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BEST AVAILABLE TECHNOLOGIES FOR PIG MANURE BIOGAS PLANTS IN THE BALTIC SEA REGION

Acknowledgements

This report was produced between July 2010 and May 2011, by experts from the following four institutes:

- AgriFood Research, Finland (MTT)
- Agro Business Park, Denmark (ABP)
- AgroTech – Institute of Agri Technology and Food Innovation, Denmark.
- Swedish Institute of Agricultural and Environmental Engineering (JTI)

Knud Tybirk from Agro Business Park has been responsible for planning, management and coordination. Main contributors from JTI have been Lena Rodhe, Andras Baky and Mats Edström. The main contribution from MTT was made by Ilkka Sipilä. From AgroTech contributions were made by Søren Lehn Petersen, Kurt Hjort-Gregersen, Kasper Stefanek, Bjørn Hjortshøj Andersen and Thorkild Qvist Frandsen. Thorkild Qvist Frandsen is main author and responsible for editing the final report.

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Foreword

To reduce eutrophication of the Baltic Sea is a main objective for Baltic Sea 2020. A previous study initiated and funded by Baltic Sea 2020[1] established that treatment of pig manure in biogas plants combined with proper handling of the digestate can reduce nutrient losses to the Baltic Sea significantly. Biogas production based on pig manure is also a cost effective way to reduce greenhouse gas emissions from agriculture and the establishment of more biogas plants will generate additional income and jobs in the rural areas.

This report is the result of a new study with the objective to identify and describe the best available technologies for biogas plants based on pig manure, including pre- and post- treatment, storing and spreading of digestate. The intention is to facilitate that more pig manure is used for biogas production, in a way that efficiently re-circulate the valuable nutrients nitrogen and phosphorus.

The report provides a comprehensive set of information for stakeholders with the ambition to make intensive rearing of livestock sustainable, with a focus on pig production:

The main section concludes findings from desk studies and field visits.

The subsequent Annexes contain extensive information on analysed technologies, including biogas technologies, pre- and post-treatment of manure/digestate, storing and spreading of manure as well as available technologies for usage of the produced biogas. Framework conditions in countries around the Baltic Sea, nitrogen-efficiency analyses, substrate consideratons and economic scenarios for the recommended technology solutions are also available.

The study is initiated by Baltic Sea 2020 as part of the “Intensive Pig Production Program”, which aims at reducing the negative environmental impact of nutrients leaching from intensive pig farms to the Baltic Sea.

Stockholm, June 2011

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[1] ”Foged, Henning Lyngsö. 2010, Best Available Technologies for Manure Treatment – for Intensive Rearing of Pigs in the Baltic Sea Region EU Member States. Published by Baltic Sea 2020, Stockholm. 12 pp.

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Executive summary

Background

The Baltic Sea is a brackish, shallow and enclosed sea and therefore a vulnerable ecosystem. Over the past century increasing amounts of nutrients led to the Baltic Sea have resulted in frequent algae blooms, depletion of oxygen in the water followed by reduction in fish population and other negative environmental impacts.

Intensive pig production is a key point source of nitrogen and phosphorous to the Baltic Sea. However, by developing and implementing improved technologies and manure management practices the loss of nutrients from the pig farms can be significantly reduced. Treatment of pig manure in biogas plants is an effective way of mineralizing manure nitrogen. As a result of the biogas treatment, a larger share of the nitrogen may be taken up by the crops and leaching can thereby be reduced, if the digestate is handled properly. Separation of slurry before the anaerobic digestion or separation of the digestate after the anaerobic digestion may be a measure to further reduce the nutrient losses by facilitating redistribution of phosphorous from areas with surplus to areas with a need for phosphorous. Furthermore, proper technologies and management practices related to storage and field application of digestate are fundamental for reducing nutrient losses.

Objective of the study

The overall objective of the study is to contribute to the reduction of loss of nitrogen (N) and phosphorous (P) from intensive pig production in the Baltic Sea Region by promoting that pig manure from IPPC regulated farms is used for biogas production. The work should facilitate the implementation of the best available technologies for biogas production based on pig manure. Biogas technologies, digestate handling technologies and technologies for biogas upgrading and utilization are described and evaluated in order to identify combinations with the highest potential for reducing the loss of nitrogen and phosphorous, and take into account the economic viability of the biogas plant.

Results and conclusions

Production of biogas based on pig manure involves many process steps and technologies. It is impossible to point out one combination of technologies that will be optimal for all situations. The choice of overall concept and specific technologies should always reflect the specific situation including both local and country specific opportunities and barriers.

In areas characterized by a large pig production distributed on many small and medium scale pig farms **centralized biogas plants** are recommended. **Farm based biogas plants** are most relevant in connection to large pig farms in areas with low pig densities.

EU legislation regulates spreading rates of manure according to its content of nitrogen. Especially for pig manure this can result in over-fertilization of phosphorous because pig manure is characterised by a high content of phosphorous relative to nitrogen. Thus, there is a need for balancing the content of phosphorous to the content of nitrogen in manure before spreading. Pre-separation of slurry in combination with anaerobic digestion in centralized biogas plants may be a useful concept in areas with high pig density for balancing nutrient contents and thereby reduce nutrient loss. Pre-separation of slurry is also a way of increasing the amounts of substrates available for centralized biogas plants and can therefore contribute to improve the profitability of the biogas plant. For pre-separation of pig slurry decanter centrifuges are identified as a cost-effective and reliable technology, but there are other relevant technologies available on the market. It is important that the solid fraction from the slurry separation is handled properly to minimize loss of nitrogen through ammonia emission.

Owners of existing biogas plants and future investors are recommended to consider **pre-treatment of biomass** for improved decomposition of organic matter and increased methane yield. Especially for biogas plants using large amounts of solid pig manure or fibre fraction from slurry separation there is a potential for economic as well as environmental benefits of pre-treatment. Extrusion and thermal hydrolysis have been identified as two promising pre-treatment technologies but still they are not widely used.

For biogas plants using pig manure as a main substrate a **reactor configuration** of mesophilic process temperature combined with relatively long hydraulic retention time and/or a two-stage anaerobic digestion is recommended. This is a robust reactor configuration, which is less sensitive to changes in the substrate mix and process temperature and the risk for process problems due to nitrogen inhibition is reduced too.

In areas characterised by high pig density it is recommended to include on the biogas plant a technology for **post-separation of the digestate** as a measure to balance the phosphorous application to the need of the crops. By concentration of phosphorous in the solid fraction transportation of the surplus phosphorous over longer distances is facilitated. Decanter centrifuges are recommended as a robust and cost effective technology for post-separation. Care should be taken to handle the solid fraction in a way to minimize ammonia emission.

To minimize nitrogen leaching **digestate should be applied to the fields** during spring time and early summer when the nutrients are needed by the crops. Autumn spreading should be avoided and it is therefore recommended to establish storage facilities for digestate with capacity of minimum 9-10 months, depending on the climate and length of growing season in the area where the pig farm is located.

For both environmental and economic reasons measures have to be taken to reduce ammonia emission during **storage and field application** of digestate and fractions from separation of digestate. It is recommended to store digestate in covered storage tanks or closed slurry lagoons. The digestate should be incorporated into the soil directly after spreading with a harrow or injected into the soil. Alternatively, acid can be added to the digestate to reduce pH and thereby reduce ammonia emission during storing and spreading.

Evaluation and comparison of different combinations of manure-digestate handling technologies can be facilitated by model calculations. As part of this study **nitrogen efficiency calculations** have been done for five manure-digestate handling scenarios. Nitrogen efficiency expresses the share of total-N in the original manure which is available for the crops after application to the field. The model calculations in this study confirm that anaerobic digestion increases nitrogen efficiency all other things being equal. The risk of nutrient leakage to water is potentially higher with digested compared to non-digested manure, stressing the necessity to optimize timing for field application and dosage digestate. The model calculations also show that spreading time is more important than anaerobic digestion of the manure in order to reduce nitrogen leaching.

Utilization of biogas for combined heat and power production is a well known technology and recommended especially for small scale plants located far from the natural gas grid and especially if the produced heat can be utilised. In countries with tax systems favouring use of biogas for vehicles (i.e. Sweden and Germany) upgrading of biogas should be considered especially for medium and large scale biogas plants.

Despite the use of best available technologies biogas production based on pig manure alone is seldom profitable. **Profitability** can be improved by using co-substrates like manure from other livestock types and other residues from agricultural production. The use of energy crops as co-substrate may also improve profitability, but results in additional organic nitrogen applied to the fields and potentially increased leaching. Energy crops are therefore not recommended from a nutrient leaching perspective, but more studies are needed.

A subsidy system including a bonus for biogas plants based on pig manure will contribute to improved profitability and can be justified due to the large positive environmental impact on nitrogen leaching and greenhouse gas emissions of using manure compared to other substrates.

1. Introduction

The Baltic Sea is a shallow and enclosed sea and therefore a vulnerable ecosystem. Since 1900 increasing amounts of nutrients have been led to the Baltic Sea from the large catchment area surrounding the sea. Eutrophication is the result and the occurrence of algal blooms has increased significantly.

Intensive pig production has been identified in the Helcom Baltic Sea Action Plan as a key point source to address in order to reduce eutrophication. Approximately 67 million pigs are found in the Baltic Sea catchment area (Gren et. al., 2008) and this figure is expected to grow in the coming years. Especially in Poland, Lithuania, and Latvia new large scale pig farms are expected to be established.

Thus, there is a challenge to develop and implement new technologies including improved management practices to reduce the loss of nutrients resulting from pig production in the Baltic Sea region. A study initiated by Baltic Sea 2020 (Foged, 2010) concluded that anaerobic digestion is the best available technology to reduce nitrogen leaching caused by intensive pig production. Furthermore, the study mentions slurry separation as a relevant technology to ensure a balanced fertilization on own agricultural areas and export of the phosphorous rich solid fraction to regions where it can be used in an environmentally safe way.

The present study goes into detail in describing and evaluating technologies used in relation to pig manure biogas plants including technologies for pre-separation of slurry and post-treatment of digested biomass.

The effect of using pig manure in biogas plants is that the content of organic matter is reduced during the process of anaerobic digestion. Compared to raw slurry a larger share of the total nitrogen will be in the form of ammonium-nitrogen in the digestate. A higher share of the nitrogen can be taken up by the crops and consequently less nitrogen is lost, assuming that there is a need for nitrogen by the plants.

In connection to centralized biogas plants pre-separation of slurry can be used to produce a solid fiber fraction with a higher energy density than raw slurry. This will make it relevant to utilize organic matter from slurry from a larger area since the transportation cost per ton of organic matter is reduced. Similarly, in order to facilitate redistribution of nutrients from areas with surplus to areas where the nutrients are needed for the crop production post-treatment of the digested biomass should be considered.

In Table 1 the effect of anaerobic digestion and post-treatment of digested biomass is shown using model calculations of the concentrations and total amounts of total-N, ammonium-N and organic N in input biomass (mainly pig manure), digestate and liquid fraction respectively. It is seen that the concentration of organic N is reduced from 3,22 kg/ton input biomass to 1,54 kg/ton digestate as a result of the anaerobic digestion. It is this conversion of organic nitrogen to plant available mineral nitrogen that leads to the positive effect of reduced nitrogen leaching. In addition, if the digestate is separated in a decanter centrifuge the concentration of organic N is reduced from 1,54 kg/ton in the digestate to 1,09 kg/ton in the liquid fraction.

Table 1.Effect of anaerobic digestion and separation of digestate illustrated by model calculations.

Parameter	Total-N		Ammonium-N		Organic N		Amount
Unit	Kg/ ton	Tons/ year	Kg/ ton	Tons/ year	Kg/ ton	Tons/ year	Tons/ year
Input biomass	5,23	594	1,84	216	3,22	379	117.500
Digestate	5,39	594	3,85	424	1,54	170	110.257
Liquid fraction from post-separation	4,59	446	3,50	339	1,09	105	97.026
Solid fraction from post-separation	11,22	148	6,41	85	4,88	65	13.231

The biogas produced in the anaerobic process can be used as heat or for power production, or upgraded for vehicle gas. It can be used at the farm/plant to reduce operational costs or if the infrastructure is available sold to the electricity/gas grid and provide an extra income for the biogas plant owner.

2. Project objectives

The overall objective of the project is to contribute to reduce the amount of nitrogen and phosphorous from intensive pig farming that is lost and discharged to the Baltic Sea. This is achieved by securing that a larger share of pig manure is used for biogas production and by securing that the digestate is handled optimally in order to minimise the loss of nitrogen and phosphorous.

The approach chosen is to facilitate the implementation of the best available technologies for biogas production based on pig manure. This is done by identifying and describing biogas technologies and combinations with the highest potential to reduce the loss of nitrogen and phosphorous but at the same time taking into account that the biogas plant has to be economically sustainable and applicable to the different country specific situations including framework conditions, characteristics of the agricultural sector, environmental legislation etc.

If the biogas production is based on technologies that make the biogas plant economically unfeasible, pig producers are not attracted to invest in biogas production at all. In that case their pig manure will be applied directly to their fields. In other words, there is a trade-off between the society´s objective of maximum degradation of the organic matter from pig manure and the biogas plant owner´s objective of maximum profit.

3. Definitions, delimitations, assumptions and methodology

3.1 Definitions and delimitations

Focus in this project is put on pig manure biogas plants. That is biogas plants using pig manure as the only substrate or as one of the main substrates for biogas production. Thus, it is assumed in this report that for the biogas plants in consideration, pig manure constitutes 50 % or more of the total biomass input measured on weight basis. Both large collective pig manure biogas plants and small farm based pig manure biogas plants are considered. The plants can be individually owned or cooperatively owned. Special attention in this project is paid to pig farms covered by the definition in the Integrated Pollution Prevention and Control Directive (IPPC farms). That is installations for intensive rearing of pigs with more than 2.000 places for production pigs (over 30 kg) or installations with more than 750 places for sows.

In most cases co-substrates are needed to boost methane production from pig manure biogas plants thereby making the plants more economically feasible. Typically, it is seen that the larger the pig farms, the larger the share of the manure is handled as slurry. Pig slurry normally has dry matter content between 3 and 8 % total solids (TS). Consequently between 92 and 97 % of pig slurry is water taking up room in the biogas reactor and it produces no energy. In most plants the aim is to achieve a dry matter content in the substrate mix between 10 and 12 % TS. In other words, pig manure is not a very good substrate for biogas production when it is used as the only substrate.

Different strategies can be applied to make it economic feasible to utilise pig slurry for biogas production. One strategy is to separate the slurry into a liquid and a solid fraction and only use the latter in the biogas plant. Another strategy is to identify and use relevant co-substrates together with slurry. During the planning phase the availability of relevant co-substrates near the pig farm shall be analysed. Relevant co-substrates can be:

- Other types of manure (e.g. cattle and poultry manure)
- Other agricultural residues (e.g. fodder of poor quality)
- Industrial waste products (e.g. slaughter house waste, glycerine etc.)
- Plant biomass from nature conservation activities (e.g. meadow grass, macro algae).

Part of the catchment area for the Baltic Sea is Russian territory. Therefore, implementation of best available biogas technologies in Russia would potentially contribute to reduce the amount of nitrogen and phosphorous led to the Baltic Sea. However, this project focus on the EU member

In this context technologies for biogas production include:

- Technologies for farm based pre-separation of slurry to increase dry matter content
- Biomass pre-treatment technologies to increase degradation and methane yields
- Biomass feed-in technologies
- Biogas reactor configuration and process technologies
- Process monitoring and controlling technologies
- Biomass post-treatment technologies
- Technologies for storage and utilisation of digestate
- Technologies for upgrading and/or conversion of biogas to energy.

3.2 Assumptions

As an overall assumption for the present study nutrients in manure are considered as resources which are needed for sustained agricultural production. Looking at the Baltic Sea Region as a whole, the amount of nutrients in manure produced covers only part of the need for nutrients for the present crop production (Foged, 2010a). Therefore, the nutrients available in manure should be used to its full potential and re-circulated in agricultural production. Anaerobic digestion is a relevant measure to achieve this by increasing plant availability through the mineralization of the nutrients.

Throughout the Baltic Sea Region there are some areas with intensive livestock production characterised by surplus nutrients in the manure. In such areas the amount of nutrients in the manure exceeds the need of the crops leading to risk for overdosing and loss of nutrients to the surface and ground waters. Especially, there is a risk of overdosing with phosphorous during field application of pig manure. This is because EU regulates manure spreading regarding its nitrogen content, but since pig manure normally contains a surplus of phosphorous relative to the need of the crop over fertilization with phosphorous is common (Foged, 2010b).

However, by separating the raw slurry or the digestate, phosphorous can be concentrated in a solid fraction. This facilitates transportation of the P-rich solid fraction to areas with lower livestock density and a need for P-fertilizer. Therefore, separation of slurry or digestate is considered a relevant measure for reallocation of nutrients from areas with surplus to areas with a need for these nutrients.

3.3 Definition of Best Available Technologies

In this report the term "Best available technologies" is not to be confused with "Best available techniques" as defined in the IPPC-Directive. In this project more weight is put on reducing loss of nitrogen and phosphorous to surface waters. On the other hand compared to the definition in the IPPC-Directive, less weight is put on reducing use of fossil fuels and on reducing emissions of ammonia, odour, particles and green house gasses. This is important to bear in mind when evaluating the different technologies.

The general requirement in order to candidate as a best available technology is that the technology shall contribute to field application of a digestate or liquid fraction with a lower concentration of organic bound N than the raw pig manure used.

In the context of this project "Best available technologies" are characterised as shown in Table 2.

Table 2. Best Available Technologies as defined in the context of this study.

Best...	...available...	...technologies
• Efficiently reduce losses of nitrogen and phosphorous originated from pig manure to surface waters. • Documentation of performance (proven efficiency). • Minimizes negative environmental side effects like for instance emissions of ammonia, odour and greenhouse gasses. • Evaluation took into account the way the technology is constructed, built, maintained, operated and shut down.	• Economic feasible • Legal to use – approved by relevant authorities with respect to occupational health and safety requirements, waste handling procedures etc. • Applicable to the farming sector in the specific country. • Reliable – long-term operational stability (fully functional also after more than two years of operation).	• An umbrella term (collective name) for tools, techniques, products, methods or systems that can be applied in relation to effective production of biogas using pig manure as a main substrate. • Technology is a broader term than technique. • Not only hardware – the term technology also includes guidelines on how to use the hardware and other management practices.

3.4 Methodology

The gathering of knowledge was done by undertaking a desk study and a field study. The desk study involved the search for useful information in relevant literature including the internet. The field study involved the following activities:

- Study tour to Poland (04.10.2010 - 08.10.2010)
- Field visit to Katrineholm Biogas Plant in Sweden (04.11.2010)
- Visit to the EuroTier exhibition in Germany (16.11.2010 - 17.11.2010)
- Visit to Agromek exhibition in Denmark (01.12.2010 - 02.12.2010)
- Participation in Seminar on Biomasses for Biogas Production (25.11.2010)
- Participation in the annual biogas economy seminar in Denmark (15.12.2010)
- Field visit to Biovakka biogas plant near Turku, Finland (25.01.2011).

The technology descriptions and the recommendations have been discussed within the project group.

For this project pig manure biogas plants have been divided into three size classes:

- Small scale plants treating manure from 2.000 - 4.000 pig production places
- Medium scale plants treating manure from 4.000 - 10.000 pig production places
- Large scale plants treating manure from more than 10.000 pig production places.

For each of these size classes a model pig manure biogas plant is described and an economic analysis carried out. The three economic analyses are made using different national framework conditions in order to demonstrate the influence on biogas plant profitability.

3.5 Organisation

The project is initiated by the Swedish private foundation Baltic Sea 2020, which is also financing the work. Project planning and management is carried out by Knud Tybirk, Agro Business Park (Denmark), who will also take part in the dissemination of the project results. Identification, description and evaluation of relevant technologies for pig manure biogas plants is undertaken by MTT – AgriFood Research (Finland), JTI – Swedish Institute of Agricultural and Environmental Engineering and AgroTech – Institute of Agri Technology and Food Innovation (Denmark).

The description and evaluation of technologies has been divided between the partners so that JTI focus on technologies for storage and utilisation of digestate and MTT on technologies for upgrading and/or conversion of biogas to energy. Other relevant pig manure biogas technologies are described and evaluated by AgroTech.

4. Biogas Technologies

4.1 Introduction to the biogas technologies evaluated

A wide range of biogas technologies have been screened to identify technologies that lead to the lowest content of organic matter in the digestate (or liquid fraction if separation is included) and/or technologies that improve the economic performance of biogas plants using pig manure as a main substrate in order to increase the share of pig manure being used as substrate in biogas plants.

With respect to the first criteria there are several strategies to increase the degradation of organic matter and mineralization of nutrients in biogas plants based on pig manure. In Figure 1 an overview is given.

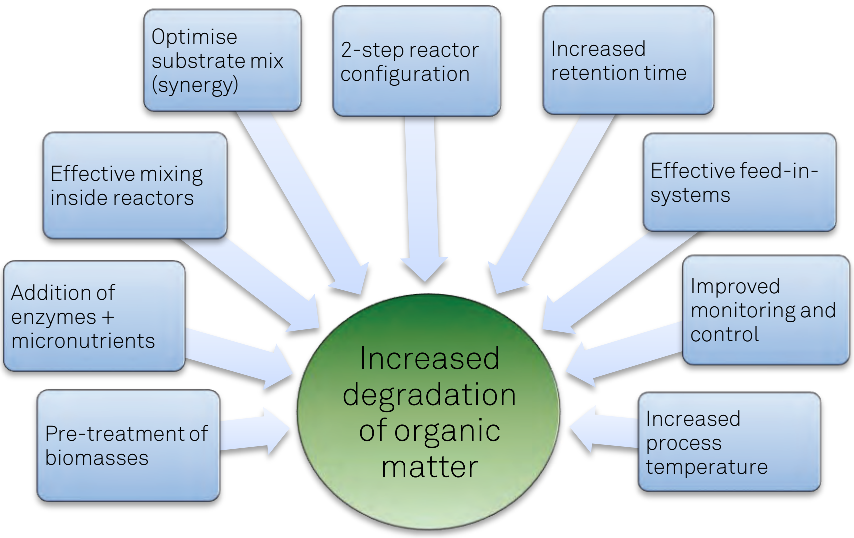

Figure 1.Overview of strategies to increase degradation of organic matter in the biogas plant.

Similarly, in order to improve the economic performance of a biogas plant a number of different strategies can be used. An overview is given in Figure 2.

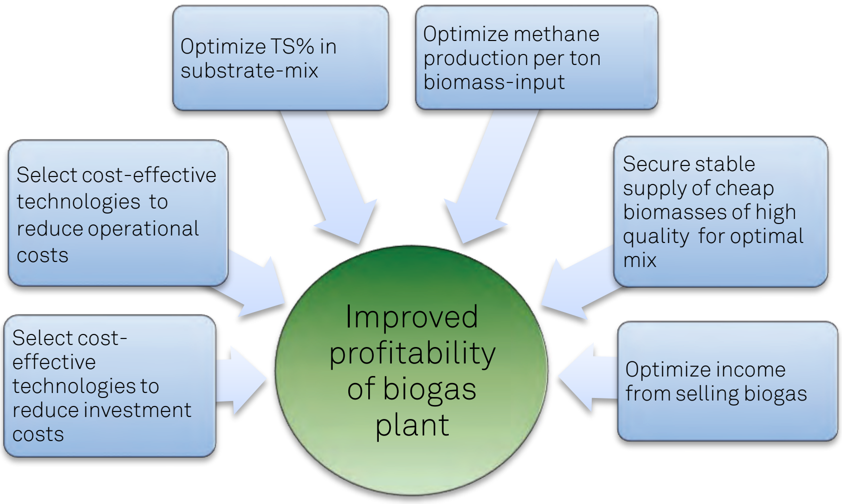

Figure 2.Overview of strategies to improve profitability of the biogas plant.

The process of utilizing manure for biogas production normally involves many steps and many different technologies. In Figure 3 an overview of a technology chain for biogas production is given. Not all steps are relevant for all biogas plants. For instance, pre-separation of slurry is relevant only for centralized biogas plants and not for farm based biogas plants.

In Figure 3 the green boxes represent processes and technologies related to handling of manure before entering the biogas plant. The blue boxes represent the core biogas processes and technologies at the biogas plant. The orange boxes relate to the handling of digestate after the core biogas processes and the brown boxes relate to the utilization of the produced biogas.

The study involves an evaluation of the individual technologies and process steps related to biogas production but focus is also to optimize the whole chain of technologies. This approach of evaluating the whole chain involves analysis of the nutrient handling from the pig via the biogas plant to the field and analysis of the energy utilization from the biogas plant to the end user of the energy.

The descriptions and evaluations of the individual technologies are included in the annexes of this report whereas the overall conclusions are found in the main sections of the report.

Figure 3. Overview of technologies involved in biogas production based on pig manure.

1
- **Pre-separation of slurry on farm**
  - Mobile separator units
  - Stationary separator units
  - Separation integrated in animal house design (source separation)

2
- **Transport of solid fraction and slurry from farm to biogas plant**
  - By tractor and trailer
  - By truck and trailer
  - Pumping directly from farm to biogas plant

3
- **Pre-treatment of biomass**
  - For increased degradability and higher rate of degradation
  - For sanitation of category II-material
  - To reduce nitrogen content
  - To make easier to handle in the biogas plants

4
- **Biomass feed-in systems**
  - All biomasses collected and mixed in one tank and then pumped into the reactor
  - Solid biomasses fed directly into the reactor

5
- **Reactor configuration and core process technologies**
  - Mesophilic versus thermophilic process temperature
  - 1-step reactor versus 2-steps reactor configurations
  - Addition of enzymes and micronutrients to the reactor
  - Short HRT+small reactor volume vs. long HRT + large volume
  - Mixing and pumping technologies

6
- **Process monitoring and controlling technologies**
  - pH-sensors
  - VFA sensors
  - Nitrogen measuring units
  - TS-measuring units

7
- **Biomass post-treatment technologies**
- Separation of digested biomass
- Drying and pelletising solid fraction from separation of digested biomass
- Composting solid fraction from separation of digested biomass

8
- **Storage of digestate/ fractions from separation of digestate**

9
- **Transportation of digestate / fractions from separation of digestate**

10
- **Application of digestate / fractions from separation of digestate**

A
- Biogas cleaning

B
- Biogas upgrading

C
- Gas usage

4.2 Centralized biogas plants versus farm based biogas plants

In Table 3 some characteristics of farm based biogas plants and centralized biogas plants are presented.

Table 3. Farm based biogas plants compared to centralized biogas plants.

Farm based biogas plants (typically individually owned)	Centralized biogas plants (typically cooperatively owned by a group of farmers)
Pros • Low costs for transportation of manure/digestate • The owner gets all the benefits/profits. • Decision making process is fast and flexible. • Good possibility of using the manure when it is fresh and thereby increase methane yield. • Normally, there is no need for sanitation units (reduced investment and operational costs) **Cons** • When biogas is used for electricity it is often difficult to utilize all the heat on the farm. • The owner has to pay the whole investment cost.	**Pros** • Large-scale operation advantages (economies of scale). • The location for establishment of the biogas plant can be chosen to optimize the utilization of the biogas or heat. • The investment and operational costs are distributed on several investors. • Can act as nutrient intermediary between farmers (nutrient distribution central). **Cons** • The benefits/profits are distributed on several investors. • Decision making process is slow and in-flexible. • High costs for transportation of manure, digestate and fractions from separation of slurry/digestate. • In some cases odour problems, especially when industrial waste products are used.

Individually owned biogas plants are most relevant in these situations:

- In connection to large livestock production units.
- In regions with low livestock densities.

Centralized biogas plants are most relevant in these situations:

- In regions with small and medium-scale livestock production units that are too small to establish their own biogas plant.
- In regions with high livestock density.

4.3 Pre-separation of slurry

Pre-separation of slurry in combination with anaerobic digestion in centralized biogas plants is a useful concept, especially in areas with high livestock density and many medium to large scale pig farms. On many pig farms in the Baltic Sea Region all the manure is handled as slurry and the larger the pig farm the larger the share of the farms are built with slurry based systems. 97% of all pig manure in Denmark is handled as slurry and the average dry matter content of the pig slurry delivered to biogas plants was approximately 4,5 % (Birkmose, 2010).

Raw pig slurry with a water content of 95 % is not very suitable for biogas production since the energy density is low. This is a challenge for biogas plants which is mainly based on pig manure. However, if slurry is separated it is possible to bypass the liquid fraction from the biogas plant and only use the solid, organic matter-rich fraction(s) for biogas production.

Many different technologies can be used for separation of slurry and some of these can be used in combination. Since year 2000 many research and technological development activities have been carried out in Denmark in order to achieve efficient, reliable and cost-effective slurry separators. Also in the Netherlands, Belgium, France and Germany work has been carried out to develop efficient slurry separation units.

Technologies for slurry separation are built as both mobile units and stationary units. Mobile units normally have relative large capacities (amount treated per hour) and they are usually installed on a tractor trailer or a truck trailer. Mobile separators are used to separate slurry on several farms thereby utilizing the high capacity. If the separator is properly cleaned when it has finished an operation on one farm the risk of spreading diseases between farms is minimized.

Table 4. Advantages of mobile slurry separators and stationary slurry separators respectively.

Advantages of mobile separators	Advantages of stationary separators
• Especially relevant in regions characterized by many small and medium sized pig production farms where it is neither profitable to establish its own biogas plant nor to invest in its own slurry separator. • Each farmer does not have to invest in his own separator. • The separator is operated by skilled persons employed for that task so the farmer can concentrate on farming. • Due to economies of scale the investment cost per ton of slurry separated is lower than for stationary separators.	• No time is wasted for moving the separator between farms and for "plugging in" and "plugging out". • Slurry can be separated as it is produced and this leads to a higher biogas yield of the solid fraction and reduced green house gas emissions. • The farmer can decide himself which separator to buy, when and how to run it.

4.4 Biomass pre-treatment technologies

Pig manure, other types of manure and energy crops contain large amounts of lignocelluloses, which is difficult to degrade under normal conditions in biogas plants. Often, the decomposition of organic matter in pig manure is only 30 – 50 % of the potential (Christensen et al, 2007). Much effort has been dedicated to the development of pre-treatment technologies that can increase the decomposition of organic matter and thereby improve the efficiency of the biogas plants. Pre-treatment can be seen as a tool to increase the methane yield of the biomass at a given Hydrologic Retenteion time (HRT). Alternatively pre-treatment can be seen as a tool to reduce the HRT and thereby increase the total annual amount of biomass treated in the biogas plant. Pre-treatment can also improve the mixing properties in the digester and facilitate higher digester concentrations of dry matter (and bacteria). That provides conditions for a more efficient utilization of the digestion volume.

Pre-treatment technologies can be based on physical, chemical or biological methods or a combination of these. As part of this project a number of pre-treatment technologies have been identified. In Annex E the identified pre-treatment technologies are described and evaluated. Highest priority is given to robust pre-treatment technologies with low investment and operational costs and a high and documented effect on the methane yield. Furthermore, it is an advantage if the technology is reliable and easy to operate.

Despite many research and technology development activities during the past 20 years pre-treatment of manure, other agricultural residues and energy crops is not common on biogas plants yet. High investment and operational costs combined with uncertainty about the efficiency and practical problems have made most biogas plant owners and new investors to decide not to install a pre-treatment technology. However, several of the technologies described in Annex E have shown promising results and probably some of these will be a natural part of the future biogas plants based on biomasses rich in lignocelluloses.

Based on the evaluation done it is concluded that extrusion of biomass and thermal hydrolysis are two of the most promising pre-treatment technologies if the operational costs can be kept at a reasonable level. Commercial versions of these technologies are marketed by several technology suppliers. Also aerobic hydrolysis and application of enzymes prior to the biogas reactor could be relevant methods to make the lignocellulosic biomass easier degradable and the anerobic process (AD) process more stable. It is recommended to consider these pre-treatment technologies when designing and building future biogas plants.

4.5 Biomass feed-in technologies

Liquid biomasses can be pumped into the digester then easily mixed with the existing material inside the digester. For solid manure, solid fraction from pre-separation of slurry, energy crops and agricultural crop residues it can be difficult to feed-in and mix into the digester. Four different methods have been identified and described in Annex E. Normally solid manure and fibre fraction from pre-separation of slurry can be fed directly into the receiving tank and mixed with the raw slurry before it is fed into the sanitation unit or biogas reactor. For co-substrates like energy crops and other plant biomasses it is a better solution to feed the substrates directly into the biogas reactor. It is important to design the feed-in system so that the solid biomasses are well homogenized before feeding into the digester.

4.6 Biogas reactor configuration and process technologies

Different technologies and management strategies can be used to facilitate a higher degree of degradation of organic matter in the biogas plant leading to higher methane production and a higher N-efficiency of digestate fertilizer. In this section different strategies are described and evaluated.

Mesophilic versus thermophilic temperature regimes

Biogas plants are normally designed to operate with a process temperature around 35 ˚C (mesophilic temperature regime) or with a process temperature around 52 ˚C (thermophilic temperature regime). In Annex E the mesophilic and thermophilic temperature regimes are described and compared. The main points are summarized in table 5.

Table 5. Advantages and disadvantages of mesophilic and thermophilic temperature regime.

Temperature regime	Advantages	Disadvantages
Mesophilic	• The biogas process is relatively robust to fluctuations in process temperature. Normally +/- 2 ˚C is acceptable. • The biogas process is less vulnerable to nitrogen inhibition. As a rule of thumb ammonium-N concentration up to 5 kg/ton can be accepted without significant inhibitions. • The energy consumption for heating the digester is lower than thermophilic.	• The biogas process is relatively slow leading to a lower biogas production per m^3 of digester volume per day. • For a given amount of substrates a mesophilic process requires longer hydraulic retention time and a larger digester volume and thus leads to higher investment costs. • A biogas plant running a mesophilic process cannot avoid investment in sanitation units if the applied substrates require this.
Thermophilic	• The biogas process is relatively fast leading to a higher biogas production per m^3 of digester volume per day. • For a given amount of substrates a thermophilic process requires smaller digester capacity and thus lower investment costs because the hydraulic retention time is shorter. • If sanitation of substrates is required a thermophilic process can in some cases replace a sanitation unit and thereby save investment costs (depend on the rules applied in the specific countries).	• The biogas process is sensitive to fluctuations in process temperature. Normally +/- ½ ˚C is required to secure a stable process. • The energy consumption for heating the digester is higher. • The biogas process is more vulnerable to nitrogen inhibition. As a rule of thumb ammonium-N concentrations have to be lower than 4 kg/ton to avoid inhibition. • Increased amounts of released CO_2 leads to up-streaming gas bubbles, which may result in formation of foam. In addition, the CO_2 leads to an increase in pH, which makes the NH_4/NH_3 balance change in favour of NH_3. This will lead to higher risk for N-inhibition.

For biogas plants using pig manure as one of the main substrates it is an important advantage of mesophilic biogas plants that they tolerate a higher concentration of nitrogen. Especially in regions with low winter temperatures the mesophilic regime has an advantage over thermophilic regime because the energy consumption for heating the digester.

1-stage AD configuration versus 2-stage AD configuration

Most biogas plants based on agricultural waste products are designed and constructed as 1-stage biogas plants. Some of these can have more than one digester but these are installed as parallel digesters. However, there are potential advantages of constructing the biogas plant where the digestion process is separated into two steps in a serial connection.

The two-stage anaerobic digestion can be designed in different ways:

- In one configuration the hydrolysis and acidinogenic phase is separated from the methanogenic phase to create optimal conditions for the different classes of microorganisms involved in these two steps. However, this configuration is most commonly used for biogas plants running on waste water.
- For biogas plants based on agricultural waste products it could be relevant with a two-stage configuration including two methanogenic phases. By introducing the two-stage configuration it is possible to reduce the risk of organic solids being lost with the effluent. If a biogas plant is running with a HRT of 20 days it means that 1/20 of the biomass in the reactor is substituted every day. For digesters that are continuously stirred, part of the material leaving the digester will be material which is not fully degraded. When a second AD stage is introduced this risk is reduced resulting in higher methane yields and more complete degradation of organic matter. According to Møller & Ellegaard (2008) an extra methane yield of 5 – 10 % can be achieved by introducing 2-stage AD configuration under normal conditions for Danish biogas plants.

Potential advantages of two-stage digestion plants:

- Reduced risk of short circuiting of particles
- In some cases a sanitation unit can be avoided because the two-stage reactor configuration is assumed to have the same effect on reducing pathogens.
- Reduced risk of ammonium inhibition
- Higher biogas production.

4.7 Process monitoring and controlling

A well functioning biogas plant is characterized by an efficient system for process monitoring and controlling. Stable conditions inside the biogas reactor are always preferred but especially for biogas plants running at thermophilic temperature regime the process is vulnerable to sudden changes. The most important process parameters to monitor and control are in order to secure an optimized process and thereby avoid expensive process break downs:

- Temperature
- pH-value
- Alkalinity
- Inflow of substrate
- Biogas production
- Concentration of methane or carbon dioxide in biogas

For large scale biogas plants and for plants with variations in substrate mix it is relevant also to monitor the following parameters:

- Volatile fatty acids
- Total-N, ammonia-N and ammonium-N
- Sulphide, hydrogen sulphide and dihydrogen sulphide
- Total organic carbon (TOC)

Reliable measuring equipment for these parameters is necessary and online equipment is preferred for fast results and early warning. However, efficient management of biogas plants also requires equipment for measuring nitrogen content, total solids content and volatile solids content in the manure, which is fed into the biogas plant. In Annex E different technologies for monitoring and controlling are described and evaluated.

4.8 Biomass post-treatment technologies

A number of relevant technologies for post-treatment of digestate are described and evaluated in Annex D. In principle, technologies for post-treatment of digestate can be used for treatment of raw slurry before anaerobic digestion. However, the more complex technologies listed can in reality only be justified on biogas plants treating large amounts of biomasses. That is because these technologies are expensive to buy and to run and a high degree of capacity utilization is needed to make it profitable. In addition these technologies require trained persons with technical knowledge to secure stable functioning technologies and such employees are more commonly present on biogas plants than on farms.

The choice of technology depends on the degree of treatment needed. For a simple separation of the digestate into a liquid and a solid fraction decanter centrifuges are recommended. Decanter centrifuges are stable machines with large capacity and relatively high efficiency with regard to concentration dry matter, phosphorus and organic nitrogen. At the same time the liquid fraction (reject) is relatively low in the dry matter content which makes it a good fertilizer and relevant for further treatment.

A screw press can be relevant as an alternative to the decanter centrifuge in some cases. Especially if the dry matter content in the digestate is relative high (6 -7 % or higher) a screw press will be able to extract a fiber fraction containing the largest particles.

Both the liquid fraction and the fiber fraction from the decanter centrifuge can be treated further, but most of the technologies evaluated are expensive to buy and operate and at the same time the performance on these types of media is often not properly documented. If ammonia needs to be concentrated, the liquid fraction can be led to microfiltration, ultra- or nano-filtration and hereafter ammonia is stripped off. If clean water is required then addition of reverse osmosis is needed. If there is a demand for reduction of volumes evaporation might be the right solution.

The fiber fraction from the decanter centrifuge can be applied directly to the fields to add carbon and improve the structure (soil conditioner) or for composting. Alternatively, (part of) the fiber fraction can be fed into the reactor again to facilitate further degradation. If this is done special attention should be given to monitor the nitrogen concentration in the reactor due to the increased risk for N-inhibition. A Danish biogas plant owner experienced N-inhibition problems in 2010. According to him the reason for this was the use of fibers from post-separation of digestate in the digester (Lunden, 2010).

Depending on the end use of the fiber fraction it might be relevant to dry the fiber to make it stable for storage and useful as fertilizer or soil structure improvement material. Drying is also relevant if the fiber fraction is to be used for energy purposes. Fiber fraction as fuel for combustion and/or gasification is not well proven and if it is not dried there is challenge with the high content of water (e.g. low calorific value). If fiber fraction is to be used for combustion/gasification it must either be dried before burning of mixed with another fuel to increase the calorific value.

Furthermore, combustion/gasification results in a loss of the nitrogen and water soluble phosphorus in the ash. If phosphorus shall be recovered and made available for plants the ash must be treated with acid. In addition cleaning of exhaust air will be necessary to avoid emissions (VOC, NO_x, SO_2, dust etc.).

Which technology is the most appropriate is not to be answered simple because it will among other depend on environmental demands, business opportunities (market), investment and running cost. And this may vary from country to country.

5. Technologies for storage and application of digestate

5.1 The special challenges of handling digestate

Nutrients can be lost during storing and spreading of raw (non-digested) manureand the same applies to digestate. In fact, the risk of losing nitrogen as ammonia emission is higher for digestate than for raw manure. The reason is that the pH of anaerobically digested manure normally is higher than the pH of raw manure. In a Danish study it was found that the average pH value of un-digested pig slurry was 7,23 (265 samples), whereas the average pH value of digested slurry was 7,66 (144 samples). In a liquid ammonium will be in equilibrium with ammonia in its aqueous and gaseous forms as follows: $NH_{4+}(aq) \langle\!-\!\!\rangle\ NH_3(aq) \langle\!-\!\!\rangle\ NH_3(gas)$

Higher pH and higher temperature will displace this equilibrium to the right. Therefore, in anaerobically digested slurry a larger share of the nitrogen is in the form of gaseous ammonia. This leads to a higher risk for nitrogen loss from digestate during storage and field application compared to raw slurry.

