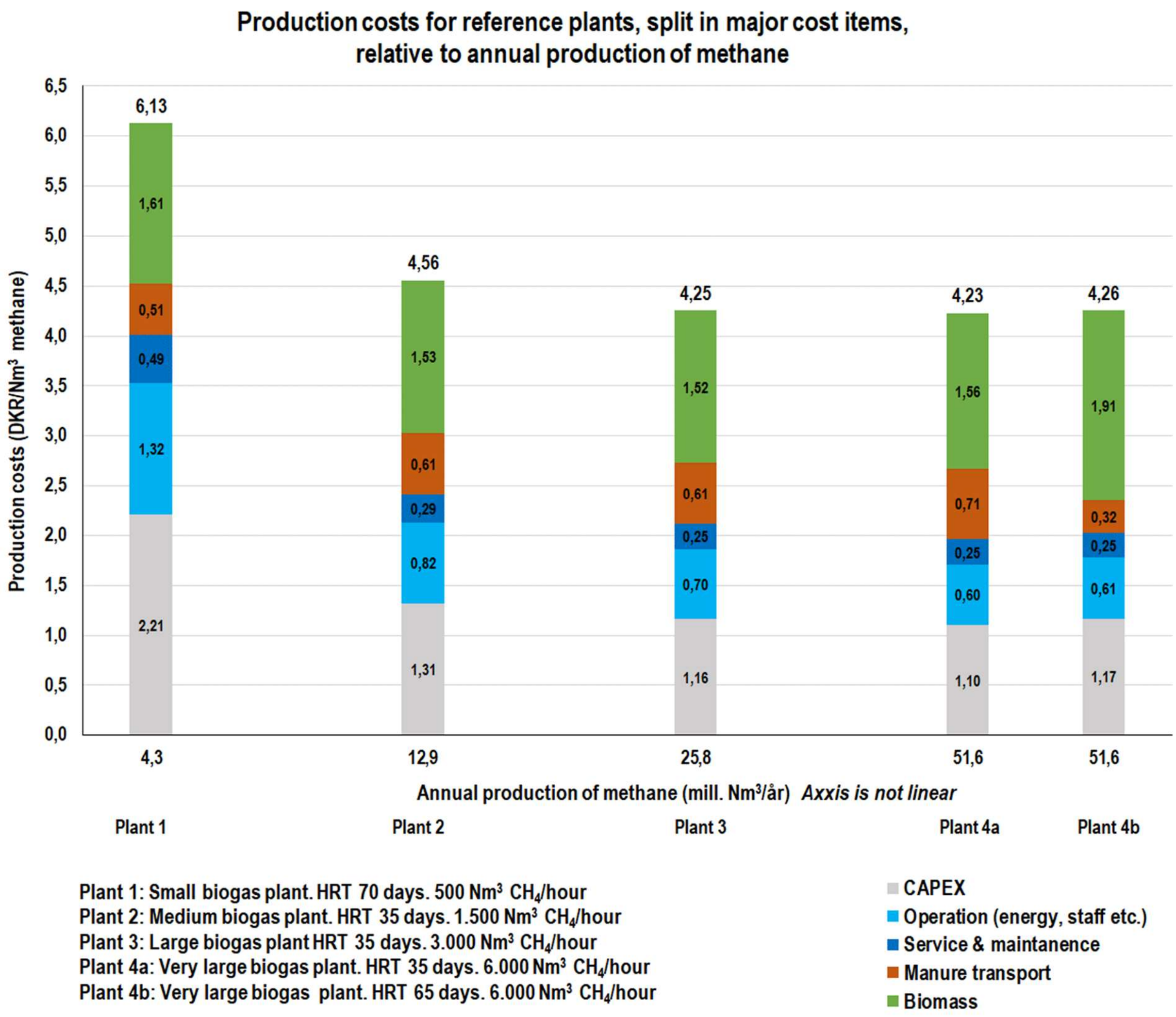

Figure 3 Production costs for reference plants split in major cost items relative to annual methane production. Costs are positive figures (+).

Costs for the production of upgraded biogas drop sharply from “Small biogas plants” (plant 1) to “Medium-sized biogas plants” (plant 2). This is primarily due to the fact that the investment per unit of productions capacity drops sharply and that energy consumption for the biogas process is lower.