Another difference between digestate and raw slurry is that in general a larger share of the total-N will be in the form of NH_4-N in the digestate. The higher content of NH_4-N will in itself lead to increased risk of ammonia emission as well as leaching. In addition, because of the smaller content of organic matter in the digestate a natural crust will seldom be formed on top of the liquid when it is stored in tanks. For raw manure such a natural crust serves as a natural cover that reduces ammonia emission. Since this is not the case when storing digestate it is relevant to consider and implement other measures of reducing ammonia emission during storage.

In the following chapter, different technologies for reducing the loss of nutrients during storage and field application of digestate and fractions from separation of raw slurry and digestate will be presented. Generally speaking, technologies that are relevant and effective for storing and spreading raw manure will also be relevant for digestate and fractions from separated slurry and digestate. Thus, if a study shows that a technology has a high effect on reducing ammonia emission from field application of raw manure this technology will normally also have a high effect if digestate is used.

5.2 Reducing nutrient losses from storage of digestate

If digestate is stored in closed tanks or lagoons where the risk of runoff is eliminated no phosphorous will be lost during storage. For nitrogen it is different since it can be lost as gaseous emissions in the form of ammonia and appropriate measures should be taken to minimize this.

In Annex F the most relevant technologies for reducing ammonia emissions during storage of digestate are presented. The most common way of reducing ammonia losses is to prevent air circulation directly above the digestate storage. This can be done by covering the digestate storage for instance with a floating plastic sheet, with a concrete lid or with a cover tent. Two types of covers are shown in figure F-1 and figure F-2 in Annex F. The effect of covering un-digested pig slurry and anaerobically digested slurry is illustrated in Table 6. See additional ammonia emission factors in Table F-1 in Annex F.

Table 6. Estimation of emission factors for ammonia loss from storage facilities with and without covering. Loss of ammonia in percent of ammonium nitrogen and total nitrogen content.

Slurry type	Covered or not covered?	Ammonia-N lost in % of NH_4-N	Ammonia-N lost in % of total-N
Pig slurry, un-digested	Stored without cover	15	9
	Covered storage	3	2
Anaerobically digested	Stored without cover	28	21
	Covered storage	6	4

Source: Poulsen et al (2001).

As a positive side effect of covering the digestate it is possible to avoid that rain water is mixed into the digestate. Rain water will dilute the digestate and thereby making it a less concentrated fertilizer. In addition, the rain water leads to extra costs of transportation and spreading since the total amount of liquid is larger.

Another way of reducing ammonia emissions from storage of digestate is to reduce the pH by adding sulphuric acid or another acid. The lower pH will displace the above mentioned ammonium-ammonia equilibrium to the left. If the pH of the digestate is constantly lower than 5.8 most of the ammonia emission will be eliminated. An advantage of acidification of the digestate is that there is also a reduction of ammonia emission during field application. The main disadvantage of this technology is the cost for buying acids. For acidification of raw pig slurry normally 4 – 6 kg concentrated sulphuric acid per ton of slurry is needed to reduce pH below 5.8. For digestate more acid is probably needed.

If the digestate is separated appropriate facilities for storing the resulting solid fraction are needed whereas the liquid fraction can be stored as non-separated digestate. Results from several research studies have shown that ammonia emission from solid fractions can be significant. Therefore, solid fractions need to be covered with e.g. air tight plastic sheets or stored in closed buildings. In addition, the storage time for the solid fraction should be as short as possible.

5.3 Reducing nutrient losses from field application of digestate

Nitrogen and phosphorous can be lost in connection with field application of digestate or fractions from separation of digestate in different ways:

- Nitrogen is lost through gaseous emission in the form of e.g. ammonia
- Nitrogen is lost through leaching, mainly in the form of nitrate
- Phosphorous is mainly lost through leaching, surface runoff and erosion

In Annex F different technologies for reducing ammonia emission from field application of digestate are described. Figure F-3, F-4 and F-5 show examples of equipment for field application of slurry that can also be used for digestate. Two effective ways of reducing ammonia emission are injection of digestate or rapid incorporation into the soil. A study performed by Huijsmans et al. (1999) showed that ammonia emission was reduced by at least 50 % if the slurry was ploughed within 6 hours. A similar effect is expected for application of digestate. Alternatively, acid can be added to the digestate during field application which leaves a reduced pH. As mentioned above ammonia emission will be significantly reduced if pH is reduced to 5,8 or lower.

When it comes to reduction of nitrogen leaching spreading time is crucial. Autumn spreading of digestate should be avoided due to the fact that nitrogen loss increases when there are no growing crops to take up the nitrogen released from mineralization during the period from November – February. In order to avoid autumn spreading there must be sufficient storage capacity for the digestate. A minimum of 9 months of storage capacity is required, however, a capacity up to 12 months to include some buffer is recommended.

Losses of phosphorous from the field have large spatial and temporal variations and can be influenced by several factors interacting with each other. It is therefore important to consider site specific factors in order to identify relevant measures to reduce P losses (Djodjic, 2001; Börling, 2003). As a general recommendation the aim should be to apply no more P than used by the crop. In other words, digestate, raw manure and mineral fertilizers should be applied in such amounts that a P-balance can be achieved at field level.

5.4 N-efficiency of digested and non-digested pig slurry

In order to facilitate comparisons of different manure handling systems a model has been developed (Brundin & Rodhe, 1994). This model can be used to calculate the N-efficiency of a given manure handling system from animal to the field. The N-efficiency in percent is a measure of the share of total-N in the original manure which is available for the crops after application to the field. A large N-efficiency indicates that only a small amount of N is lost during storage, transportation and spreading of the manure.

The N-efficiency model was used to evaluate three manure/digestate handling systems relevant for large scale centralized biogas plants and two manure/digestate handling system relevant for small scale farm based biogas plant. A detailed description of the five different scenarios is given in Annex G together with the results from the model calculations.

The model calculations confirm that anaerobic digestion increases N-efficiency all other things being equal. The risk for leaching also increases, if the digestate is not applied during the season when there is a plant uptake of N. Timely spreading is therefor very important when using digestate as fertilizer.

6. Technologies for utilisation of produced biogas

In table 7 an overview of technologies for utilization and upgrading the produced biogas is given. A detailed description of the technologies is given in Annex H.

How the biogas is utilized depends on national framework conditions like the tax system, subsidies, investment programmes, availability of natural gas grids and district heating systems. There are large variations on these parameters between the different countries in the Baltic Sea region. Furthermore, due to changing policies the situation in each country is changing over time. As a result it is not possible to recommend one way of biogas utilization which is the optimal.

The most widespread way of utilizing biogas from agricultural based biogas plants in the Baltic Sea Region is for combined heat and power generation. In most cases biogas is converted to electricity and heat using ordinary otto or diesel engines adapted to that fuel. This is well-known technologies and normally it is not complicated to find the connection to the electricity grid. One of the challenges of combined heat and power production is to utilize the produced heat so that it generates an income to the biogas plant owner.

Table 7. Overview of technologies for utilization and upgrading biogas.

Mode of utilization of biogas	Technologies
Power production as stand alone	Internal combustion
	Gas turbines
	Fuel cells
Heat production as stand alone	Biogas boilers
Combined heat and power generation	Otto and diesel engines adapted for biogas
	Gas turbines and micro turbines
	Stirling motors
	Organic Ranking Cycle (OCR)
Biogas upgrading	Pressure Swing Adsorption (PSA)
	Absorption: Water scrubbing Organic physical scrubbing Chemical scrubbing
	Membrane technology
	Cryoprocesses
	In situ enrichment
	Ecological lung

7. Analysis of the national framework conditions

According to the economic analysis pursued in this study (section 8.2), two important factors for the possibilities of making biogas production profitable are:

- The price(s) of the energy product(s) sold (i.e. electricity, heat or methane)
- The access to subsidies to cover part of the investment cost.

In Table 8 is presented what price levels can be expected for electricity based on biogas in the eight Baltic Sea Region countries. In Annex K the more details about the feed-in tariffs are given.

Table 8. Country specific feed-in tariffs for electricity based on biogas.

Country	Price (€cent/kWh)	Comments	Sources
Sweden	8	The feed-in- tariff is composed of mainly two parameters: 1) Spot price and 2) electricity certificates.	Edstöm, 2011
Finland	13	A feed-in tariff was introduced in the beginning of 2011 but it still has to be approved by the European Commission. The proposed tariff is 0,0835 EUR/kWh and additional 0,050 EUR under certain conditions.	MEEF, 2010
Estonia	5	-	Foged & Johnson, 2010a
Latvia	15	In 2010 the feed-in tariff is 0,20 EUR/kWh but this will be reduced. The mentioned 0.15 EUR is an estimated future price.	Foged & Johnson, 2010a
Lithuania	9	This price applies to electricity based on all renewable sources. As of beginning 2011 a new law on renewable energy is under preparation.	Foged & Johnson, 2010a
Poland	15	The price consists of a raw price (approximately 0,05 EUR/kWh), the value of green certificates and in some cases red certificates.	Laursen, 2010
Germany	15 – 25	In Germany a complex system for calculating the price of biogas based electricity is established taking into account e.g. the installed electric capacity of the biogas plant, the use of energy crops, the use of manure and heat utilisation.	Hjort-Gregersen, 2010
Denmark	10	This is a fixed feed-in tariff applied to all biogas plants. The price is regulated once a year according to development in price index.	Tafdrup, 2010

It is seen in table 8 that there are large variations in the national feed-in tariffs in the Baltic Sea Region. The highest feed-in tariff is seen for Germany and this explains the fast development of the biogas sector in Germany from 2000 to 2010. In this period the number of biogas plants in Germany 6-doubled starting from 1.050 in 2000 increasing to 6.000 at the end of 2010 (GBA, 2011).

Table 9. Country specific investment support schemes in the Baltic Sea Region countries.

Country	Description of investment support scheme	Sources
Sweden	Possibility of grants up to 30 % of the investment costs (in the Northern part of Sweden up to 50 % is granted). The maximum amount of grant per farmer is approx. 200.000 EUR in a 3-year period.	Edström, 2010.
Finland	Possibility of grants up to 30 % of the investment costs.	MEEF, 2010
Estonia	Possibility of grants up to 19.000 EUR per biogas plant.	Foged & Johnson, 2010a
Latvia	No grants to cover part of the investment costs.	Foged & Johnson, 2010a
Lithuania	Possibility of grants up to 65 % of the investment costs with an upper limit of 200.000 EUR.	Foged & Johnson, 2010a
Poland	Possibility of grants from different national investment funds.	Foged & Johnson, 2010b
Germany	No grants to cover part of the investment costs.	Hjort-Gregersen, 2010
Denmark	For manure based centralized biogas plants and for farm scale biogas plants on organic farms there is a possibility of grants to cover up to 20 % of the investment costs. No grants available to cover investment costs for farm scale biogas plants on farms which are not organic.	Tafdrup, 2010

It is obvious from Table 8 and 9 that there are large differences between the countries with respect to both electricity feed-in tariff and the possibilities for achieving grants to cover some of the investment costs. The analysis of framework conditions has also shown that the national subsidy schemes are frequently changed. The general tendency is that the framework conditions have been improved during the recent years (with Latvia as an exception). This illustrates that there is a political interest for supporting agricultural based biogas production.

In section 8 the framework conditions in the Baltic Sea Region countries are used for an economic analysis in order to evaluate if the different support schemes give sufficient incentives for farmers and other investors to expand biogas production in the respective countries.

8. Description and evaluation of three model biogas plants

In Annex C three model biogas plants are described and evaluated with respect to 1) potential for reducing the nitrogen loss and 2) profitability. The three model plants are described with inspiration from three real biogas plants but the model plants are not identical to these. For instance, there are differences in the substrate mix used between the real plants and the model plants.

The three model biogas plants are described in this study because they have some interesting features relevant for the future pig manure biogas plants in the Baltic Sea Region.

Table 10. Characteristics of the three model biogas plants.

Size	Key features	Relevant conditions
Large scale centralized biogas plant	• 117.500 tons of biomass treated per year including pig manure equivalent to 98.500 fattening pig places (> 30 kg) and 15.400 sow places • Built to run on manure alone and mainly pig manure. • Due to pre-separation of slurry dry matter from a large area can be used for AD. • Post-treatment of digestate improves the possibility of balancing the nutrients to the need of the plants via export of N and P from areas with surplus to areas with a need for these nutrients. • Economies of scale with respect to efficient utilization of biogas. • A strategy of short HRT is chosen to increase the amount of biomass treated. • Recirculation of solid fraction is possible.	• In areas with high density of pig farms and surplus nutrients. • For small, medium and large scale pig farms. • Where pig manure is mainly handled as slurry. • Where TS% of slurry is relatively low. • Where farmers are well organized and willing to cooperate. • Under framework conditions favouring utilization of manure for biogas production.
Medium scale centralized biogas plant	• 80.000 tons of biomass treated per year including pig manure equivalent to 19.800 fattening pig places (>30 kg) and 3.400 sow places. • Built to run on pig manure as the main substrate but with the possibility of using plant biomass as co-substrate. • No pre-separation of slurry but post-treatment of digested biomass. • The contractor is also co-investor giving incentives for sustained interest in optimization of the plant after which it is completed. • A strategy of long HRT is chosen to increase the level of degradation. • Purification and upgrading of biogas to be used for transportation purposes.	• In areas with medium to high density of pig farms and surplus nutrients. • For medium to large scale pig farms. • Where a significant part of the pig manure is handled as solid manure. • Where farmers are well organised and open to cooperate. • Where TS% of slurry is relatively high. • Where subsidy and tax systems give incentives for utilisation of biogas for transportation.

Table 10, continued.

Size	Key features	Relevant conditions
Small scale farm based biogas plant	• Built to run on pig manure alone. • 9.650 tons of slurry treated per year equivalent to 2.950 fattening pig places (> 30 kg) and 500 sow places. • No pre-separation of biomass. • Post-treatment of digestate. • Easy to operate and maintain so that it can be done by the farmer and the employees. • Focus on reducing the biogas plant´s own energy consumption. • Main purpose of the biogas plant is to reduce the environmental impact of manure; second priority is to produce energy.	• For large scale (isolated) pig farms. • In areas with low to medium pig farm density but still vulnerable to application of surplus nutrients. • Where TS% of slurry is relatively high. • Where transportation of slurry needs to be minimized. • Where the farmer faces many restrictions on manure application from the environmental authorities.

8.1 Evaluation of potential for reducing nitrogen leaching

As mentioned above the positive effect of anaerobic digestion on N leaching is related to the conversion of organic nitrogen to ammonium-N. Therefore, model mass balances for organic nitrogen have been made in order to evaluate the three model biogas plants with respect to potential for reducing nitrogen loss. The basic assumption is that the more organic N converted, the larger the reduction in nitrogen leaching all other things equal.

In the model mass balances it is estimated how much of the organic N from the total biomass input originates from pig manure used in the biogas production.

Table 11.Model calculations on the fate of organic nitrogen as a result of treatment in biogas plant.

Conversion of organic N to ammonium-N	1. Large scale centralized biogas plant	2. Medium scale centralized biogas plant	3. Small scale farm based biogas plant
	(Tons/year)	(Tons/year)	(Tons/year)
Organic N in input biomass			
Total biomass	379	225	14
From pig manure used	212	157	14
Organic N i digestate			
Total biomass	170	101	7
From pig manure used	95	70	7
Organic N converted			
Total biomass	209	124	7
From pig manure used	117	87	7

It is seen in the table that in the large scale centralized biogas plant a total of 209 tons of organic N is converted to NH_4-N as a result of the anaerobic digestion. Of this amount 117 tons of organic N originates from the pig manure used in the biogas plant.

In the medium scale centralized biogas plant 87 tons of organic N from pig manure is converted and in the small scale farm based biogas plant 7 tons of organic N from pig manure is converted per year.

Three examples of nutrient flow charts are presented in Annex H, to further illustrate the effect of anaerobic digestion followed by post-separaton of digestate as a way of reducing the amount of organic bound N applied of the fields.

1. Pig slurry not used for biogas production (baseline scenario)
2. Pigs slurry is treated in a biogas plant and the digestate is separated
3. Pig slurry is treated in a biogas plant using maize silage as a co-substrate and digestate is separated.

Calculations in cases 2 and 3 are based on an example from a small scale farmed based biogas plant.

The calculations show that treatment of pig slurry in a biogas plant can reduce the amount of organic bound N applied to the fields from 1,5kg to 0,7kg per 1.000 kg slurry. Moreover, it is possible to further reduce the amount of organic bound N from 0,7kg to 0,36kg if the digestate is separated and the solid fraction is reallocated to fields of other farms in need of N and P. Figure 4 presents the flow chart of case 2.

The model calculations also show that using maize silage as a co-substrate to increase biogas production will lead to increased amounts of organic bound N applied to the fields of the pig farm compared with case 2 where pig slurry was the only substrate. This means that the desired effect on reduced N leaching from the anaerobic digestion is reduced when energy crops are used as additional substrate.

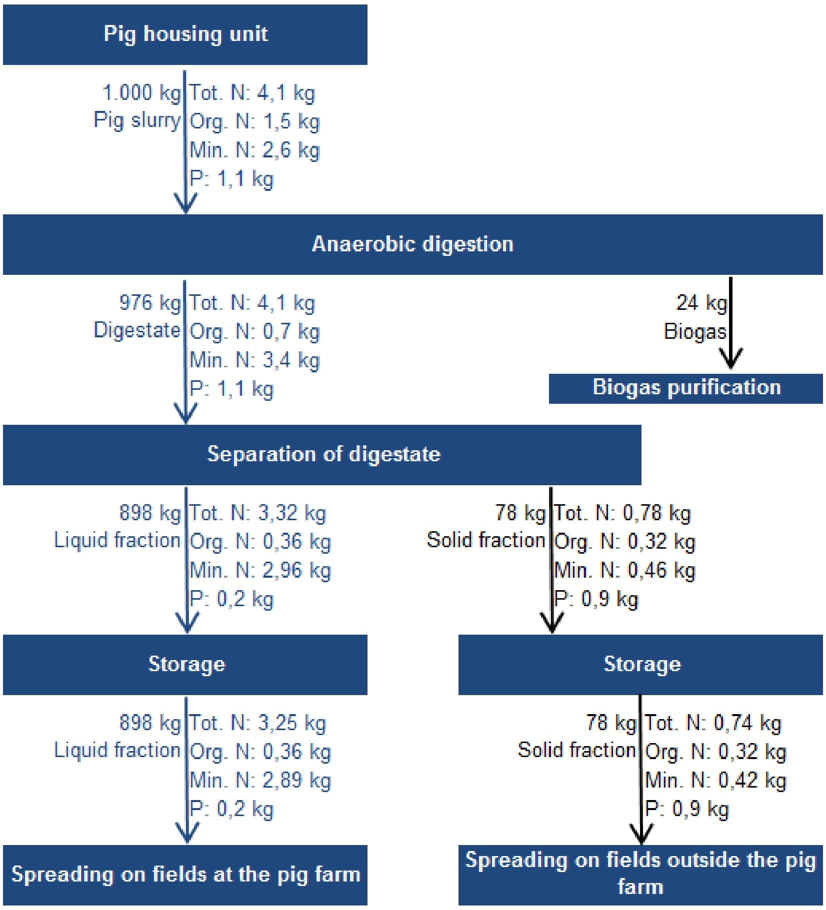

Figure 4. Flow chart for case 2. Pig slurry is treated in a biogas plant, the digestate is separated and only the liquied fraction is applied to the fields of the pig farm.

8.2 Economic analysis

An economic evaluation was undertaken for each of the three model biogas plants. This section describes the methodology used for the economic evaluation and the main results are presented.

<u>Methodology used for the economic evaluation</u>

For each of the three model biogas plants the economic analysis was carried out using model calculations. The model calculations include the following steps:

- Types, amounts and prices/gate fees of biomasses used in the biogas plant are defined.
- Basic characteristics of the biogas plant are described:
  - Mesophilic or thermophilic process?
  - Hydraulic retention time
  - What energy products are produced and sold (electricity, heat, gas)
  - Prices of the products sold are defined (electricity, heat or gas)

    - Financial parameters are described: Interest rate, maturity of loan, etc.
    - If a gas pipe is included in the investment cost the length is indicated (km)
    - If a heating pipe is included in the investment cost the length is indicated (km)
- Investment costs are estimated:
    - The model suggests some default values based on the total biomass input and the chosen configuration of the biogas plant
    - If actual investment costs are known these are used in the model calculations
- Operational costs are estimated
    - The model suggests some default values based on the total biomass input and the chosen configuration of the biogas plant.
    - If actual operational costs are known these are typed into the model
- The methane production and resulting annual income is calculated by the model
    - The model calculates the amount of methane produced and converts this to income based on the selected mode for utilization of biogas.
    - The methane production is estimated using data from literature. If better/project specific figures are available these can be used instead.
- The annual capital costs and operational costs are calculated by the model
    - Based on the data filled into the model.
- The average annual earnings after tax (economic result) is calculated
- The model also calculates some key parameters useful for analyses and comparison of different scenarios.
    - Investment costs per ton of biomass treated
    - Operational costs per ton of biomass treated
    - Operational costs per Nm^3 of methane produced
- A theoretical mass balance on nutrients through the biogas plant is calculated
    - Comparison nutrient concentrations in substrate and in digestate
    - Calculation of the amount of organic bound N converted to ammonium-N

Baseline scenarios

The main assumptions for the economic evaluations are described in Annex C under each of the model biogas plant descriptions. In the baseline scenarios it is assumed that the large scale centralized biogas plant and the small scale farm based biogas plant are operated under present Danish framework conditions. The medium scale centralized biogas plant is assumed to operate under the present Swedish framework conditions in the baseline scenario. In order to expand the economic analysis to the whole Baltic Sea Region the three model biogas plants are later evaluated using framework conditions from the other countries.

In Table 12 an overview of the cost and income profiles of the three model biogas plants in the baseline scenarios is given. Regarding the investment costs for the three plants these are estimated by the model but validated using cost data from similar real plants.

Table 12. Products sold, prices on products, amount of methane produced and the resulting income and cost profiles of the three model biogas plants in the baseline scenarios.

Description	1. Large scale centralized biogas plant	2. Medium scale centralized biogas plant	3. Small scale farm based biogas plant
Products sold	Electricity and 80 % of excess heat sold	Raw biogas sold for upgrading	Electricity and 50 % of excess heat sold
Prices for products (EUR)	Electricity: 0,103 kWh Heat: 0.040/kWh	0,533/Nm^3 methane	Electricity: 0,103/kWh Heat: 0.040/kWh
Amount of methane produced (Nm^3/year)	2.447.525	2.832.800	118.985
Total investment costs (EUR)	9.799.837	4.694.769	624.000
Annual operational costs including purchase of substrates (EUR)	575.411	629.869	43.405
Annual capital costs (EUR)	882.037	443.153	60.118
Total annual costs (EUR)	1.457.448	1.073.022	103.523
Annual income (EUR)	1.218.906	1.390.339	55.040
Annual earnings after tax (EUR)	**-238.542**	**228.468**	**-48.483**

It is seen that under the chosen assumptions for the three model plants only the medium scale centralized biogas plant will be profitable in the baseline scenario. When comparing the two centralized biogas plants it is seen that the investment cost of the medium scale plant is significantly lower than the large scale centralized biogas plant. Despite that, it is also seen that the methane production of the medium scale plant is larger than the large scale plant. In other words, at the medium scale plant much more methane is produced per EUR invested. This is the main reason for the difference in annual earnings between the two centralized biogas plants.

Profitability of the model biogas plants under different framework conditions

As part of the economic analysis the profitability of the model plants under different national framework conditions have been compared. In Figure 4 and Figure 5 the profitability of the small scale farm based biogas plant and the large scale centralized biogas plant under the country specific framework conditions are presented. Both these plants are utilizing the biogas for combined heat and power production. The aim is to illustrate the impact of the country specific feed-in tariff for electricity and the possibility of getting an investment grant. Thus, the feed-in tariff and the investment grant differ between the countries whereas the other parameters are assumed to be the identical. Therefore the following assumptions are made:

- In both cases heat is sold to a price of 4 eurocent per kWh
- Investment costs are identical in all countries
- Operational costs and maintenance are identical in all countries.

Clearly, these assumptions do not reflect reality but in this analysis the aim is to illustrate the influence of the feed-in tariff and investment grant.

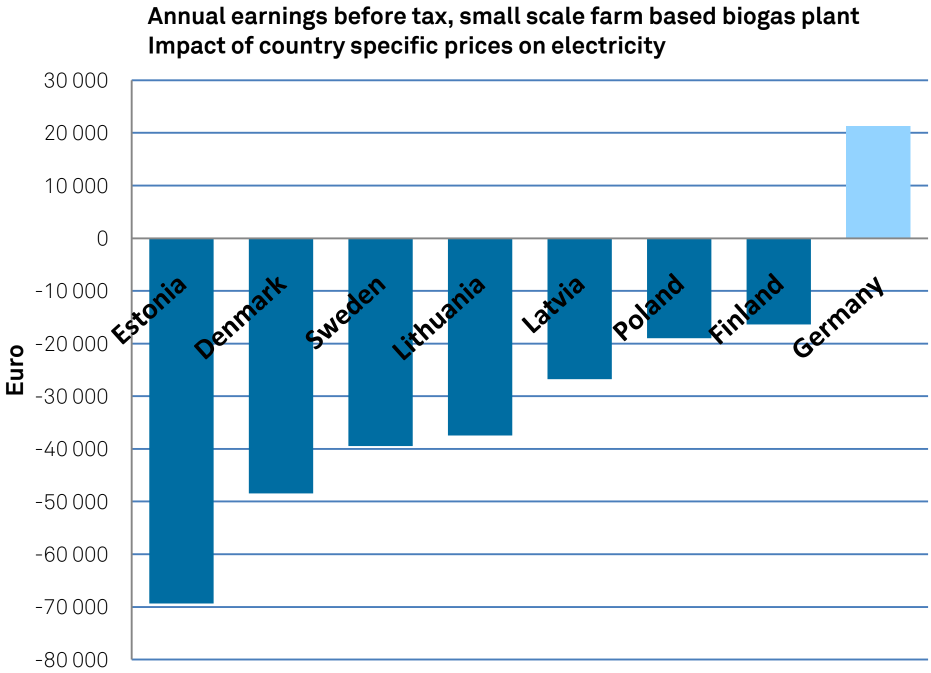

Figure 5. Annual earnings of the small scale farm based biogas plant as a result of differences in feed-in tariff and investment grant. Break-even is reached at a feed-in tariff of 0,208 EUR.

It is seen in Figure 5that there are large variations in the annual earnings between the countries in the Baltic Sea Region and this reflects large variations in the subsidy systems. It is also seen that in 7 out of 8 countries biogas production based on pig manure using the small scale farm based biogas concept is not a profitable business.

With the assumptions used positive annual earnings are seen only in Germany. Generally the German subsidy system is giving good incentives to engage in biogas production but it can be mentioned that the German subsidy system is designed to support especially the small biogas plants. The poorest profitability is seen in Estonia which reflects that there is presently no subsidised feed-in tariff for the electricity produced and the size of the grant for investment is limited.

The break-even electricity price is the price needed to achieve average annual earnings of 0 EUR in the baseline scenario. The break-even price of the small scale farm based biogas plant is 0,208 EUR/kWh electricity. This increase of 0,105 EUR/kWh (compared to the Danish feed-in tariff of 0,103 EUR/kWh) can be seen as the minimum size of the manure bonus needed to motivate farmers to invest in a small scale farm based biogas plant based on pig manure.

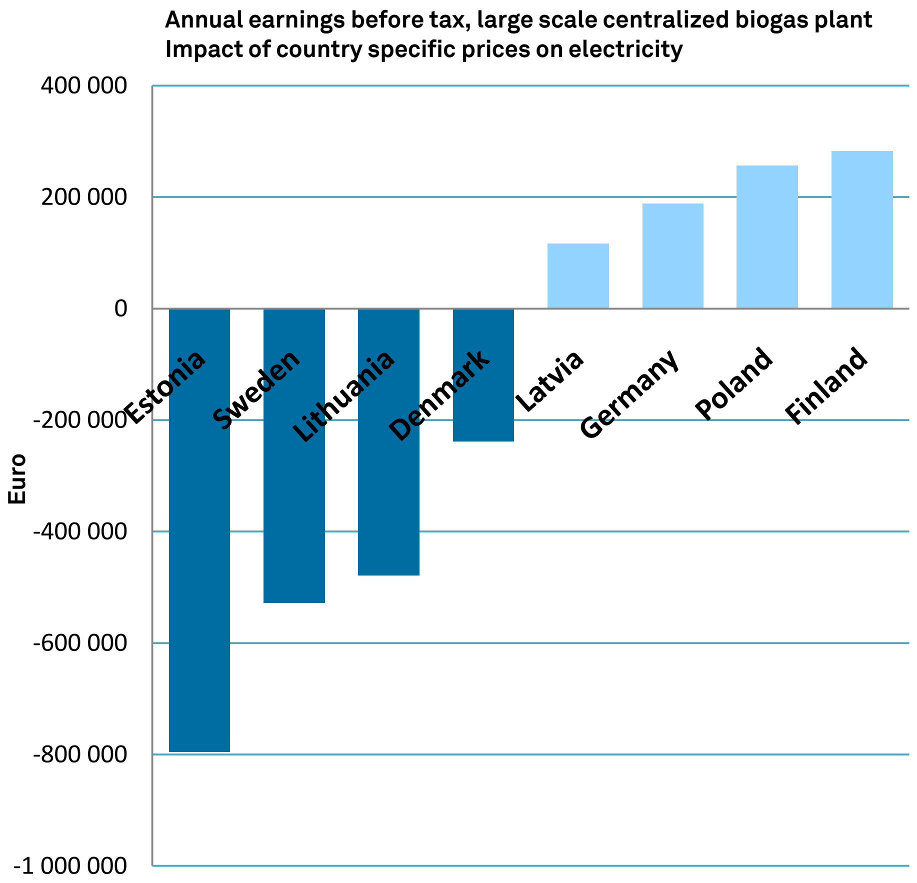

Figure 6. Annual earnings (before tax) of the large scale centralised biogas plant as a result of differences in feed-in tariff and investment grant. Break-even is reached at 0,128 EUR/kWh.

It is seen in Figure 6 that the profitability of the large scale centralized model biogas plant is generally better than for the small scale model biogas plant. Positive annual earnings are seen in Finland, Poland, Germany, and Latvia. Part of the reason for the improved profitability is economies of scale. For instance it is seen that the investment cost per Nm^3 of methane produced will decrease as the size of the biogas plant increases. For the small scale farm based biogas plant the capital cost per Nm^3 methane produced is 0,51 EUR whereas it is 0,36 for the large scale centralized biogas plant.

The break-even price of the large scale centralized biogas plant is 0,128 EUR/kWh electricity sold. This increase of 0,025 EUR/kWh (compared to the Danish feed-in tariff of 0,103 EUR/kWh) can be seen as the minimum size of the manure bonus needed to motivate farmers and other investors in Denmark to establish a large scale centralized biogas plant based on pig manure.

In the medium scale centralized biogas plant the biogas is sold for upgrading and then used for vehicle fuel. In Figure 7 the average annual earnings is shown as a result of different prices on biogas.

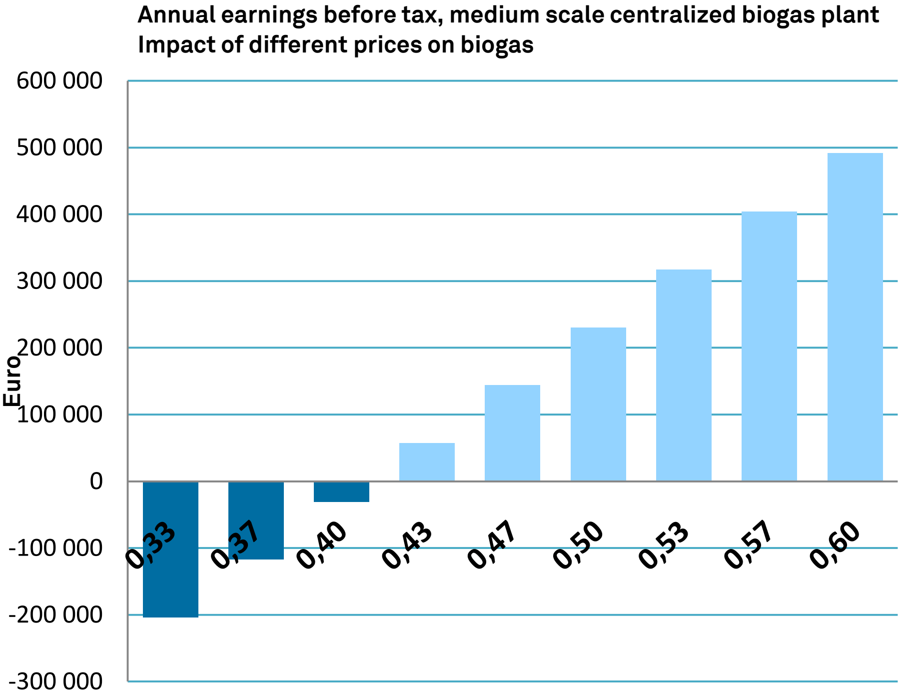

Figure 7. Annual earnings for the medium scale centralized biogas plant as a result of the price for the biogas sold for upgrading and utilization as vehicle fuel. Break-even is reached at 0,41 EUR/Nm^3.

It is seen that the break-even price for biogas is approximately 0,41 EUR per Nm^3 methane in the biogas sold. In the baseline scenario a price of 0,53 EUR per Nm^3 methane is assumed and this results in average annual earnings before tax of 317.000 EUR.

The 0,53 EUR per Nm^3 methane is an estimate of a realistic price in Sweden where the tax regulations are favouring utilisation of biogas for transportation purpose. In countries without such tax exemptions the realistic price for selling biogas will be lower.

Sensitivity analyses

Sensitivity analyses have been made for the three model biogas plants to demonstrate which factors have a large influence on the overall profitability of the biogas plant. Sensitivity analyses are also used to test how robust the profitability calculations are to uncertainties in the input data.

The bench mark for the sensitivity analyses is the set of assumptions used in the baseline scenarios. Then four parameters were increased by 10 % and decreased by 10 % one by one and the impact on the average annual earnings registered. For instance, it is demonstrated how much more the biogas owner will earn if the biogas yield is 10 % higher than in the baseline scenario (in this case 121.000 EUR). Similarly, the sensitivity analysis reveals how much the annual earnings will decrease if the biogas yield is 10 % less than expected in the baseline scenario.

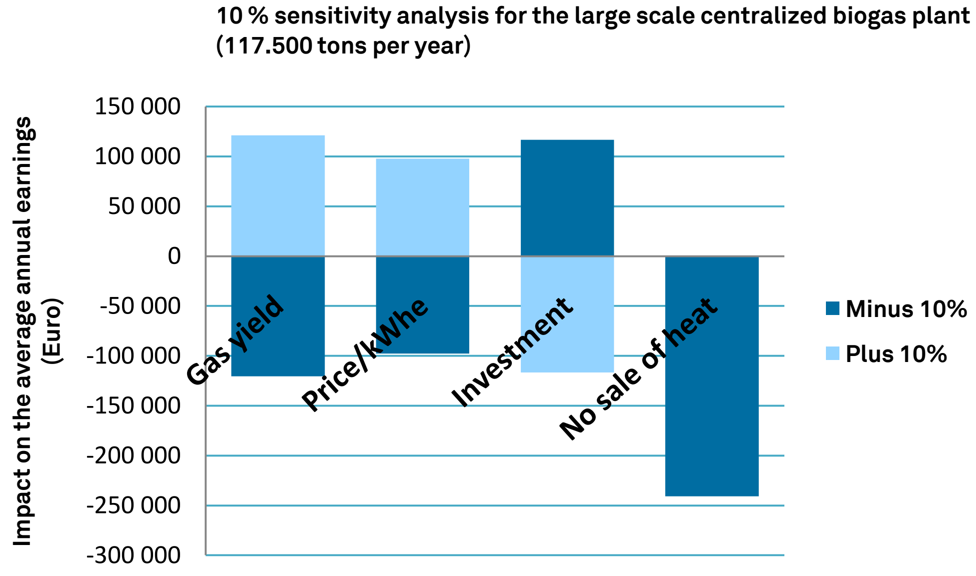

Figure 8. 10% sensitivity analysis for large scale centralized biogas plant.

It is seen from Figure 8 that a 10 % change in the biogas yield has a larger impact on the average annual earnings than a 10 % change in the feed-in tariff and a 10 % change in the investment costs. This illustrates the importance of making use of good estimates of the biogas yield during the planning phase. It is also demonstrated that it is essential for the profitability of the large scale centralized biogas plant that the heat can be sold.

The sensitivity analysis can be used to simulate differences in the cost level between the countries in the Baltic Sea Region. The baseline scenario for the large scale centralized biogas plant reflects the cost level of Denmark. In order to evaluate the profitability of a similar biogas plant in Poland reduced investment costs are expected. In Figure 8 it is seen that if the investment cost is reduced by 10 %, the average annual earnings will increase by approximately 115.000 EUR.

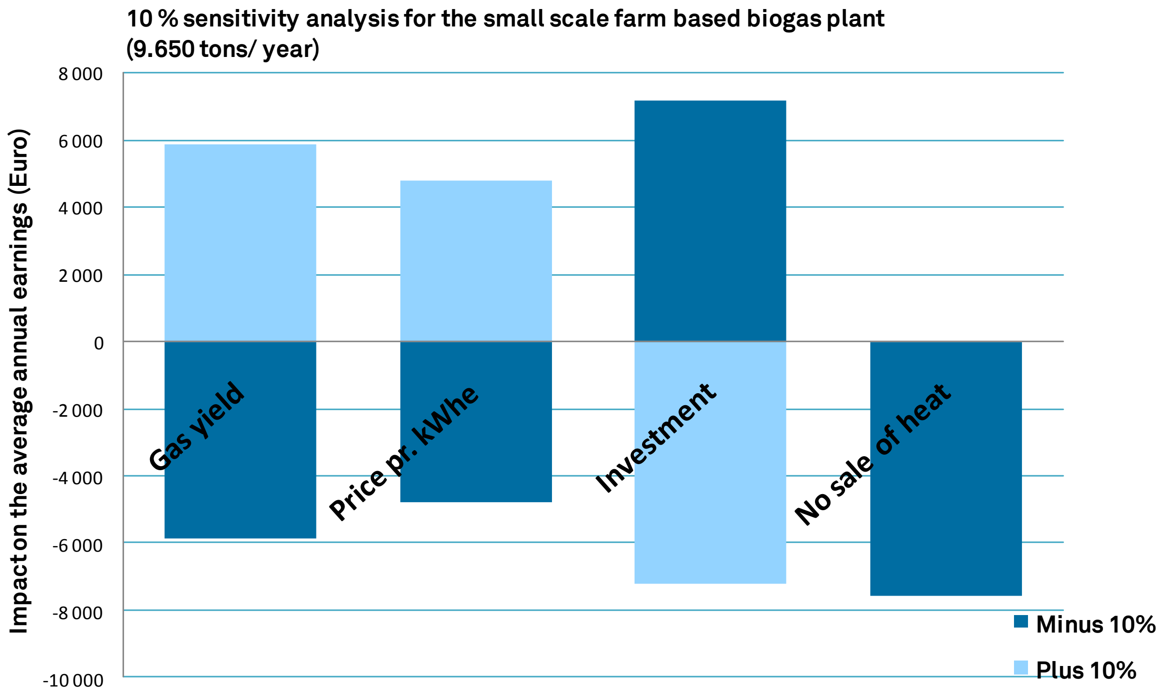

Figure 9. 10% sensitivity analysis for small scale farm based biogas plant.

It is seen in Figure 9 that for small scale farm based biogas plant a 10 % change in investment cost has a larger impact on the average annual earnings. Also for the small scale biogas plant it is crucial in order to achieve positive annual earnings that the heat produced from the CHP can be sold.

9. Conclusions and recommendations

In this section the main conclusions and recommendations from the work in this project are presented. The conclusions and recommendations relate both to the technologies and to framework conditions.

Production of biogas based on pig manure can be done in many ways and many process steps are normally involved. It is not possible to point out one best available combination of technologies that will be ideal for all potential biogas plant investors. The choice of concept and specific technologies should always reflect the specific situation –opportunities and barriers. In other words, one combination of technologies which is the best choice for one investor can be irrelevant for another investor in a different situation.

Overall biogas plant concept and plant size

Due to economies of scale, higher capacity utilization, professional management, full-time employed staff, and better possibilities for selling biogas at a high price large scale centralized, biogas plants will often show to be more profitable than the small scale farm based biogas plants. Especially in regions characterized by high pig density and many small and medium scale pig farms. Farm based biogas plants are most relevant in connection to large pig farms in regions characterized by low pig densities. In such regions there might not be a sufficient amount of pig manure for establishment of a centralized biogas plant.