From "Medium-sized biogas plants" (plant 2) to "Large biogas plants" (plant 3), there is a small decrease in production costs. This is primarily due to the fact that the investment per unit of productions capacity continues to fall, but costs for manure transport are rising due to longer driving distances.

When the size is increased to “Very large biogas plants” (plant 4), the benefits of much larger plants are offset by increased transport costs for manure.

Costs for biomass will decrease when the plants become larger due to economies of scale. Operating costs will decrease because less manpower is needed, the larger the plant, and because the large plants are more energy efficient. Service and maintenance also become relatively cheaper when the facilities become larger.

Sensitivity analyses show that 15-20% of the production costs for upgraded biogas derive from interest and depreciation at an interest rate of 10%. At an interest rate of 5%, 9-11% derive from interest and depreciation.

Costs for manure are solely composed of transport costs in the calculations for reference plants. In the calculations for reference plants, transport costs are between 21 and 28 DKK/ton, depending on the plant size (the larger the plant, the higher the price, due to a wider collection area). Sensitivity analyses show that the production price for upgraded biogas is changed by approx. ±4% when the manure price is altered by ±10 DKK/ton:

+10 DKK/ton = biogas plants are to pay for "lending" the manure

-10 DKK/ton = farmers are to pay for having the manure degassed

When the prices of biomass and industry waste are altered by ±15%, calculations show that production price for upgraded biogas is changed by approx. ±3.5%:

+15% = biomass and industrial waste will be more expensive

-15% = biomass and industrial waste will be cheaper

Recommendations

This section presents several recommendations for further work on optimizing costs and methane loss from production of upgraded biogas. The recommendations were prepared based on the analyses of the project as well as topics that were included along the way but were not part of the project.

Handling and pre-treatment of manure

Reducing the methane loss from handling of pig manure in farms has two climate effects: The climate impact of agriculture will be lower due to less evaporation of methane, and the methane yield of the biogas plant will grow, thus increasing the displacement of fossil gas from the gas system.

The climate impact of the agricultural sector is big, but at the moment the sector does not see the necessary financial incentive, as more frequent removal of manure from the stables leads to additional work with the removal and perhaps additional investment in pre-storage etc. The biogas plant, on the other hand, will get a financial gain from more frequent removal of manure as it will give increased methane yield from the same amount of manure.

This financial gain will vary depending on the suppliers of each biogas plant. Even if it will be a moderate gain, we would recommend implementing the measure to the extent possible. The measure is considered a financially attractive climate initiative for agricultural sector with a negative CO_2 shadow price. This would require a closer link between agriculture farms and biogas plants to ensure that measures are implemented more quickly and/or to a greater extent. Today, in some biogas plants, there is a link between the "value" of the manure and the methane potential, via bonus / penalty schemes, where the supplier is rewarded for delivering high dry matter in the manure.

In these project calculations, the biogas plants bear the increased costs in agriculture farms, caused by more frequent removal of manure, and receive the increased revenue from larger methane production. The calculated optimization effect thus reflects the sharing of expenses and revenue, giving both parties a financial incentive to implement the measure.

- *Recommendation: Economic linkage between agriculture farms and biogas plants, so that gains from increased methane yields to a greater extent are assigned to those who bear the costs.*
- *Support and development programs that accelerate the development of climate-friendly pig farms that would facilitate frequent removal of manure, possibly together with manure cooling.*

For cattle production, where deep litter is often stored outside, it is also expected to be profitable to transport the deep litter to the biogas plant without significant storage and handling before delivery. During storage, the deep litter emits methane, and extra handling also emits methane. Frequent removal of cattle manure is also expected to provide a potential, even though it would be less than for pig manure.

- *Identification of methane loss potentials of more frequent removal of cattle manure and of optimized handling of deep litter.*

This is also true for collection of source-separated organic domestic waste (Danish abbreviation: KOD), where, today, there is no connection between the price paid by e.g. the municipalities to dispose of the KOD and the methane potential. The municipalities and the companies collecting and pre-treating the KOD have no financial incentive for transferring the KOD quickly to the biogas plant with minimal methane and nitrous oxide losses, which would result in a larger methane potential in biogas production. It should be noted that today there is very little knowledge of methane and nitrous oxide losses in the collection and pre-treatment chains, and little knowledge of the possibilities to limit these losses. So far, attention has been given to economic optimization of collection and pre-treatment.

- *Recommendation: Identification of methane and nitrous oxide loss potentials in collection and pre-treatment chains of KOD.*
- *Proposal for economic linkage between municipalities/others collecting and pre-treating KOD and biogas plants to make it more feasible to transfer the revenue of increased biogas yield to those bearing the costs of optimized collection and pre-treatment.*

Biomass pre-treatment

Pre-treatment can help increase the gas yield of the available biomass and thereby displace the most expensive and least sustainable biomasses such as maize and glycerol. In addition to pre-treatment being able to displace the least sustainable biomasses, it could help to reduce the residual gas potential, which, all other things being equal, will result in a reduced methane emission during the subsequent storage. It is also expected that the viscosity will decrease and have a positive effect on ammonia evaporation from spreading of manure.

The most promising technology tested in the project is selective retention time, which in addition to an increased gas yield will result in lower residual gas yield. It will be possible to achieve the same effect with selective retention time as with longer retention time by establishing a larger reactor volume. The optimal solution requires analyses and economic calculations to determine the optimal design that will depend on the biomass used.

- *Recommendation: Creating a knowledge base with analyses of the total residual gas potential, as well as residual gas potentials in solid and liquid degassed material, so that the optimal composition between retention time and selective retention time can be determined.*

Biogas production

It is possible to reduce methane losses from biogas plants by various measures. Today there are no limits for methane loss e.g. in legislation, methane loss is not linked to the size of the upgrade grant, and participation in methane loss measurement programs is voluntary. Methane loss can be detected by leak detection (e.g. by a camera showing methane or a gas sniffer) showing a leakage (without being able to measure the quantity), by measuring quantities in point sources (e.g. the CO_2 exhaust of the upgrading plant), or by a tracer gas measurement determining the methane loss of the entire plant.

Experience from voluntary measurement programs shows that regular methane leakage measurements and internal control programs help to reduce methane loss, especially leaks in components and tank covers.

- *Recommendation: Mandatory regular methane leakage measurements and internal control programs for all biogas plants.*

The Minister of Climate, Energy and Supply already has legal authority[3] to regulate the area.

Methane emission limits and coupling between methane emissions and e.g. upgrade grants may be difficult to implement in a fair way due to measurement uncertainty in tracer gas measurements and uncertainty about which sources contribute to the methane emission. If, for example, there is a farm next to the biogas plant, the methane loss of the farm will affect the measurement result. The measurement result also depends on the season; in general, the methane loss will be smaller during the cold months of the year. Methane loss is measured by tracer gas measurements with an uncertainty of up to 25%. The measurements typically cost DKK 25,000 per measurement, i.e. it is rather expensive to verify uncertain measurement results by repeated measurements.

Alternatively, requirements can be set for specific plant components, where it is possible, for example, to make point measurements in exhausts etc.

- *Recommendation: Requirements for methane reduction in CO_2 exhausts from membrane and water scrubber upgrading plants. This can be solved by installing Regenerative Thermal Oxidizer (RTO).*

[3] Executive Order of the Natural Gas Supply Act (LBK no. 126 of 06/02/2020) § 35 d, subsection 4: "The Minister of Climate, Energy and Supply may also lay down rules that requirements for limitation, inspection and control of greenhouse gas emissions from plants that produce or upgrade biogas must be complied with as a condition for receiving price supplements pursuant to section 35 g. "

- *Recommendation: All pre- and post-storage tanks must be equipped with gas. At the same time, the "Executive Order regarding the control of major-accident hazards involving dangerous substances" must be complied with when it comes to gas storage facilities.*

Treatment of manure in a biogas plant can increase ammonia evaporation, as the manure is not being degassed. Ammonia evaporation from post-storage tanks can be reduced by covering the tanks (gas-tight membrane), to minimize air circulation around the surface. If a cover with gas collection has been established, it has the same effect. Cooling the manure before returning it to the farms can also reduce ammonia evaporation. This can be done with heat exchangers and the recovered heat can be utilized by using heat pumps.