Technologies for pre-separation of slurry

Pre-separation of slurry in combination with anaerobic digestion in large and medium scale centralized biogas plants is a useful concept. This concept is especially relevant in areas with high livestock density and many small and medium scale pig farms. In such areas the concept has potential for reducing loss of N and P to the surface waters. Pre-separation of slurry is a way to reduce transportation costs since the liquid fraction will stay at the farm. In addition pre-separation of slurry will also lead to increased biogas yield per m^3 of digester volume as a result of increased dry matter percentage.

For pre-separation of pig slurry decanter centrifuges are recommended as a cost-effective reliable technology performing a relatively high separation efficiency compared to other pre-separation technologies.

Biogas technologies

Even though biomass pre-treatment technologies are not commonly used on agricultural based biogas plants yet, future investors are recommended to consider including this process step when building new biogas plants. Especially for biogas plants using large amounts of solid pig manure, fibre fraction from slurry separation or energy crops there is a potential for economic as well as environmental benefits due to more effective decomposition of organic matter. Two promising pre-technologies are extrusion and thermal hydrolysis.

For biogas plants using pig manure as a main substrate a reactor configuration of mesophilic process temperature combined with relatively long HRT and/or a two-stage anaerobic digestion is recommended. This is a more robust reactor configuration than thermophilic process temperature coupled with short HRT and/or a one-stage anaerobic digestion. Some advantages of the combination of mesophilic process temperature and long HRT are that the risk for N-inhibition is reduced and that the process is less sensitive to changes in the substrate mix.

Biomass post-treatment technologies

In most regions post-treatment of digested biomass is a useful technology to enable a dosing of N and P which is balanced to the need of the crops. Many efforts have been made to develop high-tech post-treatment systems where the nutrients in the digestate are concentrated and made readily available for crops. So far these high-tech systems are only installed at a few biogas plants. The most important barriers for a more widespread use of these technologies are that they are very expensive to operate or that they are still not considered as reliable technologies.

For post-treatment of digested biomass a decanter centrifuge is recommended as a cost-effective and reliable technology with a high and flexible capacity.

Technologies for storage and field application of digestate

Measures should be taken to reduce ammonia emission during storage of digestate and fractions from separation of digestate. It is recommended to keep the digestate in covered storage tanks or closed slurry lagoons. Similarly, technologies for reducing ammonia emissions during field application should be used. For instance digestate can be incorporated into the soil directly after spreading with a harrow or digestate can be placed into the soil with an injector. Low precision equipment such as broad spreading of digestate should be avoided.

Timing is the most important factor in order to reduce N-leaching from field application of digestate. To minimize N-leaching all digestate should be applied to the fields during spring time and early summer when there is a need for plant nutrients by the crops. Autumn spreading should be avoided. Therefore, it is recommended to establish storage facilities with a minimum capacity of 9-10 months depending on the length of the growing season where the pig farm is located. This would make it possible to store the digestate from June to March-April the following year".

Evaluation and comparison of different combinations of manure-digestate handling technologies can be facilitated by model calculations. As part of this study nitrogen efficiency calculations have been done for five manure-digestate handling scenarios. Nitrogen efficiency expresses the share of total-N in the original manure which is available for the crops after application to the field. The model calculations in this study confirm that anaerobic digestion increases nitrogen efficiency all other things being equal. The model calculations also show that spreading time is more important than anaerobic digestion of the manure in order to reduce nitrogen leaching.

Technologies for utilization of biogas

The optimal way of utilizing the produced biogas depends on the local possibilities and conditions for selling electricity, heat, raw biogas or upgraded biogas for vehicle fuel or for injection into the natural gas grid.

The most widespread use of biogas in the Baltic Sea Region is for combined heat and power production in adapted otto or diesel engines. These technologies are well-known and using biogas this way will be relevant for future biogas plants, especially if all the produced heat can be sold or utilized internally and for small scale plants located far from the natural gas grid.

In Sweden and Germany biogas is increasingly upgraded and used for vehicle fuel. In these countries the tax systems are favouring this way of utilizing biogas. It is expected that upgrading for transportation purpose or for injection into the natural gas grid will be more commonly used in other Baltic Sea region countries in the future too. Especially for medium and large scale biogas plants located near natural gas grid upgrading will be relevant for future biogas plants. When establishing biogas upgrading units technologies shall be chosen to reduce methane loss from the upgrading process. A methane loss of only a few percentages from the upgrading unit can jeopardize the positive green house gas balance of the biogas plant.

Economic analysis

Given the best available technologies pig manure biogas plants are not profitable without support. The support can be given in many ways for instance investment grants, subsidized prices on the products sold by the biogas plant (electricity, gas, heat). Support can also be given as tax exemptions.

Based on the economic evaluation of the three model biogas plants in this study it is concluded that large centralized biogas plants are more profitable than small farm based biogas plants. This is mainly due to economies of scale. When biogas is used for combined heat and power production, it is crucial that the excess heat can be utilized or sold.

When co-substrates are needed to increase biogas production and profitability, it is recommended to identify and use residue biomass sources instead of energy crops. Highest priority should be given to biomasses that contribute to nutrient losses or biomass that causes other problems. Furthermore, there are potential synergy effects of taking into account manure from all animal types and not only from pig production when planning and implementing new biogas plants.

Framework conditions

There are large differences in the type and amount of support given in the Baltic Sea Region countries. In some of the countries (e.g. Finland and Latvia) the support schemes are presently being updated, which makes the framework conditions somehow unclear.

In order to motivate farmers to utilize manure for production of biogas it is recommended to introduce manure bonus systems. Such systems shall secure that the biogas plant owner will get a higher price for that part of the end product (electricity, biogas, heat) that is based on manure. The bonus can be calculated from the register of amounts and types of biomasses applied throughout the year. This is necessary because a large share of the pig manure is handled as slurry and due to the high content of water slurry has only a low potential of energy.

The daily management of the biogas plant is one of the keys to successful biogas plants. In order to increase the knowledge and skills of the biogas plant managers, a formal education could be established together with a forum for sharing of experiences from running biogas plants. In addition a hotline service could be useful in situations where the biogas manager is facing an acute problem and perhaps risking a process break down.

Discussion and perspectives

Efforts should be made to develop technological solutions for sustainable treatment and utilization of the solid fraction from separation of digested biomass. One possibility could be to use the solid fraction as an N- and P-rich input for production of compost for application outside the farming sector, e.g. for use in private gardens, golf courses etc.

The dry matter content of pig slurry on some Swedish pig farms is relatively high. Probably the main reason is that more straw is used in the animal houses compared to other countries but it is relevant to analyze this since high dry matter content benefits profitability.

As an example of a future co-substrate with potential to contribute to the objective to reduce eutrophication of the Baltic Sea are macro algae along coast lines. Machinery for collection of macro algae is presently being developed and tested in both Sweden and Denmark and it is possible this work will end up in one or more commercial technology products.

Throughout this report the main focus has been to achieve an effective conversion of organic matter during the anaerobic digestion process. It should be mentioned that there are also benefits from applying organic matter to the fields. If all crops are removed during harvest and not replaced by carbon rich organic matter there is in some areas a risk of decreased quality of the soil structure in the long run. In such areas this can result in lower yields and a higher degree of nitrogen leaching in the long run. In order to maintain a good soil structure in the long run farmers have to adopt strategies to secure sufficient carbon content in the soil.

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Annex A: Abbreviations and acronyms

AD	Anaerobic digestion
ABP	Agro Business Park
BAT	Best available technique as defined in the IPPC Directive
BAU	Business as usual
BREF	Reference Document on Best available techniques for Intensive Rearing of Poultry and pigs.
BSR	Baltic Sea Region
CBMI	Innovation Centre for Bioenergy and Environmental Technology
CHP	Combined heat and power plant
CIP	Cleaning in place
CNG	Compressed natural gas
CSTR	Continuously stirred tank reactors
DM	Dry matter = total solids, TS
EU	European Union
GHG	Greenhouse gas
HRT	Hydraulic Retention Time
IPPC	Integrated Pollution Prevention and Control as defined in the IPPC Directive
JTI	Swedish Institute of Agricultural and Environmental Engineering
N	Nitrogen
N_E	Nitrogen efficiency
N_L	Nitrogen leakage
NGV	Natural gas vehicles
OLR	Organic loading rate
ORC	Organic ranking cycle
P	Phosphorous
PSA	Pressure Swing Adsorption
SBI	Swedish Biogas International
TAN	Total ammonium nitrogen
TS	Total solids = dry matter, DM
UF	Ultra filtration
VFA	Volatile Fatty Acids

Annex B: List of persons contacted

Table B-1. List of persons contacted during the study.

	Title	Organisation
Markus Isotalo	Manager	BIOvakka centralized biogas plant, Finland
Grzegorz Wisniewski	President of the Board	Insitute for Renewable Energy, Poland
Piotr Owczarek	Biogas Director	Poldanor SA, Poland
Tadeusz Domasiewicz	Researcher	ITP, Poland
Karol Malek	Member of the Board	Polish Biogas Association
Andrzej Curkowski	Biogas Expert	Institut for Renewable Energy, Poland
Benny Hedegaard Laursen	Biogas Consultant	Poldanor SA, Poland
Sven-Göran Sjöholm	Sales Manager	Swedish Biogas International
Kazimierz Zmuda	Deputy Director	Ministry of Agriculture and Rural Development, Department of Agricultural Markets, Poland
Henrik B. Møller	Researcher	Aarhus University, Faculty of Agricultural Sciences, Denmark
Jens Peter Lunden	Pig farmer and owner of farm based biogas plant	Grøngas, Denmark

Annex C: Description of three model biogas plants

C.1 Model biogas plant 1: Large scale centralized biogas plant

<u>Basic characteristics</u>: Large scale centralized biogas plant based mainly on pig manure from many farms (most of it in the form of solid fraction from slurry separation), manure from other livestock types, and with the possibility of taking in other residues from agricultural production, energy crops and waste products from industry. Biogas used for combined production of heat and power.

Examples of full scale biogas plants similar to this model: Morso Bioenergy (Denmark), Biokraft (Denmark), Green Power Salland (Netherlands).

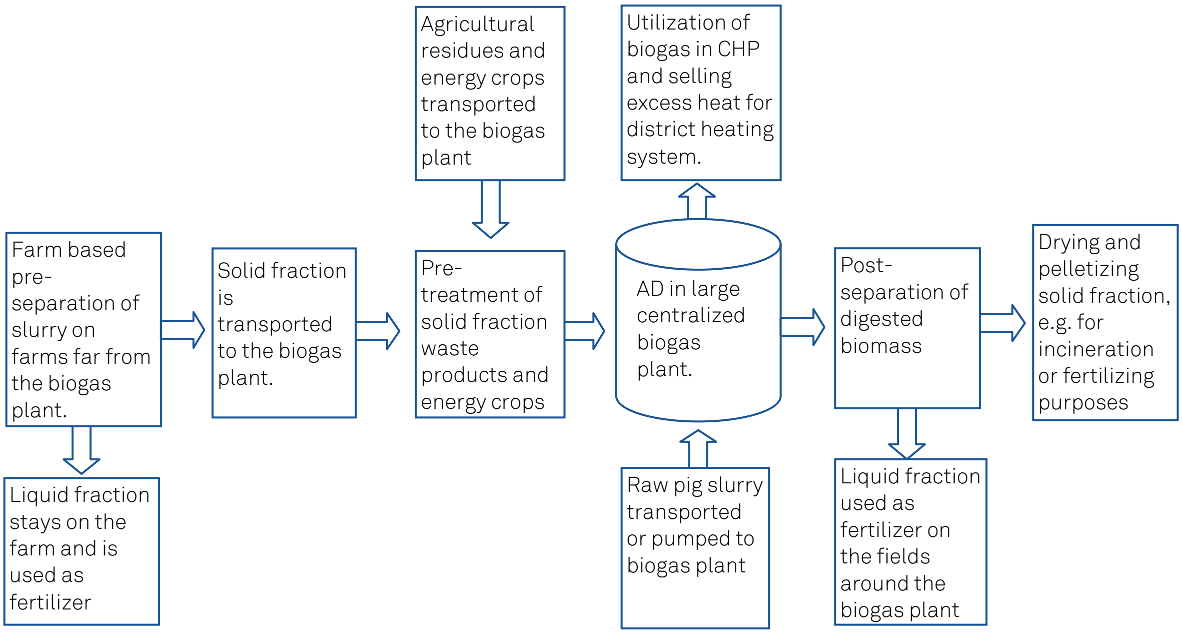


Figure C-1. Overview of the technologies involved in the large scale centralized biogas plant.

C.1.1 Technical description of the large scale centralized biogas plant

The primary scope is to solve environmentally issues such as handling and redistribution of surplus nutrients (nitrogen and phosphorous) in the area.

The biogas plant is running a mesophilic process with a temperature around 38 °C. The content of dry matter in the biomass mix fed to the biogas reactor is supposed to be held between 12 and 14 % TS in order to produce an acceptable volume of biogas/ton of biomass/m^3 of reactor volume. The biomass composition of the large scale centralized biogas plant is shown in Table C-1.

Table C-1. Composition of biomass at the large scale centralized biogas plant

Biomass input	Volume (tons pr. year)
Pig slurry (4,5 % TS)	23.500
Cattle slurry (9,0 % TS)	60.000
Fibre from pre-treated manure (30 % TS)	29.000
Mink slurry (7 % TS)	5.000
Total	117.500

Pre-separation of slurry

The 117.500 tons of biomass input represent a total amount of raw manure of approximately 390.000 tons per year of which the major part is separated locally at the farms. The pig manure included is equivalent to 98.500 fattening pig places (>30 kg) and 15.400 sow places.

Pre-separation is done by a large mobile decanter centrifuge, which is owned by the biogas plant. The slurry is separated into a liquid fraction (reject) and a solid fibre fraction. The latter has a dry matter content of approx. 30 % and is transported to the biogas plant for anaerobic digestion, while the liquid fraction stays at the farm to be used as fertilizer. On a few farms slurry is separated by a stationary separation unit (decanter, screw press, etc.) owned by the farmer.

Receiving tank

All biomasses for the biogas plant are unloaded in a building, which is under constant vacuum to prevent gaseous emissions to the surroundings. The biomass is mixed in a 600 m^3 underground concrete receiving tank equipped with shredding and stirring equipment for homogenizing the biomass before pumped to a 1.000 m^3 mixing/holding tank. This mixing/holding tank is also used as a small buffer tank to secure stable biomass input to the sanitation unit and digester during the weekends when no new biomass is transported to the biogas plant.

Sanitation

The biomass from the mixing/holding tank is pumped to a sanitation unit consisting of heat exchangers and 3 x 30 m^3 tanks where the first is a filling tank, the second a holding tank (1 hour at 70 ˚C) and the third is a pumping tank from which the now sanitised biomass is pumped to the biogas reactor. The warm sanitised biomass is heat exchanged with the cold biomass from the mixing/holding tank. This heat exchange regains a lot of the heat and reduces the need for external heat (steam and hot water from the gas engine).

Biogas reactor (digester)

The biomass from the sanitation unit is pumped to the 7.100 m^3 large digester, where the anaerobic digestion takes place. The hydraulic retention time is approx. 20 days after which the digested biomass is pumped to a 1.500 m^3 storage tank.

Storage tank and separation

Digested biomass from the digester is pumped to the storage tank, which functions as a buffer tank before post-treatment of the digestate.

The digestate is separated in a decanter centrifuge into a solid fibre fraction and a liquid fraction (reject). The liquid fraction is stored in a 1.500 m^3 fertiliser tank and then transported to the farmers who delivered the raw manure and solid fraction. The farmers use the liquid fraction as a fertilizer. The solid fraction from the decanter centrifuge is stored in a storage building under vacuum to prevent gaseous emissions (ammonia, odour). The fibre fraction can be used as an input to compost production or applied to the fields for improvement of the soil structure by increasing carbon content. The storage tank and the fertilizer tank are both equipped with a double layer gas tight membrane to prevent emission of produced biogas.

Biogas treatment

The biogas from the digester and the storage tank is treated in a biological filter to remove sulphide (conversion of H_2S to free sulphur), which is unwanted in the CHP. Except for the headspace in the storage tank and fertilizer tank there is no separate gas storage facilities at the large scale centralized biogas plant. The gas is utilized in the CHP at the same rate as it is produced.

Combined Heat and Power plant (CHP)

In the CHP the purified biogas is burned to produce heat (hot water and steam) and electricity. The electricity is delivered to the grid and most of the heat is sold to a nearby district heating system. Surplus heat is cooled away. Exhaust air from the CHP is emitted to the surrounding through a chimney. The efficiency of the CHP is as follows:

- Electricity: app. 39 %
- Heat: app. 45-50 %
- Loss: app. 10-15 %

Air pollution control

Air emission from the receiving facilities, mixing/holding tank and solid fraction storage building is treated in a sulphuric acid scrubber to remove ammonia and afterwards a biological filter to remove volatile organic compounds before emitted to the surroundings.

C.1.2 Evaluation of model biogas plant 1 – Large scale centralized biogas plant.

Environmental effects

The environmental benefits of the large scale centralized biogas plant can be summarised as follows:

- Reduced leaching of nitrogen and phosphorus due to pre-separation of slurry on the farms followed by export of solid fraction containing organic nitrogen and phosphorus.
- Reduced leaching of nitrogen from the digestate because 1) a large share (50-60%) of the organic nitrogen is converted to inorganic nitrogen (ammonium-N) during the anaerobic digestion and because 2) the digestate is post-separated in the decanter

centrifuge and the resulting solid fraction is transported to other areas with a need for nitrogen and phosphorous.

- Emission of methane, which is a strong green house gas, is reduced compared to the normal manure handling practices (storage and application of non-digested manure).

Economic evaluation

The profitability of the large scale centralized biogas plant has been evaluated using model calculations based on the above mentioned substrate mix, and estimated investment and operational costs. The key financial parameters used for the model calculations are shown in Table C-2.

Table C-2.Key financial parameters used for the model calculations.

Parameter	Unit	Value
Interest rate	% pro anno	7,0
Inflation rate	% pro anno	1,5
Tax rate	%	30,0
Maturity of loan	Years	15,0
Scrap value	EUR	0,0
Investment grant	% of total investment cost	8,5

Experience from running the large scale centralized biogas plant in full scale

The Danish biogas plant Morsoe can be mentioned as an example of the large scale centralized biogas plant. Morsoe is a relatively new biogas plant, which has been operating only since spring 2009. The idea of Morsoe biogas plant was to use animal manure as the only substrate for the biogas production and pre-separation of slurry is done in order to by-pass a great part of the liquid fraction and thereby increase the TS% in the digester. However, based on preliminary experiences it seems that the methane yield of the solid fraction used is lower than expected.

Another experience is that the use of large amounts of fibre fraction requires special pumps, heat exchangers, shredders and pipes. Otherwise, system failure will stop the biogas process. At Morsoe biogas plant some adjustments have been made since biogas production started up and these have improved the functionality.

One of the main assumptions in order to achieve the environmental benefits of Morsoe biogas plant is that the solid fraction from the post-treatment of digestate shall be exported out of the local area. However, up to now the solid fraction has no positive market value. The biogas plant is transporting the solid fraction to crop producing famers with a need for fertilisers. Part of the solid fraction is used locally and part of the solid fraction is transported to crop producers far from the biogas plant (20 km or more).

Strengths and Weaknesses of the large scale centralized biogas plant

The biogas plant is relatively simple using tested and well proven technologies. The idea of using only manure as biomass is well in line with the Danish governmental plans for utilizing manure for energy purposes.

On the weak side is that there is only one large digester, which means that if the biological process is inhibited, there will be a total breakdown in the gas production for a period of time. Also cleaning and removal of sediment (sand) in the digester means a stop of the biogas production for a shorter or longer period of time.

Due to the use of separated fibre fraction in order to increase the biogas yield the level of nitrogen (ammonia) in the digester is high. The biogas process might be close to the upper limit with regard to content of nitrogen and is therefore sensitive towards changes.

C.2 Model biogas plant 2: Medium scale centralized biogas plant

Basic characteristics: Medium scale centralized biogas plant based mainly on pig manure from approximately 10 pig farms (most of it in the form of slurry), manure from chicken production, energy crops and fatty residual products from industry. The produced biogas is upgraded and used as fuel for transportation sector.

Example of full scale biogas plants similar to this model: Katrineholm Biogas Plant AB (Sweden).

C.2.1 Technical description of the medium scale centralized biogas plant

Table C-3. Composition of biomass input at the medium scale centralized biogas plant.

Biomass input	Volume (tons pr. year)
Pig slurry (8 % TS)	65.000
Solid pig manure (25 % TS)	5.000
Chicken manure (46 % TS)	3.000
Energy crops – maize silage (30 % TS)	5.000
Glycerine	2.000
Total	80.000

Due to the large share of pig manure co-substrates are needed to balance the C/N-ratio in the reactor. Co-substrates are also added to boost the energy production.

Receiving tank

The pig slurry and the solid pig manure are delivered in a receiving tank with a capacity of 800 m^3 which is regularly mixed. Slurry is transported to the biogas plant by trucks (normally 7 – 8 truck loads per day). The average distance from farmer to biogas plant is approximately 10 km. The distance to the pig farmer nearest to the biogas plant is 5 km and those pig farms most far from the biogas plant are located 25 km from the biogas plant. Pumping part of the slurry from the farms to the biogas plant could be relevant but is not part of the model biogas plant concept.

Sanitation

From the receiving tank the slurry is led via a macerator (for homogenization of biomass) and heat exchangers into the sanitation unit. Three sanitation tanks with a capacity of 11 m^3 each are installed. The slurry is heated up 72 degrees C for one hour. The heat for the sanitation unit is produced in a wood chips burner with a capacity of nearly 1 MW.

Sanitation of pig manure is required by the Swedish authorities because slurry from several farms is mixed, used for biogas production and then transported back to a number of farmers. The sanitation process adds costs to the biogas production but there are also some positive side effects from the sanitation. An increased biogas yield is expected due to the heating. Furthermore, the biomass is easier to pump and mix after the sanitation process. Energy crops and chicken manure is fed directly into the digesters via a two mixing containers. There is no requirement of sanitation of such substrates.

Biogas reactor (digester)

The medium scale centralized biogas plant includes two parallelly installed digesters built in stainless steel with a capacity of 4.500 m^3 each. Each digester is equipped with two types of mixers: a) two fixed installed mixers and b) three mixers that can be moved up and down in order to secure optimal stirring of the biomass.

The biogas process is running mesophilic and the hydraulic retention time is approx. 40 days, which is relatively long time compared to manure based centralized biogas plants in Denmark. On top of the two digesters there is capacity for storing the produced biogas.

Post-treatment of digestate

The dry matter content in the digestate is 6 - 8 TS%. A screw press is installed in order to take out part of the dry matter and thus reduce the TS% to 2-3 %. The solid fraction is transported to farmers without livestock production and with a need for phosphorous to their fields.

Biogas upgrading unit

The biogas produced in the two digesters is led into the upgrading unit. First some compression is done and then the biogas is led through a purification unit (carbon filter) to reduce sulphur content and to reduce odor emission.

After the air purification unit the biogas is led to the first upgrading column, which contains filter material to create a large surface area. The upgrading is based on the “turbulent flow technique” using only water and no chemical additives in the process. When water is sprinkled through the filter material CO_2 and sulphur is taken up. Later the CO_2 is released into the atmosphere from the water so that most of the water used in the process can be circulated. The net water consumption of the upgrading unit is about 1 m^3 only.

As a result of the upgrading process the methane content in the gas is increased from approximately 65% in the raw biogas to approximately 97 % in the upgraded gas delivered from the biogas plant.

After the upgrading the gas is compressed so that is can be collected by a truck with a capacity of 3 gas containers. The gas is sold to a gas distribution company, which is responsible for the collection of the produced gas and transportation to the location where it is used for transportation purposes. Steel tanks are used for transportation of the gas and they have a capacity of 1900 m^3 at a pressure of 200 bar. It means that one truck load can collect 3 * 1900 m^3. If gas tanks of carbon fibres are used instead the capacity can be increased to 3 * 5400 m^3 per truck load.

Technical evaluation of the medium scale centralized biogas plant

The upgrading unit can be a relevant way of utilizing the produced biogas in other Baltic Sea countries and regions too. The technology used for the "core biogas process" is well known and well documented technology. However, compared to centralized biogas plants in Denmark the hydraulic retention time is longer at model biogas plant 2.

Post-treatment of digestate gives better possibilities for redistribution from areas with surplus nutrients to areas needing these nutrients. The screw press separator is a well known and reliable technology but the separation efficiency is not very high.

Economic evaluation

The profitability of the medium scale centralized biogas plant has been evaluated using model calculations based on the above mentioned substrate mix, and estimated investment and operational costs. The key financial parameters used for the model calculations are shown in Table C-4.

Table C-4. Key financial parameters used for model calculations.

Parameter	Unit	Value
Interest rate	% pro anno	7,0
Inflation rate	% pro anno	1,5
Tax rate	%	30,0
Maturity of loan	Years	15,0
Scrap value	EUR	0,0
Investment grant	% of total investment cost	0,0

C.3 Model biogas plant 3: Small scale farm based biogas plant

Basic characteristics: Farm scale biogas plant based solely on pig slurry. Post-treatment of digested biomass based on natural separation (flotation and sedimentation). Biogas used for combined production of heat and power. Example of full scale biogas plants similar to this model: Gosmer Biogas plant (Denmark).

C.3.1 Technical description of the small scale farm based biogas plant.

Table C-5. Composition of biomass input at small scale farm based biogas plant.

Biomass input	Volume (tons pr. year)
Pig slurry (5,5 % TS)	9.650
Total	**9.650**

The post-treatment concept is based on natural separation. An overview of the separation system is given in Figure C-2. First, the digested biomass is led to a sedimentation tank. In this tank part of the dry matter will sink to the bottom of the tank due to sedimentation and part of the dry matter is gathered in the top of the tank due to flotation caused by remaining biogas in the digestate. With regular intervals part of the liquid from the mid-section of the sedimentation tank is pumped out and led to a collecting tank.

The remaining dry matter (sludge) in the sedimentation tank is led to the filtration unit 1, where it is drained off. The liquid from the filtration unit 1 is led to the collection tank. The sludge from the filtration unit 1 is taken to a dewatering unit where more liquid is drained off and led to the collection tank. From the collection tank the liquid is led through a second filtration unit and then finally is pumped to the fertiliser storage tank.

The solid fraction from the dewatering units is moved to a storing facility that includes covering the solid fraction.

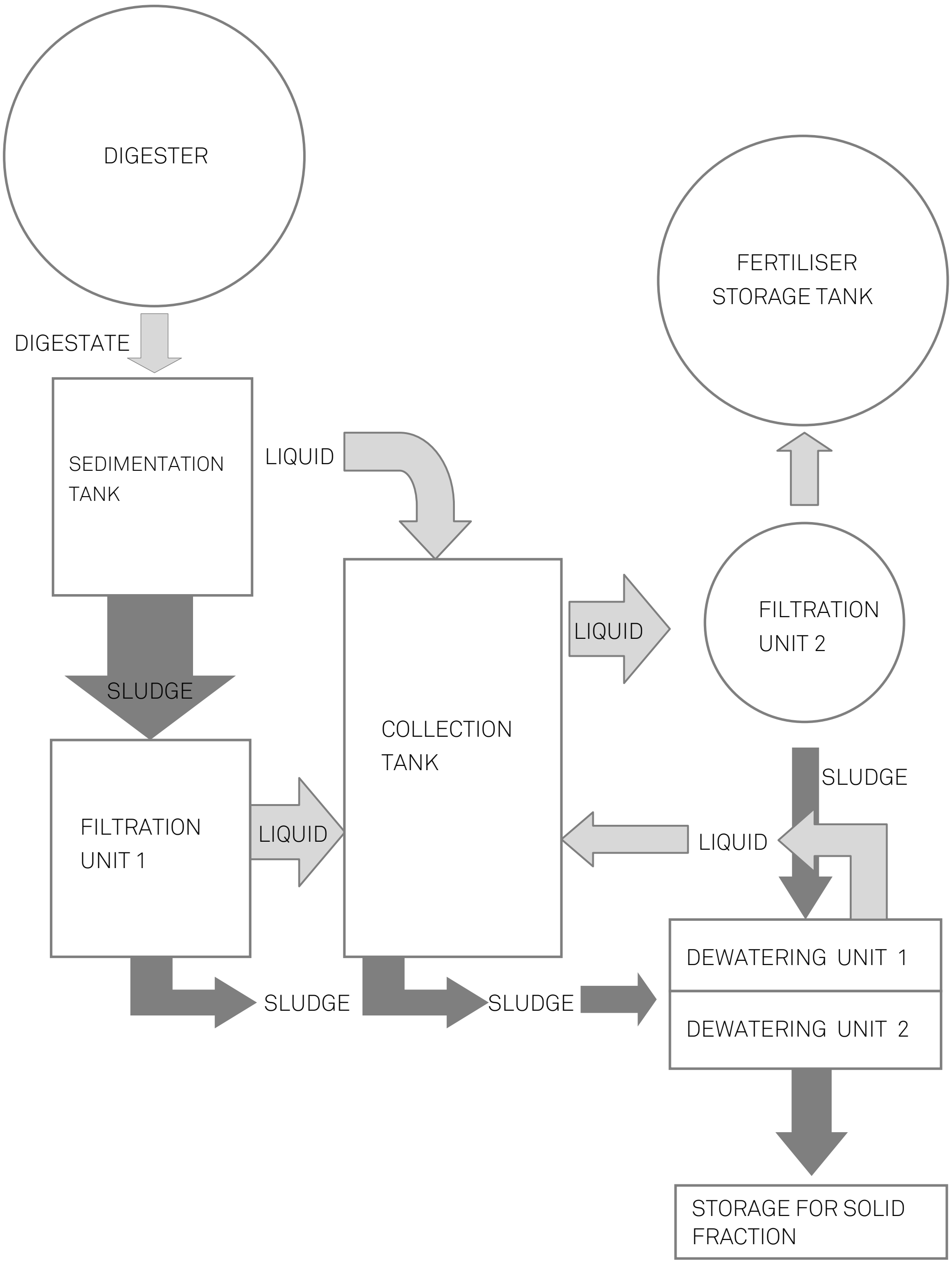
Economic evaluation

The profitability of the small scale farm based biogas plant has been evaluated using model calculations based on the above mentioned substrate mix, and estimated investment and operational costs. The key financial parameters used for the model calculations are shown in Table C-6.

Table C-6. Key financial parameters used for the model calculations.

Parameter	Unit	Value
Interest rate	% pro anno	7,00
Inflation rate	% pro anno	1,50
Tax rate	%	30,00
Maturity of loan	Years	15
Scrap value	EUR	0
Investment grant	% of total investment cost	0

Figure C-2. Overview of process steps for the small scale farm based biogas plant.



Annex D: Pre-separation and digestate post-treatment technologies

In this Annex eleven different technologies relevant for pre-separation and/or post-treatment of digestate are described and evaluated. An overview of the technologies is given in table D-1.

Table D-1. Overview of screened technologies for slurry pre-separation and digestate post-treatment.

Ref. no.	Name of technology	Relevant for slurry pre-separation?	Relevant as post-treatment of digestate?
D-1	Screw press	Yes	Yes
D-2	Decanter centrifuge	Yes	Yes
D-3	Coagulation/flocculation systems	Yes	Yes
D-4	Ammonia stripping by air	Yes	Yes
D-5	Ammonia stripping by use of steam	Yes	Yes
D-6	Ultra filtration	Yes	Yes
D-7	Reverse osmosis	Yes	Yes
D-8	Evaporation systems (vacuum)	Yes	Yes
D-9	Drying and pelletizing solid fraction of digestate	No	Yes
D-10	Composting solid fraction of digestate	No	Yes
D-11	Combustion and gasification	No	Yes

The screened technologies have been evaluated with respect to development stage (technological maturity) and potential benefits/relevance for biogas plant owners. The codes used for the evaluation is presented and explained in table D-2.

Table D-2. Explanation of codes used for evaluation of technologies.

Technological maturity/development stage		Potential benefits / relevance	
More research needed. Preliminary results from pilot scale installations.	0	Not relevant for the specific scale of the biogas plants	-
Limited experience from full scale installations on test plants/pilot plants.	+	Low level of potential benefits for the specific scale of the biogas plants	*
Some experience. Technology installed on some commercial biogas plants.	++	Medium level of potential benefits for the specific scale of the biogas plants	**
Well known technology installed on several biogas plants.	+++	High level of potential benefits for the specific scale of the biogas plants	***

<table>
<tr><td>Name of technology</td><td colspan="2">Screw press</td><td>Ref. no.</td><td>D-1</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="4">A screw press is a simple separation technology, which separates the stream into a solid and liquid fraction. In a screw press manure is pumped into a horizontal and cylindrical screen. Some of the water flows due to the force of gravity through the screen. The press screw conveys the rest of the water with the solid particles into the press zone in the last section of the screen. Here a permanent regenerative compact solid matter is generated which is pressed out of the last section of the machine and then can easily be filled into containers. The separated liquid flows through the outlet underneath the machine. Due to the narrow inside tolerances between screen and screw the screen is permanently kept clean.
The dry matter content in the solid can be adjusted through applied backpressure at the outlet zone. Replaceable screens with different slots widths are normally available.
A screw press is normally applied before the biogas plant to separate manure – not as post-treatment of the digested biomass.</td></tr>
<tr><td>Development stage technology maturity</td><td>+++</td><td>Investment and operational costs related to the technology</td><td colspan="2">Investment costs: 10,000 – 50,000 EUR
Operational costs: 0.25 – 0.65 EUR/ton</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="2">Disadvantages</td></tr>
<tr><td colspan="2">Low investment
Simple and easy to operate
Robust
Little maintenance
High TS in fiber fraction</td><td colspan="2">Not well suited for smaller particles as in digested biomass since smaller particles of dry matter are not recovered.
High content of dry matter (suspended solids) in the liquid phase.</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td>Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">*</td><td>*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="4">www.becker-seesen.de; www.wamgroup.com; www.itt.com; www.biogastechnik.de www.fan-separator.de; www.svea.dk</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="4">Not well known in Denmark as post-treatment of digested biomass/manure.
Well known in Germany as separation of digested biomass.</td></tr>
<tr><td>References</td><td colspan="4">Møller et al, 2003. Concentration of N and P is low for this type of separator and the efficiency strongly depends of the dry matter in the manure. Concentration of N is less than 9 % and for P less than 15 %.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="3">Decanter centrifuge</td><td>Ref. no.</td><td>D-2</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">A decanter centrifuge separates solids from a liquid phase by centrifugal forces that can be well beyond 3000 times greater than gravity. When subject to such forces the denser solid particles are pressed outwards against a rotating bowl wall, while less dense liquid phase forms a concentric inner layer. Different dam plates are used to vary the depth of the liquid as required. The sediment formed by the solid particles is continuously removed by a screw conveyor, which rotates at a different speed than the bowl. As a result the solids are gradually “ploughed” out of the pond and up a conical beach.
The centrifugal force compact the solids and expels the surplus liquid. The dried solids then discharge from the bowl.
The clarified liquid phase or phases overflow the dam plates at the opposite end of the bowl. baffles within the centrifuge casing direct the separated phases into the correct flow path and prevent any risk of cross-contamination
The speed of the screw conveyor may be automatically adjusted.</td></tr>
<tr><td>Development stage technology maturity</td><td>+++</td><td>Investment and operational costs related to the technology</td><td colspan="3">Investment: 120,000 – 185,000 EUR
Operational costs: 0.65 – 1,00 EUR/ton</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Easy to run
Robust
Good separation efficiency
Application well suited for separation of digestate</td><td colspan="3">Relatively high investment
Medium to high running cost
Noisy</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">**</td><td colspan="2">***</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.westfalia-separator.com, www.alfalaval.com
www.pieralisi.com</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">Preferred post treatment technology in Denmark.
Morsø Bioenergi, Biokraft (Bornholm), Fangel Biogas, Green Farm Energy (over Løjstrup), Grøngas.</td></tr>
<tr><td>References</td><td colspan="5">Møller et al 2003. Concentration of N and P is high for this type of separator especially with regard to P (50-80 %) and organic N (50-80 %). For total N the efficiency is low (11-28 %).</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="3">Coagulation/flocculation</td><td>Ref. no.</td><td>D-3</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Coagulation and flocculation are chemical processes which help separating suspended solids from liquid.
In wastewater treatment operations, the processes of coagulation and flocculation are employed to separate suspended solids from water.
Coagulation is the destabilization of colloids (suspended solids) by neutralizing the forces that keep them apart. Cationic coagulants provide positive electric charges to reduce the negative charge of the colloids. As a result, the particles collide to form larger particles (flocks). Rapid mixing and no overdose of the coagulant are essential to the process.
Flocculation is the action of polymers to form bridges between flocks and bind the particles into large agglomerates or clumps. Bridging occurs when segments of the polymer chain adsorb on the different particles and help particles aggregate. An anionic flocculant will react against a positively charged suspension, adsorbing on the particles causing destabilization either by bridging or charge neutralization. In this process it is essential that the flocculating agent is added slowly and gently mixed to allow for contact between the small flocks and to agglomerate them into larger particles.
The agglomerated particles are quite fragile and can be broken by shear forces during mixing.
The agglomerated particles are removed from the liquid by sedimentation, filtration or dewatered by gravitation by use of band filter or decanter centrifuge.
Coagulants are normally multivalent cations, while flocculants normally are long chain polymers.</td></tr>
<tr><td>Development stage technology maturity</td><td>+++</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">High separation efficiency (the separated liquid has a low content of dry matter)</td><td colspan="3">Dewatering must be done afterwards (band filter or centrifuge)
Relatively high investment
Running cost high (due to chemical consumption)
Flocks sensitive towards physical forces
Sensitive towards change in chemical composition of the liquid to be separated</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.al-2.dk;
www.kemira.com
www.generalchemical.com</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">Data not available.</td></tr>
<tr><td>References</td><td colspan="5">Møller et al, 2003. Concentration of organic N (up to 89 %) and P (up to 89 %) is high for this type of separator. For total N the efficiency is average (11-28 %). The efficiency depends on the type of dewatering technology used after flocculation.</td></tr>
</table>

Name of technology	**Ammonia stripping by air**		Ref. no.	D-4
Brief description of functionality / operating principle	Ammonia is stripped from liquid in a counter current flow with air in a packed column. Ammonia containing liquid is pumped to the top of the column and ammonia is removed from the liquid by a counter current stream of air. Ammonia from the airstream is removed by absorption in a column with acid (usually sulfuric acid). Ammonia air stripping is normally done in a closed loop system where large volumes of atmospheric air respectively remove ammonia respectively is being washed with acid to remove ammonia from the air. For proper air stripping the liquid to be stripped is often heated and pH adjusted (pH>10) by adding basic chemicals to convert ammonium to ammonia and to convert CO2 to CO3--. This improves the stripping considerably. Stripped ammonia is absorbed in an acidic absorber. To avoid fouling of the column it is important that there are no or little particles or suspended solids in the liquid stream to be stripped.			
Development stage technology maturity	+ to ++	Investment and operational costs related to the technology	Data not available.	
Assessment of technology	Advantages		Disadvantages	
	Concentrated ammonium fertilizer with no loss of ammonia Reject water with low concentration of ammonia		Relatively high investment cost Relatively expensive to run (consumption of chemicals and power) Maintenance cost (especially for CIP-chemicals) The liquid stream must be pretreated to remove particles and CO2. Fouling of column (participation of struvite, carbonates)	
Potential benefits / relevance	Small scale plants	Medium scale plants	Large scale plants	
	-	-	**	
Examples of technology suppliers	Branch Environmental, air stripping and absorption, www.branchenv.com Envimac Engineering, air and steam stripping (atmospheric and vacuum), www.envimac.de			
Examples of biogas plants where the technology is installed	Data not available.			
References	Data not available.			

Name of technology	**Ammonia stripping by use of steam**			Ref. no.	D-5
Brief description of functionality / operating principle	Ammonia is stripped from liquid in a counter current flow in a packed column. Ammonia containing liquid is pumped to the top of the column and ammonia is removed from the liquid by a counter current stream of steam. Stripped ammonia is rectified in a separate column and the final stream of ammonia/steam is condensed to a liquid ammonia-water solution. Ammonia steam stripping can be done by using direct or indirect steam. To reduce the consumption of heat or if only low value heat is available the process can be run under vacuum. Using steam the process is more complex: CO2 is stripped of as the first step in a separate column (packed). Then ammonia is stripped of in a second column (packed). Stripped ammonia and water is rectified in a third column (packed).Finally concentrated ammonia from the rectifier is condensed. For a good stripping result it is important that there are no particles or suspended solids in the liquid stream to be stripped. For good result the major part of CO2 must be removed in the first column, either by stripping or by applying chemicals (base).				
Development stage technology maturity	+ to ++	Investment and operational costs related to the technology	Data not available.		
Assessment of technology	Advantages		Disadvantages		
	Concentrated ammonia fertilizer Reject water with low concentration of ammonia		High investment cost Expensive to run (consumption of chemicals and/or steam) Maintenance cost (especially for CIP-chemicals) The liquid stream must be pretreated to remove particles and CO2. Fouling of column (participation of ex. struvite, carbonates)		
Potential benefits / relevance	Small scale plants	Medium scale plants		Large scale plants	
	-	-		*	
Examples of technology suppliers	Process Engineering, steam stripping at atmospheric pressure, www.proeng.dk Envimac Engineering, steam stripping (atmospheric and vacuum), www.envimac.de,				
Examples of biogas plants where the technology is installed	Biokraft (Bornholm) not running. Green Farm Energy (not running)				
References	Data not available.				