- *Recommendation: Cover all post-storage tanks to reduce ammonia evaporation.*
- *Recommendation: Cool the manure before returning it to the farms.*

Better planning of service, internal control of components and possibly establishing a spare parts stock can in most cases provide large savings for the plant in connection with downtime. There will always be a risk that components are backordered by suppliers, that spare parts must be ordered from abroad etc. If the component is critical, such as gear for the agitator, gas blower, large electric motors or a pump, it may result in prolonged downtime. If the plant does not have a large gas storage capacity, the downtime will result in large expenses for the plant, as the biogas produced must be flared. Frequent internal control will have a positive effect on the methane loss of the plant, as the control will help detect leakages from components like overpressure valves.

Frequent shutdowns can be avoided with frequent internal control of the technical parts of the plant and with better planning of service, e.g. when the upgrading plant and the receiving station are to be serviced. Other parts of the system can be serviced at the same time so that these components do not give additional downtime.

- *Recommendation: Establish a spare parts stock with key components to avoid prolonged downtime.*
- *Recommendation: Systematic planning of downtime to service as many system parts as possible at the same time.*

Installing frequency converters can reduce electricity consumption. In the case of the biogas plant type with submerged propeller agitators (which are often seen in plants with concrete tanks), it should be considered to replace direct start and soft start with frequency converters reducing energy consumption, because the agitator can be set to provide exactly the necessary agitation. The replacement must be done by a supplier with experience in the field, as harmonic currents of electrical components pose a challenge, which can create erroneous measurements on other components, e.g.

level meters. An analysis from Dansk Energi (Danish Energy) predicted an average reduction in electricity consumption of approx. 15% if all motors use frequency converters instead of direct start.

- *Recommendation: Consider installing frequency converters on biogas plants with submerged propeller stirrers. Already in the design phase it should be considered installing frequency control.*

Upgrading plants and desulphurization

Some of the recommendations are general for upgrading plants, while others are specific for each upgrading technology.

For all upgrading technologies desulphurisation is expensive. Therefore, it is recommended to use the cheapest possible method suitable for the specific upgrading technology and for the specific plant size. This is not always the case for existing plants, and new plants can achieve large savings by choosing the cheapest technology, where both CAPEX and OPEX are part of the economy.

- *Recommendation: Investigate desulphurization alternatives, and implement the cheapest possible solution, where both CAPEX and OPEX are included in the calculations.*

The uptime/availability is a very important parameter. In the event of prolonged downtime, it is necessary to flare the biogas produced. Although it can be costly in spare parts and redundancy, the lost profits of just a few days of downtime would make it a sound investment to ensure the highest possible uptime. The highest possible guaranteed uptime through investments and round-the-clock service is therefore a good investment to improve the overall plant economy.

- *Recommendation: Increase the plant uptime as much as possible with redundant components and instant access to repairs and spare parts.*

Membrane-based plants are sensitive to impurities in the biogas that can reduce the efficiency of or destroy the membranes. The membranes must therefore be protected against impurities. Suppliers are already working on this, but it seems that problems and risks are not communicated satisfactorily, as many plants are experiencing difficulties with membranes.

- *Recommendation: Invest in measuring equipment that can detect impurities in the biogas before it enters the membranes.*
- *Recommendation: Systematic knowledge sharing between suppliers and membrane plant owners.*

Membrane-based upgrading plants require compression of the biogas to a high pressure, with an ensuing large electricity consumption. Part of the energy can be recovered by installing heat recovery at the compressor.

- *Recommendation: Install heat recovery at the compressor of the membrane-based plants.*

Amine-based upgrading plants have a high heat consumption, with good opportunities for heat recovery, though. In addition, increased heat recovery will reduce the costs for cooling.

- *Recommendation: Optimize heat recovery at amine-based plants, in combination with heat pumps, if possible.*

Membrane-based and water scrubber-based upgrading plants have high methane losses in the CO_2 exhaust compared to amine-based upgrading plants. The methane losses may be reduced by burning the methane to CO_2 in a Regenerative Thermal Oxidizer (RTO).

- *Recommendation: Install RTO at the membrane-based and water scrubber-based upgrading plants.*

Energy integration

The energy consumption to produce upgraded biogas is of significant importance from an economic and climate perspective. Large amounts of heat are used to heat biomass to process temperature and for use in a possible amine-based upgrading plant.

Increased heat exchange between the biomass that is pumped into the plant and the low-temperature excess heat from the upgrading plant has been investigated and found profitable. As a start, many plants choose a limited heat exchanger solution to get started with production, and when increasing the biomass input, the capacity of heat exchange becomes too low. The missing heat transfer will typically be reflected in increased heat consumption. It should, therefore, be considered to contact relevant suppliers of heat exchanger solutions to get an idea of the feasibility of implementation at the biogas plant.

- *Recommendation: Investigate the feasibility of increased heat exchange on the plant, e.g. between the degassed manure and raw manure, or increased heat exchange between. amine-based upgrading and raw manure.*

In connection with heat exchange, efficiency can be improved by installing "Cleaning in Place" (CIP) systems, where pipe systems and heat exchangers can be cleaned without taking them out of operation and disassembling them. This can ensure a cost-effective cleaning of internal coatings, so that the efficiency of heat transfer in the heat exchangers is increased.

- *Recommendation: Investigate the possibility of installing CIP systems.*

Integration of heat pumps in biogas plants in connection with optimization of heat flows from, for instance, the degassed biomass has been found to be profitable. Cooling the manure can also help to reduce ammonia evaporation when the manure is returned to the farms. Furthermore, it has been found that high-temperature heat pumps are close to being able to compete with gas boilers for the supply of hot water for amine upgrading. This can ensure lower operating costs and a reduction in the consumption of fossil fuels.

- *Recommendation: Investigate the possibility of better utilization of heat flows in the specific plant design via a heat pump.*

Connection to the gas system

In connection with the merger of all gas distribution companies into one, the gas distribution company Evida has developed uniform practices and cost-optimization, e.g. by using framework agreements with suppliers and uniform connection principles. Therefore, there are no specific recommendations for optimization, but a recommendation to follow up on an ongoing basis on:

- *Standardization of receiving stations, injection strings and other components.*
- *Standardization of work regarding regulations and system layout by using as few standardized components and layouts as possible.*
- *Consider whether the gas quality in the receiving station can be measured with cheaper gas analysis equipment instead of gas chromatograph.*
- *Lower the pressure in the distribution network.*
- *Connect several MR stations to reduce compressor operating costs.*
- *Minimize compressor inspection by installing additional sensors for monitoring.*
- *Higher pressure in the connecting line for large plants with a large distance to the nearest MR station.*
- *More frequent use of quality trackers to replace gas chromatographs and measuring equipment.*

General recommendations

The Danish Energy Agency's Technology Data section on biogas production and upgrading was prepared in 2017, and therefore does not include the rapid development of plant size we have seen since 2017. The Technology Data catalogue contains data for biogas plants that are slightly smaller than the medium-sized plant calculated in this project. For upgrading plants, The Technology Data catalogue contains data for plants that correspond to the smaller biogas plants in this project, and there is no distinction between the essentially different upgrading technologies in relation to energy input, methane loss, etc.

- *Recommendation: Update the Technology Data section on biogas production to include plant sizes corresponding to the largest plants established today, the current biomass composition and retention times.*

- *Recommendation: Update the Technology Data section on upgrading to include plant corresponding to the largest plants established today, and to distinguish between different upgrading technologies.*

Appendix 1: List of project reports

Kortlægning af produktionskæde for opgraderet biogas (projekt AP 2)
(Mapping of production chain for upgraded biogas (project WP2))
ISBN: 978-87-7795-429-0
Prepared by: Danish Gas Technology Centre. Contact person: Thomas Hernø (email: the@dgc.dk)

Gyllehåndtering og forbehandling, optimering (projekt AP 3)
(Handling and pre-treatment of manure, optimization (project WP3))
Prepared by: PlanEnergi. Contact person: Karl Jørgen Nielsen (email: kjn@planenergi.dk)

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