Name of technology	**Ultra filtration**			Ref. no.	D-6
Brief description of functionality / operating principle	Ultra filtration (UF) is a pressure driven barrier to suspended solids, bacteria, proteins, endotoxins and other pathogens to produce water with relatively high purity and low silt density. UF often serves as pretreatment for surface water, seawater, and biologically treated municipal effluent (wastewater) before reverse osmosis and other membrane systems (e.g. nanofiltration). The size of the membrane pores decides the separation efficiency. The purified liquid is called permeate and the concentrated stream is called concentrate of retentate. The accumulation of retained molecules may form a concentrated gel layer. The impact of the gel layer is that it can significantly alter the performance characteristics of the membrane. Fundamentally, the gel layer will limit filtrate flow rate and any increase in pressure will have no beneficial effect. Before UF pretreatment (filtration) is necessary to prevent plugging or damaging of the membranes. UF uses pressures up to 10 bars. Membranes of polymers (e.g. polysulfone, polypropylene, etc.) or ceramic membrane (SiliciumCarbide, aluminia, titania, zirconia, etc.)				
Development stage technology maturity	+	Investment and operational costs related to the technology	Data not available.		
Assessment of technology	Advantages		Disadvantages		
	Consistent water quality (permeate)		Power consumption Liquid containing suspended solid must be pretreated before UF Use of chemicals for CIP		
Potential benefits / relevance	Small scale plants	Medium scale plants		Large scale plants	
	-	-		*	
Examples of technology suppliers	www.geafiltration.com, www.veoliawater.com (Krüger)				
Examples of biogas plants where the technology is installed	Biokraft (Bornholm)				
References	Data not available.				

Name of technology	**Reverse osmosis**		Ref. no.	D-7
Brief description of functionality / operating principle	Osmosis is diffusion of water molecules through a semi permeable membrane, which allows passage of water, but not ions (e.g. Na^+, K^+, Ca^{2+}, Cl^-) or larger molecules (e.g. glucose, urea, bacteria, protein). With normal osmosis water moves from a region of low concentration of components to a region with a higher concentration until equilibrium is reached. Reverse osmosis occurs, when sufficient pressure is applied to the membrane from the region with high concentration. Reverse osmosis occurs when the water is moved across the membrane against the concentration gradient, from lower concentration to higher concentration. Reverse osmosis is often used in commercial and residential water filtration (seawater). Reverse osmosis requires liquid with low concentration of other components and no suspended solids. This means that digestate must be pretreated to remove fiber and suspended solids and filtrated (UF and/or NF) to remove di- and trivalent ions and larger molecules to avoid fouling of the membrane.			
Development stage technology maturity	+	Investment and operational costs related to the technology	Data not available.	
Assessment of technology	Advantages		Disadvantages	
	Clean water		Relatively high investment High power consumption due to high pressure Not suited for liquid with higher concentration of ions or larger molecules Sensitive to fouling Cost for CIP Does not remove herbicides, pesticides, etc.	
Potential benefits / relevance	Small scale plants	Medium scale plants	Large scale plants	
	-	-	*	
Examples of technology suppliers	www.geafiltration.com, www.veoliawater.com (Krüger)			
Examples of biogas plants where the technology is installed	Biokraft (Bornholm)			
References	Data not available.			

<table>
<tr><td>Name of technology</td><td colspan="3">Evaporation systems (vacuum)</td><td>Ref. no.</td><td>D-8</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Vacuum evaporation is the process of causing the pressure in a liquid-filled container to be reduced below the vapor pressure of the liquid, causing the liquid to evaporate at a lower temperature than normal at atmospheric pressure. Although the process can be applied to any type of liquid at any vapor pressure, it is generally used to describe the boiling point of water by lowering the containers internal pressure below standard atmospheric pressure and causing the water to boil at a lower temperature.

When the process is applied to the liquid fraction from digested and separated biomass the water and volatile component are evaporated and removed. The vapors are condensed and the remaining concentrate is stored for use as a fertilizer (DM-concentration in the concentrate varies depending of the inlet concentration, but is normally between 10 and 15 % DM).

Before applying vacuum evaporation acid is added to the inlet stream to remove dissolved CO2 (HCO3-) and to avoid preticipation of salts in the heat exchangers. Volatile fatty acids and other volatile components will evaporate together with the water and be condensed. Treatment of the condensate might be necessary.

Vacuum evaporation is often (normally) carried out as multiple process, which increases the efficiency significantly.

Heating source can be steam, hot water as well as electricity.</td></tr>
<tr><td>Development stage technology maturity</td><td>+</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Reduces the amount of liquid to be stored (concentrate)
Generates a concentrated fertilizer</td><td colspan="3">High investment
Running cost high
Risk of precipitation
Handling of condensate</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">-</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.atlas-stord.dk
www.alfalavel.dk
www.bjornkjaer.dk; AquaSystems LtD.</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">Hegndal biogas (not running)</td></tr>
<tr><td>References</td><td colspan="5">Data not available.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="3">Drying and pelletizing solid fraction of digested biomass</td><td>Ref. no.</td><td>D-9</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Drying is a mass transfer process consisting of removal of water moisture or moisture from another solvent, by evaporation from a solid, semi-solid or liquid. To be considered drying the final product must be a solid. To achieve this there must be a source of heat, and a sink of the vapor thus produced. In drying of separated fiber from the digestate the solvent to be removed is water.
In the most cases, a gas stream, e.g. air, applies the heat by convection and carries away the vapor as humidity. By drying directly by means of a gas stream (air), large volumes of gas are needed to achieve sufficient efficiency. The gas stream must be post treated to reduce unwanted emissions.
Other possibilities are vacuum drying, where heat is supplied by conduction radiation while the vapor thus produced is removed by the vacuum system. Another indirect technique is drum drying, where a heated surface is used to provide the energy and aspirators draw the vapor outside the drum. When drying the separated fiber ammonia and other volatile components will evaporate together with water and post treatment of the condensed vapor are needed.
By indirect drying the heated surface (in a drum) must be moving to prevent the dry matter from becoming fixed on the surface.
Drying can be done either in an open or closed circuit.
In order to reduce the volume and to make the fiber storable the moisture content must be less than 15 %. Further treatment of the dried fiber could be pelletizing, where the fiber under high pressure are extruded to form pellets, briquettes, etc.</td></tr>
<tr><td>Development stage technology maturity</td><td colspan="2">+</td><td>Investment and operational costs related to the technology</td><td colspan="2">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="3">Advantages</td><td colspan="2">Disadvantages</td></tr>
<tr><td colspan="3">Reduces the volume and mass of separated fiber
Storable product
Product used as fuel and/or fertilizer</td><td colspan="2">Emission of ammonia and other volatile compounds (post treatment of condensate)
Expensive process (running cost high)
High investment</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">-</td><td colspan="2">**</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.atlas-stord.dk (drying)
www.cimbria.com (drying)
www.grainwood.dk (pellets)</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">Fangel biogas (Odense)</td></tr>
<tr><td>References</td><td colspan="5">Data not available.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="4">Composting solid fraction of digested biomass</td><td>Ref. no.</td><td>D-10</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="6">Composting is a process where degradation of organic matter is accelerated under controlled conditions. At its most essential, the process of composting requires simply piling up waste outdoors and waiting a year or more. Modern, methodical composting is a multi-step, closely monitored process with measured inputs of water, air and carbon- and nitrogen-rich material. The decomposition process is aided by shredding the plant matter, adding water and to ensure proper aeration by regularly turning the mixture. Worms and fungi further break up the material. Aerobic bacteria manage the chemical process by converting the input into heat, carbon dioxide and ammonium. Most of the ammonium is further refined by bacteria into plant-nourishing nitrites and nitrates. Some ammonium will leave the mixture as free ammonia.

The final compost is rich in nutrients and can be used as soil improver/conditioner and fertilizer and be a good replacement for sphagnum.

Fiber from separated digestate is mixed with shredded straw or other shredded plant material. Due to the high content of ammonium/ammonia and to avoid emissions of ammonia to the surroundings the composting process must be carried out in closed building, where the ammonia vapors are captured and concentrated.

Important things for the composting process are:
— Carbon – for energy (microbial oxidation of carbon produces heat)
— Nitrogen – to grow and reproduce more organisms to oxidize the carbon.
— Oxygen - for oxidizing the carbon, the decomposition process.
— Water – in the right amounts to maintain activity causing anaerobic conditions.</td></tr>
<tr><td>Development stage technology maturity</td><td colspan="2">+</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="3">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="3">Good soil conditioner</td><td colspan="3">Emission of ammonia – air cleaning required
Closed building</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="3">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="3">*</td><td colspan="2">*</td></tr>
<tr><td>Examples of tech-nology suppliers</td><td colspan="6">www.komtek.dk</td></tr>
<tr><td>Examples of biogas plants where the tech-nology is installed</td><td colspan="6">Data not available.</td></tr>
<tr><td>References</td><td colspan="6">Data not available.</td></tr>
</table>

Name of technology	**Combustion and gasification**		Ref. no.	D-11
Brief description of functionality / operating principle	Combustion or burning is a chemical reaction between fuel and an oxidant accompanied by the production of heat and conversion of chemical species. Combustion of biomass such as separated fiber is a reaction between oxygen and the organic matter thus producing heat, carbon dioxide, oxides (NOx, metal oxides, phosphorus oxides, etc.) and water. Complete combustion is almost impossible to achieve and in reality a wide variety of major and minor species will be present such as carbon monoxide and pure carbon (soot and ash). Combustion in atmospheric air will also create nitrogen oxides. Gasification is a process that converts carbonaceous materials, such as coal, petroleum, or biomass, into carbon monoxide and hydrogen by reacting the fuel at high temperatures with a controlled amount of oxygen and/or steam. The product is a gas mixture called synthetic gas or syngas and is itself a fuel. Gasification is a method for extracting energy from many different types of organic materials. The advantage of gasification is that the syngas can be utilized in different ways. It can be burned directly for energy production, used to produce methanol and hydrogen or converted into synthetic fuel and used for transportation. Both combustion and gasification are well known technologies, which have been used for many years. Using biomass as fuel –especial in gasification - is not well documented and still under development. Nitrogen in the fuel (biomass) is lost as fertilizer as it is emitted through the flue gas. By combustion as well as gasification ash is also a product, which contains all the phosphorus in the fuel. A part of this phosphorus is not water soluble and therefore not useful as fertilizer unless the ash is chemically treated to release the phosphorus. Even there is little knowledge about the availability of phosphorus in ash it is believe that the lower the combustion/gasification temperature the more available the phosphorous is.			
Development stage technology maturity	0	Investment and operational costs related to the technology	Data not available.	
Assessment of technology	Advantages		Disadvantages	
	No risk for leaching of nitrogen to recipients Gasification – more path for utilization of the produced gas		Investment Phosphorous is bound in the ash Loss of nitrogen as fertilizer Treatment of exhaust air (DeNOx and other)	
Potential benefits / relevance	Small scale plants	Medium scale plants	Large scale plants	
	-	-	-	
Examples of technology suppliers	www.dongenergy.dk www.weiss-as.dk			
Examples of bio-gas plants where the technology is installed	Not known			
References	Data not available.			

Annex E: Biogas technologies

E.1 Biomass pre-treatment technologies

In this section twelve different technologies relevant for pre-treatment of biomass are described and evaluated. An overview of the screened technologies is given in table E-1.

Table E-1. Overview of screened technologies for pre-treatment of biomass for biogas production.

Ref. no.	Name of technology
E-1	Electrokinetic disintegration
E-2	Aerobic hydrolysis
E-3	Shredding
E-4	Extrusion
E-5	Selective hydrolysis
E-6	Thermal-chemical hydrolysis
E-7	Ultra sound treatment
E-8	Addition of enzymes before biogas reactor
E-9	Thermal-pressure hydrolysis
E-10	Ozone treatment
E-11	Chemical treatment
E-12	Microwave treatment

The screened technologies have been evaluated with respect to development stage (technological maturity) and potential benefits/relevance for biogas plant owners. The codes used for the evaluation is presented and explained in table E-2.

Table E-2. Explanation of codes used for evaluation of technologies.

Technological maturity/development stage		Potential benefits / relevance	
More research needed. Preliminary results from pilot scale installations.	0	Not relevant for the specific scale of the biogas plants	-
Limited experience from full scale installations on test plants/pilot plants.	+	Low level of potential benefits for the specific scale of the biogas plants	*
Some experience. Technology installed on some commercial biogas plants.	++	Medium level of potential benefits for the specific scale of the biogas plants	**
Well known technology installed on several biogas plants.	+++	High level of potential benefits for the specific scale of the biogas plants	***

<table>
<tr><td>Name of technology</td><td colspan="3">Electrokinetic disintegration</td><td>Ref. no.</td><td>E-1</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Disintegration is a well-known technology in various industrial fields. Cell membranes are damaged by a high-voltage field, releasing more of the cell content. This increases the biogas and consequently the power yield of the plant. The bacteria are stimulated at the same time, hence producing more biogas. It means that the substrates that are used are better utilized.
According to one technology suppliers (BioCrack) the overall increase in biogas production is up to 18 % more biogas compared to no pretreatment. As a positive side effect the biomass input will be more homogeneous after the electrokinetic disintegration. This will drastically reduce the required mixing and pumping power for the process, giving the biogas plant a better efficiency and economy.</td></tr>
<tr><td>Development stage technology maturity</td><td>+
Limited experience from full scale installations.</td><td>Investment and operational costs related to the technology</td><td colspan="3">The BioCrack unit is a one-size equipment available for a price of 14.000 EUR pr. unit. More units can be installed in series to achieve higher efficiencies.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Low energy consumption, 35 W per unit
Maintenance and wear can be disregarded
Easy for upgrade, units can be installed horizontal, vertical or diagonally
High availability for operation</td><td colspan="3">No documentation to prove the efficiency.</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>*</td><td colspan="2">*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.vogelsang-gmbh.com</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">No data available, but installed at more biogas plants in Germany</td></tr>
<tr><td>References</td><td colspan="5">According to a sales representative from the company Vogelsang during the Eurotier-fair an increase in biogas production of up to 18 % can be achieved but no documentation and no guarantee was given.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="4">Aerobic hydrolysis</td><td>Ref. no.</td><td>E-2</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="6">In the aerobic hydrolysis larger organic molecules in the substrate are degraded to smaller components (among others acetic acid), which makes the substrate easier and faster degradable by the methanogenic bacteria in the anaerobic process. As a result the retention time in the anaerobic step can be reduced. According to one technology supplier the retention time in the anaerobic step can be reduced from 80-100 days to only approximately 21 days. This leads to improved use of digester volumes since the same amount of substrate can be treated in smaller digesters.

The aerobic hydrolysis is relatively fast and the retention time is only 1 day. Only atmospheric air is introduced to the biomass through different types of diffusers. No extra thermal energy is required for the process.

Aerobic hydrolysis is especially relevant for biogas plants using nitrogen rich substrates and substrates with long fibers like for instance litter manure with straw.</td></tr>
<tr><td>Development stage technology maturity</td><td>+
Limited experience from full scale installations.</td><td>Investment and operational costs related to the technology</td><td colspan="4">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="4">Disadvantages</td></tr>
<tr><td colspan="2">Aerobic hydrolysis can both be installed at existing biogas plants and new plants.
Reduced viscosity, which makes pumping and stirring easier.
Reduced foaming in the digester.
Reduced floating layers of biomass in the digester.
Reduced odor nuisance.
Fewer problems when changing substrates, with substrate fluctuations or marginal pollution.</td><td colspan="4">Still more documentation is needed to prove the improved efficiency and the other advantages.</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td colspan="2">Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td colspan="2">*</td><td colspan="2">**</td><td colspan="2">**</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="6">Avantec Biogas (www.avantec-biogas.de)</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="6">RegTec Regenerative Technologien GmbH, Naumburg, Germany
Rinderhof-Agrar GmbH Seubtendorf, Germany
LVVÖkozentrum Werratal/Thür. GmbH Vachdorf, Germany</td></tr>
<tr><td>References</td><td colspan="6">According to a sales representative from the company Avantec during the Eurotier-fair the HRT can be reduced from 80 to 21 days.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="4">Shredding</td><td>Ref. no.</td><td>E-3</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="6">Shredding as pre-treatment of biomass for biogas production is widespread and covers different types of shredding equipment. At most biogas plants there is a shredding unit in the mixing tank in order to homogenize biomass before it is pumped into the digester. This is done mainly to be able to pump the biomass but the treatment also makes the biomass easier degradable in the digester.
Shredding can also be carried out in a more intensive way where the biomass (especially dry biomass with high content of cellulose, hemi-cellulose and lignin) is shredded thoroughly to increase the surface of the biomass. The aim is to increase the biogas yield as well as the degradation rate.
More investigations have to be carried out to determine the effects of shredding.</td></tr>
<tr><td>Development stage technology maturity</td><td>+
Limited experience from full scale installations.</td><td colspan="2">Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="3">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="3">Data not available.</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td colspan="2">Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td colspan="2">*</td><td colspan="2">**</td><td colspan="2">**</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="6">Cellwood (Sweden):
AL-2 Agro (Denmark): www.al-2.dk</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="6">Data not available.</td></tr>
<tr><td>References</td><td colspan="6">Sweden</td></tr>
</table>

Name of technology	**Extrusion**		Ref. no.	E-4
Brief description of functionality / operating principle	Extrusion causes cell disruption by application of mechanical energy (friction, squeezing, crushing). The process is performed under alternating pressure and relief, which causes production of steam and disruption of the cells. The system consists of 2 parallel screws which squeezes and crushes the biomass. No additives are used in the process. As a result of the pre-treatment in the extruder cellulose and hemicelluloses become available for the methanogenic bacteria, which allow the use and better exploitation of solid manure, straw, grass and other biomasses containing lignocelluloses. Extrusion leads to higher decomposition rates during the anaerobic digestion in the digester. This decomposition of biomass allows a higher loading rate and shorter retention time in the digester. This means that the biogas yield per unit digester volume is increased. A test carried out by Aarhus University has shown an increase in biogas production with up to 70 % after 28 days and up to 28 % after 90 days of anaerobic digestion. The electricity consumption varies according to the biomass treated in the extruder. Grass, solid manure and other different substrates with a dry matter content of 20-35 % consumes from 2,5 to 24,5 kWh per ton of biomass. Straw with approximately 85% dry matter content consumes 75-95 kWh/ton. As part of the test carried out by Aarhus University the electricity consumption of the extruder was measured. For all substrates tested the electricity consumption was lower than the increase in energy production resulting from the higher biogas yield.			
Development stage technology maturity	+ Limited experience from full scale installations.	Investment and operational costs related to the technology	The investment cost for a single unit varies from 150.000-250.000 EUR, installation, piping, etc. not included.	
Assessment of technology	Advantages		Disadvantages	
	Retention time can be reduced due to the disruption process. Increased biogas yield Treatment of lignocellulose		Relatively high investment cost. Operational costs are not known.	
Potential benefits / relevance	Small scale plants	Medium scale plants		Large scale plants
	*	**		***
Examples of technology suppliers	Lehmann Maschinenbau GmbH (www.lehmann-maschinenbau.de)			
Examples of biogas plants where the technology is installed	Bioenergi Pöhl, Germany Agrofarm 2000 GmbH, Eichigt/Vogtland region, Germany Biogas plant Möschwitz municipality of Pöhl/Vogtland region, germany			
References	Hjorth, 2010. Test up to 28 % increase in biogas yield According to an operator of Möschwitz biogas (H. Hertel) no floating layers are seen and a surplus in biogas of 19 % for the applied substrates due to bioextrusion. According to the director of Agrofarm 2000 (K. Rank) an extra yield of approx. 20-27 % in biogas can be achieved. In addition, the digester can run at a high dry matter content (approx. 14 % TS) with a minimal own energy consumption of 2.4 % and still a minimal maintenance work.			

<table>
<tr><td>Name of technology</td><td colspan="3">Selective hydrolysis</td><td>Ref. no.</td><td>E-5</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">The aim of the thermal hydrolysis is to introduce a “degrading” step between 2 digesters. The hydrolysis breaks down the less degradable components to smaller compounds, which are more available towards bacteria to produce biogas as the final component.
The processing is as follows: Untreated biomass from primary storage tank is added digester step 1, running at about 40°C. Digested biomass from step 1 is added the selective hydrolysis plant and heated to about 75°C. During this process the organic matter is hydrolysed by a biological-chemical process. No additives are used in the process. The hydrolysed biomass is added to digester step 2, running at about 50°C. The digested biomass from digester step 2 is then led to the final holding tank.
It is claimed that during this processing near to 80% of added organic matter is converted to biogas; thus the system is extremely efficient.
Due to effective heat exchanging the energy consumption for the process is small compared to the increase in degradation and biogas yield. During a full scale test at Overgaard (Denmark) the increase in biogas yield were measured up to 100 % with an average increase of 35 % depending on the composition and type of biomass. However, other test of selective hydrolysis has shown no or little effect on the biogas yield. Still, the concept is promising but more tests have to be run to confirm the effectiveness of the system.
The hydrolysis technology and process is available on the market but still not widespread. It is installed in full scale only at Overgaard where the test was performed.</td></tr>
<tr><td>Development stage technology maturity</td><td>+
Limited experience from full scale installations.</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Increased biogas yield of lignocellulose
Reduced retention time in fermentor</td><td colspan="3">No official and approved documentation</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td colspan="2">Small scale plants</td><td>Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td colspan="2">*</td><td>*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">Westcome Renewable (Denmark): www.westcome.com</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">www.overgaardgods.dk</td></tr>
<tr><td>References</td><td colspan="5">Østergaard, 2010.</td></tr>
</table>

Name of technology	**Thermal-chemical hydrolysis**		Ref. no.	E-6
Brief description of functionality / operating principle	A thermal-chemical process can be used for pre-treatment of biomass to increase biogas production. This is the result of a combined effect of temperature and alkaline hydrolysis at pH around 10 by adding lime (CaO) to the biomass. Lime is added to increase pH and to speed up the hydrolysis process.As a result of the hydrolysis the organic compounds are degraded into smaller and more easily digestible compounds. Due to the addition of heat and lime free ammonia is liberated and organic nitrogen in the proteins is partly converted to ammonia in the water phase. The later formed ammonia is removed through a pressure valve and collected in an acidic absorber and used as fertilizer. This removal of nitrogen/ammonia makes it possible use nitrogen rich biomass for biogas production without inhibiting the process in the digester. The system consists of a pressure cooker which can treat biomass at pressures up to 6 bar (160 ˚C). The process pressure and temperature is reached by adding steam directly into the cooker and by heating the outside of pressure cooker using indirect steam. The cooker rotates during the process to ensure mixing of biomass water and lime. Electricity is used for rotating of the cooker and steam is applied directly into the cooker and indirectly by applying steam to the outside of the cooking chamber. In order to reduce the energy consumption heat exchanging is applied where possible, but no documentation of the total steam consumption is available yet. Tests have shown increases in methane yield up to 100 %. The increase depends of type and composition of biomass. The thermal-chemical pre-treatment technology is available on the market but still not widespread.			
Development stage technology maturity	+ Limited experience from full scale installations.	Investment and operational costs related to the technology	Data not available.	
Assessment of technology	Advantages		Disadvantages	
	Increase in biogas yield from lignocellulose. Reduced HRT Removal of ammonia from biomass		High investment Running cost	
Potential benefits / relevance	Small scale plants	Medium scale plants	Large scale plants	
	*	**	**	
Examples of technology suppliers	Xergi A/S (Denmark): www.xergi.com			
Examples of biogas plants where the technology is installed	It is installed in full scale at the GFE biogas plant in Langaa (Denmark).			
References	Danish Technological Institute, ETV-test GFE Pressure cooker, 2010. More tests needed.			

<table>
<tr><td>Name of technology</td><td colspan="3">Ultra sound treatment</td><td>Ref. no.</td><td>E-7</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Ultra sound treatment of waste water sludge is a well known technology which makes cells disrupt and thereby increases the biogas yield. In addition the amount of sludge is reduced and the dewatering properties are improved.
Up to now ultra sound has not been used commercially for pre-treatment of biomasses on agricultural biogas plants and therefore the experience is limited. As the major part of the biomass for agricultural biogas production contains relatively large shares of lignocelluloses it is not likely that ultra sound pre-treatment will be widespread on these biogas plants in the future.</td></tr>
<tr><td>Development stage technology maturity</td><td>0
More research needed.</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Data not available.</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>*</td><td colspan="2">*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">Data not available.</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">No data available.</td></tr>
<tr><td>References</td><td colspan="5">Data not available.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="2">Addition of enzymes before biogas reactor</td><td>Ref. no.</td><td>E-8</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="4">Enzymatic pre-treatment of biomass can be used to break down components to smaller compounds, which are easier and faster degraded by the microorganisms.
Depending of the type and moisture content of the biomass water is added in order to optimize the conditions for the enzymes added. Furthermore, heat is often applied to speed up the process.
Also handling of the biomass through the biogas plant is improved due to lower viscosity, which means less power consumption for agitation and pumping.</td></tr>
<tr><td>Development stage technology maturity</td><td>++
Some experience from full scale installations.</td><td>Investment and operational costs related to the technology</td><td colspan="2">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="2">Disadvantages</td></tr>
<tr><td colspan="2">Homogenization of biomass
Easier handling
Easier agitation
Reduction of HRT
Easy to implement (no expensive equipment needed)</td><td colspan="2">Enzymes are often expensive</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td>Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>*</td><td>*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="4">Novozymes A/S
www.bioreact.de
www.methanconcept.com</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="4">No data available.</td></tr>
<tr><td>References</td><td colspan="4">According to a sales representative from the company DSM Biogas an extra biogas yield of up to 20 % can be achieved and at the same time 50 % reduction in relative viscosity and reduced HRT.
According to a sales representative from the company Bioreact reduced viscosity and reduced HRT can be achieved.</td></tr>
</table>

<table>
<tr><td>Name of technology</td><td colspan="3">Thermal-pressure hydrolysis</td><td>Ref. no.</td><td>E-9</td></tr>
<tr><td>Brief description of functionality / operating principle</td><td colspan="5">Thermal pressure hydrolysis is used as a pre-treatment step in production of second generation bio-ethanol (for hydrolysis of lignocelluloses) and for treatment of waste water sludge. The biomass/sludge is put under pressure and heated with steam in order to hydrolyse the biomass into smaller components. In some cases pure oxygen is applied to speed up the reaction and increase the outcome of the process. Cells (especially bacteria cells in sludge) are disrupted, leaving the cells mass easily available for anaerobic digestion.

With regard to sludge the treatment results in higher biogas yields, improved dewatering properties and reduced amounts of waste (sludge). Also sanitation/sterilization is an important effect of the thermal pressure hydrolysis treatment of the sludge. As for second generation bio-ethanol the treatment is only one of more steps to degrade lignocelluloses into sugars (C5 - C6 sugars).

It is likely that thermal pressure treatment of different biomass will result in increasing biogas yields, but is has to be taken into account that the investment in equipment and the running cost for the process are quite high.

In most cases thermal pressure treatment of biomass for anaerobic digestion is too expensive and therefore not a widespread technology within biogas production.</td></tr>
<tr><td>Development stage technology maturity</td><td>++
Some experience from full scale installations at sludge plants.</td><td>Investment and operational costs related to the technology</td><td colspan="3">Data not available.</td></tr>
<tr><td rowspan="2">Assessment of technology</td><td colspan="2">Advantages</td><td colspan="3">Disadvantages</td></tr>
<tr><td colspan="2">Increse in biogas yield from lignocellulose.
Reduced HRT
Removal of ammonia from biomass
Increased dewatering properties</td><td colspan="3">Investment cost</td></tr>
<tr><td rowspan="2">Potential benefits / relevance</td><td>Small scale plants</td><td colspan="2">Medium scale plants</td><td colspan="2">Large scale plants</td></tr>
<tr><td>-</td><td colspan="2">*</td><td colspan="2">*</td></tr>
<tr><td>Examples of technology suppliers</td><td colspan="5">www.cambi.no
www.biogasol.dk
www.dongenergy.dk</td></tr>
<tr><td>Examples of biogas plants where the technology is installed</td><td colspan="5">No data.</td></tr>
<tr><td>References</td><td colspan="5">Data not available.</td></tr>
</table>

Name of technology	**Ozone treatment**		Ref. no.	E-10
Brief description of functionality / operating principle	Ozone is an extremely reactive oxidation chemical and will react with almost any organic matter. This makes the use of ozone difficult. However, ozone is used for treatment of wastewater. Treatment of biomass for anaerobic digestion with ozone is not taking place on commercial basis and it is believed that this technology will be used only in rare cases.			
Development stage technology maturity	0 More research needed.	Investment and operational costs related to the technology	Data not available.	
Assessment of technology	Advantages		Disadvantages	
	Data not available.		Data not available.	
Potential benefits / relevance	Small scale plants	Medium scale plants	Large scale plants	
	*	*	*	
Examples of technology suppliers	Data not available.			
Examples of biogas plants where the technology is installed	No data.			
References	Data not available.			

Name of technology	**Chemical treatment**			Ref. no.	E-11
Brief description of functionality / operating principle	Chemical pre-treatment of biomass normally involves addition of acidic or basic chemicals and often also heat. A Swedish investigation showed a high increase in biogas yield of chemical treated chicken feathers, straw and spruce wood chips. Chemical pre-treatment is not a well known and widespread technology and primarily used at uneasily degradable biomass such as feathers and other keratin containing biomass.				
Development stage technology maturity	0 More research needed.	Investment and operational costs related to the technology	Data not available.		
Assessment of technology	Advantages		Disadvantages		
	Easier handling Increased biogas production		Data not available.		
Potential benefits / relevance	Small scale plants	Medium scale plants		Large scale plants	
	-	*		*	
Examples of technology suppliers	Data not available.				
Examples of biogas plants where the technology is installed	Data not available.				
References	Waste refinery: www.wasterefinery.se/sv/publications/reports/Sidor/default.aspx				

Name of technology	**Microwave treatment**			Ref. no.	E-12
Brief description of functionality / operating principle	Pre-treatment of biomass with microwave is not a known technology. A few companies have used microwaves and a catalyst to break down organic matter (straw) to liquid substance. The liquid is used as fuel for heating and/or transportation purposes. Microwave as pre-treatment in relation to anaerobic digestion is not investigated so far.				
Development stage technology maturity	0 More research needed.	Investment and operational costs related to the technology	Data not available.		
Assessment of technology	Advantages		Disadvantages		
	Data not available.		Data not available.		
Potential benefits / relevance	Small scale plants	Medium scale plants		Large scale plants	
	-	-		*	
Examples of technology suppliers	Data not available.				
Examples of biogas plants where the technology is installed	Data not available.				
References	Data not available.				

E.2 Biomass feed-in technologies

Whereas liquid biomasses are simply pumped into the digester and mixed it is more challenging to feed in solid biomasses like solid manure, solid fraction from pre-separation of slurry, energy crops and agricultural residues. Four different methods have been identified:

The solid biomass is delivered in a mixing tank where it is mixed with a portion of digestate taken from a side-stream of the digester. After that it is possible to pump the biomass and it is then fed into the digester in batches. Sometimes a macerator pump is used to homogenize the liquid. This is a rather simple feed-in system. One disadvantage is that it is not a closed system and therefore some biogas is lost due to the warm digestate used for mixing the solid biomass. This system is shown in Figure E-1.

Figure E-1. Solid biomass delivered in a 500 m^3 mixing tank.

The solid biomass is delivered in a container placed next to the digester. From this container the biomass is fed directly into the digester without adding liquid to it. This can be done using a conveyer belt or a screw transport system. Sometimes the biomass is mixed inside the container to homogenize the biomass before it is fed into the digester. To maintain anaerobic conditions in the digester the biomass has to be delivered below the surface of the biomass inside the digester. This system is shown in Figure E-2.

Figure E-2. Feed-in system where the solid biomass is not mixed with a liquid before feeding in.

The solid biomass can be delivered in a small mixing tank and mixed with raw slurry or other liquids than digestate. Here the solid fractions are used for making batches (approximately 10 m^3 per batch) which are pumped into the digester sometimes through a macerator pump.

The solid biomass is delivered in a container with a mixing system installed. The biomass is mixed into a side-stream of digestate on a continuously basis. In this system no mixing tank is included. The stream is fed into the digester under the surface of the digestate. This is a closed system and therefore no biogas is lost even though it is taken out of the digester and used for mixing the solid biomass.

E.3 Mesophilic versus thermophilic operation temperature

In general two main operation temperature strategies are implemented among biogas plants. Normally mesophilic plants are operated at approx. 35 C^o. An anaerobic digestion process running at temperatures below 20 C^o is named psycrophilic, but is not used commercially for biogas production. AD processes running at temperatures above 52 C^o are defined as thermophilic, but normally commercial anaerobic digestion processes reach their maximum at 55 C^o.

Earlier, at least in a Danish context, the thermophilic process was considered less robust than the mesophilic one. However, from 1990 the thermophilic process became predominant among Danish centralized plants. Farm biogas plants were still designed for a mesophilic process. Main advantages and disadvantages are listed below:

- One significant argument for implementation of the thermophilic process is that the digestion of the organic material runs faster at higher temperatures. Normally, Danish plants running at thermophilic temperatures have 12 – 15 days retention time and mesophilic plants approximately 25 days. However, in Germany, where corn silage is the main substrate often 60-80 days retention times are found at mesophilic installations. For the same amount of substrate thermophilic plants need less digester volumes than do mesophilic plant, a reduction of digester volume of 40 % compared to mesophilic plants. That means lower investment costs, as far as the digester capacity is concerned, which is a major incentive.

- Another aspect is the design of the sanitation system. Mesophilic plants which digest types of material that needs sanitation must contain a separate sanitation facility in which the material is sanitized 1 hour at 70 C^o. For many years, however, Danish legislation allowed other combinations of temperature and retention times to be considered equal to 1 hour 70 C^o. For example 55 C^o in 6 hours as well as 52 C^o in 10 hours equaled the requirements. Thus, the sanitation step was so to speak integrated directly in the digestion process. However, these time and temperature combinations do not directly comply with the sanitation requirements according to EU regulation 1774/2002, (revised in regulation 1069/2009) even though it appears that methods similar to 1 hour 70 C^o could be approved. For the time being only one thermophilic plant obtained approval of an integrated sanitation method corresponding to the 1069/2009 requirements. This plant (Lemvig Biogas) controls a two-step thermophilic process and introduced special documentation of temperature levels, retention times and pathogen kill. However, for the time being it is not clarified if this method can be generally applied among thermophilic plants in Denmark

- Heat consumption is an issue to be considered in the decision process of the choice of a thermophilic or mesophilic process temperature. The decision should depend on the need for sanitation and the potential heat loss due to the difference in retention time. But also, what is the value of heat in each case, which is also decisive for the need of heat optimization. Thus the net heat consumption depends of the design and capacity of the heat exchangers and the efforts to insulate heated tanks, so an unambiguous evaluation of which temperature strategy is most optimal is not easily given.

- At higher temperatures CO_2 is increasingly released from the substrates, which may lead to at least two reasons for process instability. Firstly, the release of CO_2 leads to an increase in PH, which makes the NH_4/NH_3 balance changes in favor of NH_3. A thermophilic process is at a higher risk for this to happen, which, dependent on the substrates digested, may lead to an inhibition or instability of the process. Secondly, the release of CO_2 lead to up-streaming gas bubbles. That may support the formation of foam, which in some cases cause operation disturbances that need immediate attention.

- A range of technical concepts for substrate heating is found. Heating takes either place internally in the digesters or externally by the application of heat exchangers. Where heat exchangers are applied, heat from the digested substrate is widely recovered. Thermophilic plants often apply at least two steps, where hot water is used in the last step to reach the desired process temperature. The operation strategy is designed to allow heating and in-pumping of substrate in just one work flow, as digested substrate is simultaneously pumped out and heat from it recovered.

At mesophilic plants substrates are more often internally heated by heating pipes, especially at smaller on-farm installations. However, larger facilities, where a sanitation step is needed, a separate sanitation tank is often found, which may include heating pipes. Otherwise substrates are heated in heat exchangers in which out-going hot substrates and/or hot water is applied. More heat is needed than in case of the thermophilic plant, as the temperature in the sanitation tank must reach 70 C^o.

- The most important parameter to take into account when considering which operation temperature to apply is which substrates are intended to be used. This is mainly due to the above mentioned NH_3 inhibition, which may be a problem if the C/N ratio is too low. According to literature the C/N ratio should optimally be approximately 15-25 (some some claim 10-30). In general the pig manure holds a relatively low C/N ratio (4-8) whereas it is higher in cattle manure (5-10) depending on production system and feeding intensity. The overall C/N ratio may be adjusted by supplying carbon-rich substrates like certain organic wastes (fat and sugar) or energy crops like corn silage or straw. But if the substrate composition on hand is dominated by pig manure, potential inhibition problems may be avoided by applying a mesophilic process temperature. If cattle manure is dominant, a thermophilic temperature is more likely to be successfully applied. Other substrates like wastes with high protein contents (potentially high nitrogen levels) may likewise indicate that a mesophilic process may be the optimal solution.

- A thermophilic system may be preferred if sufficient carbon rich substrates are available, especially if time/temperature combinations corresponding to 70 C° can be applied, and not too long retention times are needed.

If only substrates with relatively low C/N ratios are available and 70 C° in 1 hour is required, a mesophilic system may be most optimal.

When it comes to investment costs, they are normally lower for the thermophilic system (all things being equal) because lower digester capacity is needed, and no separate tanks for sanitation are needed.

E.4 One-stage AD configuration versus two-stage AD configuration

The term "serial anaerobic digestion" is used to describe a configuration where the digestion process for different reasons is separated into two digestion steps in a serial connection. Serial anaerobic digestion can be divided into at least three main groups depending on the process parameters, e.g. temperature, hydraulic retention time and volume distribution:

E.4.1 Two-stage anaerobic digestion including a short initial hydrolysis and acidification step.

In this configuration the hydrolysis and acidinogenic phase is separated from the methanogenic phase. Different classes of microorganisms are involved in these processes. By physical separation of the processes it is possible to create optimum process conditions for microorganisms involved in the hydrolysis and acidinogenic phase as well for microorganisms involved in the methanogenic phase. Hydraulic retention time of the initial hydrolysis is very short, 2-4 days. The configuration is widespread in anaerobic treatment of waste water but not applied in the agricultural sector (Avfall Sverige – utveckling, 2010).

E.4.2 Two-stage anaerobic digestion including a very long post-digestion without heat.

The primary digestion takes place in a reactor with a hydraulic retention time of typically 2-4 weeks. Post-digestion is carried out without any heat input and often for several months. This post-digestion often takes place in a traditional slurry storage tank covered with a membrane to facilitate collection of biogas. The methane yield of the post-digestion is approximately 10 % of the total methane yield, depending on the substrate used.

E.4.3 Two stage anaerobic digestion including two methanogenic phases.

Danish biogas plants are typically operated with a hydraulic retention time of 2-4 weeks. During the process only part of the organic solids are degraded and converted to methane and CO_2. One of the reasons for this incomplete conversion is due to loss of organic solids with reactor effluent. The phenomenon is also known as “short circuiting” and describes the situation where a particle passes through the reactor with a shorter retention time than the hydraulic retention time (figure E-3). The risk of “short circuiting” is reduced when operating in a serial configuration with to methanogenic phases. The theoretical methane potential is 5-10 % higher for serial digestion compared to one step digestion (Møller & Ellegaard, 2008).

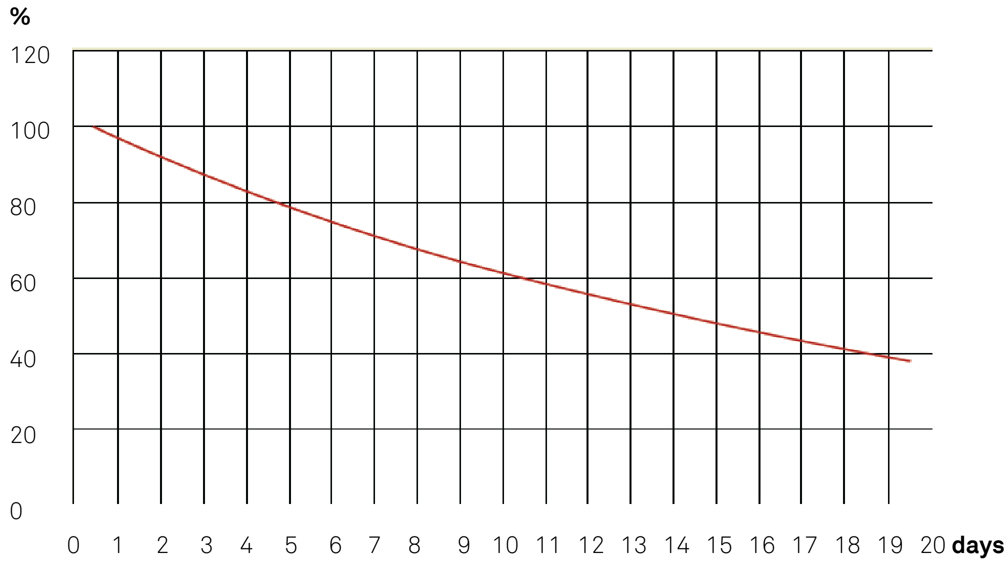


Figure E-3. Amount of input material retained in the reactor as a function of time. In this case the hydraulic retention time is 20 days, which means that 1/20 of the material is substituted every day. The organic material fed into the reactor at day 0 is gradually decomposed so that after 20 days approx. 40% of the material is left. 60% of the material is decomposed during the biogas process (Jørgensen, 2009).

E.4.4 Laboratory and pilot scale experiments

During the last years a department of the Danish Technical University (DTU-Risoe) has made several laboratory and pilot scale experiments with different serial CSTR digester configurations (Kaparaju, 2009).

Volume distributions of 90/10, 80/20, 70/30, 50/50, 30/70, 13/87 at total HRT at 15 days were tested in lab scale experiments and results were compared to results of one step CSTR (Boe, 2006 and Kaparaju, 2009). Both systems were fed with cow manure and operated at thermophilic temperature. Increased biogas production was obtained in the range between 11-17.8% for serial configurations with volume distributions of 90/10, 80/20, 70/30, 50/50, 30/70 compared to one step configuration. Only for the volume distribution of 13/87 a decreased in biogas production of was obtained compared to one step digestion (-1.7 %).

Serial configurations with a small first step (13/87 and 30/70) were poorer than combinations with a larger first step, regarding process parameters as VFA, methane yield and microbial composition. And it is concluded that volume allocated to the first reactor in a serial digestion must be sufficient large to maintain a stable process with low VFA level, as a healthy main reactor is a precondition of a successful serial digestion.

Similar to the lab scale experiments also a thermophilic pilot scale study was performed with cow manure, a HRT of 20 days and a volume distribution of 77/23%. During periods with serial configuration higher biogas yield of 1.9-6.1 % were obtained compared to one step digestion.

Based on the pilot and lab scale studies it is estimated that in full scale with it is possible to obtain an increased biogas production 7-10 % with a serial configuration compared to a one step digestion.

E.4.5 Full scale experiments at Lemvig Biogas Plant

The use of two stage anaerobic digestion has been demonstrated the last 2 years at Lemvig Biogas Plant in Denmark. Volume distributions of 70/30, 82/18 and 85/15 were tested with a total HRT of 26 days.

Operating in a one-step configuration 86.5 % of the ultimate methane potential of the influent was obtained during the anaerobic digestion. When the biogas plant was operating in a serial configuration between 90.5 and 94.9 % of the ultimate methane potential of the influent was obtained. Mean value was 91.9 %, which corresponds to an increase in the production of 6.2 %.

But it is difficult to isolate the serial effect because this value is disturbed by other parameters, for example the ammonium concentration increased during the test period which probably caused that the efficiency of the primary step did not increased although the HRT of this step is 19.5-21 days when operating in a serial configuration and only 13 days when operating in one step.

Nevertheless, it is estimated that the serial configuration is responsible of an increased biogas production of 5 %. In the future operation of the biogas plant the volume distribution of 85/15 is implemented although it was not possible in the test period to identify which of the tested volume distributions increased the total biogas production most. Theoretically, the difference in efficiency among the different volume distributions tested (70/30, 82/18 or 85/15) is very small. The 85/15 has a large primary step and ensures a robust system??

Previously, it was necessary to treat category 3 waste one hour at a temperature of 70°C. As a result of the serial configuration with applied HRT and temperature of 26 and 53°C, respectively, the process is now approved as an alternative sanitation treatment of category 3 wastes. However, it is unclear whether this will be accepted in the future (Gregersen, 2011).

Another side effect is that the biogas plant after operating in serial configuration is more tolerant to ammonium. As a result the plant is now able to accept more type of substrates than when operating in one step configuration.

The possibility of operating in a serial configuration will be considered when the existing Danish biogas plants are renovated and when new plants are designed and built (Kristensen, 2011).

E.4.6 Characteristics of the two-stage AD process:

Volume distribution

A long primary step (minimum 50/50 volume distribution) is needed to insure a stable process and production. But the exact volume distribution is less important.

Process temperature

The post digester must be operated at a temperature very close to the temperature in the primary digester to maintain optimum activity. In the pilot scale study of DTU/RISOE biogas production decreased dramatically when the temperature of the post digester was only 1°C lower than the temperature of the primary digester.

Substrate

Serial digestion reduces the risk of "short circuiting". The advantage of this reduced risk is bigger for systems which use low degradable substrates, e.g. slurry and energy crops, compared to systems using highly degradable substrates.

E.5 Process monitoring and controlling technologies

Efficient process monitoring and controlling is useful to optimise the production of biogas. The basic process parameters to monitor are temperature, pH, alkalinity, gas production and biogas quality. These parameters are central for a reliable process control in a relatively stable process environment. If the biogas plant must be able to process very special and different substrates, more control parameters may be necessary.

Small biogas plants may not justify a large investment in monitoring equipment and control system, however if process failure is an economical issue you must invest in some basic instrumentation and use manual control methods and planning to assure a stable biogas production. Large biogas plants with highly variable substrates should invest in more sensor and control systems.

E.5.1 Temperature

Temperature monitoring and control can be done online with simple and well tested thermistors. As a standard industrial technology you have many suppliers and models to choose from.

Biogas reactors are normally run at about 35°C (mesophilic process) or about 52- 55°C (thermophilic process). The bacterial communities are highly adapted to the ambient temperature and it is important to keep it stable. Even a few degrees fluctuation in temperature may show up as reduction in biogas production.

E.5.2 pH

pH is a measure of the hydrogen ion activity in solution. It is a standard process parameter in many industries and a large amount of suppliers and well tested and proven online equipment is available on the market. The most common method is by electrochemical pH sensors.

Methane production is only possible within a very narrow pH range (pH 6,8 - 7,2). The growth of methane bacteria is highly reduced under pH 6,6 and if pH get alkaline it may lead to disintegration of the bacterial granules and process failure. Biogas plant operators have a very delicate balance between the optimal pH for fermentation 5,5 - 6,5 and optimum for methane production which is about pH 7. pH is a central chemical parameter controlling the amount of ammonia and hydrogen sulphide in solution. Both compounds are toxic to methane bacteria, and deviations from neutral pH in both directions will increase either of them.

Many other chemical systems are influenced by pH and they will not be described here. However, it is enough to stress that pH is a very important process parameter.

E.5.3 Alkalinity

Alkalinity (buffer capacity) is a measure of the ability of a solution to neutralize acids to the equivalence point of carbonate or bicarbonate. The alkalinity is equal to the stoichiometric sum of the bases in solution. Alkalinity is measured by adding a controlled amount of acid to a sample and then the change in pH with a pH sensor is followed. You can do this with automated equipment which can handle the mechanical aspects of the analysis, and which calculates the alkalinity value and feed it to a control system. It is not a simple piece of equipment but it is fairly well tested in industrial environments and several solutions are available from different suppliers. This equipment is not used for online process control in any biogas plant. Instead manual titration or chemical kits are used.

For an advanced equipment example see this link:

- http://www.metrohm-applikon.com/Online/Products/ADI2040.html

Buffer capacity is the ability of a solution to resist a change in pH when acids or bases are added to the solution. The chemical mechanism is the existence of compounds which can absorb or release hydrogen ions. When most of the buffer capacity comes from bicarbonate we call it alkalinity. If you ad acid to a solution containing bicarbonate it will absorb the H^+ and release CO_2 and pH will not change very much. However when all the bicarbonate is exhausted the pH will suddenly plunge if more acid is added and the biogas production will fail.

If the fermentation step and the methane production are not balanced volatile fatty acids (VFA) will accumulate and start using up the bicarbonate. pH will not change until the pool of bicarbonate is gone, then very fast the reactor will fail. In order to get an early warning you need to monitor VFA or alkalinity on a continuous or semi-continuous basis so you can detect a beginning unbalance. Monitoring of alkalinity may be used to optimize biogas production in a reactor and to stop a process failing before it is too late.

E.5.4 Biogas components

Gas phase components can be analyzed online through a combination of electrochemical and infrared sensors. Hydrogen and hydrogen sulfide are analyzed electrochemically and methane and carbon dioxide with infrared sensors. Other systems based on photo acoustics or gas chromatography are also available.

- http://www.gassensor.com.cn/English/Product/118656347.html
- http://lumasenseinc.com/EN/products/gas-monitoring-instruments/gas-monitoring/innova-1412.html
- http://english.chemec.de/Biogas-Controller-BC20-Node_14008.html

The composition of the biogas, especially the relative proportions of CO_2 and CH_4, gives the plant operator valuable information about how well the reactor works. The primary hydrolysis and fermentation processes produce hydrogen and fatty acids. If the methane process in any way is inhibited or the system is overloaded, the relative amount of CO_2 will increase. Monitoring of gas phase components will make it possible to detect a beginning failure of the reactor. The content of hydrogen sulfide is important to control as gas motors used for electricity production does not tolerate to high concentrations.

E.5.5 Amount of biogas produced

Biogas production is normally measured by different kinds of flowmeters. It is not necessarily an easy parameter to measure in a reliable way, but it is a very common industrial parameter, and a lot of different technical solutions are available for online control. To know how much biogas is produced is necessary for many reasons. Economics and process control are the most obvious. It is a fairly simple way of telling if the biogas process is working or not. But in order to pinpoint process problems and improve the production systematically you will need more information.

E.5.6 Parameters relevant to larger plants

Volatile fatty acids (VFA)

VFA are generally analyzed off line with a GC (gas chromatograph) or by titratration. The analytical methods are somewhat laborious and the equipment expensive and difficult to maintain. A newer technology which has been tested in different experiments is Infrared spectroscopy. MIR (midrange infrared) and NIR (near infrared) have been tested. The instruments are expensive and need intensive calibration but according to the experimental reports and scientific papers they show good correlation with standard analyses and are able to analyze several parameters online without sample preparation. However at present this technology must be considered experimental.

VFA are primary acetate, propionate and butyrate. They are the end products from the fermentation of glucose. Acetate is usually present in the highest concentration and is converted to methane by the methane bacteria. If there is a higher production of fatty acids than the methane bacteria can convert acid begins to accumulate. At some stage they will have used up the alkalinity in the solution, pH will drop and the process will fail as methane production will be totally or severely inhibited. If you can monitor VFA on line it would be possible to detect process deviations on an early stage and control the bioreactor more precisely.

However there is no simple sensor or sensor system available which can detect VFA online. GCs are very complex systems to operate in an industrial environment and they are not very suited to standard control in a biogas plant. Online systems are known from the petrochemical and pharmaceutical industries, but that must be considered special cases. It ought to be possible to build an automated system for the analysis of VFA, but it has not been possible to find any documented industrial system for this purpose.

Total-N, ammonia, and ammonium-N

Digestion of nitrogenous compounds such as proteins release ammonium and ammonia. Which species is dominant depends on pH. Ammonium (NH_4^+) is only in the liquid phase, whereas ammonia may be found in water and in the gas phase.

Electronic sensors and automated analytical systems have been developed to detect all species. Ammonia and ammonium can be measured with electrochemical sensors or Infrared based detectors, whereas the systems for monitoring of total-N are based on automated sample preparation and analysis and the result is transferred online. It is not a real time measurement but a fast sampling and analysis procedure. The technology seems to be widely used and commercial sensors for online control are available.

Some examples of equipment for measurement of total-N can be seen on these web sites:

- http://www.systea.it,
- http://larllc.com/quickton.html

An example of equipment for measurement of ammonium can be seen on this web site:

- http://www.coleparmer.com/1/1/70924-ise-electrode-ammonia-controller-56105-00-yo-27077-00.html

Examples of equipment for measurement of ammonia can be seen on these web sites:

- http://www.manningsystems.com/products/ir-nh3.asp
- http://www.directindustry.com/industrial-manufacturer/ammonia-detector-75117.html

Nitrogenous compounds are not directly a part of the methane production, but by monitoring total N and soluble ammonia you may be able to follow the digestion of substrate with high nitrogen content and prevent a buildup of ammonia which will inhibit methane production in high concentrations.

Sulphides

Sulphides can be detected in water or air by electrochemical, and semiconductor based sensors which easily are connected to online systems. The technology is mature and well tested. Sulphide, hydrogen sulphide and dihydrogen sulphide is an equilibrium system controlled by pH. Low pH means most of the sulphide is in the form of H_2S, High pH that sulfide is in dissociated form as S^{--}

H_2S is a relevant control parameter because it is toxic to the methane bacteria and will inhibit the methane production. Feeding the reactor high amounts of sulphurous compounds like proteins or water with sulphate may lead to a buildup of inhibiting conditions. Monitoring sulphide makes it possible to follow this buildup and to prevent it. Examples of monitoring equipment can be found on these web sites:

- http://www.pem-tech.com/gas-sensors/hydrogen-sulfide.html
- http://sensing.honeywell.com/index.cfm/ci_id/154366/la_id/1.htm

Total organic carbon

Total organic carbon (TOC) analyzers measure the amount of total organic carbon present in a liquid sample. Generally, all TOC analyzers employ the same basic technique. A liquid sample is initially introduced to an inorganic carbon (IC) removal stage, where acid is added to the sample. At this point, the IC is converted into carbon dioxide (CO^2) gas that is stripped out of the liquid by a sparge carrier gas. The remaining inorganic carbon-free sample is then oxidized and the carbon dioxide generated from the oxidation process is directly related to the TOC in the sample.

The analysis methods total organic carbon (TOC) analyzers use to oxidize and detect the organic carbon may be combustion, UV persulfate oxidation, ozone promoted, or UV fluorescence. With the combustion method, analysis is determined when carbon compounds are combusted in an oxygen-rich environment, resulting in the complete conversion of carbon-to-carbon dioxide. In UV persulfate oxidation, the carbon dioxide is purged from the sample and then detected by a detector calibrated to directly display the mass of carbon dioxide measured. This mass is proportional to the mass of analyte in the sample. Persulfate reacts with organic carbon in the sample at 100 degrees Celsius to form carbon dioxide that is purged from the sample and detected. The ozone-promoted method for total organic carbon (TOC) analyzers oxidizes the carbon by exposing it to ozone. UV fluorescence is a direct measurement of aromatic hydrocarbons in water. Fluorescence occurs when a molecule absorbs excitation energy of one wavelength to be measured as concentration of the hydrocarbon. This may also be referred to as spectrophotometry or colorimetry.

Fairly mature online systems are available for use in waste water but some mechanical modification is needed if this technology shall be used in biogas plants. For an example see the following web site:

- http://www.ssi.shimadzu.com/products/product.cfm?product=tocv

Depending on where in the system you put the sensors and how the biogas reactors are constructed, TOC can give online information about the quality of the substrate, the loading of the reactor and how much solids are in the system at a given time. This may be especially important if you are feeding your plant solid substrate as an overload of solids may lead to mechanical problems with stirring and failure of the process. You can also get information about how much substrate is transformed into biogas and CO^2 and at which rate. As such this analysis may supplement analysis of gas quality and produced amount.

A low tech approach is manual analysis of dry solids and volatile solids. It is simple and cheap. However this is not an online measurement but has to be done at short intervals (several times a day) if the same degree of information is wanted.

How to use control parameters in small and large scale biogas production

Biogas plants are complicated systems and to get the largest possible amount of information from sensor systems it is necessary to understand how the chemical and biological processes are interconnected. A failing reactor will show up in many control parameters and so will a perfect operating reactor. Sensor systems can be used to optimize a process and to plan a loading pattern if you are changing between substrates. It is for example important to have the right Carbon/Nitrogen relation if you want to be able to all the available substrate. TOC, Total-N, ammonium and pH sensors can tell you how to mix different substrates to get the maximum biogas production.

Annex F: Technologies for storing and spreading digestate

The aim of fertilizing the crop with manure, digestate or mineral fertilizers is to increase yield and to achieve desired properties of the harvest product making it suitable as a nutrient source for human or animal consumption. In order to achieve the most from the fertilizers e.g. high nutrient efficiency, two main things are crucial; spreading time and spreading technology (Brundin & Rodhe, 1994).

Different properties of the digestate dictate which time and techniques is the most appropriate concerning utilization of nutrients. Examples of important properties are liquid or solid, form of nitrogen, ratio of nitrogen to phosphorus to potassium (N:P:K). Furthermore, it is assumed that the manure/digestate has been handled in a way minimizing losses of nutrient losses through ammonia volatilization or leakage to water. To avoid leaching, storage must be tight.

F.1 Reducing N leaching from spreading of digestate and manure

Several research studies have been carried out to quantify the magnitude of leaching following different management practices at field level, and to develop countermeasures against leaching (for example, Bergström, 1987; Macdonald *et al.*, 1989; Djuurhus, 1992; Thomsen *et al.*, 1993). The research results have been applied in recommendations through development of training and extension services and formulation of good fertilization practices.

An efficient way of reducing plant nutrient losses from arable land during the autumn and winter is to keep the land under vegetative cover (green land) during this period, particularly in areas with light soils and gentle climate (Aronsson, 2000). In Sweden, the rules state that in the very Southern parts, 60% of arable land shall be under vegetative cover during the autumn and winter. In the rest of southern Sweden, the requirement is 50%. There are also rules when certain crops must be sown and ploughed up in order for the area to be considered as being under vegetative cover during autumn and winter (SJV, 2006).

Excessive N fertilizer applications of mineral N or animal manure undoubtedly increase leaching and an N application adapted to the needs of the crop is a key factor to limit the N leaching (for example, Bergström and Brink, 1986; Vinten et al., 1991).

The timing is also important where autumn-applied manure on uncropped fields was found to be one of the most important sources of large nitrogen leaching loads (Djuurhus, 1992; Torstensson et al., 1992).

When animal manure is applied, it can be more difficult to estimate the most suitable additional amount of mineral N. There is also a considerable uncertainty about how much of the ammonium-N in applied manure becomes available to the crop, when volatile losses and possible N immobilization after spreading are taken into account (Van Faassen and Van Dijk, 1987; Jackson and Smith, 1997).

Spring application before sowing is recommended for manure, where ammonia-N is the major part of N, as it, on average, leads to a significant yield increase (Torstensson, 1998). When manure is applied in the autumn, it should preferably be spread in early autumn and on fields with an actively growing crop with high N consumption, such as leys or grass catch crops (Lindén et al., 1993).

F.2 Reducing P losses from spreading of digestate and manure

A great number of studies have been conducted on the relationship between soil P status and P losses into water. When the soil P values increase beyond agronomical optimum ranges, there is a reasonable consistent pattern whereby P losses increase significantly (Sims *et al.*, 2000). However, P losses have large spatial and temporal variations and can be influenced by several factors interacting with each other.

Phosphorus applications of mineral fertilizers or manure should be avoided at sites and during occasions when P transport (surface run-off or preferential flow) is likely to happen. It is therefore important to consider site-specific factors to be able to find measures to reduce P losses (Djodjic, 2001; Börling, 2003). The aim should always be that no more P is added than the crop can use. High rate applications of P fertilizer should be avoided as much as possible, especially in areas sensitive to leaching (Djodjic, 2001; Börling, 2003).

The development of risk assessment tools and Decision Support Systems (DSS) can be valuable for an overview, processing and understanding of P problem-related issues. Hydrologic and nutrient models working in a GIS environment may improve the understanding of temporal variations and processes of importance for P behaviour in soil (Djodjic, 2001).

When adding P fertilizer, it should be incorporated into the soil rather than surface applied. Application of tillage practices that are more efficient in P incorporation and mixing into the soil are preferable, which enhances P sorption to the soil particles. The practice of ploughing down surface applied P fertilizers should be closely examined due to the risk for ponded conditions above the plough pan in the top soil.

F.3 Reducing ammonia emission from storage of digestate

Ammonia losses can be sharply reduced if the air directly above the slurry store is prevented from circulating. A method that efficiently reduces NH_3 losses is to cover the slurry stores with, for instance, a roof, a floating plastic cover or a stable natural crust (Sommer et al., 1993; Karlsson, 1996a; Smith et al., 2007). Two types of covers are shown in Figure F-1 and Figure F-2. If the slurry storage is filled underneath the cover, this can be kept intact even during filling, which reduces the risk of NH_3 emission (Muck et al., 1984).

Lowering the pH of the slurry can be another way to reduce NH_3 emissions from storage and spreading of slurry. In Denmark a system has been developed for houses with slurry collection where the pH is lowered with the help of sulphuric acid. The acid is added automatically to the slurry in a container outside the house. Aeration prevents dangerous hydrogen sulphide being formed in the slurry. The slurry, with a pH of 5,5, is then returned to the slurry channels of the house. The system uses 4-6 kg concentrated sulphuric acid per ton of manure. With this system NH_3 emissions are reduced by 70% (Pedersen, 2004). The acid could also be added on the tanker when applying the slurry.

Figure F-1. A tent cover of storage is an effective way of minimizing ammonia emissions.

Figure F-2. A closed lagoon covered with a membrane is an effective way of minimizing ammonia emissions from storage of digestate.

Ammonia losses could be high from storages with solid manure, especially if composting take place at high temperature (Karlsson, 1994). Peat included in the bedding material will also reduce NH_3 losses during storage (Jeppsson et al., 1997; Karlsson, 1996a; Rogstrand et al., 2004) and in Finland and Sweden where the peat lands are growing more than consumed it is recommended as a bedding material. In some countries, there used to be roofs on solid manure storages, but with increasing numbers of animals and thereby big amount of manure, it is today not so common. However, it could be an effective measure to reduce NH_3 losses also from solid manure storages (Karlsson, 1996b).

Additionally, a roof keeps rainwater away, which could prevent nutrient leakage from the manure pad if it has insufficient or lacking drainage leading to a collection pit. If slurry is separated into a liquid and a solid product, be aware of the risk of high ammonia losses from the solid product.

The Swedish emission factors for storage of manure from dairy cows and pigs are: 1) 20% of total N if stored as solid manure 2) 1 to 9% of total N if stored as slurry and 3) 5 to 40% of total N if it is urine (Karlsson and Rodhe, 2002), See Table F-1. If the manure is composted, the emission factors are also high (30%).

F.4 Reducing ammonia emission from field application of digestate

Good contact between soil and manure reduces the risk of NH_3 emission (Malgeryd, 1998). Results clearly show that the most effective way to reduce NH_3 emission after spreading is to inject or incorporate the manure into the soil.

When applying slurry to a growing crop, placing the slurry in the canopy bottom in bands (band spreading) gives a lower emission than broadcasting (See figure F-3, F-4 and F-5). The reduction occurs because the crop canopy changes the microclimate near the soil surface, lower wind speed, temperature and radiation, and increased relative humidity (Thompson *et al.*, 1990).

Irrigation after spreading also reduces NH_3 emission (Malgeryd, 1996; Rodhe et al., 1996). Solid manure can give rise to substantially greater NH_3 emission than slurry when applied at the same rate under identical environmental conditions and should not generally be considered as a low-concentrated N fertilizer (Malgeryd 1996).

Figure F-3. Rapid incorporation into the soil.

Figure F-4. Injection of slurry into soil at the time of spreading.

Figure F-5. Shallow injection of slurry into ley.

In a crop, special devices are required in order to achieve an efficient incorporation. For grassland, there are shallow injectors available that incorporate the slurry into the upper soil level to a depth of less than 0,1 m. The injectors are not designed to work for all soil conditions and, especially in dry and hard soils, the injectors do not penetrate to a sufficient depth (Smith *et al.*, 2000; Rodhe and Etana, 2005) and reduction of NH_3 losses is consequently not achieved. However, in many cases, injection of slurry into the soil in grassland could be an efficient way to reduce NH_3 losses after spreading compared with surface bandspreading (Huijsmans et al., 2001; Misselbrook et al., 2002; Mattila and Joki-Tokola, 2003; Rodhe and Etana, 2005; Rodhe et al., 2006).

Emission factors for NH_3 losses from field applied manure are related to time of year when the spreading take place, type of manure (slurry, solid manure, urine) and spreading technique with or without incorporation in the Swedish inventories (Karlsson and Rodhe, 2002). An overview of the emissions factors is given in Table F-2. Losses vary between 3 to 90% of the NH_4^+-N applied with manure. The lowest default value 3% is valid for band spread slurry in the late autumn, immediately incorporated and the highest 90% are for broad cast spread manure on leys in the summer time.

Table F-1. Nitrogen losses caused by ammonia emission during storage of manure (% of Total-N).

Type of manure, handling	**Type of animal**					
	Cattle	Pigs	Layers and growers	Broilers	Horses	Sheep
Solid manure	20	20	12		25	25
Semisolid manure	10	10				
Liquid manure, uncovered						
Filled from underneath	6	8	8			
Filled from above	7	9	9			
Liquid manure, covered						
Filled from underneath:						
roof	1	1	1			
floating crust	3	4	4			
other	2	2	2			
Filled from above:						
roof	1	1	1			
floating crust	4	5	5			
other	3	3	3			
Urine, uncovered						
Filled from underneath	37	37				
Filled from above	40	40				
Urine, with cover						
Filled from underneath:						
roof	5	5				
floating crust	17	17				
other	10	10				
Filled from above:						
roof	5	5				
floating crust	20	20				
other	12	12				
Deep litter manure	30	30	20	5		33

Source: Karlsson & Rodhe, 2002.

Table F-2. Nitrogen losses caused by ammonia emission during spreading of manure (% of TAN).

Season/ Spreading method	Spreading strategy and tillage timing	Solid manure*)	Urine	Liquid manure (slurry)
Early spring/late winter				
Broadcast	Spread on frozen ground	20	40	30
Trailing hoses			30	20
Spring				
Broadcast	Immediately	15	8	10
	Tillage after 4 h	33	14	15
	Tillage after 5-24 h	50	20	20
	Spread on pasture	70	35	40
	Spread on grain		11	20
Trailing hoses	Immediately		7	5
	Tillage after 4 h		14	8
	Tillage after 5-24 h		20	10
	Spread on pasture		25	30
	Spread on grain		10	15
Shallow injection	Spread on pasture		8	15
Early summer, summer				
Broadcast	Spread on pasture	90	60	70
	Spread on grain		10	20
Trailing hoses	Spread on pasture		40	50
	Spread on grain		10	7
Shallow injection	Spread on pasture		15	30
Early autumn				
Broadcast	Immediately	20	15	5
	Tillage after 4 h	35	23	18
	Tillage after 5-24 h	50	30	30
	No tillage	70	45	70
Trailing hoses	Immediately		10	3
	Tillage after 4 h		18	9
	Tillage after 5-24 h		25	15
	No tillage		30	40
Late autumn				
Broadcast	Immediately	10	10	5
	Tillage after 4 h	15	15	8
	Tillage after 5-24 h	20	20	10
	No tillage	30	25	30
Trailing hoses	Immediately		4	3
	Tillage after 4 h		11	4
	Tillage after 5-24 h		18	5
	No tillage		25	15

Source: Karlsson & Rodhe, 2002.

*) *The figures include deep litter manure, semi-solid manure and anaerobicly digested sewage sludge.*

Annex G: Nitrogen-efficiency model calculations

G.1 Introduction to N-efficiency model

In order to facilitate comparisons of different manure handling systems a model has been developed (Brundin & Rodhe, 1994), see figure G-1. This model can be used to calculate the N-efficiency of a given manure handling system from animal to the field. The N-efficiency in percent is a measure of the share of total-N in the original manure which is available for the crops after application to the field. A large N-efficiency indicates that only a small amount of N is lost during storage, transportation and spreading of the manure. The organic N in manure must be broken down by soil microorganisms, mineralized, before it can be utilized by plants, which can take from a few weeks up to several years. Here, the organic N is added to the losses, as it is assumed not available for plants during the season.

Figure G-1. The managing strategy includes decisions about choice of spreading time/s and methods for storing and spreading the manure/digestate. The decisions influence the economical profitability as well as the utilization of the nutrients in manure/digestate by plants. With low N and P utilizations there may be a high risk of leakage of nutrients to water, mainly N and P.

Results show that slurry systems will generally give a higher utilization of plant nutrients than solid manure systems, and thereby it is beneficial to turn solid manure to slurry by digestion. However, slurry systems are associated with high risks of leakage as the water soluble nutrients as ammonium nitrogen (NH_4-N) and nitrate (NO_3-N) could easily be lost to water if it is spread when there are no growing crops to utilize the nutrients as in autumn.

Additionally, the properties of high part of nitrogen as NH_4-N as well as increased pH after digestion, increase the risk of ammonia losses during storage and after spreading (Sommer et al., 2006) which put high demands on low emissions technology for storing and spreading of the digested slurry. In the model, the NH_4-N in manure is assumed to have the same effect as chemical fertilizers on the crop when applied in the same degree of precision (evenness and placement). Leaching losses originating from NH_4-N in manure are related to clay-content in soil, time of application and crop rotation. Only the additional leaching losses over and above those resulting from spring application are used here. Organic nitrogen utilized in the following 10 yr after application is supposed to replace N in chemical fertilizers. The part not utilized is treated as a leaching loss. No emission losses for organic nitrogen are considered. For more information, see Brundin & Rodhe (1994).

Lost nutrients from manure/digestate must be replaced by mineral fertilizers. In order to be able to spread at a time with high plant uptake of nutrients, the storage capacity should make it possible to spread all slurry in spring or in early summer, which means a minimum storage capacity of 9-10 months depending on the climate and length of growing season in the area where the farm is located. An investment in low emission technique for storage and spreading technology and with high precision in dosage as well as high evenness of spreading will be more economically profitable when the price for commercial fertilizers is high. In some cases there is a need for subsidizing environmental-friendly technology as the price for N or agricultural products produced with the manure/digestate is too low. There is also a scale effect, making some investments like low emission technology profitable (break-points) only above certain amounts of manure/digestate to be handled per year. For smaller farms this is solved by several farmers invest together in more advanced spreading equipment, or use a contractor for spreading the produced amount of manure.

The N-efficiency model was used to evaluate 3 manure handling systems relevant for large scale centralized biogas plants and 1 manure handling system relevant for small scale farm based biogas plant. The 5 different scenarios are described in detail and an overview is given in Table G-1.

Table G-1. Overview of the scenarios.

A. Large scale centralized biogas plant scenarios	Description
A1. No anaerobic digestion of the manure.	All manures are stored and applied to the fields on the farm.
A2. Anaerobic digestion and no post-separation of digestate.	The main part of the pig slurry is pre-separated into two fractions. Only the solid fraction is transported to the biogas plant and digested. The digestate is transported back and applied on the farms without any separation.
A3. Anaerobic digestion followed by post-separation of digestate.	The main part of the pig slurry is pre-separated into two fractions. Only the solid fraction is transported to the biogas plant and digested. The digestate is transported back and applied on the farms without any separation. The digestate is separated into two fractions which are spread to the fields separately.

B. Small scale farm based biogas plant scenario	Description
B1. No Anaerobic treatment of pig slurry	The pig slurry is spread on arable land without additional treatment
B2. Anaerobic digestion of slurry from one pig farm.	The digested pig slurry is spread on arable land without additional treatment.

In each of the 5 scenarios the model was used to make N-balances for two manure treatment systems:

- Reference situation -business as usual (BAU): Both slurry and digestate are spread with trailing hoses and incorporated into the soil after 4 hours (e.g. with a harrow). 70 % of the pig slurry/digestate is spread during spring and 30 % is spread in autumn.
- Best available technologies (BAT): Both slurry and digestate are spread using trailing hoses but are incorporated into the soil immediately after spreading. No autumn spreading is included – all manure is spread in spring or early summer.

G.2 Material and methods

G.2.1 Common input data for all scenarios

In general, the calculations of N-efficiency are based on practical examples from Denmark. Set conditions for all scenarios are that manure/digestate is spread once per year and field. Spreading times are March, April, May and September (Brundin & Rodhe, 1990). All manure/digestate are applied to cereal crops. The application rate is 26 tonnes per hectare. In Denmark the average amounts of nitrogen (N) and phosphorus (P) allowed annually is 140 kg N-tot and 30 kg of P-tot per hectare. The 30 kg limit per hectare for P is calculated as an average over 3 years.

Two cases are studied, Business As Usual (BAU) where 30% of the manure/digestate is applied in autumn and Best Available Technology (BAT), where all slurry/digestate is spread in spring or early summer. Slurry and digestate are assumed to be stored in covered storages. Losses of ammonia (NH_3) occur during storing and after spreading of manure/slurry and digestate. Losses of NH_3 during storage of liquid fractions are set to 1 % of total nitrogen and for solid fractions, 20 % of total nitrogen is lost during storage. Parameters for storage losses are collected from Karlsson & Rodhe (2002), see also Appendix F, Table F-1 and F-2.

Differences in nitrogen content between slurries and digestates are assumed as losses in handling from farm to biogas plant and handling at biogas plant prior to storage of digestate.

Liquid fractions is spread using band spreader with trailing hoses and solid fractions are spread using broadcast spreader. At BAU, spreading of manure and digestate is done using technology according to Table G-2. Manure and digestate are incorporated within 4 hours after spreading. In the BAT case all spreading are done in the spring (March to May) and manure and digestate are incorporated into the soil directly after spreading.

Table G-2. NH_3-N losses at spreading as percentage of total ammonium nitrogen (TAN) in manure/digestate. See also Appendix F.

Spreading technology and spreading season	Nitrogen lost as ammonia, % of total ammonium nitrogen (TAN)
N losses after spreading when incorporating into soil after 4 hours:	
Broadcast spreading in spring (solid fraction)	33 %
Broadcast spreading in autumn (solid fraction)	15 %
Band spreading with trailing hoses spring (slurry),	8 %
Band spreading with trailing hoses autumn (slurry),	4 %
N losses after spreading with direct incorporation into soil:	
Broadcast spreading in spring (solid fraction),	15 %
Broadcast spreading in autumn (solid fraction),	10 %
Band spreading with trailing hoses spring (slurry),	5 %
Band spreading with trailing hoses autumn (slurry),	3 %

Nitrogen is also lost through leakage. The leakage presented in this study is only the additional leakage caused by spreading at times when no crop is available to utilise the nitrogen. The calculation assumes that spreading other times of the year than in spring and early summer leads to additional leakage. For the sandy soil, the additional leaching is 52 % TAN spread in autumn (Brundin & Rodhe, 1990).

Some of the organic nitrogen in manure and digestate is mineralised and become plant available. The mineralised and plant available nitrogen is not accounted for in the calculations as the available data concerns mainly manure with larger part of organic nitrogen compared to digestate and pig slurry. Nitrogen efficiency (N_E) in percent describes part of total nitrogen in original manure available for plants.

G.2.2 Calculating nitrogen efficiency for large scale co-digestion

By using the above described model, nitrogen efficiencies were calculated for 3 scenarios:

1. All manures are stored and spread undigested on the farms, Figure G-2.
2. Most manures are transported to the large scale biogas plant and digested, Figure G-3. The main part of the pig slurry, approx. 90 % is separated into two fractions on the farms and the solid fraction (about 10%) is sent to the biogas plant while the liquid fraction is spread untreated to arable land on the farms. The digestate is transported back and used on the farms without any separation and spread with a slurry tanker.
3. The same scenario as in Scenario 2, except that the digestate is separated into two fractions, liquid and solid fractions which are spread separately, Figure G-4.

This study focuses only on nitrogen efficiency and no phosphorous leakage is included. No economic calculations are performer neither is energy turnover analysed. Impact on greenhouse gas formation is also outside the study.

Scenario 1: Undigested manure

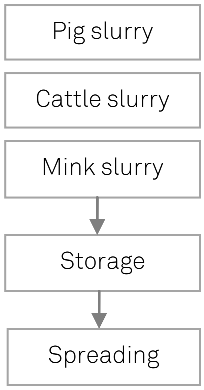


Figure G-2. Schematic description of scenario 1: All manure is stored and spread on the farm.

The scenario assumes that the manures are not digested and it is stored and spread on arable land at the farms producing the manure, Figure G-2. All animal slurries are stored in covered tanks on farm. Spreading is done with a slurry tanker equipped with boom with trailing hoses (band spreading). In total, the farms produces 387.000 tonnes of animal slurry containing 1.426 tonnes of N, 344 tonnes of P and 893 tonnes of K per year (Table G-3). If spreading 26 tonnes slurry per hectare, 14.800 hectares are needed annually.

Table G-3. Amount and composition of manure produced at farm per year.

	Pig slurry	Cattle slurry	Mink slurry	Total	Unit
Wet weight	322.500	60.000	5.000	387.500	tonnes
Tot-N	1.128.750	222.000	75.000	1.425.750	kg
NH_4-N	483.750	96.000	15.000	594.750	kg
P	290.250	48.000	5.261	343.511	kg
K	677.250	210.000	5.416	892.666	kg
TS	14.513	5.460	375	20.348	tonnes
VS	11.610	4.317	300	16.227	tonnes
Part VS of TS	80	79	80	80	%

Scenario 2: Digestion and un-separated digestate

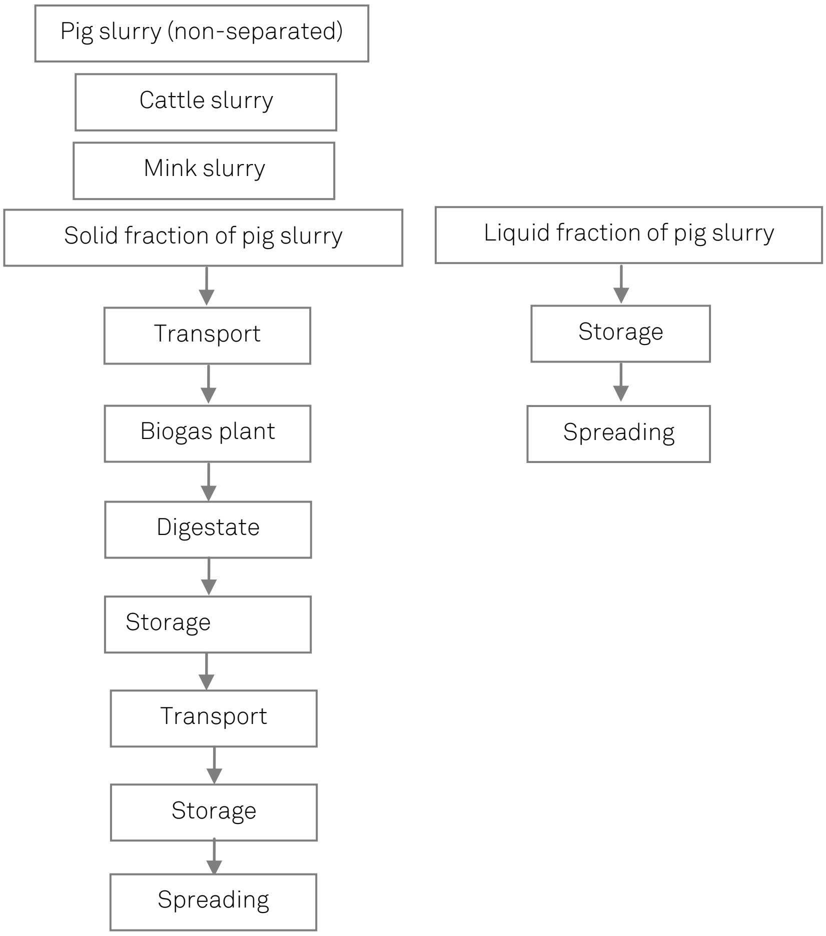


Figure G-3. Schematic description of scenario 2: Manure is transported to biogas plant, digested, stored and the digestate is returned to the farms and spread on arable land.

About 90% of the pig slurry is separated on the farms in two fractions (Table 4). Spreading 270.000 tonnes liquid fraction from pig manure at farms with 26 tonnes per ha requires 10.400 ha. And spreading 110.257 tonnes of digestate requires 4.200 ha in total 14.600 ha of agricultural land annually.

Table G-4. Amount and composition of fractions sent to biogas plant and fraction remaining on farm.

	Pig slurry	Cattle Slurry	Mink Slurry	Solid fraction from sep. of pig slurry	Liquid fraction from sep. of pig slurry	Total	Unit
Wet weight	23.500	60.000	5.000	29.000	270.000	387.500	tonnes
Tot-N	82.250	222.000	75.000	234.900	811.600	1.425.750	kg
NH_4-N	35.250	96.000	15.000	69.600	378.900	594.750	kg
P	21.150	48.000	5.261	145.000	124.100	343.511	kg
K	49350	210.000	5.416	63.800	564.100	892.666	kg
TS	1.058	5.460	375	8.700	4.755	20.348	tonnes
VS	846	4.317	300	7.656	3.108	16.227	tonnes
Part VS of TS	80	79	80	88	65		%

At the biogas plant 110.300 tonnes of digestate are produced per year (Table G-5). The digestate is transported to the farms and spread on arable land.

Table G-5. Amount and composition of digestate produced at biogas plant per year

	Digestate	Unit
Wet weight	110.257	tonnes
Tot-N	594.285	kg
NH_4-N	424.489	kg
P	219.411	kg
K	328.566	kg
TS	8.371	tonnes
VS	5.897	tonnes
Part VS of TS	70	%

Scenario 3: Digestion and separation of the digestate

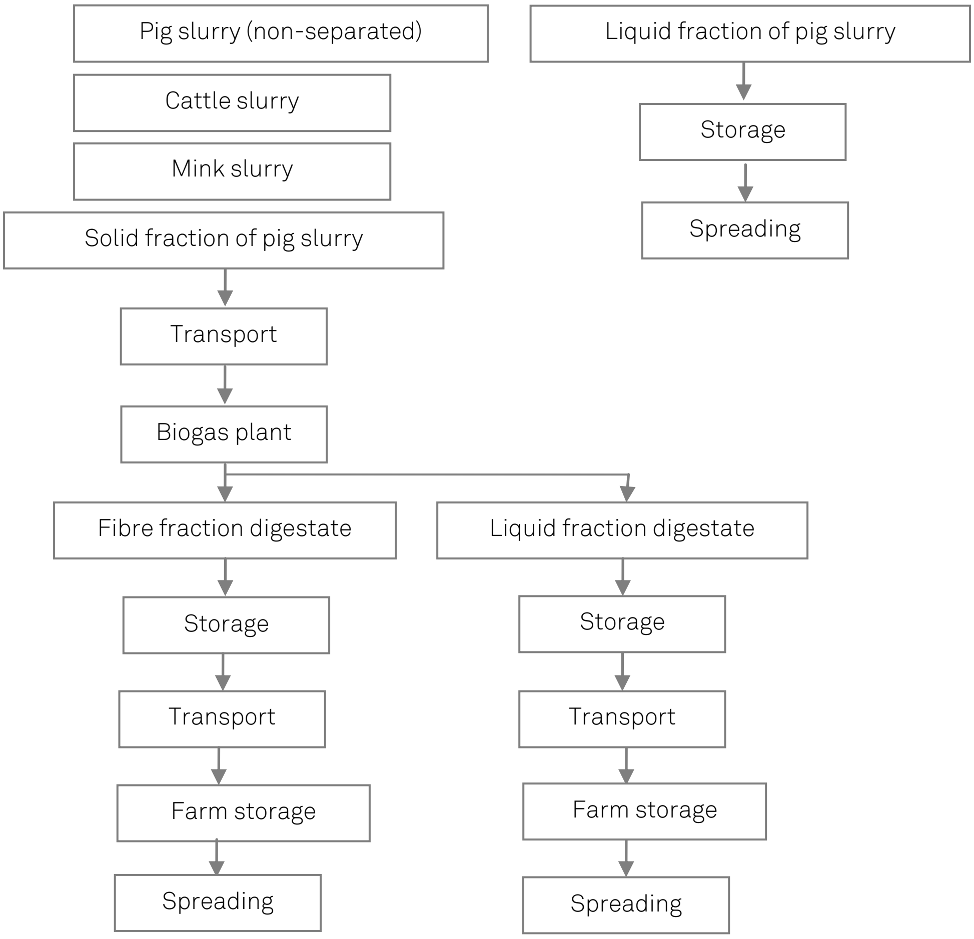


Figure G-4. Schematic description of scenario 3: Manure is transported to biogas plant. Digestate is dewatered and spread to arable land.

Scenario 3 (Figure G-4) uses the same incoming slurries and manures as scenario 2 (Table G-4) but the outputs are two digestate fractions, liquid and solid fractions (Table G-6). The liquid fraction of the pig slurry is spread without digestion directly on the farms. If applying 26 tonnes of liquid fraction to each hectare 14.100 ha are needed for liquid fraction of pig manure and liquid fraction of digestate. The solid fraction of the digestate requires between 1.050 to 5.070 hectares annually, in total 15.200 to 19.200 hectares.

Table G-6. Amounts and composition of wet and dry fraction digestate after dewatering at biogas plant per year.

	Wet fraction	Dry fraction	Unit
Wet weight	97.026	13.231	tonnes
Tot-N	447.421	146.864	kg
NH_4-N	341.134	83.355	kg
P	67.255	152.157	kg
K	289.137	39.429	kg
TS	4.269	4.102	tonnes
VS	2.814	3.083	tonnes
Part VS of TS	66	75	%

G.2.3 Calculating nitrogen efficiency for small scale biogas production

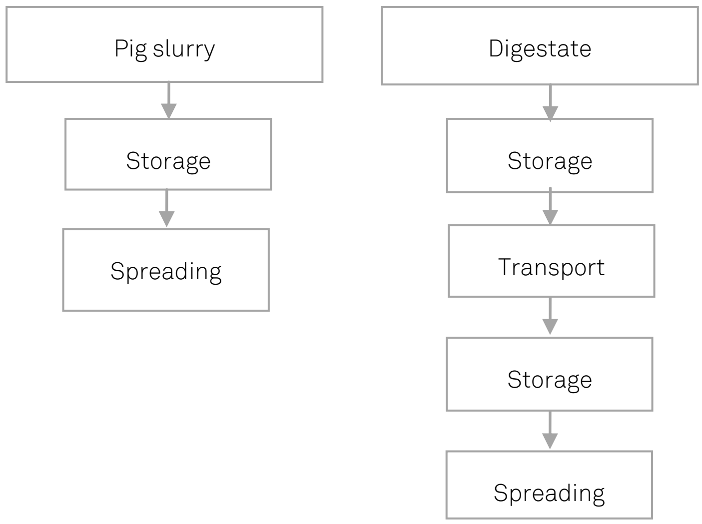


Figure G-4. Pig slurry and digestate handling chain from biogas plant to field application.

The small scale case includes only one substrate, pig slurry from a model pig farm with integrated pig production. The theoretical farm is assumed to have 500 sows producing 12.000 piglets per year which resulting in 11.000 fattening pigs per year. A farm of this size corresponds to approximately 3.433 pig places, 500 sows and 2.933 fattening pigs. From a farm of this size 9.650 tonnes of pig slurry with 5,5 % dry matter content is produced each year (Table G-7).

Table G-7. Amount (tonnes/ year) and composition (kg/ ton wet weight) of pig slurry produced at farm and digestate produced at biogas plant. Total solids (TS) and volatile solids (VS) are expressed as percentage of wet weight.

	Pig slurry	Digestate
Wet weight, tonnes	9.650	9.416
Tot-N, kg/tonne	4,10	4,20
NH_4-N, kg/tonne	2,60	3,51
P, kg/tonne	1,10	1,13
K, kg/tonne	2,70	2,77
TS,%	5,50	2,50
VS, %	4,40	1,37
Part VS of TS, %	80	55

It is assumed that neither any other substrates nor water are added to the pig slurry at the biogas plant. Losses of nitrogen when handling pig slurry at farm during transportation and at the biogas plant are low, 0,45 %, calculated from the difference in nitrogen content between pig slurry and digestate.

The digested pig slurry is spread on arable land without any additional treatment. It is assumed that 95 % of both pig slurry and digestate are spread in spring and remaining 5 % in autumn.

Both pig slurry and digestate are band spread using boom with trailing hoses. In the reference case (BAU), the slurry and digestate are incorporated into soil after 4 hours for example with a harrow. In the BAT case the same technique is used for spreading, together with incorporation of slurry/digestate immediately after spreading. In the BAT case all slurry and digestate is spread in the spring or early summer.

G.3 Results from N-efficiency calculations

G.3.1 Large scale centralized biogas plant

The nitrogen balances for handling manure and digestate, when handling with BAU, are presented for the three scenarios in Table G-8 and when handling with BAT in Table G-9. The NH_3 emissions from storage and after field application range from 2 to 7 % of total nitrogen. Storage of solid fractions in uncovered heaps as in Scenario 3 gives higher losses compared to liquid manure/digestate stored in covered storage as in Scenario 1 and 2.

Leaching losses presented in the tables below are additional leaching from spreading at unfavourable times, in this case spreading in autumn instead of in spring. The additional leaching of N disappears when BAT technology is used, as it includes no autumn spreading. Instead, all spreading occurs in spring or early summer when there are crops that can utilise the readily available nitrogen.

Organic nitrogen is not readily plant available. Nitrogen is mineralised from the amount spread in digestate and manure, but may also be immobilised in the nitrogen pool in the soil and thereby not available for plants.

The highest N efficiency is achieved in Scenario 2, caused by increased plant available nitrogen by digestion of manures with high organic nitrogen content together with that the digestate is handled in liquid form avoiding high NH_3 losses from storing and spreading. Also, the solid fraction produced on farm is assumed to be digested directly after production (storage before digestion).

Table G-8. N-balances for handling manure/digestate in the three scenarios when handling with BAU.

	Scenario 1	Scenario 2	Scenario 3	Unit
Production	1.425.750	1.425.750	1.425.750	kg
Losses digestion	0	19.865	19.865	kg
NH_3-N losses, storage	14.258	14.059	41.963	kg
NH_3-N losses, spreading	39.744	53.674	63.005	kg
Additional leakage	86.794	118.210	113.105	kg
Total losses incl. immobilisation	971.796	808.304	840.434	kg
Plant available	453.954	617.446	585.316	kg
Nitrogen efficiency (N_E)	32	43	41	%

In general, the N-efficiency is higher with BAT compared with BAU mainly because of there is no manure/digestate spread in autumn and also to some part because of lower NH_3-emissions (Table G-8 and Table G-9). The highest N-efficiency (53 %) is achieved in Scenario 2 with BAT.

Table G-9. N-balances for handling manure/digestate in the three scenarios when handling with BAT.

	Scenario 1	Scenario 2	Scenario 3	Unit
Production	1.425.750	1.425.750	1.425.750	kg
Losses digestion	0	19.865	19.865	kg
NH_3-N losses, storage	14.258	14.059	41.963	kg
NH_3-N losses, spreading	29.025	39.467	43.470	kg
Additional leakage	0	0	0	kg
Total losses incl. immobilisation	874.282	675.886	707.794	kg
Plant available	551.468	749.864	717.956	kg
Nitrogen efficiency (N_E)	39	53	50	%

In total, the N-efficiency increased with around 11-14 % units in Scenario 2 and 3 compared to spreading of non-digested manures (Scenario 1) in the large scale co-digestion case.

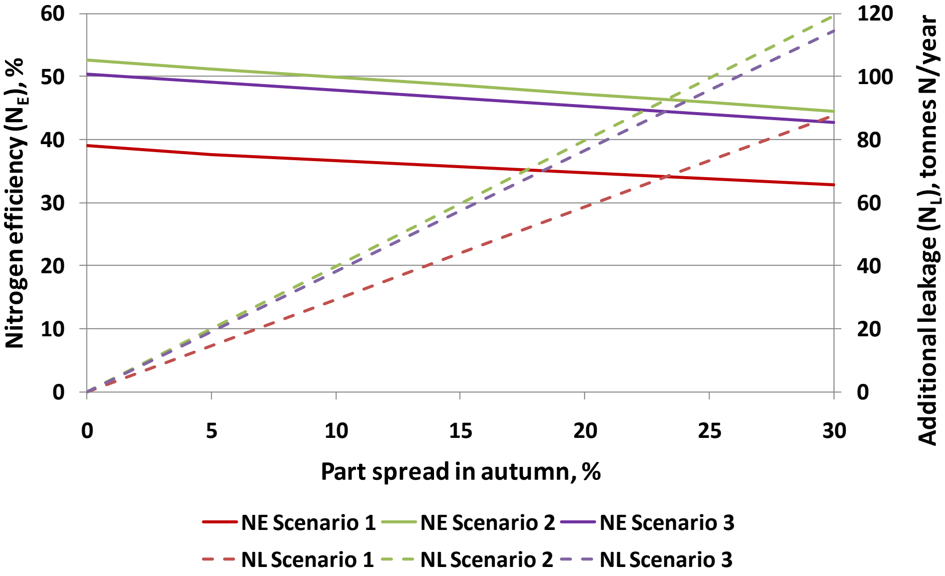


Figure G-5. Nitrogen efficiency (N_E) and additional nitrogen leaked (N_L) per year as function of part spreading of manures and digestate in autumn for the three scenarios of the large scale co-digestion with low emission technology as in BAT. In scenario 1 all manures are stored and spread undigested on the farms. In scenario 2 most manures are transported to the large scale biogas plant and the digestate is transported back to the farms. Scenario 3 is the same as scenario 2 except that the digestate is separated into two fractions, which are spread separately.

Increased part of the manure or digestate spread in autumn, decreases the N_E and in the same time the additional nitrogen leakage (N_L) to water recipient increases, Figure G-5. Changed spreading strategy from 30% of the digestate spread in autumn to only spring application, decreases the nitrogen losses through leakage with 120 tonnes per year when using low emission technology with BAT. This corresponds to almost 10 % of all nitrogen handled on this plant in one year.

G.3.2 Nitrogen efficiency for small scale farm based biogas plant

The increase in N_E for pig slurry is 10 % when introducing BAT technology and for digestate 14 %, Table G-10. The main contributor to the increase in efficiency is the avoided additional leaking caused by spreading in autumn and to a smaller extent decreased NH_3-N losses during spreading. Anaerobic digestion increases plant available nitrogen (ammonium nitrogen) and the difference between nitrogen efficiency when using untreated pig slurry or digestate is allocated to that increase (Table G-10). Digestion increase N_E with 15% in BAU, and with 19% in BAT.

Table G-10. Results for BAU and BAT treatment of pig slurry and digestate.

	BAU		BAT		
	Pig slurry	Digestate	Pig slurry	Digestate	Unit
Production	39.565	39.565	39.565	39.565	kg N
Losses digestion	0	18	0	18	kg N
NH_3-N losses, storage	396	395	396	395	kg N
NH_3-N losses, spreading	1.679	2.214	1.235	1.628	kg N
Additional leakage	3.698	4.876	0	0	kg N
Total losses incl. immobilisation	20.248	14.077	16.105	8.615	kg N
Plant available	19.317	25.470	23.460	30. 933	kg N
Nitrogen efficiency	49	64	59	78	%

In Figure G-6, the nitrogen efficiency and the additional nitrogen leaked is presented for different amounts spread in autumn. A changeover from 30% autumn spreading to spreading all pig slurry and digestate in spring decreases additional leakage with about 3,7 tons N for pig slurry and 5 tons N for digestate per year. These amounts of decreased nitrogen leakage correspond to 10 % of the total nitrogen produced for pig slurry and 13 % for the digestate (Table G-10).

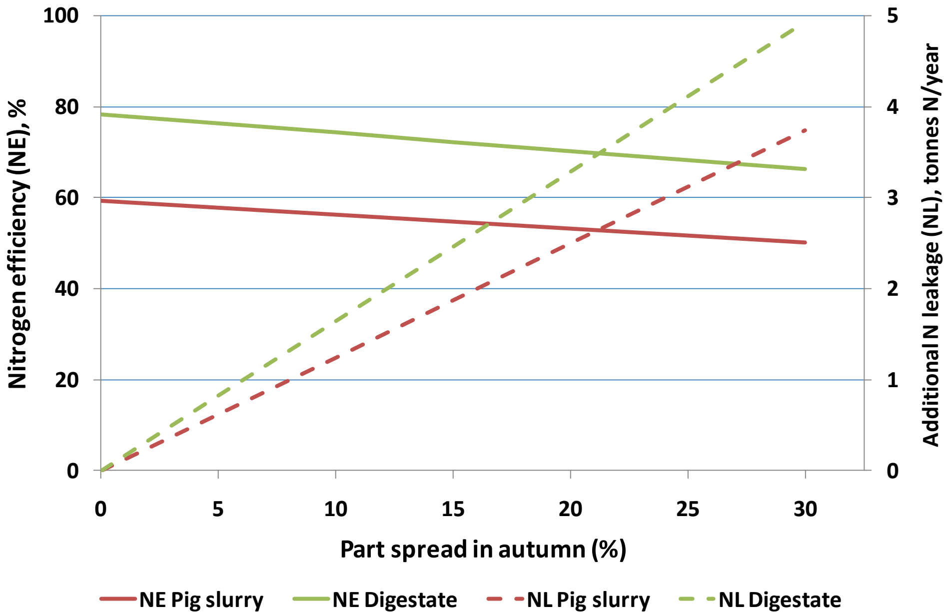


Figure G-6. Nitrogen efficiency (N_E) and additional nitrogen leaked (N_L) per year as function of part spreading of manures and digestate in autumn for pig slurry or digestate from the small scale digestion plant with low emission technology as in BAT.

G.4 Discussion

Anaerobic digestion increases the nitrogen efficiency. The nitrogen efficiency is an effect of the amount of plant available nitrogen in the manure/digestate. Anaerobic digestion has a positive impact on increasing plant available nitrogen. In general, if the ratio between plant available nitrogen (TAN) and total nitrogen is low (around 50% or less), anaerobic digestion can increase nitrogen efficiency with up to 20 % (Møller, 2006). However, substrates with high TAN content (78%) of total nitrogen seemed to give a smaller increase in plant available nitrogen, by 8% units in a study performed by Møller *et al.* (2007). Our calculations are mainly based on data from plants in Denmark and the small-scale plant had a re-circulation of the solid digestate phase, which could have contributed to the rather high increase in part of TAN of total-N in the digestate. When it concerns digestion of solely pig slurry, the knowledge is very limited as slurry nearly always is co-digested with more carbon rich substrates. So it is a need of more data concerning the increase in TAN content of digested pig slurry, when digested without any other substrates or water additions, because this influence very much the results on nitrogen efficiency.

As the digestate has a higher rate of TAN of total-N, the more there are to gain in N_E with BAT as well as there is a higher leakage losses of nitrogen and ammonia emissions if it is not handled with care. The digestate, as well as pig slurry, should be spread when there is a plant uptake of nitrogen and low emission technology should be used for storing and spreading. In this case, there were already covered storages and incorporation within four hours of the manure/digestate in BAU, so the reduced ammonia emissions when introducing BAT did not decrease the NH_3 emissions so much. Instead, avoiding autumn spreading had the highest effect on decreasing nitrogen losses on these sandy soils. It will be harmful for the Baltic Sea environment if introducing digestion of pig slurry without sufficient storage capacity on farm in combination with precision and low emission technology for storage and at spreading.

When co-digestion with solid manure, the length of storage of the solids are important for the results as the ammonia losses could be high from stored solid manure (default value 20% of total-N) and there could also be greenhouse gas (GHG) emissions in the form of nitrous oxide (N_2O), a strong GHG. In this study, it is assumed that the solid fraction produced on the farms in Scenario 2 and 3 are immediately transported and fed into a digester (no storage time). If the solid is stored for some time, additional ammonia will be lost, which should be added to the NH_3 losses from storage in Scenario 2 and 3.

The N_E is in general at a higher level for the small scale biogas production than the large scale co-digestion, which could be explained by the properties of the substrates going into the digesters. In the large scale, manure with low percentage of TAN of total-N is used, for instance mink manure (20% TAN) and solid fraction of pig slurry. In the small scale, pig slurry with a high percentage of TAN (71%) is used. In the large scale co-digester, N_E increased (9 - 17%) with digestion compared to non-digestion while the corresponding increase in the small scale digester were 15 - 19%.

Although some studies have found higher NH_3 emissions from digested than from non-digested slurry (Sommer *et al.*, 2006), the same NH_3 emission factors have been used for non-digested and digested slurry at field application in this study. This could be questioned. However, it is presumed not to have so big influence on the results.

So far, leakage of phosphorus (P) has not been included. It should be considered that autumn spreading will give higher losses of P than spreading during the growing season. Separation of the digestate and export of the solid fraction from a region with high amounts of manure would be a solution for reducing the P leakage and in the same time improve soil fertility and P status on farms with poor soils. The additional leakage of N in autumn is set to 52% of applied NH_4-N with manure/digestate reduced with NH_3 losses for Danish conditions for soils with 10% clay content.

Other not calculated nitrogen losses are emissions of N_2O from storage and after application of slurry/digestate to farmland. According to IPCC (2006), N_2O emissions from agricultural soils range between 0.25 to 2.5 % of applied N and the default value of 1,25 % of total N could be used in national inventories reports. This default value may be replaced by national measured N_2O emissions from agricultural soils, more relevant for the regional conditions.

G.5 Conclusion from N-efficiency calculations

N-efficiency (N_E) is higher when handling digested manure than non-digested, but the leakage from digestate compared to non-digested manure is also higher if spread in autumn or to land without growing crops with a demand of nitrogen. Sufficient storage capacity on farm in combination with precision and low emission technology at spreading is prerequisite before considering digestion of animal manure.

High precision technology for field application is less important for leakage to Baltic Sea than spreading time, as autumn spreading increases leakage significantly. Low emission technologies for storage and spreading are important in order to minimize nitrogen losses as ammonia, especially for digested manure with high content of ammonium nitrogen.

The N_E is in general at a higher level for the small scale biogas production than the large scale co-digestion, which could be explained mainly by the properties of the substrates going into the digesters, respectively. Storage of solid manure fractions should be avoided as the emissions of ammonia and the greenhouse gas nitrous oxide (N_2O) may be high. Solid fractions created for digestion should there for be feed directly to digester without longer interterm storage. Storage of liquid products is preferable to solids, as it is easier to reduce NH_3 losses from liquid fractions than from solid fractions. Recirculation of solid fraction of digestate back to digester will improve the part of plant availability of nitrogen in digestate.

Annex H: Nutrient flow calculations

To illustrate the effect of anaerobic digestion and post-separation of the digestate examples of nutrient flows through a biogas plant are described in this annex. Model calculations have been made for three simplified cases:

- Case 1: Pig slurry is stored and applied to the fields without anaerobic digestion and without separation of slurry (baseline scenario).
- Case 2: Pig slurry is treated in a biogas plant, the digestate is separated and only the liquid fraction is applied to the fields of the pig farm. The solid fraction is exported from the pig farm to fields of other farms with a need for N and P.
- Case 3: Pig slurry is treated in a biogas plant where maize silage is used as a co-substrate to increase the methane production. The digestate is separated and only the liquid fraction is applied to the fields of the pig farm whereas the solid fraction is exported to other farms like in case 2.

The results of the model calculations are presented below in three flow charts. The flow charts show the fate of total N (Tot. N), organic bound N (Org. N), mineralized N (Min. N) and P contained in the pig slurry and the maize silage (case 3). To simplify the calculations and the flowcharts some assumptions have been made:

- No N is lost during the anaerobic digestion process so that all N entering the biogas reactor is contained in the digestate.
- No mineralization of organically bound N is taking place during storage of slurry, digestate and fractions from separation of digestate.
- The number of produced pigs per year is the same in all three cases.
- In all three cases a pig farm with a fixed amount of land available for spreading pig slurry or digestate/fractions from post-separation of digestate is assumed.
- Methodologies and technologies for storing and spreading raw slurry (case 1) and liquid fraction from separation of digestate (case 2 and 3) are assumed to be the same. Thus, the model calculations and the flow charts do not take into consideration the effects on N and P losses resulting from different practices for storing and spreading.
- Mineralization of organic bound N in anaerobic digestion combined with optimal timing of the field application is a tool to reduce N leaching.

The starting point for the model calculations is 1.000 kg of pig slurry with a total N content of 4,1 kg distributed on 1,5 kg of organic N and 2,6 kg of mineralized N. The P content is assumed to be 1,1 kg/ton raw slurry.

In <u>case 1</u> the pig slurry is stored and then spread on the fields at the pig farm without any further treatment. It is assumed that 2 % of the total N is lost during covered storage of slurry and consequently only 4,0 kg of total nitrogen are spread on the field. In figure H-1 the flow chart for case 1 is presented.

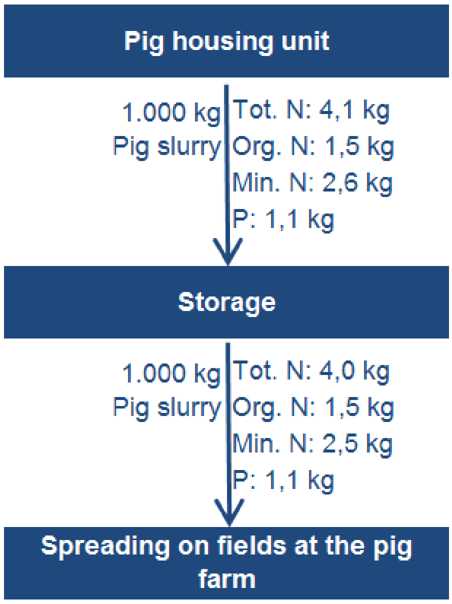


Figure H-1. Flow chart for case 1. Pig slurry is applied directly to the fields without treatment in biogas plant.

It is seen in figure H-1 that 1,5 kg of organic bound N and 1,1 kg of P are spread on the fields of the pig farm for 1.000 kg of raw pig slurry produced.

In case 2 the pig slurry is used for biogas production and the digestate is separated into two fractions using the technology described under Model Biogas Plant 3 (See Annex C3). This technology for post-separation of digestate is based on natural separation (flotation and sedimentation). The separation efficiency of the post-separation technology is assumed to be similar to the efficiency achieved during a demonstration of such a separation technology carried out in Denmark (Tellerup & Frandsen, 2009). The liquid fraction is applied to the fields of the pig farm and the solid fraction is assumed to be transported to other farms with fields in the need of N and P. It is assumed that the solid fraction is stored in closed containers immediately after separation and gaseous emissions are controlled all the way from the separation unit to the application on the field. In figure H-2 the flow chart for case 2 is presented.

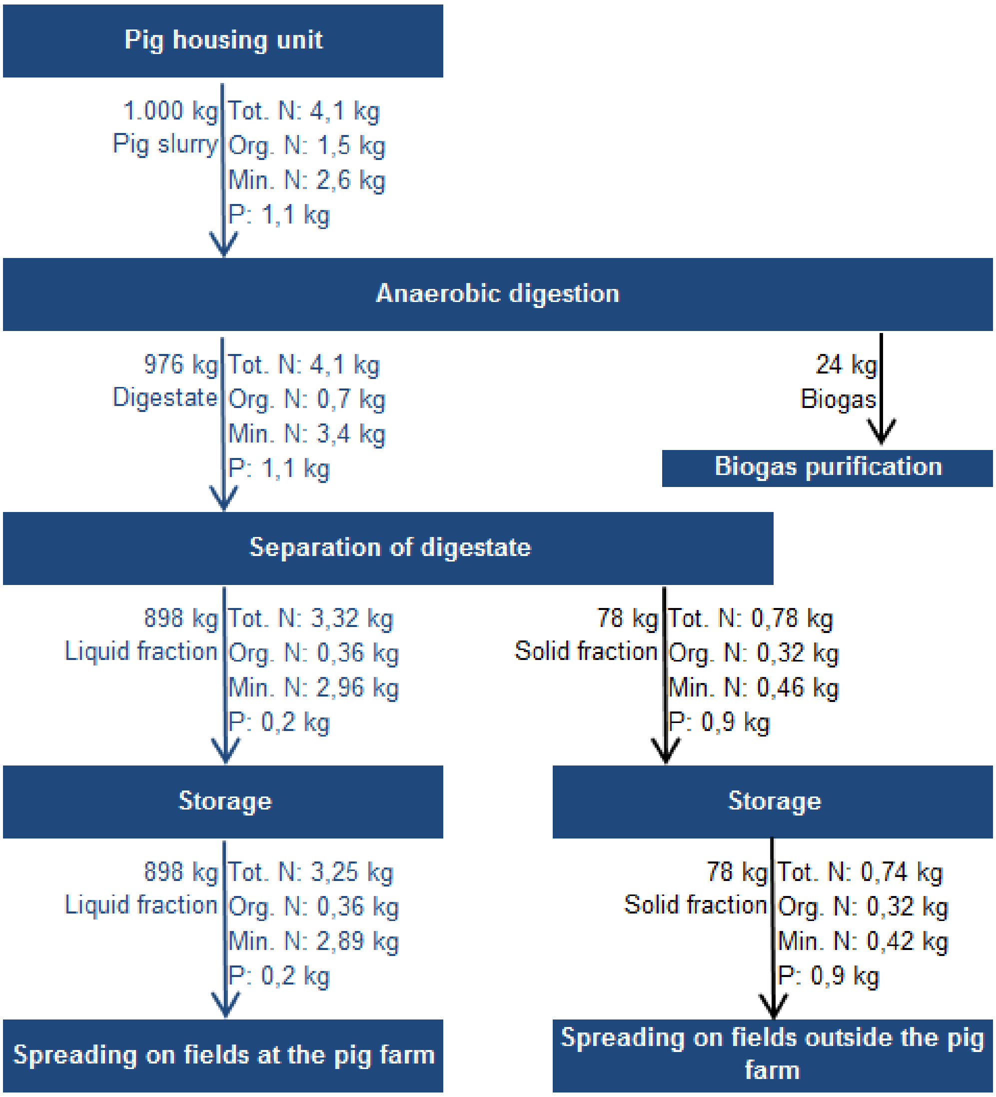


Figure H-2. Flow chart for case 2. Pig slurry is treated in a biogas plant, the digestate is separated and only the liquid fraction is applied to the fields of the pig farm.

When comparing figure H-1 with figure H-2 it is seen that the amount of organic bound N applied to the fields of the farm can be reduced from 1,5 kg to 0,7 kg for 1.000 kg of pig slurry if the slurry is treated in a biogas plant. Moreover, the organic N applied to the fields can be further reduced from 0,7 kg to 0,36 kg if the digestate is separated and the solid fraction is exported to other farms with fields in need of N and P. Similarly, it is seen that the amount of P applied to the fields of the pig farm can be reduced from 1,1 kg to 0,2 kg for 1.000 kg of pig slurry if the solid fraction is exported to other farms.

In case 3 the pig slurry is used for biogas production and maize silage is added to increase methane yield. It is assumed that the maize is produced on fields that would otherwise have been used to produce cereals to be sold from the farm and not used for fodder at the farm. In order to facilitate comparison with case 1 and 2 a total biomass input of 1.000 kg is assumed in case 3. This is done in the model calculations by replacing 206 kg of raw pig slurry with maize silage. In case 3 post-treatment of the digestate is done using the same technology as in case 2. Figure H-3 shows the resulting flow chart for case 3.

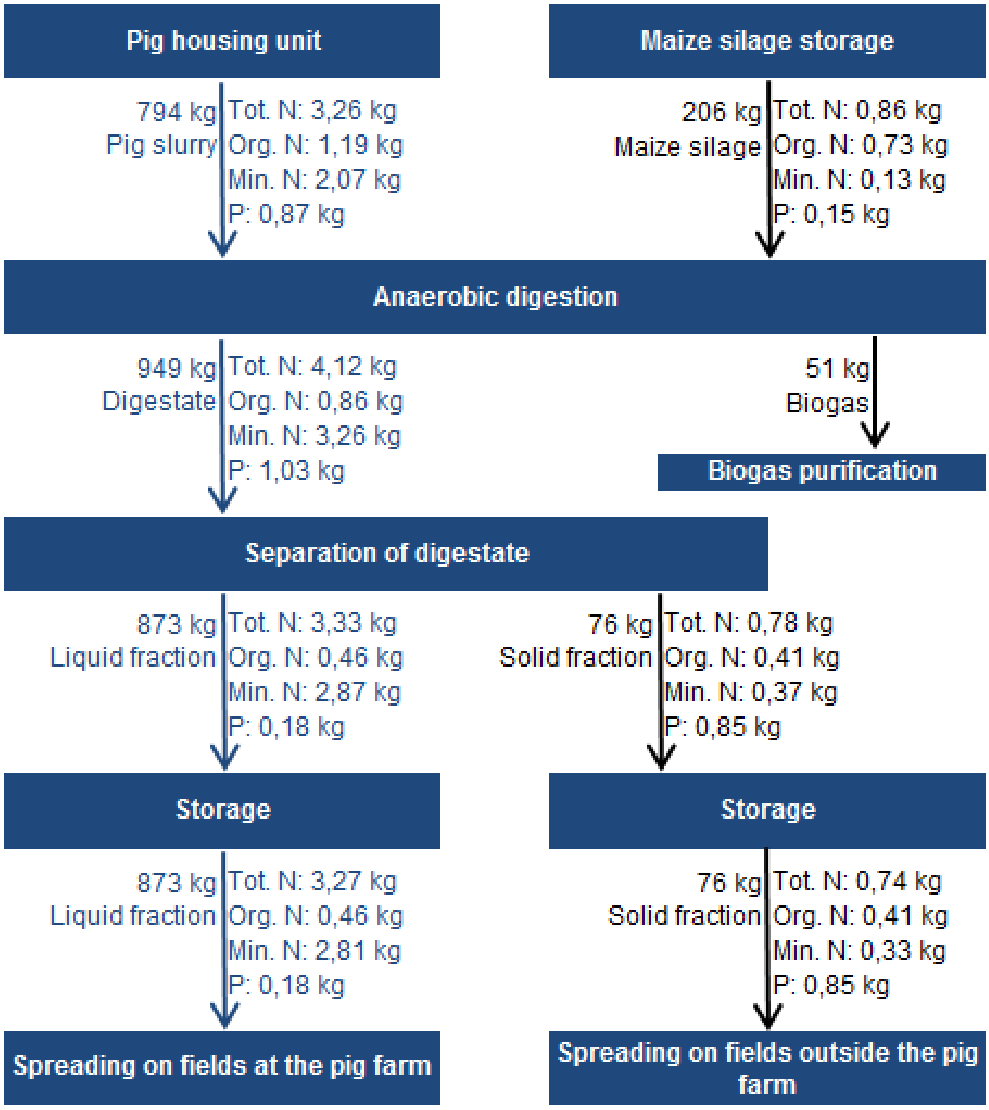


Figure H-3. Flow chart for case 3. Pig slurry is treated in a biogas plant using maize silage as co-substrate to increase methane production. The digestate is separated and only the liquid fraction is applied to the fields of the pig farm.

Case 3 illustrates that using maize silage as a co-substrate for biogas production will increase the amount of organically bound N that is applied to the fields of the pig farm compared to case 2. When 1.000 kg of the pig slurry/maize mixture is treated, 0,46 kg of organic bound N is spread on the fields of the pig farm. In case 2 where no maize was used treatment of 1.000 kg pig slurry resulted in 0,36 kg of organic bound N being spread on the fields of the pig farm. This will reduce the desired effect of the anaerobic digestion and increase the risk for leaching of N compared to case 2, all other things being equal. It is also seen in figure H-3 that the amount of P applied to the fields in case 3 is slightly lower than in case 2 (0,18 kg and 0,20 kg P respectively). The reason is that maize silage is characterized by a lower concentration of P than the pig slurry in the model calculations.

As mentioned above nutrient amounts in the three flow charts are based on a total biomass input of 1.000 kg to allow for easier comparison of the nutrient flows in the three cases. However, to see the real effect on the nutrient flows in case 3 the maize silage should have been added to the 1.000 kg of slurry since the pig production is assumed to be the same as in case 1 and 2. This results in a larger total amount of digestate being produced and more organic bound N spread on the fields of the pig farm in case 3. To illustrate this situation an example is presented in the following. For a pig farm producing 10.000 tons of slurry per year the following total amounts of nutrients will be applied to the fields of the farm:

Case 2 (pig slurry used as the only substrate for biogas production):

- 3.600 kg organic N (10.000 * 0,36 kg)
- 2.000 kg of P (10.000 * 0,20 kg)

Case 3 (maize silage added to the pig slurry for increased biogas production):

- 5.793 kg organic N ((1.000 / 794) * 10.000 kg * 0,46 kg)
- 2.267 kg P ((1.000 / 794) * 10.000 * 0,18)

Table H-1 sums up the most important points concerning nutrient flows resulting from anaerobic digestion combined with post-separation of the digestate.

Table H-1. Nutrient amounts applied to the fields of the pig farm in each of the three cases according to model calculations. Case 1 and 2 are based on 1.000 kg of pig slurry whereas case 3 is based on a mixture of pig slurry and maize silage.

Case no.	Nutrient amounts from pig slurry	Nutrient amounts from maize silage	Nutrients to the fields of the pig farm*	Nutrients exported to other farms
1	4,1 kg Tot. N -Org. N: 1,5 kg -Min. N: 2,6 kg 1,1 kg P		4,0 Kg Tot. N -Org. N: 1,5 kg -Min. N: 2,5 kg 1,1 kg P	
2	4,1 kg Tot. N -Org. N: 1,5 kg -Min. N: 2,6 kg 1,1 kg P		3,25 kg Tot. N -Org. N: 0,36 kg -Min. N: 2,89 kg 0,2 kg P	0,74 kg Tot. N -Org. N: 0,32 kg -Min. N: 0,42 kg 0,9 kg P
3	3,26 kg Tot. N -Org. N: 1,19 kg -Min. N: 2,07 kg 0,87 kg P	0,86 kg N- Tot - Org. N: 0,73 kg - Min. N: 0,13 kg 0,15 kg P	3,27 Kg Tot. N -Org. N: 0,46 kg -Min. N: 2,81 kg 0,18 kg P	0,74 kg Tot. N -Org. N: 0,41 kg -Min. N: 0,33 kg 0,85 kg P

From table H-1 it is concluded that in order to minimize the amount of organic bound N applied to the fields of the pig farm the slurry should be treated according to case 2.

General comments on the use of additional substrates for biogas production

When pig manure is handled as slurry it is often difficult to make biogas production profitable based on this single substrate alone. The reason is the relatively low methane yield per ton of slurry, which is caused by a low content of organic matter in pig slurry (commonly around 4 % VS). One way of increasing the methane yield and biogas plant profitability is to add co-substrates to the slurry and thereby increase the content of organic matter in the substrate-mix fed into the digester. Co-substrates can also be relevant as a way to achieve a better C:N ratio and to minimize inhibition of the biogas process caused by high N-concentrations in manure based digesters.

However, adding co-substrates to the pig slurry will increase the amount of digestate produced and potentially increase the amount of N and P to be handled after the anaerobic digestion. As a result there is a risk that adding co-substrates will result in increased amounts of N and P led to the recipients as illustrated in case 3 above where maize silage is added to the pig slurry. The effect of using co-substrates on the N and P load to the Baltic Sea depends on the type and the amount of co-substrate used among other things.

To minimize increased N and P losses co-substrates with a low content of N and P should be preferred and glycerol ($C_3H_8O_3$) is an example of such a co-substrate. However, there are other relevant industrial waste products (e.g. from the food industry) with high energy potential and a low N and P content. The challenge is that such substrates can be scarce or expensive. Whether the use of industrial waste products can improve the profitability of the biogas plant depends on the price paid by the biogas plant owner to get access to these additional substrates.

Solid manure and deep litter from production of poultry, cattle and pigs are relevant co-substrates to be used together with pig slurry for biogas production. Also solid fraction from separation of pig or cattle slurry can be used as co-substrate to increase the dry matter content in pig slurry based biogas plants. The use of these substrates will increase the amount of digestate produced at the biogas plant and increased amounts of N and P needs to be handled. On the other hand, the use of solid manure from other farms as a co-substrate will have a positive effect on the N balances of these manure supplier farms. It can be organized so that these farms deliver the solid manure with a relatively high content of organic bound N to the biogas plant. In return these farms receive digestate or liquid fraction from separation of digestate containing the same amount of total N but with a lower content of organic bound N. The total effect of such a biogas plant importing solid manure from surrounding farms to be used as a co-substrate may be a reduced N load to the Baltic Sea.

In some countries energy crops (e.g. maize silage, grass silage, sugar beet) are commonly used as main substrate or co-substrate for biogas production. Such substrates are characterized by high carbon content per ton of biomass and when used as a co-substrate in slurry based biogas plant they are useful to increase methane production of the plant. Energy crops can be produced by the farmers themselves making the biogas plant less dependent on external suppliers of co-substrates. Here it is assumed that the livestock production and the area used for fodder in a certain region is unaffected by the establishment of a biogas plant. In that case energy crops for biogas production are normally grown on fields that were previously used for crops (e.g. wheat, barley, rape etc.) to be sold from the farm. Replacing crops that were previously sold and nutrients consequently exported out of a certain area with crops used for biogas production within the area will result in a larger amount of nutrients to be handled within the area.

It follows from above that use of additional substrates must be preceded by a careful calculation of nutrient balances taking into account well defined system boundaries. Nutrient balances can be made on different levels. For instance, nutrient balances can be made at farm level or regional level. Nutrient balances can also be made for very large areas like for instance the whole Baltic Sea catchment area. Clearly, the higher the levels and the larger the area the more complex is the task of making the nutrient balances. To evaluate the effect on the N and P load to the Baltic Sea resulting from a new pig manure based biogas plant using co-substrates delivered by external suppliers it is not sufficient to make nutrient balances for the pig farm where the biogas plant is established. Nutrient balances have to be made for all suppliers of substrates within the catchment area and for all those receiving digestate or fractions from separation of digestate within the catchment area.

It is beyond the scope of this study to make actual nutrient balances but a few comments are made in the following. To improve the basis for making nutrient balances knowledge about the nutrient contents of the different manure types, digestate and fractions from separation of digestate is needed. Such knowledge can be made available for farmers and biogas plant owners through systematically sampling and analyzing different manure types at farm/biogas plant level or through establishment of general manure standards. This knowledge can be combined with implementation of fertilizer norms to facilitate calculations of the right dosages of manure or digestate in the field. The fertilizer norms reflect the estimated nutrients uptake from manure and digestate for each crop type.

One key factor that is important for biogas plants apart from biogas production is digestate handling. From an economical and efficiency point of view, it is important to maximize biogas production, using the available substrates efficiently. Location and size of the plant is in many cases a factor determined by this availability of substrates. Exporting solid fraction is a tool to balance the nutrient application to the need of the crops in areas with intensive pig production but if not handled correctly the solid fraction can cause problems on a larger regional scale depending on where it is utilized.

Annex I: Technologies for utilisation of produced biogas

I.1 Introduction

Biogas produced from organic waste digesters is a mixture of mainly methane (60 - 70 %), carbon dioxide (30 - 40 %) and nitrogen (<1 %) (Jönsson et al. 2003) but contains also small amounts of water, hydrogen sulphide (10-2.000 ppm), ammonia and small particles. It can be used as it is for heat production but other utilization either benefits (power production) or requires (fuel replacement, injection into gas net) higher quality. The utilization of biogas is governed by national frameworks like the tax system, subsidies, investment programmes, availability of gas and heat grids etc. (Persson et al. 2006).

Biogas can be converted to energy in several ways, directly in boilers for heating purposes or steam production, for combined heat and power production or it can be upgraded to biomethane and used as vehicle fuel or injected to gas network. In Germany most common way is combined heat and power generation but a great amount of heat in local units is not used. Only a small fraction of it is needed for the digestion process and other heating at the biogas plant. Biogas plants are usually far away both from industrial heat demand and existing district heating networks which restricts efficient utilization of the heat generated in power production.

In some countries, like Sweden and Switzerland, a growing proportion of the biogas is used as vehicle fuel (Persson et al 2006). To replace fuel, high requirements are to be met and in addition to water, hydrogen sulphide and particles must be removed. The concentration of methane is raised to 95-99 % by removing the carbon dioxide in biogas. The biogas is converted to biomethane.

Depending on the quality of the upgraded biogas and the national requirements, biomethane can be injected in existing natural gas grid. There are several incentives for using the gas network for distribution of biomethane. One important advantage is that the grid connects the production site with more densely populated areas which enables the gas to reach new customers. It is also possible to increase the production at a remote site and still use 100% of the gas (Persson et al., 2006).

I.2 Power production

There are a number of different technologies for power or combined heat and power generation, like internal combustion, gas turbines and fuel cells.

I.2.1 Internal combustion

The most common technology for power generation is internal combustion. Engines are available in sizes from a few kilowatts up to several megawatts. Gas engines can either be otto-engines (spark ignition) or dual fuel engines. Otto-engines are equipped with normal ignition systems and a gas/air mixing system that provides a combustible mixture to the engine. Dual fuel engines with injection of diesel (10% and up) or sometimes plant oil are very popular in smaller scales because they have good electric efficiencies up to 43%. (Persson et al., 2006).

I.2.2 Gas turbines

Gas turbines are an established technology in sizes above 800 kW. In recent years also small scale engines, so called micro-turbines in the range of 25 to 100kW have been successfully introduced in biogas applications. They have efficiencies comparable to small otto-engines with low emissions and allow recovery of low pressure steam which is interesting for industrial applications. (Persson et al., 2006).

I.2.3 Fuel cells

Fuel cells have a potential to become the small scale power plant of the future. Fuel cell technology is old, more or less the same age as the combustion engine and the Stirling engine. Nevertheless, widespread commercial use is yet to be achieved. Fuel cells have a potential to reach very high efficiencies (>60%) and low emissions. (Persson et al., 2006).

I.3 Heat production

Biogas can be used for heating or for steam production in industrial applications, where the seasonal variation in heat demand is low. Heating greenhouses can bring extra value since the CO_2-content of the exhaust gases can be used to promote growth in greenhouse instead of buying it (Christensson et al., 2009).

Burning biogas in a boiler is well known and reliable technology. The requirements for gas quality are low but it is recommended to reduce the level of H_2S content below 1.000 ppm which allows to maintain the dew point around 150 °C (Persson et al., 2006).

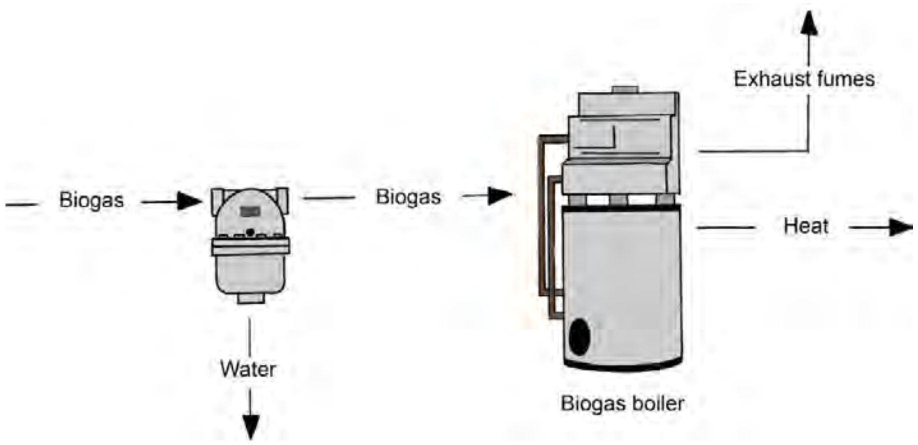


Figure I-1. Biogas used for heat production (based on Latvala, 2009).

I.4 Combined heat and power production

There are numerous techniques to convert biogas into electricity and heat. Most common are ordinary otto or diesel engines converted to use biogas. Other methods are gas turbines, micro turbines, stirling motors and fuel cells.

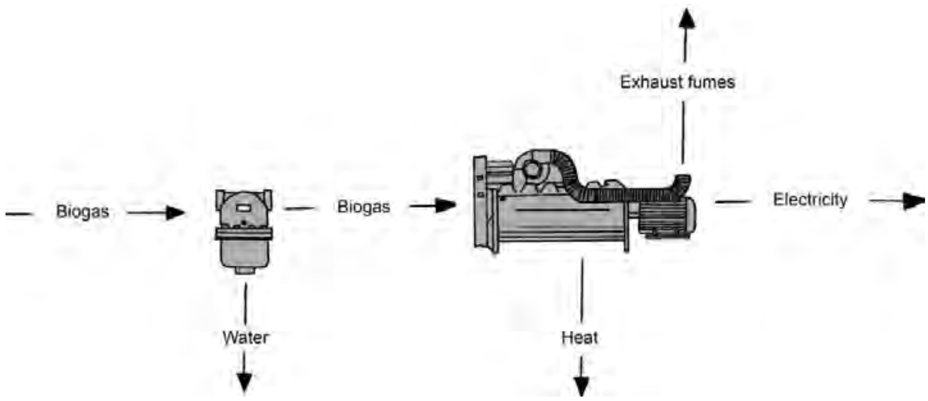


Figure I-2. Combined heat and power generation (CHP) using biogas (based on Latvala, 2009).

I.4.1 Otto and diesel engines adapted for biogas

In an otto-engine (gas or gasoline) air and fuel are mixed before entering engine cylinders where the mixture is fired by spark plugs. In diesel engines converted to biogas the fuel-air mixing is basically similar to otto-engines. Since biogas does ignite by the cylinder compression unlike diesel fuel, a small amount of diesel is used to ignite the mixture (a dual fuel engine). Another way is to add an ignition system with spark plugs etc. to a diesel engine.

Usually with diesel engines 35- 45 % of the energy content of the fuel can be converted into electricity, depending on the size of the unit. In comparison with similar size the efficiency of otto-engines is in general lower, about 27-38 % (Figure I-3). With both engines the efficiency increases with the size and since the rest of fuel´s energy content is converted into heat (radiation, coolant, exhaust gases), more electricity means less heat (Figure I-4).

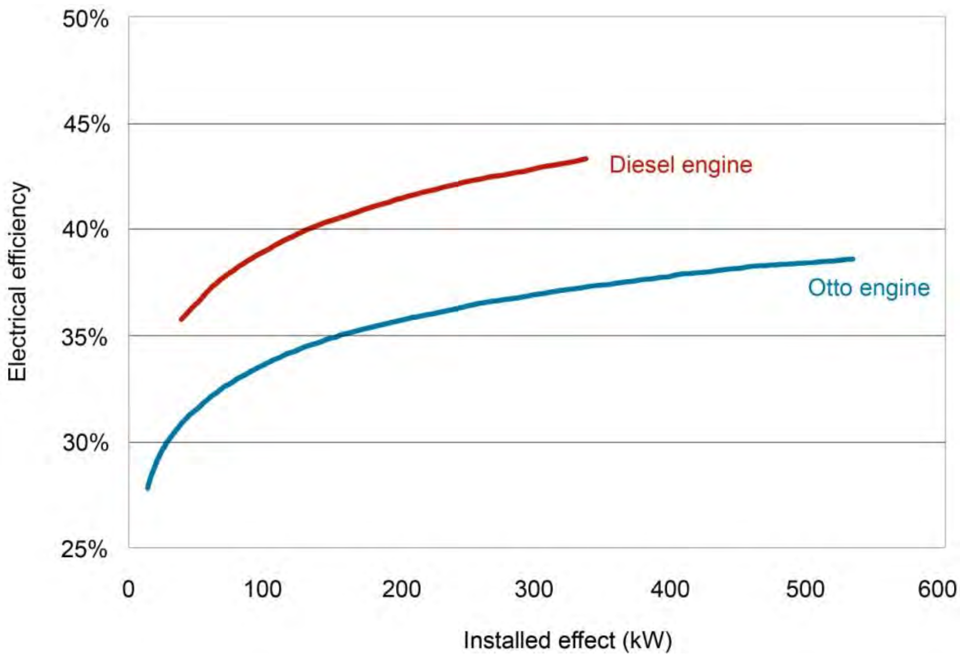


Figure I-3. Efficiencies of otto- and diesel-engines in power production (based on Christensson et al. 2009)

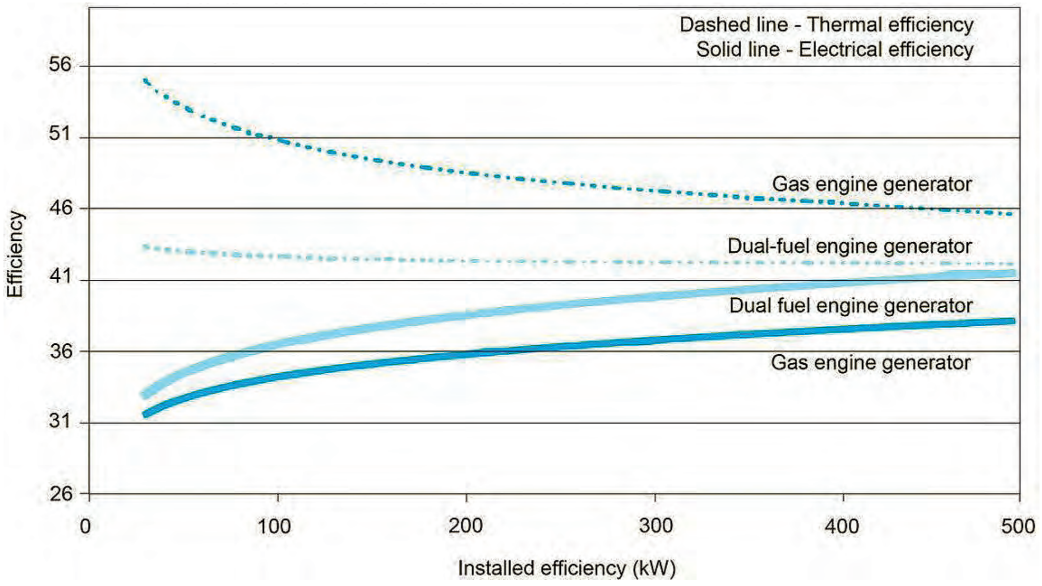


Figure I-4. Thermal and electrical efficiences of dual-fuel and gas engine generators (based on Eder & Schulz, 2006).

Table I-1. Comparison of engine types running on biogas.

Dual fuel diesel engines	Gas engines
Pros	**Pros**
- electrical effiency 30-40 % - also available in size less than 100 kW - robust to gas quality - economical	- electrical efficiency 34-40 % from 300 kW - long lifetime (60.000 h) - low service demand
Cons	**Cons**
- ignition fuel needed (diesel fuel) - clogging of injection nozzles - soot on heat exchange surfaces - higher service demand - usually smaller than 500 kW - shorter lifetime (35.000 h)	- usually bigger than 100 kW - requires at least 45 % methane content - expensive - low electrical efficiency below 300 kW

Source: (Eder & Schulz, 2006).

I.4.2 Gas turbines, micro turbines

In a gas turbine compressed fuel-air mixture burns continuously and the velocity of the exhaust gases rotate a turbine which is connected to a generator producing electricity (Figure I-5). Electrical efficiency is usually somewhat lower than in otto- or diesel engines (Christensson et al. 2009), e.g. Capstone states 26 % electrical efficiencies for their micro turbines and 33 % for their 1.000 kW unit (www.capstoneturbine.com). In small units, micro turbines, hot exhaust gases can be used for heating and in big units exhaust gases can generate steam which can rotate a turbine generating power.

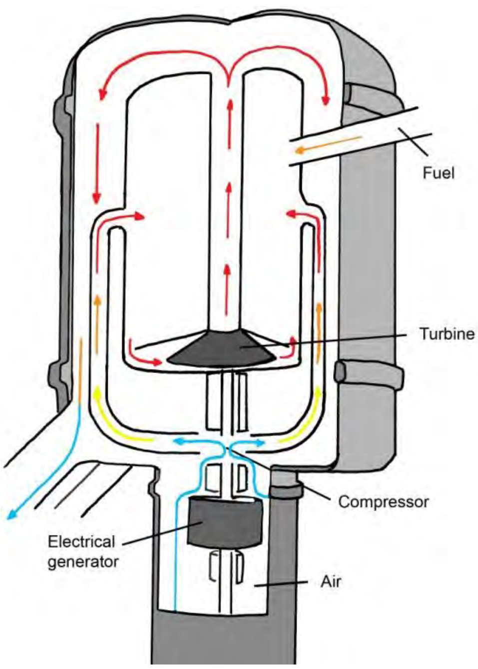


Figure I-5. Microturbine (based on www.wbdg.org/images/microturbines_2.jpg)

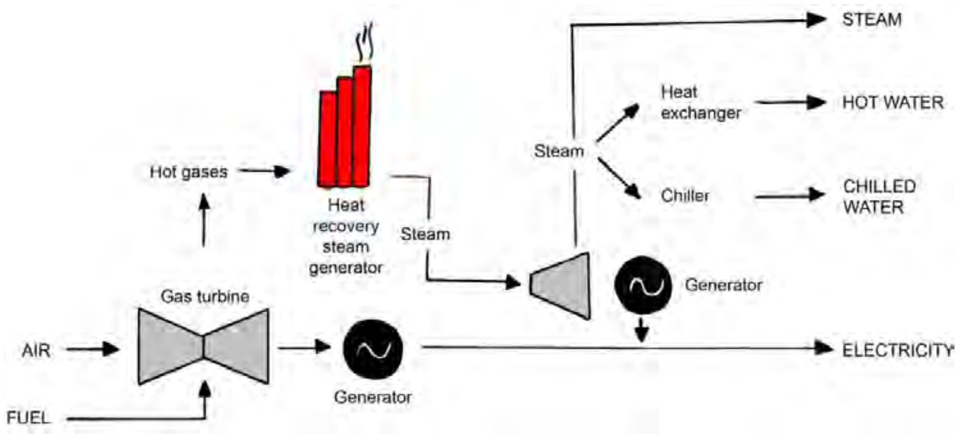


Figure I-6. Gasturbine (based on www.combinedheatandpower.net)

I.4.3 Stirling motors

In addition to internal combustion engines, also external combustion engines can be used to convert the energy of biogas to power and heat. Since the combustion takes place outside the engine and combustion products do not come into contact with the internal parts of the engine, almost any kind of fuel can be used as heat source. In comparison to internal combustion engine, stirling engine is quieter, and more reliable with less need for maintenance.

In a stirling engine external heat source heats the internal working fluid, gas. The expansion of the gas is converted to mechanical work which can be used to run a generator for example. A stirling engine encloses a fixed quantity of permanently gaseous fluid that never leaves the engine. The cycle consists of compressing cool gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle.

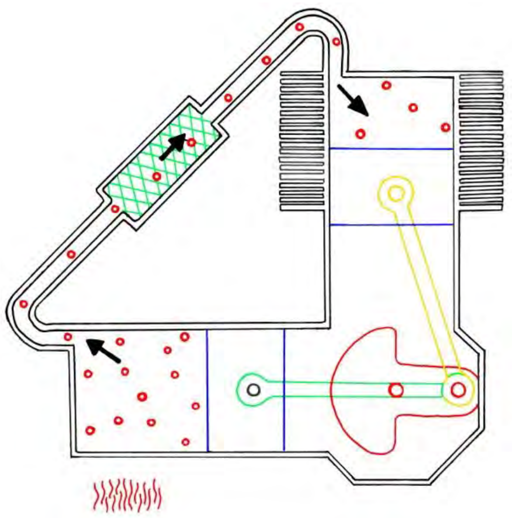


Figure I-7. Schematic construction of an alpha sterling containing two pistons, one hot and one cold and a regenerator in the connecting pipe.

The thermal efficiency of stirling cycle/engine depends on the temperature difference, with a large difference it can be as high as 40 % but due to material and design limitations efficiencies are usually lower (http://www.bekkoame.ne.jp/~khirata/academic/kiriki/begin/general.html).

Stirling engines are suitable for applications where the cost per unit energy generated is more important than the capital cost per unit power. On this basis, Stirling engines are cost competitive up to about 100 kW (www.localpower.org/deb_tech_se.html).

I.4.4 Organic ranking cycle (ORC)

For biogas plants it can be difficult to get full advantage of heat produced all year around. Recovering the waste heat in such cases can increase the electricity generation further. Use of external combustion engines like stirling motors or organic ranking cycle technology (ORC) are ways to do it.

The Organic Rankine Cycle works as a steam turbine installation using an organic matter instead of water as working fluid. This is because it suits the low temperatures and the scale size of the installation better. The heat source can be a motor's exhaust pipe, waste heat from an industrial process or the burning of bio fuel, flare gas or other (waste) matter (www.triogen.nl/en/technology/orc-principle).

The working fluid is expanded in a turbine in the form of overheated vapour under high pressure (Figure I-8). The pressure then drops and power is delivered to the High Speed Generator. The expanded vapour still has usable heat that is supplied to the cold working fluid in the recuperator (heat exchanger). Afterwards the vapour is condensed in the condenser and the fluid is pressurized to the required high pressure. The liquid is then warmed in the already mentioned recuperator and then vaporized and overheated in the Boiler. The Boiler is heated by the external heat that the ORC converts to electricity.

ORC technology can be used to convert some of the heat energy from the exhaust gas and cooling water in power generation (Figure I-9). GE Jenbacher has developed a consept that uses both heat sources in a cascaded system with two different working fluids. An additional electricity yield of 6 % was demonstrated in a long-term test. (http://ec.europa.eu/energy/renewables/bioenergy/doc/anaerobic/d21.pdf)

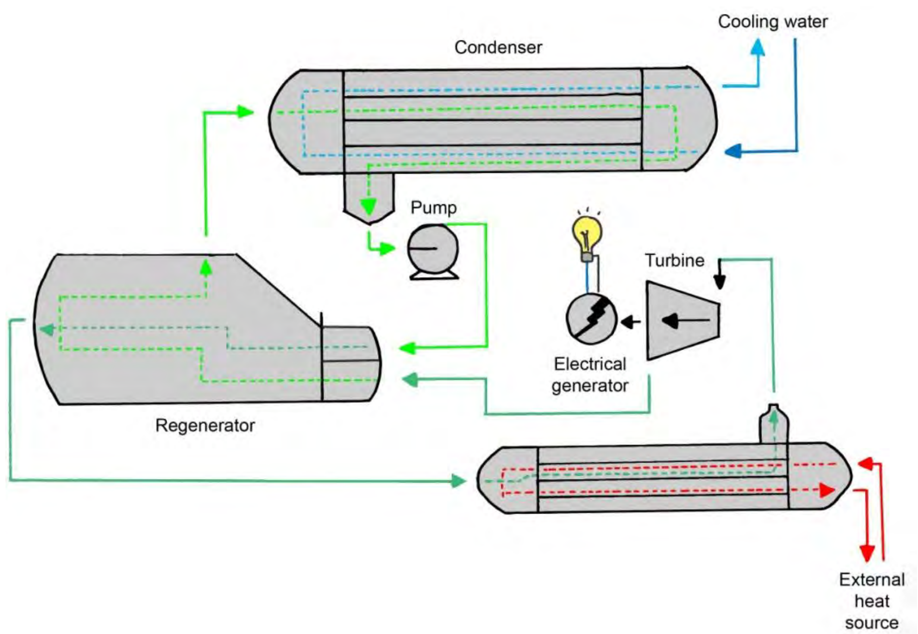


Figure I-8. ORC process flow diagram (based on www.3me.tudelft.nl).

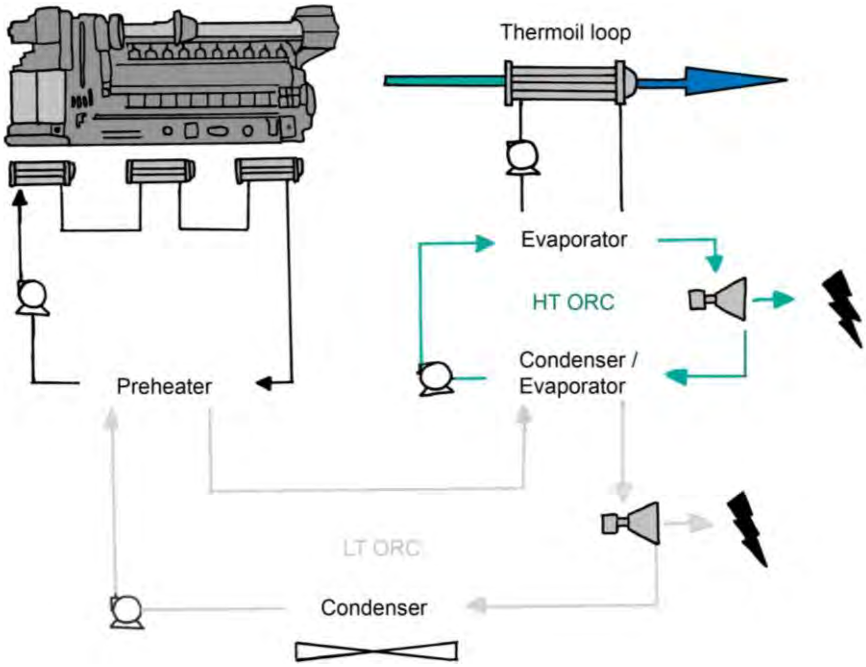


Figure I-9. A cascaded organic ranking cycle –system developed by GE Jenbacher utilizing cooling water and exhaust gas energy to produce electricity (based on http://ec.europa.eu/energy/renewables/bioenergy/doc/anaerobic/d21.pdf).

I.5 Biogas upgrading to biomethane

I.5.1 Objectives of upgrading and biomethane requirements

Biogas for vehicles replacing diesel or gasoline

Raw biogas must be upgraded before it can be used as transport fuel. Upgraded biogas can also be fed into a natural gas network (Persson et al., 2006). There is an international standard for the use of natural gas as transport fuel: ISO 15403 "Natural Gas –Designation of the quality of natural gas for use as a compressed fuel for vehicles" but there is so far no common standard for the use of biogas in vehicles. Biogas is widely used as transport fuel in Sweden, and a quality standard for vehicle use of biogas has been issued. This standard also applies to the feeding of biogas into a natural gas network (Petersson and Wellinger 2009).

In Europe, it has been possible to feed biogas into natural gas networks since the Gas Market Directive entered into force in 2003. The purpose of the Directive is to guarantee all gas producers equal rights to distribution and particularly to facilitate the market entry of small producers investing in renewable energy. Under the Directive, biogas may be fed into a natural gas network if it fulfils the specified quality, technical and safety requirements (Directive 2003/55/EC). In practice, this means that the biogas must be purified of carbon dioxide and any harmful substances.

Feeding biogas into a natural gas network is advantageous when biogas is used as a transport fuel. Distributing biogas through a natural gas network makes it possible to exploit the available production capacity fully. Also, the distribution infrastructure for biogas can be expanded more quickly if natural gas filling stations are also used for biogas. Moreover, natural gas can initially be used alongside biogas to ensure continued availability of fuel for gas-powered vehicles.

Injection into gas network

There are national standards for feeding biogas into natural gas networks for example in France, Switzerland and Germany (Table I-2). France and Germany have set separate quality requirements for lower quality L-biogas and for higher quality H-biogas. There are also two standards in place in Switzerland: one for limited feeding of biogas into a natural gas network (A in the table) and the other for unlimited feeding (B in the table). The quality requirements for unlimited feeding are stricter to prevent depletion of the energy content of the gas in the network.

The composition of gas mixtures can be compared by the Wobbe number ($W_{lower,}$ W_{upper}), which is defined by the calorific value divided by the square root from the relative density. Gases or gas mixtures that have the same wobbe number will have the same combustion properties.

Table I-2. Quality requirements in certain countries for the use of biogas as a transport fuel and for feeding biogas into a natural gas grid.

Parameter	Unit	Sweden	Switzer-land		Germany		France		USA (California)
			A	B	L	H	L	H	
Wobbe number lower	MJ/Nm^3	43,9-47,3	-		-		-		-
Wobbe number upper	MJ/Nm^3	-	-		37,8-46,8	46,1-56,5	42,48-46,8	48,24-56,52	-
CH_4	Vol-%	95-99	>50	>96	-		-		min 88
CO_2	Vol-%	-	<6		<6		<2		max 1
O_2	Vol-%	-	<0,5		<3		-		-
	ppm_v	-	-		-		<100		-
H	Vol-%	-	<5		-		<6		-
H_2O	mg/Nm^3	<32	-		-		-		-
$CO_2+O_2+N_2$	Vol-%	<5	-		-		-		1,5-4,5
Dew point	°C	<t[1]-5			<t[2]		<-5		-
Relative humidity	Phi	-	<60 %		-		-		-
S	mg/Nm^3	<23	<30		<30		<100[3] <75[4]		-
	ppm	-	-		-		-		16
H_2S	mg/Nm^3	-	<5		-		-		-
Nitrogen compounds (NH_3)	mg/Nm^3	<20	-		-		-		-

Particles, diameter max	µm	<1	-	-	-	-
Dust	mg/Nm^3	-	-	-	<5	-
Hg	mg/Nm^3	-	-	-	<10[5]	-
					<50[6]	
Cl	mg/Nm^3	-	-	-	<1	-
F	mg/Nm^3	-	-	-	<10	-
CO	Vol-%	-	-	-	<2	-

[1] Ambient temperature, [2] Ground temperature, [3] Single level, [4] Average level, [5] Natural gas, [6] Liquid natural gas. Sources: (Rutledge 2005, Persson et al. 2006, Petersson & Wellinger 2009).

I.5.2 Upgrading methods

In practice upgrading of biogas means extraction at least of carbon dioxide, hydrogen sulphide, ammonia, particles and water, or their reduction to acceptable levels. Biogas upgrading is usually carried out in two stages. The main emphasis is on carbon dioxide removal, which usually also removes other impurities (NSCA 2006). It can be advantageous to clean the biogas before upgrading it to prevent corrosion and mechanical wear of the upgrading equipment (Petersson & Wellinger, 2009).

The most widely used technologies for biogas upgrading are pressure swing adsorption (PSA), water scrubbing, organic physical scrubbing and chemical scrubbing (Figure I-10). Their characteristics are shown in Table I-3.

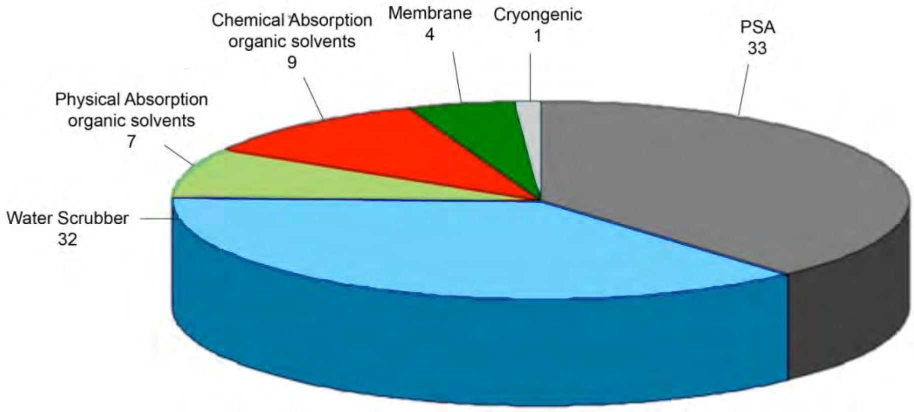


Figure I-10. Number of biogas upgrading plants in Europe (based on Beil, 2010).

Table I-3. Comparison of selected parameters for common upgrading processes (Urban et al. 2009).

Parameter	PSA	Water scrubbing	Organic physical scrubbing	Chemical scrubbing
Pre-cleaning needed [1)]	Yes	No	No	Yes
Working pressure (bar)	4 -7	4 – 7	4 – 7	No pressure
Methane loss[2)]	< 3 % / 6-10 % [3)]	<1 % / < 2 % [4)]	2 – 4 %	< 0,1 %
Methane content in upgraded gas[5)]	> 96 %	> 97 %	> 96 %	> 99 %
Electricity consumption (kWh/Nm^3_{biogas}, compressed in 7 bar)	0,25	< 0,25	0,24 – 0,33	< 0.15
Heat requirement (°C)	No	No	55 -80	160
Controllability compared to nominal load	+/- 10 – 15 %	50 – 100 %	10 – 100 %	50 – 100 %
References	> 20	> 20	2	3

[1)]Refers to raw biogas with less than 500 mg/m^3 of H_2S. For higher concentrations, pre-cleaning is recommended also for the other techniques
[2)]The methane loss is dependent on operating conditions
[3)]CarboTech < 3%, QuestAir 6-10 %
[4)]Malmberg < 1 %, Flotech < 2 %
[5)]The quality of biomethane is a function of operational parameters

The best technology to a certain plant depends on the plant-specific parameters, such as the availability of cheap heat and the electricity price (Petersson & Wellinger, 2009). Some methane is lost in the upgrading process. Technologies to prevent methane slip to the atmosphere are reviewed in section I.6.

Adsorption

Adsorption is the adhesion of atoms, ions, biomolecules or molecules of gas, liquid, or dissolved solids to a surface. This process creates a film of the adsorbate (the molecules or atoms being accumulated) on the surface of the adsorbent.

PSA (Pressure Swing Adsorption)

With this technique, carbon dioxide is separated from the biogas by adsorption on an activated carbon and/or zeolite surface under pressure (4-7 bar). The adsorbing material is regenerated by a sequential decrease in pressure before the column is loaded again. A PSA upgrading plant has usually four, six or nine vessels working parallel so that as the adsorbing material in one vessel becomes saturated the raw gas flow is switched to another vessel in which the adsorbing material has been regenerated. Regeneration of the saturated vessel is done by stepwise depressurization. The desorbing gas from the first and second pressure drop will contain some methane and may be returned to the inlet of raw gas. The gas from following pressure drops is led to next column or if it is almost methane free it can be released to the atmosphere (Petersson & Wellinger 2009).

Raising the quality of the upgraded gas (methane content) leads to increasing methane losses, and wice versa, unless more adsorbers are used. Some suppliers concentrate on minimizing the losses (< 2 %, Schmack CARBOTECH GmbH, Cirmac) while other emphasize gas quality (QuestAir Technologies). In the latter case the waste gas contains enough methane to be burned as it is and utilize the produced heat. (Urban et al. 2009))

The PSA-process requires water and hydrogen sulphide free gas since latter is irreversibly adsorbed and water can destroy the structure of the adsorbing material. Hydrogen sulfide is removed in a tank containing activated carbon which is changed after it is saturated. Water vapour is usually condensed in a cooler.

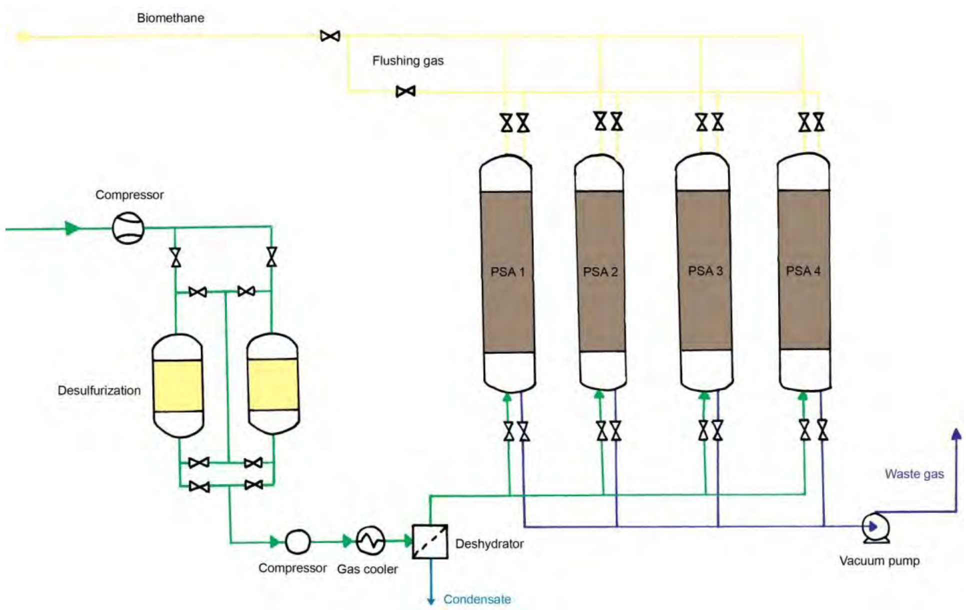


Figure I-11. Schematic view of pressure swing adsorption (PSA) system (based on Beil, 2010).

Absorption

In absorption the pollutants from the gas stream are dissolved into a liquid since carbon dioxide dissolves easier than methane. The most common solvent used in biogas upgrading prosesses is water (Rasi 2009). Other commonly used solvents are polyethylene glycol and alkanol amides, which are more efficient in absorbing carbon dioxide and hydrogen sulphite but more expensive than water.

The solubility of gases depends on factors such as pressure, temperature, liquid/gas ratio etc. There are different absorber designs but it is common to all to increase the contact area between the liquid and gas phases.

Water scrubbing

A water scrubbing system consists of a scrubber column, a flash tank and a stripper column (Figure I-12). Biogas is compressed and fed into the bottom of scrubber column, filled with packings to increase the contact surface. In the column biogas meets a counter flow of water and carbon dioxide is dissolved in the water, while the methane concentration in the gas phase increases. The water saturated, enriched biogas, is brought out from the column top and lead to gas drying system.

The water leaving the absorption column is transferred to a flash tank where the pressure is reduced and most of the dissolved gases are released. It contains mainly carbon dioxide but some methane, and it is led back to the raw gas inlet. The water can be recycled by transferring it to a desorption column filled with plastic packing. There it meets a counter flow of air, into which carbon dioxide is released. The water is cooled down to achieve the large difference in solubility between methane and carbon dioxide before it is recycled back to the absorption column (Petersson & Wellinger, 2009; Persson et al., 2006).

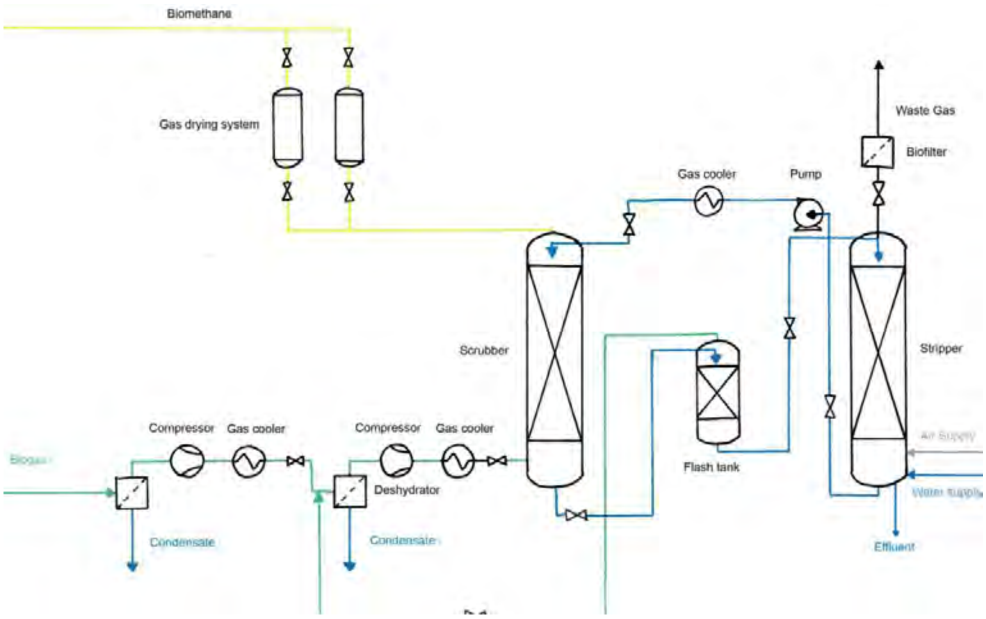


Figure I-12. Water scrubbing of biogas with recycling (based on Beil, 2010).

Table I-3. Examples of suppliers of water scrubbing technologies.

Company	Website
Flotech Sweden AB	www.flotech.com
Malmberg Water	www.malmberg.se
Metener Oy	www.metener.fi
Biorega AB	
Biosling	www.biosling.se

Organic physical scrubbing

Instead of water an organic solvent like polyethylene glycol can be used for the absorption of carbon dioxide. Selexol® and Genosorb® are trade names for the chemicals. In this solvent, like in water, carbon dioxide and hydrogen sulphide are more soluble than methane and the process proceeds in the same way as water scrubbing with regeneration. The main difference to water is that carbon dioxide and hydrogen sulphide are far more soluble in organic solvents than in water. This can reduce the size of the upgrading plant. In the process also water, hydrogen sulphide, oxygen and nitrogen may be removed together with CO_2. However a lot of energy is needed to regenerate the organic solvent from hydrogen sulphide and therefore it is often better to separate the hydrogen sulphide prior to the absorption. (Persson et al. 2006)

Chemical scrubbing

Other organic solvents that can be used are alkanol amines like mono ethanol amine (MEA) or di-methyl ethanol amine (DMEA). The gas meets a counter-flow of liquid and the carbon dioxide reacts with the chemical at low pressure (Figure I-13). Carbon dioxide is not only absorbed in the liquid, but also reacts chemically with the amine in the liquid. Since the chemical reaction is strongly selective, the methane loss might be as low as <0.1%. The chemical is regenerated in a reverted reaction usually driven by heat and/or vacuum which is energy consuming. If hydrogen sulphide is present in the raw gas, it will be absorbed in the amine scrubber solution and higher temperatures will be needed for the regeneration. Therefore it is advisable to remove it before absorption in the amine scrubber (Persson et al. 2006; Petersson & Wellinger, 2009).

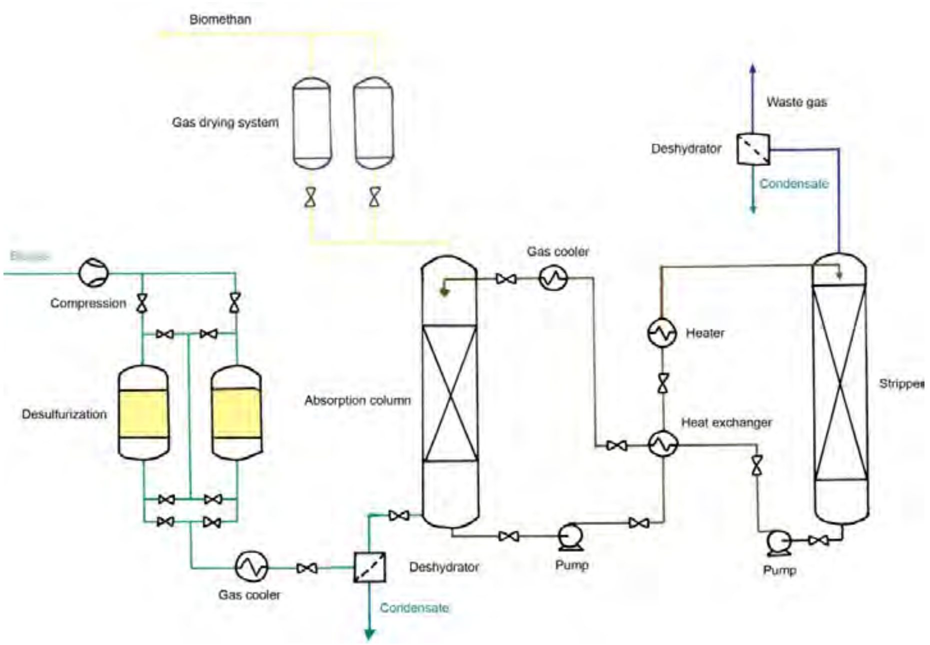


Figure I-13. Chemical scrubbing of biogas with recycling (based on Beil, 2010).

Membrane technology

There are different processes with membrane separation. Either it is a separation with a gas phase on both sides of the membrane or it is a gas-liquid absorption which means that a liquid absorbs the carbon dioxide diffusing through the membrane. The liquid can be an amine and the system has high selectivity compared to solid membrane systems. Separation takes place at low pressure, approximately atmospheric pressure.

Membranes with gas phases on both sides can also be called dry membranes. The separation is driven by the fact that different molecules of different size have different permeability through the membrane. Other important factors are the pressure difference between the two sides of the membrane and temperature of the gas. Carbon dioxide and hydrogen sulphide pass through the membrane to the permeate side whereas methane and nitrogen are retained on the inlet side.

The process is often performed in two stages. Before the gas enters the hollow fibres it passes through a filter that retains water and oil droplets and aerosols, which would otherwise negatively affect the membrane performance. Additionally, hydrogen sulphide is usually removed by cleaning with activated carbon before the membrane. Further separation of hydrogen sulphide is needed before the biogas can be used for vehicles or fed into the gas grid. (Persson et al. 2006).

High levels of methane in the upgraded gas can be achieved with larger size or several membranes in series. However, this leads to high losses of methane into the permeate stream since some methane passes through the membrane. If the permeate stream can be used for instance in a combined heat and power plant together with raw gas or in a flox burner, it is possible to utilise the lost methane and at the same time reduce cost for investment and energy consumption for the upgrading. The early designs operating at elevated pressures (up to 30 bars) suffered from considerable methane losses (up to 25%). Newer designs operate around 8 bars with far lower methane losses (Petersson & Wellinger, 2009).

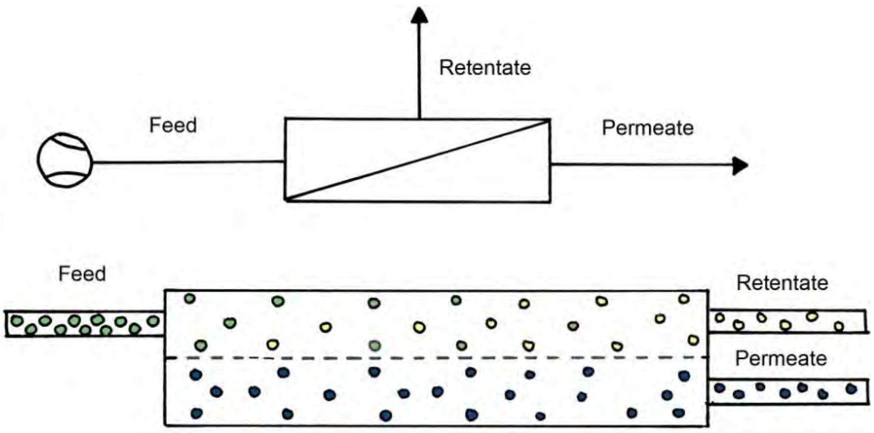


Figure I-14. Membrane separation (based on Beil, 2010).

Cryoprocesses

Methane has a boiling point of -160 °C at atmospheric pressure whereas carbon dioxide has a boiling point of -78 °C. Therefore carbon dioxide can be separated from the biogas as a liquid by cooling the gas mixture at elevated pressure. However the content of methane in the biogas affects the characteristics of the gas, i.e. higher pressures and/or lower temperatures are needed to condense or sublimate carbon dioxide when it is in a mixture with methane. Methane can be taken out in gas or liquid phase, depending on how the system is constructed. The separated carbon dioxide is clean and can be sold (Persson et al. 2006).

The raw biogas is cooled down to the temperatures where the carbon dioxide in the gas condenses or sublimates and can be separated as a liquid or a solid fraction, while methane accumulates in the gas phase. Water and siloxanes are also removed during cooling of the gas. The sublimation point of pure carbon dioxide is 194,65 K. Cooling usually takes place in several steps in order to remove the different gases in the biogas individually and to optimize the energy recovery. In the GPP® system (Figure I-15) biogas is first compressed to 17–26 bar and then cooled to -25°C. In this step water, hydrogen sulphide, sulphur dioxide, halogens and siloxanes are removed from the gas. The gas is then led through a coalescence filter and then through a SOXSIA® catalyst which removes any remaining contaminants. Carbon dioxide is removed in two further stages. In the first stage the gas is cooled down to between -50°C and -59°C where 30-40% of the carbon dioxide is removed as a liquid. In the second stage the remaining carbon dioxide is removed as a solid. Since the carbon dioxide is solid at this stage the process needs a second column, which is used while defrosting and removing carbon dioxide from the first column. Gastreatment Services B.V. is developing the GPP®plus system which in addition to upgrading biogas will produce liquid methane as an end-product. This system is in the research phase and a pilot plant has been in operation in the Netherlands since the beginning of 2009.

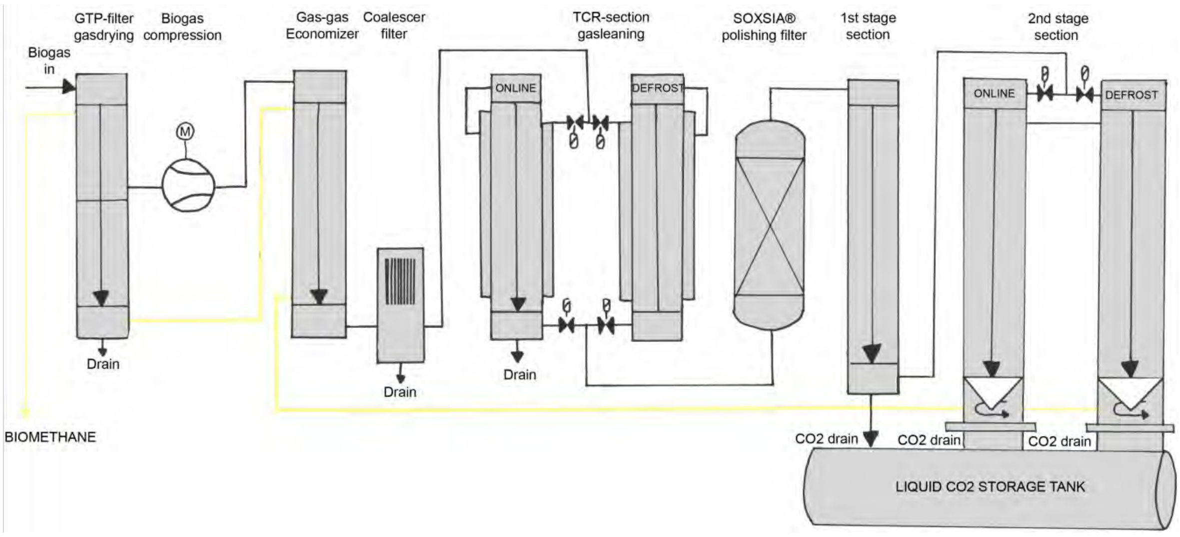


Figure I-15. Schematic view of cryogenic upgrading system (GPP® of Gastreatment Services).

In situ methane enrichment

Conventional techniques for separating carbon dioxide from biogas are usually suited for large plants in order to reach a sufficient economy. In-situ methane enrichment is a technology under development which promises a better economy also for smaller plants.

Process simulations have shown that it may be possible to reach a biogas quality of 95% methane with a methane loss below 2%. In experiments where different sludge and air flows were tested the highest methane content obtained was 87% with 2% nitrogen and a methane loss of 8% in the off-gas from the desorption column (Nordberg et al. 2005).

Cost estimations have shown that for a raw gas flow of below 100 Nm^3/h, the cost can be one third of the cost of conventional techniques. A pilot plant with a digester volume of 15 m^3 and a 140 dm^3 bubble column has been constructed and tested (Nordberg et al. 2005). In-situ methane enrichment will change the buffer capacity of the sludge, but results of the same study showed that desorption with air did not have a negative effect on the methane yield in the digester. The technology is relatively simple and there is no need for much auxiliary equipment such as pressurized tanks. However, the process is limited to smaller plants where a high methane concentration (>95%) is not needed. It is primarily suited for sludge that is easy to pump. If the technique is applied to a digester using fibrous substrates, the concentration of nitrogen might increase due to air bubbles attaching to the material when it passes through the desorption column.

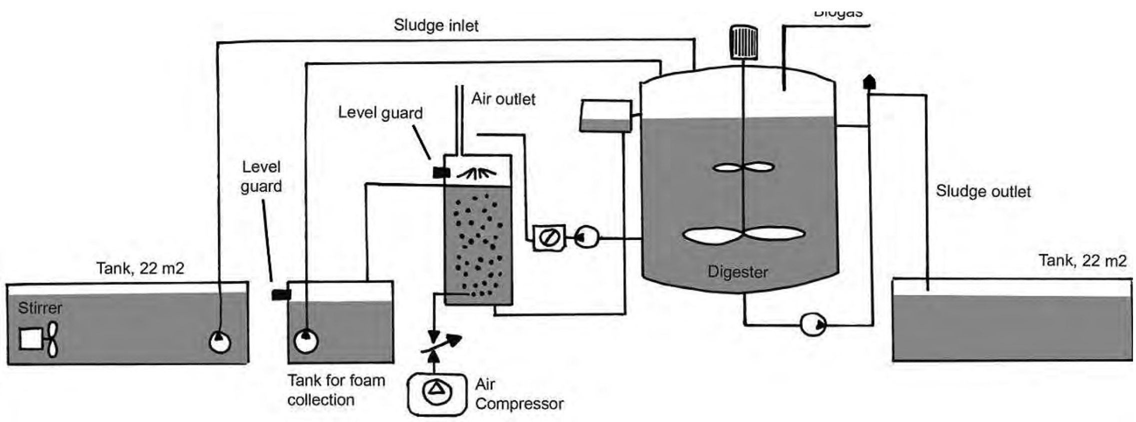


Figure I-16. Schematic view of in situ methane enrichment research plant by Åke Nordberg, SLU Sweden (based on Nordberg et al. 2005)

Ecological lung

The enzyme carboanhydrase is present in our blood where it catalyses the dissolution of carbon dioxide that is formed during metabolism in our cells. The enzyme catalyses the reaction:

$H_2O + CO_2 \leftrightarrow H^+ + HCO_3^-$

The dissolved carbon dioxide, in the form of carbonate, is then transported to our lungs where the same enzyme catalyses the reverse reaction where carbon dioxide and water is formed.

The enzyme can also be used to dissolve carbon dioxide from biogas and thereby remove it from the gas. The production cost of the enzyme is still high and the viability of the process is affected by factors such as the lifetime of immobilized enzyme. A research group in Lund, Sweden, has studied the use of the enzyme for biogas upgrading (Mattiasson, ref. (Benjaminsson 2006). In the same study it was shown that biogas can be purified up to a methane content of 99%. CO2 Solution Inc. is a Canadian company that has developed this technique and has a patent for a bioreactor using the enzyme for dissolving carbon dioxide.

I.6 Environmental effects

Burning biogas produces mainly CO_2, O_2 and H_2O and some environmentally harmful substances like CO, NO_x, SO_2 and formaldehyde. In Germany there are exhaust gas emission limits for different types and sizes of engines used for power generation (TA-Luft and Bundesimmisionsschutzverordnung). In order to fulfil these emission limits the engines are usually lean mixture engines with a λ-value from 1,2 to 1,6. This lowers the engine efficiency slightly compared to stoichiometric engines operating without air excess (Eder and Schulz 2006).

Within all upgrading systems some methane is lost which is both an environmental and an economical issue. Usually a 2 % loss is considered acceptable but some suppliers give figures less than 0,1 % (Christensson et al. 2009).

In the upgrading process methane can be lost in the off-gas leaving a PSA-column, in air from water scrubber with water recirculation or in water from a water scrubber without water recirculation (Petersson & Wellinger, 2009).

The off-gas seldom contains enough methane to maintain a flame without addition of natural gas or biogas. The off-gas can be mixed with air that is used for combustion. Methane can be oxidizied also by thermal or catalytic oxidation. The VOCSIDIZER from Megtec is an example of thermal oxidation. Once running, the heat generated by the oxidation is enough to maintain the function. In another thermal oxidation system, FLOX®-LCV from e-flox GmbH, the surplus heat in the exhaust gas after preheating of the off-gas is recovered with heat exchanger and used for heating purposes.

Methane can also be oxidized catalytically. The catalyst (platinum, palladium or cobolt) lowers the energy needed to oxidize the methane thus enabling reaction at a lower temperature (Petersson & Wellinger, 2009).

I.7 Energy balance

Efficiency of cogeneration can be defined in multiple ways (Eder & Schulz, 2006):

- mechanical efficiency: gives the relation between the mechanical energy produced and the energy content of the fuel used in an engine, depends on engine type and size, for dual-fuel and gas engines up to 45%
- generator efficiency: mechanical energy is converted to electricity, usually with an efficiency of 90 to 96 %, rest is converted to heat in the generator
- electrical efficiency: product of mechanical efficiency and generator efficiency
- thermal efficiency: gives the relation between the heat energy harvested (from exhaust gases and cooling water) and energy content of the fuel used in an engine
- overall efficiency: is the sum of electrical and thermal efficiency

Pöschl et al. (2010) evaluated the energy efficiency of different biogas systems in Germany. The energy balance was evaluated as Primary Energy Input to Output ratio (PEIO). The results show that the PEIO in biogas utilization pathways for small and large-scale plants typically ranged between 4,1– 45,6% and 1,3–34,1%, respectively (Figure I-17). The ranges of variation arise from the difference in efficiency of the respective energy conversion systems and substitution of different fossil fuels used in feedstock-to-biogas process. The range of variation in each case depicts the inherent potential for enhancing efficiency in biogas utilization. The proportion of energy input to biogas utilization ranged between 6,0% (Small scale – CHP) and 18,1% (Small scale – micro gas turbin + ext. heat), depending on process energy requirements and efficiency of different technologies.

These results suggest that the most energy efficient conversion pathway (lowest PEIO) for small-scale biogas plants is the Stirling engine with utilization of the generated heat (Base SS-e: 4,1%).

The utilization of waste heat for secondary electricity generation with ORC process recorded only a marginal gain in PEIO (43,7% versus 45,6%). Therefore, the ORC technology may only be recommended for systems that do not include heat applications in the vicinity of a biogas plant (Figure I-17). Available data also suggests that the most viable utilization pathway for small-scale biogas systems compared to Small scale - CHP is CHP generation with external heat utilization at relatively short transmission distance (approximately 2 km).

In large scale systems, the use of biomethane as transportation fuel represents an attractive utilization pathway with PEIO of 8.7% (Figure I-17). In preparation of biomethane for injection into natural gas network, the proportion of energy input for biogas plant operation increased by 22,9% compared to base case with 51.8% (large scale – CHP). This was attributed to digester heating demand, and feedstock sterilization and gas upgrade technology based on fossil fuels. With coupled small-scale CHP unit, where part of waste heat is used for heating the digester(s) instead of fossil fuels, the energy input for plant operation was almost halved to 38,8% compared to large scale – uprgrading and injection. Based on the outlined analyses, the most energy efficient conversion pathway for large scale biogas systems include: (i) upgrading of biogas specifically for gas grid injection, but using small-scale CHP to service process and biogas upgrading energy loads (estimated PEIO 1,3%) and (ii) fuel cell technology with heat utilization (estimated PEIO 6,1%).

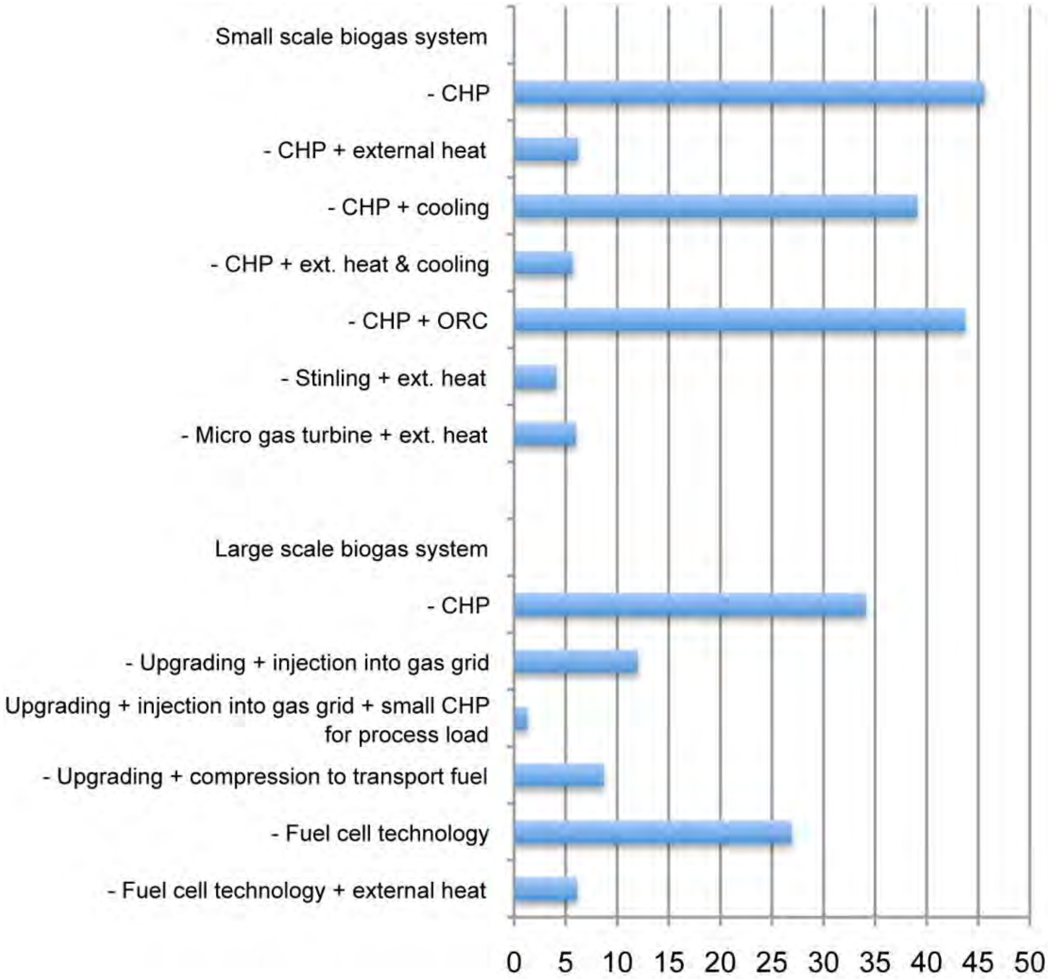


Figure I-17. The influence of different biogas utilization pathways on Primary Energy Input Output (PEIO) ratio (%) for small and large scale biogas systems (based on Pöschl et al. 2010), Small scale = kW_{el} <500 kW, Large scale = kW_{el} > 500 kW.

Table I-4. Energy efficiencies related to transmission of heat, CHP and biogas upgrading (Pöschl et al. 2010).

	Estimated loss by transmission distance, %			
	0,5 km	2 km	3 km	5 km
Small-scale biogas plants	3,5	13,5	20	32
Large-scale biogas plants	1	4	6	10

	Efficiency and electricity input for CHP generation, %		
	CHP electrical efficiency	CHP thermal efficiency	Electricity input running CHP
Small-scale biogas plants	33	50	3
Large-scale biogas plants	40	48	4,5

	Energy input and heat demand for upgrading of biogas	
	(MJ m^{-3} $_{biogas}$)	(MJ t km^{-1})
Electricity input	1,1	
Heat demand	0,36	
Compression to 1,6 MPa	0,18	
Transmission of gas		0,2
Compression to 20 MPa	0,47	

I.8 Economy of upgrading biogas

Today, technological developments have led to cheaper and more efficient plants. The demand for more plants has also led to the development of standardized upgrading units which also decreases the costs.

Because the economy of scale, biogas upgrading takes only place in larger biogas units (Figure I-18 and Figure I-19). It is obvious that economical production requires large units even in future although smaller upgrading units are developed. However, biogas can be transported in a local gas net to a central upgrading unit instead of transporting the raw material into a large biogas plant (Christensson et al. 2009).

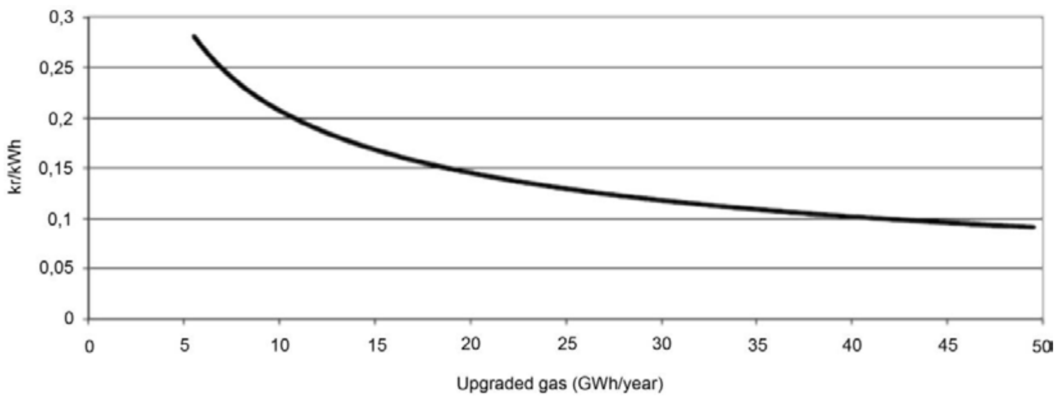


Figure I-18. The effect of volume on the upgrading cost of biogas (based on Christensson et al. 2009).

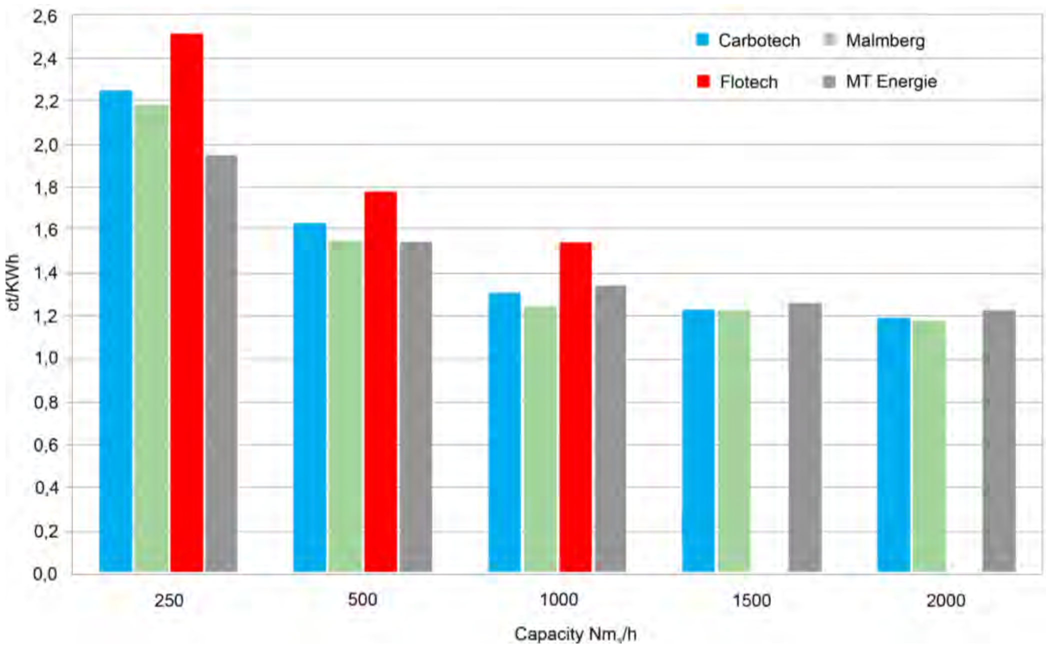


Figure I-19. Estimated costs of biogas upgrading using different technologies, (water scrubbing: Malmberg, Flotech; PSA: Carbotech; chemical scrubbing: MT Energie (based on Urban et al. 2009).

Annex J: Biogas stakeholders in selected Baltic Sea countries

In this Annex some of the organizations relevant for the development of the biogas production in the Baltic Sea Region are presented.

Table J-1. Universities and other knowledge institutions with biogas activities.

Sweden	JTI – Swedish Institute of Agricultural and Environmental Engineering SLU – Swedish Agricultural University Lund University Linköping University
Finland	MTT - Agrifood Research University of Eastern Finland Helsinki University Turku University VTT
Denmark	Aarhus University, Faculty of Agricultural Sciences Technological University of Denmark University of Southern Denmark University of Copenhagen, Life Sciences University of Aalborg Danish Technological Institute AgroTech Agro Food Park
Poland	Institute for Renewable Energy – EC BREC (www.ieo.pl) Virtual Institute of Sustainable Agriculture (www.ibmer.waw.pl/wirz/main.htm) Gdansk University of Technology Baltic Eco-Energy Cluster Biobaltica / POMCERT Institute for Buildings Mechanization and Electrification of Agriculture (IBMER)
Germany	Fachagentur für Nachwachsende Rohstoffe - FNR (http://www.fnr.de) Technologie-und Förderzentrum - TFZ (http://www.tfz.bayern.de) German Society for sustainable Biogas and Bioenergy Utilisation (http://www.gerbio.eu/) Ttz Bremerhaven – Environment (www.ttz-bremerhaven.de)

Table J-2. Ministries, public organizations and non-governmental organizations relevant for biogas production.

Sweden	Swedish Energy agency Swedish Environmental Protection Agency Survey Stat. Sweden Swedish Board of Agriculture (Jordbruksverket) County Boards (Länstyrelsen) Municipalities
Finland	Ministry of Agriculture and Forestry Ministry of Trade & Industry Ministry of Environment Evira – Food Authority Municipalities
Denmark	Ministry of Food and Agriculture Ministry of Environment Ministry for Energy & Climate Danish Energy Agency Danish Environmental Protection Agency The Municipal Biogas task force 98 municipalities
Poland	Ministry of Agriculture and Rural Development – MARD (www.minrol.gov.pl) Ministry of Regional Development – MRD (www.mrr.gov.pl) Agricultural Market Agency – ARR (www.arr.gov.pl) Agency for Restructuring and Modernization of Agriculture-ARMA (www.arimr.gov.pl) Polish Agency for Enterprise Development – PARP (www.parp.gov.pl) Energy Regulatory State Office –URE (www.ure.gov.pl) Energy Market Agency – ARE (www.are.waw.pl) National Centre for Agricultural Advisory – KCD (www.cdr.gov.pl) Regional Advisory Services Network – MODR (www.modr.mazowsze.pl) Polish Biogas Association – PBA (www.pba.org.pl) Federation of Scientific and Technical Organizations –FSNT-NOT (www.not.org.pl/not) Polish Biomass Association – POLBIOM (www.polbiom.pl)
Germany	Bundesverband Bioenergie e.V. - BBE (http://www.bioenergie.de) Bundesverbandes Erneuerbare Energie e.V. –BEE (http://www.bee-ev.de) Bundesverband der deutschen Gas- und Wasserwirtschaft–BNG (http://www.bgw.de) Centrales Agrar-Rohstoff-Marketing- und Entwicklungs-Netzwerk (http://www.carmen-ev.de) Fachverband Biogas e.V. (http://www.fachverband-biogas.de)

Table J-3 Examples of consultants and engineering companies with relevance for biogas production.

Sweden	WSP group Anox Kaldnes Swedish Biogas International Scandinavian Biogas Grontmij BioMil Ramböll Sweco Hushållnings-sällskapet HS
Finland	Watrec Jyväskyla Innovation Bionova Engineering Oy (www.bionova.fi) Bioste Oy (www.bioste.fi) Citec Engineering Oy Ab (www.citec.com) MK Protech Oy (www.mk-protech.fi) Watrec Oy (www.watrec.fi)
Denmark	Knowledge Centre for Agriculture Rambøll Cowi Niras PlanEnergy PlanAction
Poland	Biogaz Zeneris (www.biogaz.com.pl)
Germany	Elbe Bioenergie GbR (www.elbe-bioenergie.de)

Table J-4. Examples of technology suppliers relevant for the biogas sector.

Sweden	Götene Gårdsgas Läckeby Water Browik Elis Johansson smide Malmberg Biorega Artic Nova ITT Flygt
Finland	Alstom Finland Oy (www.alstom.com) AxFlow Oy (www.axflow.com) Biovakka Suomi Oy (www.biovakka.fi) Biower Oy (www.biower.com) GasPower Oy (www.gaspower.fi) Greenvironment Oy (www.greenvironment.com) MetaEnergia Oy (www.metaenergia.fi) Metener Oy (www.metener.fi) NHK-keskus Oy (www.nhk.fi) Preseco Oy (www.preseco.eu) Sarlin Oy Ab (www.sarlin.com) YIT Oyj (www.yit.fi)
Denmark	Xergi Bigadan BW Scandinavian Contractors Green Farm Energy Lundsby Biogas Gosmer Biogas Alfa Laval GEA Westfalia Pierlisi Agrometer SWEA Staring Purliq Hjortkjaer AL-2
Poland	Energa Bio Odys Shipyard Poldanor SA
Germany	EnviTec Biogas (www.envitec-biogas.de/en/home.html) Weltec Biopower (www.weltec-biopower.de) Biogas Nord (www.biogas-nord.com) Biomasse Energie GmbH (www.rottaler-modell.de) Smack Biogas (www.schmack-biogas.com)

Annex K: Relevant EU legislation, action plans and projects

Table K-1. EU legislation of relevance for implementation of improved manure management.

Document and reference (year)
Nitrate Directive
Industrial Emissions Directive (former Integrated Pollution Prevention Control (IPPC) Directive)
Water Framework Directive
Renewable Energy Directive

Table K-2 Political agreements, action plans and projects of relevance for implementation of biogas production based on pig manure.

Initiative
HELCOM Baltic Sea Action Plan
EU Baltic Sea Regional Strategy
Baltic Compass. 3-year project supported by EU under the Baltic Sea Region Programme 2007-2013
Baltic Deal. 3-year project supported by EU under the Baltic Sea Region Programme 2007-2013.
BATMAN
Baltic Biogas Bus (www.balticbiogasbus.eu). 3-year project supported by EU under the Baltic Sea Region Programme 2007-2013.
FARMAGAS (www.farmagas.eu). 2-year project supported by EU under the Intelligent Energy Europe Programme.
GasHighWay (www.gashighway.net)

Annex L: Country specific data of relevance for biogas production

This annex includes an overview of framework conditions, pig production, manure treatment technologies, digestate handling techniques, gas usage etc.

L.1 Tax, Taxation, regulation and incentives

L.1.1 Denmark

In Denmark, the biogas is mainly used for CHP, and this is reflected in the present regulations. New cooperative biogas plants can obtain 20% support for construction from the Rural Development programme in 2010-12 if they are based on > 75% manure.

The biogas used for CHP production is subsidized by:

- 0,104 EUR/kWh electricity if biogas is used alone (guaranteed minimum level). The price is regulated by 60% of price index.
- 0,056 EUR/kWh electricity added to market price of electricity if biogas is combined with other energy sources (e.g. natural gas). The price is regulated by 60% of price index.

In addition, the value of tax exemption (both CO_2 and energy tax) as compared with all fossil fuels can be calculated as a value/incentive of biogas.

However, in the future the option of upgrading biogas to the natural gas grid may become an option as the Government has decided to equalize the conditions for sale of biogas to CHP and gas grid. However, as of February 2011 this change has not yet been implemented.

L.1.2 Finland

Fuel tax is an excise tax that has to be paid normally for petrol, diesel and light and heavy fuel oils. Fuel tax consists of basic tax, supplementary tax and supply security fee. In Finland methane based transport fuels, including biogas, are free from fuel tax. However, like from all the other transport fuels, a value added tax (VAT) of 23 % has to be paid (Laki ajoneuvoverolain muuttamisesta 21.12.2007/1311, Nylund et al., 2009).

A new feed-in tariff for electricity generated with renewable energy sources (wind power, biogas and wood-based fuel) was approved in Finland on 30 December 2010 (MEEF, 2010). This concerns only electricity production. The notification procedure of state subsidies is still under way and once they are approved by the Commission of the European Union they will enter into force under a Government Degree. The target price for the feed-in tariff is 83,5 EUR/MWh. Additional support for electricity generated by biogas would be 50 EUR/MWh, provided the plant in question is involved in combined production of heat and electricity and its total efficiency is at least 50 per cent. The tariff would be paid for 12 years. The feed-in tariff would be financed by a fee to be levied directly on electricity consumers. The nominal output capacity of the generators of biogas plants included in the scheme should be at least 100 kVA (Laki uusiutuvilla energialähteillä tuotetun sähkön tuotantotuesta 30.12.2010/1396).

In the future the feed-in tariff will support production of electricity and heat in Finland, but biomethane production is not included to this support scheme. Since 2003 the gas vehicle taxation has been alike the taxation of fossil fuelled vehicles, and there has been no fuel tax for gaseous fuels. However, the fuel tax system is changing and the new model of biomethane taxation is not known yet.

The first – and only – biomethane filling station was opened to public in 2002 at the Kalmari farm. At the moment, there are total about 20 cars refuelling regularly on farm. At the moment there are 14 compressed natural gas (CNG) filling stations (12 owned by Gasum) in Finland and two stations are under construction. The aim is also to start to distribute biomethane on these filling stations in the near future. There are today 700 gas driven vehicles operating in Finland. (www.gashighway.net).The construction costs of renewable energy plants are co-financed by the government with grants of up to 30% (MEEF, 2010).

L.1.3 Germany

The impressing development in German biogas business in which more than 4.000 plants have now been installed derive from the 2004 legislation; Ernaubare Energien Gesetz. This legislation supports an increase in the utilization of crops and plant material for energy production (NAVARRO, nachwachsende rohstoffe). The system was initiated in consequence of the recognition that a major enlargement of biogas productions could not be based solely on manure and organic waste resources, of which the latter had become scarce. The idea was that a new development could be based mainly on corn silage, and the power prices, as a consequence, had to be high enough to allow procurement of large amounts of silage.

Table L-1 Overview of the structure and 2010 level of the German subsidy system.

German biogas power prices, 2010	Capacity class: kw electric installed			
EUROCENTS per kwh	<150 kw	150 - 500 kw	500 kw-5Mw	5 Mw-20Mw
Basic price	11,55	9,09	8,17	7,71
NAVARRO (Energy crops)	6,93	6,93	3,96	3,96
Slurry bonus (minimum 30 % slurry	3,96	0,99	0	0
Heat utilisation bonus (100 %)	2,97	2,97	2,97	2,97
Total	25,41	19,98	15,1	14,64
Actual price at 150, 500, 5000,10000 kw	25,41	21,609	15,75	15,20
Optional landscaping bonus (grass)	2,97	2,97		
Optional technology bonus 1)	1,98	1,98	1,98	1,98
1) Special requirements for energy efficiency				

Source: E-on/Avacon (www.eon-avacon.com).

Main configuration of the system is a distinction between capacity classes, of which the smaller ones are considerably favored. It seems there has been a political motivation to support small, on-farm installations. All categories receive a basic price, highest for the smaller plants. Then there is a bonus for the use of energy crops (presumably as an alternative to organic waste). The bonus is reduced for larger installations. This structure made it much more favorable to use energy crops than manure, and thus a special slurry bonus for smaller plant categories was later introduced. Also the focus on smaller plants made heat utilization difficult, and consequently a heat utilization bonus was introduced in order to encourage improved heat utilization. According to Henning Foged, CBMI, (Biogasproduktion I Tyskland), for example a 600 kW plant receives up to 25,4 eurocents for the production corresponding to 0-150 kW and up to 19,98 eurocents for the production corresponding to 150-500 kW and 15.1 for the production corresponding to 500-600 kW. So the actual price is slightly higher than the sum for each category.

In addition, smaller plants (0-500 kW) may optionally obtain a landscaping bonus if they use certain amounts of vegetation from extensive areas. Finally, all plants may receive a special technology bonus if certain requirements for energy efficiency can be met.

L.1.4 Poland

In 2006 there were about 150 biogas plants in Poland out of which only one agricultural (Roguslka & Kunikowski, 2009). By 2010 the number of agricultural based biogas plants had increased to 7 and 5 of them are owned by a company Poldanor S.A.

The Polish Policy for Renewable Energy from 2010 includes measures to achieve the EU target 20 % renewable energy sources by 2020 and is dedicated to create optimal conditions for the agricultural biogas production. The political objective is to have 2.000 biogas plants by 2020, one in each municipality.

The Polish government has initiated different support schemes for potential biogas plant investors. Investment support for building biogas plant is available from (Foged & Johnson, 2010b):

- The National Fund for Environmental Protection and water management which grants loans with low rent up to 75 % of the investment cost exceeding 10 million PLN
- The Bank of Environment Protection grants loans with subsidized interest rate
- The EU Regional Development Program supports installations for renewable energy sources, 40 % of verifiable cost

By 2010 there was no fixed minimum feed-in tariff for electricity produced out of biogas in Poland. Instead the price for the sold electricity consists of different components (Foged & Johnson, 2010b):

- a raw price received by the biogas plant is about 5 cents/kWh
- in addition the biogas plant can sell green certificates for 7 cents/kWh, and sometimes also red certificates for 2.5 cents/kWh.

Altogether, in 2010 a realistic price for the biogas based electricity delivered to the net is about 15 cents/kWh or more (Foged & Johnson, 2010b).

L.1.5 Sweden

In 2009 the biogas was utilized for heat (49%), upgraded for fuel or injection (36%) and for power generation (5%). As much as 10% was flared. In total, biogas and landfill gas was produced at 230 sites (Energimyndigheten, 2010).

In Sweden a farmer or rural entrepreneur can get a maximum investment subsidy of 30 % to produce, store and upgrade biogas. In the Northern part of Sweden the subsidy can be up to 50 %. The maximum value of the subsidy is limited to 200.000 € within a three year period.

Directly related consulting and other costs can also be included. The substrate should contain at least 50 % manure but other combinations can be allowed. The investment subsidy is provided by the Swedish Board of Agriculture.

(http://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Jordbruksstod/LSI14.pdf).

The price of the biogas based electricity is dictated by the Nordpool spot price and by the value Swedish electricity certificates. In 2010 the average spot price in Sweden was 53 €/MWh (www.nordpoolspot.com) and value of electricity certificates 26,7 €/MWh (calculated by Mats Edström from Tricorona monthly values), making a total of 7,7 €/MWh.

The reason why the trend of biogas utilisation is in favour of natural gas vehicles (NGV) applications rather than electricity generation depends on the characteristics of the Swedish energy utilisation. Swedish needs of heat and electricity are nowadays well covered by renewable and nuclear sources, instead of as before fossil oil. Thus, the national certificate system on renewable electricity in Sweden is a magnitude lower than the one in Germany, which specifically targets electricity production on farm-scale level from anaerobic digestion (Lantz et. al 2007), while the energy policy instruments in Sweden with regard to renewable energy are weaker and more general in character compared to the ones of for e.g. Denmark and Germany, leading to a situation where more ready-at-hand and cost efficient solutions such as centralized co-generation of heat and electricity from low-cost forestry residues are preferred compared to smaller scale biogas CHP applications with more limited profitability.

The main challenge in Sweden lies in the oil dependency of the transportation sector. Automotive fuel applications for renewables, such as biogas, therefore enjoy the benefits of several market incentives: considerable tax exemptions; reduced tax (40% less) for the use of bi-fuel passenger cars provided by the employer; free parking in some cities; and subsidies on a national and local level for investment in bi-fuel cars (Lantz et. al 2007, http://www.regeringen.se/sb/d/8827/a/79672). The national subsidy of 10.000 SEK (approximately 1.000 EUR) of eco-labelled cars will be terminated from 2010.

A new type of subsidy has been proposed, where all new eco-labelled cars are exempt of vehicle tax for a period of 5 years after purchase http://www.regeringen.se/sb/d/8827/a/79672). In addition to these benefits, the climate mitigation state programme funds in effect from the 90's and up to today have turned out to favour biogas projects in general, and projects related to biogas as vehicle fuel in particular.

Programme regulations gave preference to applications from municipalities and for them biogas offered a way to, in one move, get rid of waste of different kinds and reduce city centre air pollution and emissions of greenhouse gases (Lantz et. al 2007, Sandén & Jonasson 2005). The introduction of NGV buses in their captive fleets turned out to provide the necessary niche for the growth of the emerging market of gas powered vehicles in Sweden during the 90's, facilitating the later introduction of a larger and more diversified market (Sanden & Jonasson, 2005). In terms of volume, the captive bus fleets are still market leading, and the joint vision of the four largest regional government actors and the national association in eventually reaching 100%

renewability shows the necessity of providing more and more renewable methane in order to meet customer expectations.

L.2 Number of agricultural biogas plants

Table L-2. Number of agricultural biogas plants in operation by the end of 2010.

Country	Number of biogas plants in operation	Source
Sweden	28	Edström, 2010
Finland	9	Kuittinen et al. 2010
Estonia	1	Foged & Johnson, 2010a
Latvia	6	Foged & Johnson, 2010a
Lithuania	1	Foged & Johnson, 2010a
Poland	7	Wisniewski, 2010
Germany	Approximately 6.000	German Biogas Association, 2011
Denmark	85	Tafdrup, 2010

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